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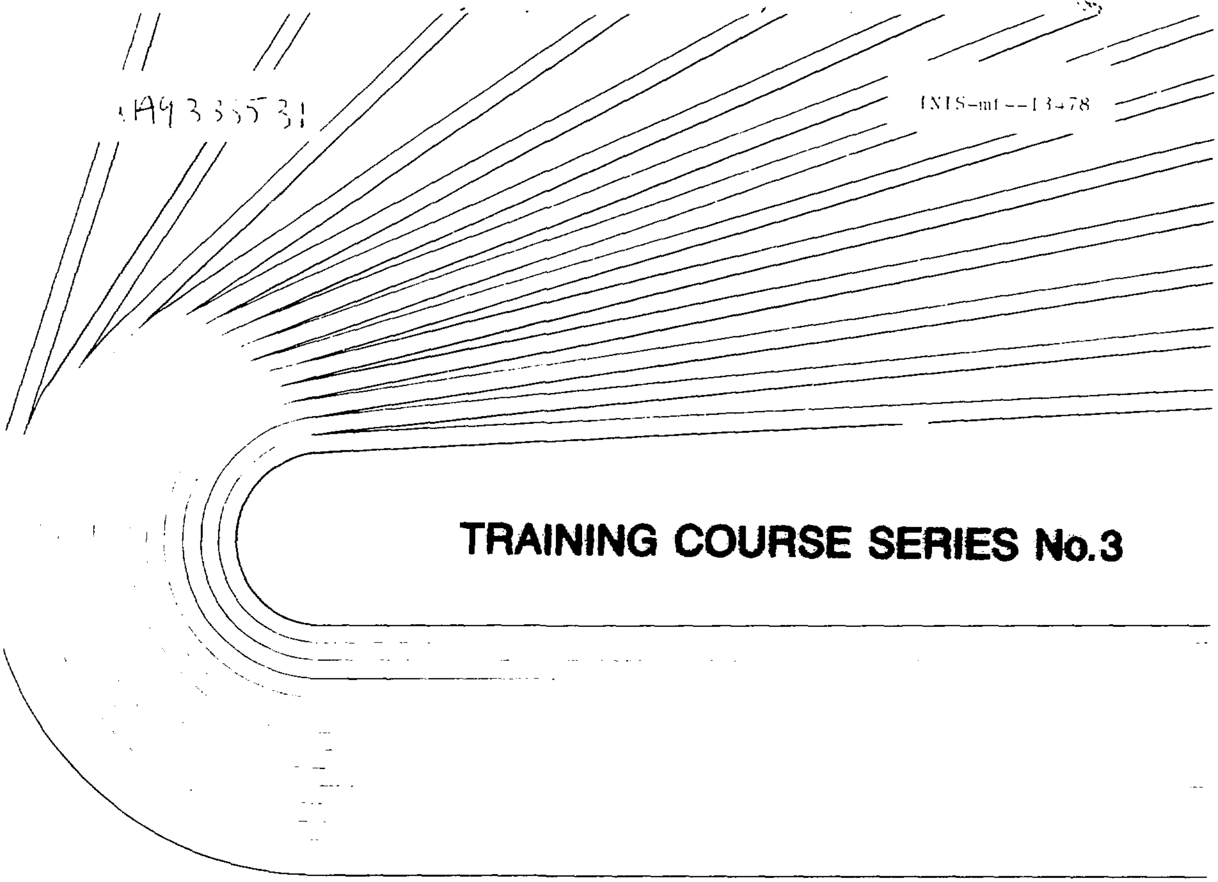

TRAINING COURSE SERIES No.3

Industrial Radiography

Manual for the Syllabi Contained in IAEA-TECDOC-628, "Training Guidelines in Non-destructive Testing Techniques"

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1992

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FOREWORD

Industrial radiography is a non-destructive testing (NDT) method which allows components to be examined for flaws without interfering with their usefulness. It is one of a number of inspection methods which are commonly used in industry to control the quality of manufactured products and to monitor their performance in service.

Because of its involvement in organising training courses in all the common NDT methods in regional projects in Asia and the Pacific* and Latin America and the Caribbean ** and in many country programmes, the Agency is aware of the importance of standardising as far as possible the syllabi and training course notes used by the many experts who are involved in presenting the training courses.

IAEA TECDOC 628 " TRAINING GUIDELINES IN NON-DESTRUCTIVE TESTING " presents syllabi which were developed by an Agency executed UNDP project in Latin America and the Caribbean taking into account the developmental work done by the International Committee for Non - destructive Testing. Experience gained from using the radiography syllabi from TECDOC 628 at national and regional radiography training courses in the Agency executed UNDP project in Asia and the Pacific (RAS/86/073) showed that some guidance needed to be given to radiography experts engaged in teaching at these courses on the material which should be covered. The IAEA/UNDP Asia and Pacific Project National NDT Coordinators therefore undertook to prepare Radiography Training Course Notes which could be used by experts to prepare lectures for Level 1,2 and 3 radiography personnel. The notes have been expanded to cover most topics in a more complete manner than that possible at a Level 1, 2 or 3 training course and can now be used as source material for NDT personnel interested in expanding their knowledge of radiography.

While all National Coordinators contributed to the production of these training notes, particular mention needs to be given to Mr. A.A.Khan, Pakistan Atomic Energy Centre, Mr. N. Ooka, Japan Atomic Energy Research Institute, Mr. R. R. Wamorkar, Bhabha Atomic Research Centre, India, Mr. J. Rodda, Australian Institute for NDT, Mr. Nassir Ibrahim, Nuclear Energy Unit, Malaysia and Mr. R. Gilmour, Project Expert NDT.

The Agency wishes to express its appreciation to all those who have contributed to the production of these Training Course Notes and to the governments and organisations whose financial and technical support made this publication possible.

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* Australia, Bangladesh, China, India, Indonesia, Japan, Democratic Peoples' Republic of Korea, Republic of Korea, Malaysia, Pakistan, Philippines, Singapore, Sri Lanka, Thailand and Vietnam.

** Argentina, Barbados, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, Guatemala, Guyana, Jamaica, Mexico, Paraguay, Peru, Trinidad and Tobago, Uruguay, and Venezuela

EDITORIAL NOTE

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1. GENERAL KNOWLEDGE

1.1. BASIC PRINCIPLES OF NON DESTRUCTIVE TESTING

1.1.1. Importance of Non Destructive Testing

An industrial product is designed to perform a certain function for a certain period of time to the satisfaction of its user. Any premature failure of the product in carrying out its job is in no way desirable, as besides monetary losses it may endanger human life as well.

One of the most important factors which adversely affects the mechanical strength of a product and may cause its premature failure, is the presence of discontinuities in the structure of the product. In older design procedures, the presence of discontinuities in products was taken care of by including a safety factor in the design of the product. But nowadays since high emphasis is being placed on the use of as little material as possible during the manufacture of the product to reduce its cost and weight, the presence of discontinuities is in no way tolerable. The discontinuities in an industrial product may be due to:

(i) the presence of discontinuities in the raw material used in the manufacture of the product,
(ii) faulty manufacturing processes,
(iii) the environmental and loading conditions during service.

To get a product which conforms to the design specifications, a means of monitoring the quality of the product at every stage of its manufacture and during its service life is required. The means should be such that it in no way interferes with the service performance of the product. Non destructive testing (NDT) provides that means. NDT methods, as the name implies, are testing methods which can be used to detect discontinuities in an industrial product without affecting the service performance of the product in any way.

1.1.2. Basic Methods of NDT

There are five basic NDT methods which are used widely in industry for the detection of defects. These methods are:

(i) liquid penetrant testing method,
(ii) magnetic particle testing method,
(iii) eddy current testing method,
(iv) ultrasonic testing method, and
(v) radiographic testing method.

In the following a brief description of all these methods except radiographic testing is given.

1.1.3. Liquid Penetrant Testing

This is a method which can be employed for the detection of open-to-surface discontinuities in any industrial product which is made from a non porous material. In this method a liquid penetrant is applied to the surface of the product for a certain predetermined time, after which the excess penetrant is removed from the surface. The surface is then dried and a developer is applied to it. The penetrant which remains in the discontinuity is absorbed by the developer to indicate the presence as well as the location, size and nature of the discontinuity. The process is illustrated in Fig. 1.1.

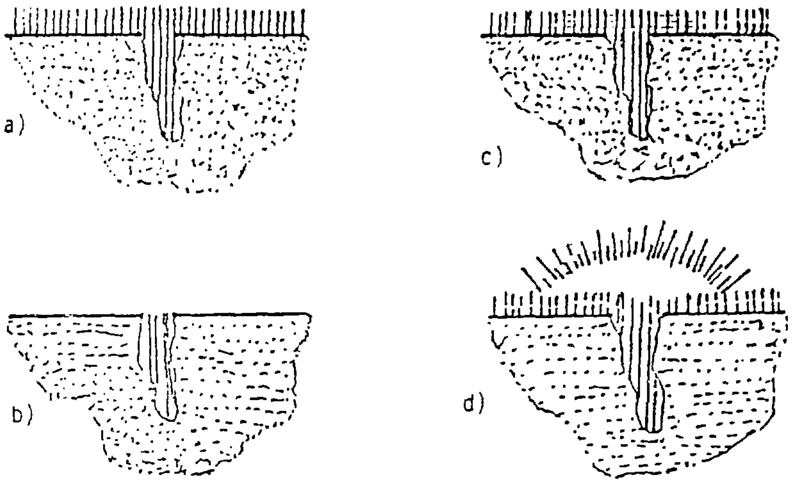


Figure 1.1 Four stages of liquid penetrant process
(a) penetrant application and seepage into the discontinuity
(b) removal of excess penetrant
(c) application of developer, and
(d) inspection for the presence of discontinuities

1.1.3.1. General Procedure for Liquid Penetrant Inspection

(a) Cleaning the surface to be examined

There should be no material such as paint , plating or coatings of oxide or loose dirt covering the surface. This is to prevent false indications and to expose hidden discontinuities to the penetrant. Solid contaminants such as carbon, engine varnish, paints and similar materials should be removed by vapour blast, chemical dip or other acceptable methods. Methods such as shot blasting, sand blasting, emery cloth, wire brushing or metal scrapping should not be used, especially for soft materials, since these cleaning methods will cover up defects by cold working the surface. Contamination can occur due to the presence of lubricants, protective oils, metal dust, polymerisation, oxidation, carbonaceous deposits, protective paints etc. Various solvents have been developed by different companies to remove them. Contamination due to inorganic corrosion products, heat treatment scale, operationally formed refractory oxides etc. is conveniently removed by abrasive blasting with glass beads etc. combined with a chemical cleaning. Which ever method is employed the use of trichlorethylene vapour degreasing as a final stage is strongly recommended.

(b) Drying the surface

If, for any reason, separations are filled with liquid, they will prevent entry of penetrant, hence drying is an essential operation. It should be realised that although the surface may seem dry, separations may still be filled with liquid. With "dismountable cracks" used to evaluate penetrants, it is remarkable how long a liquid can stay in a small separation after the outer surface has become dry. The lesson is that improper drying may be worse than no cleaning, because the remaining solvent may present a barrier to the penetrant too. If penetrant liquid does reach into the separation, it will be diluted by the solvent, and this also makes the treatment less effective.

(c) Application of penetrant

The penetrant is applied with the help of a brush or by spray or by dipping the test piece into a bath of the penetrant. After this a certain residence time is allowed for the penetrant to seep into discontinuities. The residence time varies with the temperature, the type of penetrant, the nature of the discontinuity and the material of the test specimen. It usually varies between 5 and 30 minutes. In special cases it may be as long as one hour.

(d) Removal of superfluous penetrant

The excess penetrant on the surface should be removed to obtain optimum contrast and to prevent misleading indications. The appropriate remover is usually recommended by the manufacturer of the penetrant. Some penetrants are water washable, others need application of an emulsifier before they can be removed with water. The removal method is to use a sponge or water spray. There are special penetrant removers which are essentially solvents. It is most important that removal of the penetrant is restricted to the surface and that no penetrant is washed out of the flaws. This can easily happen when the cleaning is too rigorous. When the surface is smooth, washing can be less intensive than for rough surfaces; in the latter case there is a definite risk that penetrant may be washed out of small imperfections.

A general criterion for the removal operation is that it must be fast and should be prolonged long enough to make the surface almost clean. It is better to leave small traces of penetrant on the surface than to carry out excessive cleaning. When removing fluorescent penetrants, the effect of the treatment should preferably be watched under black light.

(e) Drying the surface

The surface can be dried with a dry cloth or an air blower. Drying is generally needed to prepare the surface for the application of a powder developer, which would otherwise clot at wet places. It also decreases the adverse effect of insufficiently removed traces of penetrant. Here again excess should be avoided. Penetrant liquid left in flaws should not be allowed to dry. This can happen when hot air is used for drying.

(f) Application of developer

Developers are usually of two types, namely, dry or wet developer. Dry developer consists of a dry, light coloured powdery material.

It is applied to the surface after removal of excess penetrant and drying of the part. It can be applied either by immersing the parts in a tank containing powder, or by brushing it on with a paint brush (usually not a desirable technique) or by blowing the powder onto the surface of the part.

Wet developer consists of a powdered material suspended in a suitable liquid such as water or a volatile solvent. It is applied to the parts immediately following the water-washing operation.

Developers should be such that they provide a white coating that contrasts with the coloured dye-penetrant, and draw the penetrant from the discontinuities to the surface of the developer film, thus revealing defects.

The dry developers are applied generally with fluorescent penetrants. They are applied just prior to the visual inspection process. The wet developers are also generally used in connection with fluorescent penetrants. They are applied after the washing operation and before the drying operation. The solvent based developers are generally used with the visible dye-penetrants. They are applied after cleaning off extra penetrant. A short time should be allowed for development of indications after the developer has been applied. This time should be approximately one half that allowed for penetration. Developer coating is removed after inspection by water stream, spray nozzle, brush etc. The powder concentration of the liquid developer should be carefully controlled to obtain the required thin and uniform layer over the surface.

(g) Observation and interpretation of indications

An indication in the developer will become visible after a certain lapse of time. Because all penetrant inspection methods rely upon the seeing of an indication by the inspector, the lighting provided for this visual examination is extremely important. For best results, inspection for fluorescent indications should be done in a darkened area using black light. For the interpretation of indications, it is very important to observe their characteristics at the very moment they appear. As soon as the flaws have bled out, the indications may run to larger spots, depending on size and depth, and at this stage it is difficult to derive characteristic information from the flaw.

The extent to which observation of developing indications can be realised in practice depends largely on the size and complexity of the surface to be examined as well as on the number of components to be tested. A brief guide to the penetrant indications is given here. A crack usually shows up as a continuous line of penetrant indication. A cold shut on the surface of a casting also appears as a continuous line, generally a relatively narrow one. A forging lap may also cause a continuous line of penetrant indication. Rounded areas of penetrant indication signify gas holes or pin holes in castings.

Deep crater cracks in welds frequently show up as rounded indications, Penetrant indications in the form of small dots result from a porous condition. These may denote small pin holes or excessively coarse grains in castings or may be caused by a shrinkage cavity. Sometimes a large area presents a diffused appearance. With fluorescent penetrants, the whole surface may glow feebly. With dye penetrants, the background may be pink instead of white. This diffused condition may result from very fine, widespread porosity, such as microshrinkage in magnesium. The depth of defects will be indicated by richness of colour and speed of bleed out. The time required for an indication to develop is inversely proportional to the volume of the discontinuity.

1.1.3.2 Penetrant Processes and Equipment

Penetrants are classified depending on whether the dye fluoresces under black light or is highly contrasting under white light. A second major division of penetrants is determined by the manner is which they can be removed from the surface. Some penetrants are water washable and can be removed from the surface by washing with ordinary tap water. Other penetrants are removed with special solvents. Some penetrants are not in themselves water washable but can be made so by applying an emulsifier as an extra step after penetration is completed. During a short emulsification period this emulsifier blends with the excess penetrant on the surface of the part after which the mixture is easily removed with a water spray.

The Fluorescent Penetrant Water Washable Penetrant Process uses this method. The fluorescent is used for greater visibility; can be easily washed with water; is good for quantities of small parts; is good on rough surfaces;is good in keyways and threads; is high speed, economical of time and good for a wide range of defects.

The Post Emulsification Fluorescent Process has fluorescence for greater visibility; has highest sensitivity for very fine defects; can show wide shallow defects; is easily washed with water after emulsification; has a short penetration time; high production; especially satisfactory for chromate surfaces.

The Water Emulsifiable Visible Penetrants Process has greater portability; requires no black light; can be used on suspected local areas of large parts; aids in rework or repair; can be used on parts where water is not available; can be used where parts are to be repaired in ordinary light. Best of all techniques on contaminated defects; sensitive to residual acidity or alkalinity; high sensitivity to very fine defects.

Fluorescent materials generally respond most actively to radiant energy of a wavelength of approximately 3650Å . This is just outside the visible range on the blue or violet side but not sufficiently far removed to be in the chemically active or ultraviolet range. This is black light. Four possible sources of black light are incandescent lamps, metallic or carbon arcs, tubular "BL" fluorescent lamps and enclosed mercury vapour arc lamps. Mercury vapour arc lamps are generally used. One of the advantages of this is that its light output can be controlled by design and manufacture. At medium pressures, from 1 to 10 atmospheres, the light output is about evenly distributed between the visible, black light and hard ultraviolet ranges. These medium pressure lamps are ordinarily used for inspection purposes. A red purple glass is used to filter the light not desired. Factors such as the nature of inspected surface, extraneous white light entering the booth, the amount and location of fluorescent materials near the inspector and the speed with which inspection is to be carried out, have an effect on the black light intensity necessary at the inspected surface. The light level, once it is set for a practical job, should be maintained. Good eye-sight is also a requisite.

1.1.3.3. Areas of Application of Liquid Penetrants

Liquid penetrants can be used for the inspection of all types of materials such as ferrous and non-ferrous, conductors and non-conductors, magnetic and nonmagnetic and all sorts of alloys and plastics. Most common applications are in castings, forgings and welds.

1.1.3.4. *Range and Limitations of Liquid Penetrants*

All imperfections which have an opening to the surface are detectable no matter what their orientation. Sub-surface defects which are not open to the surface will not show up and consequently will not interfere with the interpretation. No indications are produced as a consequence of differences in permeability (a weld in dissimilar steels, transition zones etc.). There is no risk of surface damage which may occur, for example, during careless magnetisation with prods in the current flow method. The equipment is also low cost.

Flaws may remain undetected by penetrant inspection if magnetic particle testing has been previously used, because the residual iron oxide may fill or bridge the defect. Similarly fluorescent penetrant will often fail to show discontinuities previously found by dye penetrant because the dye reduces or even kills fluorescence. Reinspection should be done with the same method. Surface condition may affect the indications.

Surface openings may be closed due to dirt, scale, lubrication or polishing. Rough or porous areas may retain penetrant producing irrelevant indications. Deposits on the surface may dilute the penetrant, thus reducing its effectiveness.If all the surface penetrant is not completely removed in the washing or rinse operation following the penetration time, the unremoved penetrant will be visible. Such parts should be completely reprocessed. Degreasing is recommended. Another condition which may create false indications is where parts are press fitted to each other. The penetrant from the fit may bleed out and mask the true defect.

Some of the precautions necessary for liquid penetrant inspection are briefly summarized here. Only one process should be used. Change of process is not advisable for reinspection. The test materials should not be contaminated. Contamination leads to a loss of test sensitivity and reliability. Contamination of water with penetrants should be avoided. Wet developer bath should be at the recommended concentration. The temperatures should not exceed certain limits depending on the materials used. The penetrant should not be heated. Avoid contact of penetrant with skin by wearing gloves. Keep penetrants off cloths. Check for traces of fluorescent penetrant on skin and clothes and inside gloves by examining under black light. Excessive amounts of dry penetrants should not be inhaled. Improperly arranged black lights may cause some eye fatigue. The materials used with visible penetrant process are flammable and should not be stored or used near heat or fire. Do not smoke while using them.

1.1.4. **Magnetic Particle Testing**

Magnetic particle testing is used for the testing of materials which can be easily magnetised. This method is capable of detecting open-to-surface and just below the surface flaws. In this method the test specimen is first magnetised either by using a permanent magnetic or an electromagnet or by passing electric current through or around the specimen. The magnetic field thus introduced into the specimen is composed of magnetic lines of force. Whenever there is a flaw which interrupts the flow of magnetic lines of force, some of these lines must exit and re-enter the specimen. These points of exit and re-entry form opposite magnetic poles and whenever minute magnetic particles are sprinkled onto the surface of the specimen, these particles are attracted by these magnetic poles to create a visual indication approximating the size and shape of the flaw.

Fig. 1.2(a,b) illustrates the basic principle of this method.

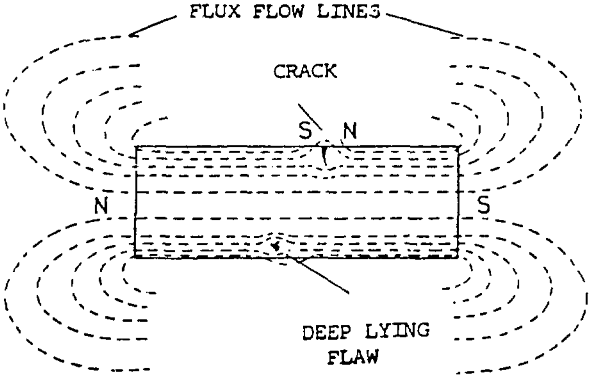


Figure 1.2(a): The effect of defects on the flux flow

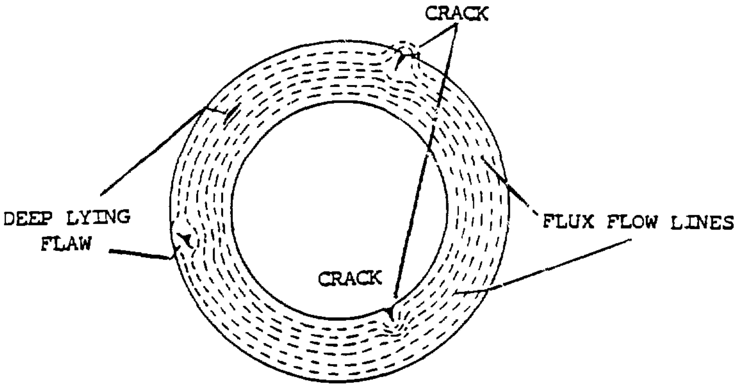


Figure 1.2(b): The effect of defects on the flux flow in a magnetised ring.

1.1.4.1 Methods of Magnetisation

Electric currents are used to create or induce magnetic fields in magnetic materials. Several types of magnetisation are in use for magnetic particle inspection Some of the types are D.C. magnetisation , half wave rectified current magnetisation and A.C. magnetisation. All these three types are mainly used for magnetic particle inspection.

Direct Current obtained from storage batteries was first believed to be the most desirable current to use, since it penetrates more deeply into test specimens than any other current. The big disadvantage of the current obtained from storage batteries is that there is a specific limit to the magnitude and duration of current which can be drawn from the battery before recharging. Battery maintenance is costly and can become a source of trouble. Battery current can be replaced by the current obtained through dry plate rectifiers from a.c. power lines. This has the advantage of permitting an almost unlimited supply of D.C.

Half wave rectified current is the most effective current to use for detection of surface and sub-surface defects using dry magnetic particles. It gives mobility to magnetic particles and aids in the formation of indications.

Alternating current is also used for detection of surface cracks like fatigue cracks. A.C. inspection units should be equipped with proper current controls. An advantage of using A.C. is that the parts being inspected with this current can be easily demagnetised.

Some of the commonly used methods of magnetising the test specimens of different configurations are given below:

(a) Circular magnetisation

Electric current passing through any straight conductor such as wire or bar creates a circular magnetic field around that conductor.

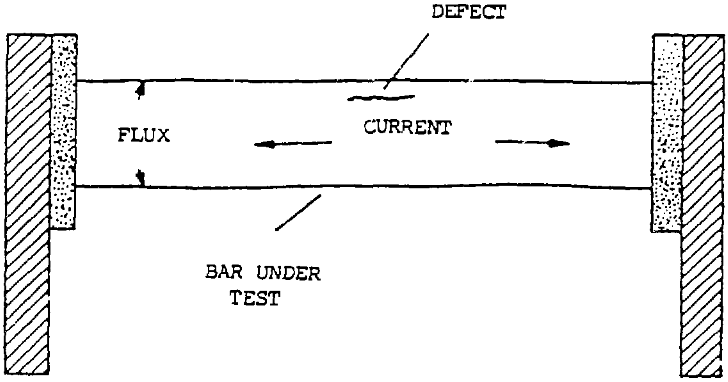


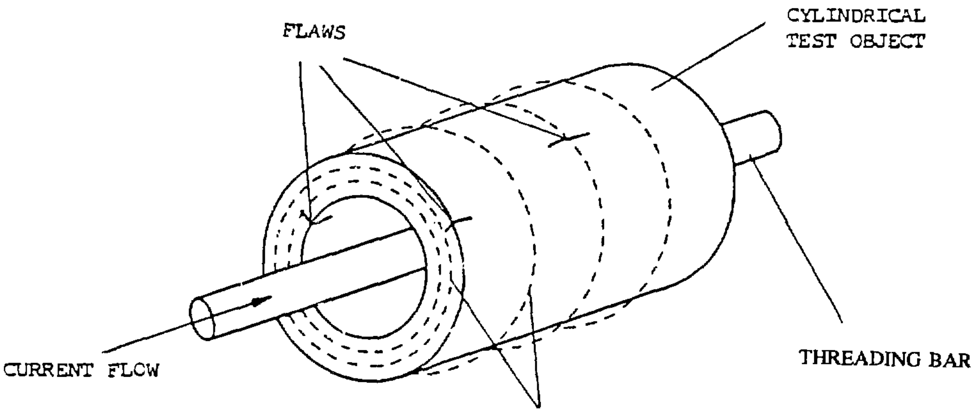
Figure 1.3 : Flux flow in a bar carrying current.

For inspection of axial cracks in a solid or hollow part, the part can be magnetised circularly. For a solid part the current is passed through the test piece and a circular field is developed inside and around the piece. In the case of hollow or tube like objects, a central conductor is used to carry the magnetising current. The central conductor is always a copper rod. The conductor is placed inside the hollow piece and current is then applied to it. This induces a circular magnetic field on the inside and outside surfaces of the hollow piece as shown in Figure 1.4.

(b) Longitudinal magnetisation

Parts can be magnetised longitudinally using a permanent magnet (Figure 1.5) or by using an electromagnet , Figure 1.6.

Parts can also be magnetised longitudinally by the application of electric current. When electric current is passed through a coil of several turns, a magnetic field is established



Flux flow in cylindrical specimens using threading bar.

Figure 1.4 : Flux flow in cylindrical specimens using threading bar.

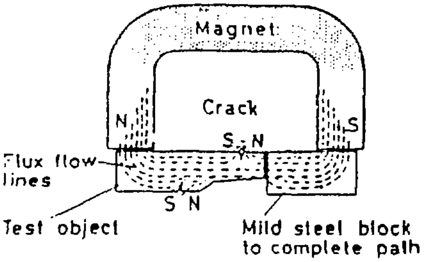


Figure 1.5 : Use of permanent magnet.

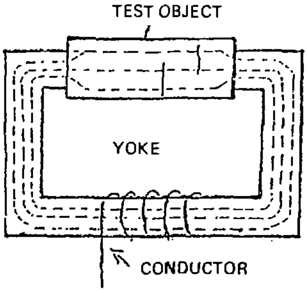


Figure 1.6 : Electromagnet

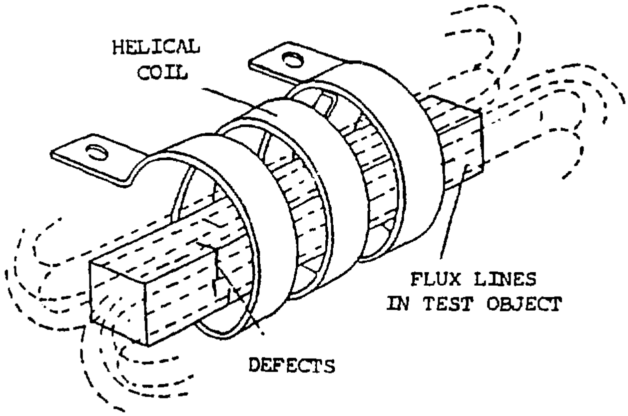


Figure 1.7 : Helical Coil

lengthwise or longitudinally within the coil. The nature, and direction of this field is the result of the field around the conductor which forms due to the number of turns in the current carrying coil. A crack at right angles or tangential to this field can be revealed. Longitudinal magnetisation may be achieved by surrounding the test specimen with helical coils and passing current through them Figure 1.7

(c) Magnetisation of irregular parts

Parts of irregular shape sometimes have to be tested. They can be tested using the magnetic particle inspection method. Local magnetisation is created by applying prods to the area to be tested. The area is magnetised circularly and any defect in the path of the magnetic lines of force can be indicated as shown in Figure 1.8.

The inspection of irregular parts by this method is time consuming since a magnetising current has to be applied many times to achieve thorough inspection of a component. However the testing time is not a large problem, due to the quick testing capability of the magnetic particle inspection method.

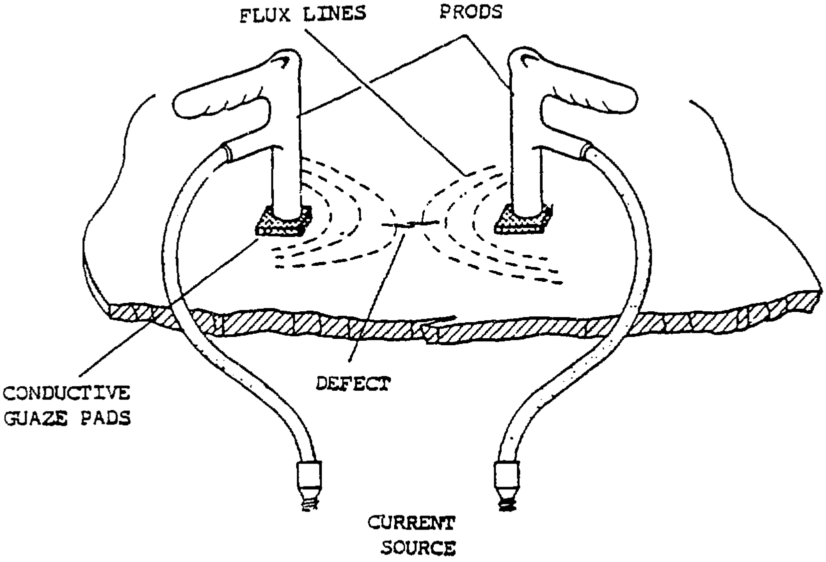


Figure. 1.8 : Magnetisation of irregular specimens.

1.1.4.2. General Procedure for Magnetic Testing

The steps and sequence involved in the magnetic method are as follows:

(a) Preparation of the test specimen

Loose rust and scale should be removed from the component. Machined parts should be degreased using appropriate solvents. In painted parts the paint should be removed locally to provide adequate contact areas for the current flow tests. Other painted parts will only require degreasing unless the colour of the paint is the same as that of the particles in the ink to be used and is likely, therefore, to provide poor contrast. In the latter case a contrast aid may be applied. This is normally a thin white coating. The application of a white emulsion paint is an alternative procedure. Components which have been in a magnetic field may be carrying residual magnetism. It is advisable to remove this residual magnetism to avoid false indications.

(b) Magnetisation of the test specimen

The test specimen may be magnetised depending on its shape and configuration by using any of the methods outlined in Section 1.1.4.1. It is advisable to devise and write down the technique to be used listing the operations required with all details of directions of tests and jigs needed. Many components may not have simple geometric shapes but instead may have what can be considered to be combinations of simple shapes. In such cases more than one magnetising technique may be necessary to be able to test the whole specimen. When multi-diameter or multi-thickness specimens are to be tested in the same direction, then testing of the larger diameter/thickness portion will over-saturate the smaller diameter/thickness portion. Therefore the lower value tests should be made first. The sensitivity of defect detection improves with the level of magnetisation.

Theoretically a level just below saturation would give the most sensitive results but this is impractical owing to the variety of non- regular shapes encountered and therefore in practice, lower levels are quite adequate. For most critical work about 40% of saturation is sufficient. With this level of magnetisation large defects of 2.5 mm depth below the surface can always be found and up to about 1.5 mm deep all defects of a serious nature can be detected. Practically the saturation flux value for the test specimen may be found by increasing the flux level until background is formed. Variables affecting the flux for permanent magnets and electromagnets include the cross section and length of the test specimen and the total length of the flux path including the machine poles. For the current flow method a value of 9 A/mm of perimeter of the test specimen is the recommended level of magnetisation for critical work. For basically round components this can be expressed as 28 A/mm of diameter. While testing using a coil, the factors that influence the magnetic flux are number of ampere turns of the coil, fill factor of the coil, length over diameter ratio of the test specimen and the coil shape. To obtain a suitable test value in this case, the current in the coil is increased with the component in position until saturation is obtained and the suggested standard would then be 40% of the saturation value. Alternatively for rigid coils and provided that the component is placed near the coil perimeter and has a cross sectional area not more than 10% of the coil cross sectional area, the test current may be calculated using the equation $A = 9000/CT$ where A is the current in amperes, C is the coil diameter in millimeters and T is the number of coil turns.

(c) Application of the magnetic powder

Magnetic particles are available in red or black colours. The red material improves visibility on dark surfaces. There are also fluorescent materials available. These magnetic particles may be applied to the test specimen either in dry or in wet form. If a dry powder is used it should be applied to the magnetised component such as to achieve an even distribution. Tapping the test specimen with a rubber hammer is often helpful. For the wet magnetic particles it is best that these are applied during magnetisation. They should cease flowing just before excitation ceases. They can be applied to the test specimen by brush, ladle or hose. Whichever method is used, care should be taken to avoid violent flow over the test specimen, otherwise faint indications from flaws are disturbed. Such faint indications will also be washed away if the magnetic particles are reapplied after the current has ceased to flow. The application of magnetic particles may also be made by immersing the test specimen in a suspension of the particles. As the particles in the wet method are generally finer than those in the dry method, the wet method is more sensitive for the detection of fine surface defects. On the other hand it is not as sensitive as the dry method for the detection of subsurface discontinuities. Greatest sensitivity is achieved through the use of fluorescent magnetic particles.

(d) Viewing and recording of indications

The whole of the surface under test should be viewed. Viewing of under surfaces may need a mirror. Bores may need special lighting and viewing of end faces may necessitate removing the test specimen from between the contacts. Doubtful indications are often more evident if the component is allowed to drain for a few minutes. Any indications found can be marked with a grease pencil after allowing the ink to drain. It is frequently desirable to record not only the appearance of indications on a part but also their locations. For a permanent record the indication can be lifted from the test specimen and transferred to white paper using adhesive tape.

(e) Demagnetisation

For many industrial applications the tested specimens are required to be free from magnetism. Demagnetisation may be achieved by inserting the part in the field of an alternating current solenoid and gradually withdrawing it from the field. Larger parts may be demagnetised by subjecting them to an alternating current field that is gradually reduced in intensity by means of a current controller. When large masses of steel or iron are involved, alternating current has insufficient penetration to demagnetise such pieces thoroughly. In such cases direct current should be used. Hammering or rotating in the field will sometimes assist demagnetisation. Heat treating or stress relief will demagnetise weldments and total demagnetisation is always accomplished when the work piece is heated above the curie temperature of the metal. The efficiency of demagnetisation should be checked by using a compass or a commercial magnetic field indicator.

1.1.4.3. Equipment for Magnetic Particle Inspection

It is emphasised that magnetic particle testing is an important process in the production of steel components which are not checked at any subsequent manufacturing stage. The provision of adequate equipment for use by a reliable operator will more than justify the initial cost and will ensure that the tests are correctly carried out. Equipment is available in the range of from small hand tools to big universal type testing equipment. In both categories i.e. portable and nonportable, more than a hundred types are used in industry. Portable equipment can be taken to the site for the inspection of large castings, weldments, assembled or welded structures or parts of assemblies tested without disassembly. Small parts, on the other hand can be brought to a fixed inspection station. In industry, inspection is a part of the production line.Therefore inspection of in process parts can be done by sampling or on a 100% basis at one or more locations along the production line. Sometimes inspection is needed where mass production of a single piece is done. For this purpose specialised testing equipment may be best for minimum testing cost per piece. At other places inspection of various types of parts may be required in a very high volume. Here there is need for an equipment where eight, ten or twenty different parts can be inspected on a single piece of equipment in lots of several thousand per hour. In many industries various types of parts are produced on a low production basis. For this a single piece of test equipment can be used with greater efficiency. Other factors which need to be kept in view when selecting equipment are the types of defects of interest, the required sensitivity and whether the whole or a localised area of the test specimen is to be inspected.Different types of equipment available in the market are briefly reviewed here. Hand operated small fixed or stationary units are widely used for small manufactured parts.These units normally contain a built-in tank with pump which agitates the wet particle bath and pumps inspection fluid through a hand held hose for application to test objects. A part is clamped within the magnetising coil between the copper contact faces. At the operator's option, the parts can be magnetised circularly with current between the head, or longitudinally with current through the coil, or both if desired. While the part is magnetised, the operator applies the liquid inspection medium, and then views the surface for indications. Most units are provided with inspection hoods and black lights, so that fluorescent magnetic particles can be used. This increases the rate of inspection and reduces the possibility of missing an indication. This type probably accounts for about 75% of magnetic particle inspection.

For bulkier work up to say 1.5m long and 0.3m in diameter more power is needed to maintain the desired flux level. Such units have a magnetising current up to 5OOOamp. A.C. and a magnetic field of about 1500 oersteds (120 K A/m). A demagnetiser which is built in can accommodate a part of 360x250mm. Sensitivity may be controlled to reveal only surface cracks with a.c. or surface and subsurface cracks with half wave current. For site testing, equipment must be capable of being handled manually up ladders and to be located remote from mains supply. Many standard sizes of portable magnetic particle inspection equipment are in use. They vary from small hand held yokes made from permanent magnets to electromagnets.

Several types of completely automatic equipment are used for magnetic particle inspection in hundreds of plant locations. Inspection is carriedout automatically on parts carried by a continuous conveyer. Loading and unloading may be manual or automatic. The inspector is required to view the parts as they pass on the conveyer and must only see and react to readily visible indications. Parts bearing indications are diverted for later evaluation and salvage or rejection. Accepted parts remain on the conveyer and pass through an automatic demagnetiser before being discharged from the unit. Such equipment permits a rapid and low cost inspection where slower inspection may not be worth its cost. Special purpose equipment for checking automatically large numbers of identical parts of simple form can be designed in such a way that a current flow test and a coil test are applied at the same time, thus enabling both longitudinal and transverse defects to be found.

1.1.4.4. Applications of the magnetic method of testing

In general engineering practice, a large proportion of components are made of steel or iron which are capable of being magnetised. This is fortunate because this testing method is not expensive and it can reveal all the surface faults in parts which are subjected to light stresses and fatigue and in those which have been cast, welded or heat treated during fabrication. Many inspection specifications for aerospace, atomic and other critical work specially call for this type of test.When non metallic inclusions occur in areas of high stress or in certain special locations, they may be a cause for rejection. A subsurface condition which is much more likely to be dangerous is the presence of inclusions which were not plastic at the time of rolling or forging e.g. refractory materials. Usually the inclusions are very fine and are revealed with magnetic particle inspection only when they occur near the surface. They are most likely to be shown on highly finished surfaces by applying the wet method with high magnetisation levels. Inspection before machining is not helpful, and if inclusions are considered a cause for rejection, parts should be inspected after surface finishing.

Surface seams in rolled bars result from cracks or other defects (surface) in the billets from which they are rolled or from some defects introduced by the rolling operation itself. The great elongation of the metal draws out such surface defects into long, straight seams, usually parallel to the direction of rolling. Cooling cracks which occur in rolled bars are similar to seams but usually differ in appearance in some respects. When magnetic particles are applied to such a surface for inspection, the indications are sharp and well defined, but deviate some what from the rolling direction.

Porosity in castings caused by gases trapped during the solidification of the molten metal can sometimes be located with magnetic particle inspection. Subsurface blow holes and thermal cracks in castings can also be revealed with magnetic particle inspection.

Magnetic particle inspection is used extensively on welds. It is possible to find porosity, slag inclusions, shrink cracks, inadequate penetration and incomplete fusion. With d.c. magnetisation a subsurface discontinuity like a lack of penetration at a root can be revealed.

Cracks caused by faulty heat treatment processing are readily found with magnetic particle inspection. Such cracks may occur during either the heating or quenching cycle and may be enlargements of conditions existing in the part from some previous operation. Heat treatment cracks which are created by the quench cycle and which are also called quench cracks are usually found at sharp changes of section, which cause unequal cooling rates, or at fillets or notches which act as stress concentration points.

Fatigue cracks are produced in service under repeated stress reversals or stress variation. A crack almost invariably starts at a highly stressed surface and propagates through the section until failure results. A fatigue crack will start more readily where design or surface condition provides a point of stress concentration. Sharp fillets, poor surface finish, seams, grinding cracks, and other such defects act as stress raisers and assist in the start of fatigue cracking.

All magnetic particle inspection to eliminate seams, inclusions, cooling cracks, laps, porosity, heat treatment cracks and grinding cracks is for the purpose of preventing fatigue or service failure after the part goes into service. Consistent use of magnetic particle inspection as well as other non destructive tests in a well planned preventive maintenance program, can in many cases reduce service failure from fatigue to practically zero.

1.1.4.5 Range and limitations of magnetic particle inspection

Magnetic particle testing is a method of finding surface and near surface defects in any steel or iron sample capable of being magnetised. It is essential that the flux path crosses the flaw and ideally it should be at right angles to it. Fortunately, with an adequate level of magnetisation, defects oriented by as much as 50 degrees with respect to the direction of the flux will show up and any object can be tested completely provided at least two tests are made. The flux direction in the object for the second test should be at right angles to the flux direction for the first.

To ensure an adequate test, the factors that need to be considered include the shape of the component, the dimensions of the component, the magnetic permeability, surface finish, possible defects and their orientation, suitable flux direction and strength and a suitable testing stage during manufacture. Unless due consideration is given to all these factors, the test is unreliable, although it may reveal some defects,but it is quite possible that serious defects may not be revealed.

Because every component differs and at least two tests are required to find all defects, it is good to establish a proper technique for each. For components having complex shapes, this technique may consist of as many as a dozen tests at varying field strengths and using different methods to ensure 100 percent coverage. Provided that adequate equipment is available, it is feasible to test any type and size of magnetic object. The size of defects which can be detected will depend upon surface finish and other factors.

Magnetic particle inspection is not expensive. The testing can be performed in the presence of an overlay of paint or non-magnetic plating. The inspection can be undertaken by semi-skilled labour without requiring elaborate protection such as that needed for radiography.

The presence of non-conducting surface coatings, such as paint, may preclude the use of contact current flow tests. The material must be capable of being magnetised which precludes the testing of austenitic steels and other non-magnetic materials. Since every test requires at least two directions of flux, each component must be tested at least twice. Therefore components of complex shapes may need numerous tests which becomes cumbersome and time-consuming. Demagnetisation is another of the shortcomings. The ink particles can clog fine passages and their removal is sometimes laborious.

1.1.5. Eddy Current Testing

An alternating current of known frequency is applied to an electric coil placed adjacent to the material to be inspected. This current will produce its own magnetic field known as the excitation field and will also induce currents in the metal part known as eddy currents according to Faraday's law of electromagnetic induction. These eddy currents will produce their own magnetic field which will oppose the excitation field. The resultant field is thus reduced which will change the coil impedance.

In Figure 1.9 an alternating current of a given frequency is generated in the primary or exciting coil. An alternating magnetic flux is consequently produced. This induces an alternating current of the same frequency in the secondary coil. With the introduction of the specimen, the alternating flux of the primary induces in it (the specimen) an eddy

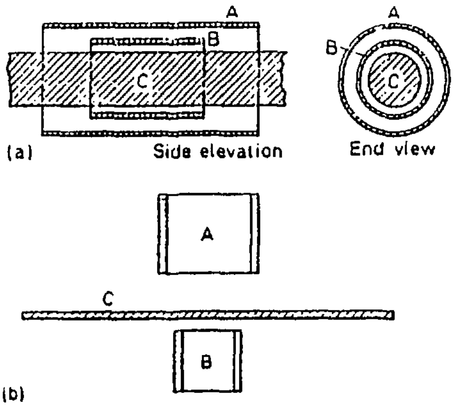


Figure 1.9.

current flow which gives rise to an alternating magnetic flux in the opposite direction. The current in the secondary coil is consequently reduced. For given conditions the reduction in current should be equal for all identical specimens placed in the same position relative to the coils. Any observed inequality in the value of the reduced current could indicate the presence of a defect, a change in dimensions, or a variation in the electrical conductivity or in the magnetic permeability of the test specimen due, perhaps, to a change in its physical or chemical structure.

The coil impedance which is usually measured in practice instead of the current or flux, is a vector quantity having resistive and inductive components. These are 90° out of phase with each other. The other quantity that may be measured in practice is the voltage across the coil. The coil impedance as well as voltage is related to the effective permeability of the test specimen, the test frequency of the coil, the limiting or boundary frequency of the test specimen and the fill factor of the coil. This relationship is shown in Figure 1. 10. The boundary frequency is defined as

$$f_g = 2/(\pi \mu_0 \sigma D^2)$$

where μ_0 is the permeability for air and almost all other non-ferromagnetic materials,
σ is the electrical conductivity and,
D is the diameter of the specimen.

The fill factor is defined as

$$\eta = D/D$$

where D is the inside diameter of the coil.

Figure 1.10 shows variations of impedance with frequency for different values of η . The dashed lines join all points on the curves corresponding to similar values of f/f_g. Continuous lines represent variations of conductivity for constant diameter D and the dashed lines represent changes in D for constant values of σ.

For ferromagnetic materials the relative permeability is greater than unity and therefore f_g must be defined as $2/(\pi\mu_r\mu_0 D^2)$. If the specimen is kept magnetised to well above saturation level then the value of u_r can be taken as unity and curves such as in Figure 1.10 remain valid. But if the specimen is not saturated magnetically then fresh curves have to be drawn.

The inspection frequencies used in eddy current inspection range from 200 Hz to 6 MHz. The choice of the frequency depends on the thickness of the material, the desired depth of

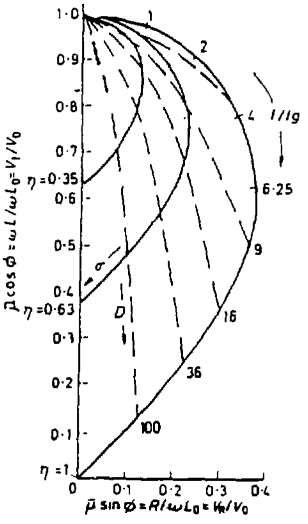


Figure 1.10

penetration, the degree of sensitivity or resolution and the purpose of inspection. Selection of inspection frequency is normally based on a compromise between the depth of interest and sensitivity to flaws. Increasing the frequency lowers the depth of penetration but increases the resolution and vice versa.

Normally the highest inspection frequency compatible with the penetration depth required is selected. For surface flaws frequencies up to several mega hertz may be used. For the inspection of ferromagnetic materials, relatively low frequencies are normally used.

The inspection probe will give a certain indication on the instrument when placed in air. This indication will begin to change as the probe is brought close to the test piece and will continue to change until the probe is directly on the piece. This change in indication with change in spacing between the probe and the material to be tested is termed lift off. Lift off has a draw back as well as an advantage. The drawback is that many indications resulting from conditions of primary interest are masked by small changes in spacing. The advantage is that by utilising the lift-off effect, the eddy current testing instrument can be employed excellently for measuring the thickness of nonconductive coatings such as paint and anodised coatings on metals. When an eddy current inspection probe approaches the edge of a part, the eddy currents are distorted because they are unable to flow beyond it. The indication obtained from it is called "edge effect" and is very dominant, thereby limiting inspection near edges. It is not advisable to inspect any closer than 1/8" from the edge of a part.

The distribution of eddy currents in the part being inspected is such that these are densest at the surface closest to the probe and progressively become less dense with increasing distance from the surface. This phenomenon is known as skin effect. The depth at which the density is reduced to about 37% of the density at the surface is defined as standard depth of penetration. It depends on the electrical conductivity, magnetic permeability of the material being inspected and the frequency of exciting signal.

1.1.5.1. Equipment and procedure for eddy current testing

The main component of eddy current equipment is the probe of which there are several different types. The probe could be the encircling type, the internal type or the external type. The main coil arrangements which may be present in these probes can be divided mainly into three categories depending upon the methods of measurement. In the absolute method the primary and secondary coils are matched so that in the absence of any test specimen the voltages across them are equal and opposite. Introduction of the test piece results in a change in impedance and a voltage change appears which is measured.

The comparison method consists of the use of two identical coil assemblies. A standard defect free specimen is placed in one coil and the test specimen in the other. Changes arising from the differences in the two samples are measured. In the auto-comparison method two different parts of the same sample are compared with one another.

A wide variety of eddy current testing equipment exists, but only some of its typical types are mentioned here. The simplest is the AC bridge. The bridge is unbalanced when a probe passes over the defect because its impedance is changed. Forster's analysis has been applied in the design of some versatile instruments which can be used for conductivity testing, investigation of dimensional variations and flaw detection. The two components of the voltage across the secondary coil are separated in phase and fed to the X and Y plates of an oscilloscope. On the screen appears a bright spot representing a point on the Forster's impedance analysis graph. The movement of this spot is then related to different measurements such as crack detection, conductivity measurements and determination of dimensional variations. Such instruments can be applied to automatic testing, for example, for sorting of materials.

Another type of Foster's equipment uses the ellipse method. A reference voltage in phase with the signal applied to the primary coil is fed to the X-plates of a cathode ray oscilloscope. The output voltage from the secondary coil is fed to the Y-plates. Now two vibrations at right angles to one another produce a Lissajous figure, which in this case is an ellipse. The shape of this ellipse depends on the phase difference between the two voltages and hence the phase angle of the impedance. Different types of defects in the specimen, say cracks, correspondingly produce different shapes of the ellipse. The ellipse degenerates into a straight line for a crack-free specimen. Such equipment can be used for testing ferromagnetic as well as non-ferromagnetic materials provided that a d.c. magnetic saturation unit is used.

There is equipment available which is used for testing tubes,rods and bars which are passed through an encircling coil assembly at a steady speed of up to 200m/min. The test coil assembly consists of two single coils of slightly different impedances placed next to one another and wound in opposite directions. They are excited by an oscillator. The impedances of these coils are balanced by two comparison coils and a potentiometer device. The effect of eddy currents on the test coils is to produce two opposing out of balance signals the resultant of which passes through an amplifier, a phase sensitive detector and a filter to an output stage. A reference voltage supplied by the oscillator to the phase sensitive detector enables one to phase-out unwanted components. This equipment is available for use at different frequencies. The output of such instruments can be connected with a high speed pen recorder to mark the position of defects on the test specimen. Some equipment employs the principle of frequency modulation and is used for testing rods and tubes in continuous motion. The velocity of the component relative to the coil and the changes in the impedance of the coil combine to give rise to a modulation of the operating frequency when variations of eddy current distribution occur. Conductivity changes produce a low frequency modulation while dimensional changes cause a somewhat higher frequency modulation. The sharp discontinuities produced by defects such as cracks and blow-holes give rise to modulations at very much higher frequencies. The equipment can be operated at different frequencies. The signals are detected with an oscilloscope and a pen recorder.The eddy current equipment for measuring conductivity of materials employs a single probe coil acting simultaneously as an exciter and pick-up. The probe is moved by hand over the surface of the test material. The impedance of the coil is initially balanced with that of a similar coil inside the main body of the apparatus. Changes in the impedances of the probe coil due to eddy currents in the material under test give rise to an out of balance voltage which is indicated by a meter directly in units of conductivity. The frequency chosen for operation depends on the range of values of conductivity to be measured and the thickness of the material. Applications of this type of equipment include sorting of mixed materials, hardness testing, control of homogeneity, measurement of porosity and investigating degrees of heat treatment. The determination of the thickness of non-conducting coatings on non-ferromagnetic metal surfaces is done with the help of eddy current equipment by measuring the lift-off effect for a probe coil. The probe coil is coupled by a transformer to a tuned circuit which is connected to a highly sensitive and stable frequency oscillator. When the probe is placed in contact with the surface of the coating, the oscillations decrease in amplitude by an amount depending on the coating thickness. The amplitude is then restored to a fixed level indicated on a meter by manipulating a potentiometer calibrated in the appropriate units of thickness. The potentiometer readings are zeroed by locating the probe on an uncoated metal surface.

Ferromagnetic materials can be tested by subjecting them to magnetic hysteresis. The equipment for this includes two identical coil assemblies of either the encircling or probe type which are located at right angles to one another in order that the flux passing through one set of coils does not pass through the other. The secondary coils are both connected through an amplifier to the Y-plates of an oscilloscope, the X- plates of which are controlled by a time base. An alternating current is fed through each primary coil in such a way that the two currents are 180 degrees out of phase with one another. The time base can be adjusted so that a single cycle, or part of a cycle, of the output from each secondary coil is displayed on the screen. The two signals are superimposed on one another and, in the absence of a test sample, the phases cancel out and a horizontal straight line is observed. When a test specimen is introduced to one of the coils, the material undergoes magnetic hysteresis, the loop of which is modified by the action of induced eddy currents. The straight line becomes disturbed and the trace assumes a shape which is characteristic of the electrical conductivity, the magnetic permeability and the dimensions of the material. On applying an identical specimen to the second coil in exactly the same relative position, the trace again becomes a straight line. If, however, the permeability, conductivity or dimensions of two specimens differ in any way, the trace assumes a shape which is characteristic of this difference. The equipment can be used to test ferromagnetic components of various shapes and sizes for such properties as hardness, composition, heat treatment, depth of case hardening, the existence of internal stresses, machinability etc. Manufacturers usually supply along with the equipment standard shapes of traces characteristic of some of these properties.

1.1.5.2. Applications of eddy current testing

Most of the applications of eddy current testing have already been mentioned while describing the basic principles, equipment and procedures in the previous sections. In the following, a summary of these applications is given.

Eddy current testing is employed for the detection and measurement of defects such as cracks, porosity, blow-holes, inclusions, overlaps, shrinkage and soft spots, in a wide variety of test specimens in solid cylindrical, hollow cylindrical or other complex shapes. Corrosion and cracking due to stress corrosion can also be detected. Changes in electrical conductivity and permeability can be measured which in turn have a bearing upon the material properties such as hardness, homogeneity, degree of heat treatment, existence of internal stresses, decarburisation, diffusion, alloy composition, presence of impurities etc. Thickness measurements can be made on metallic plates, foils, sheets, strips, tubes and cylinders. Typically it is possible to determine the thickness of non-metallic coatings on metals such as, for example, the insulating layers on cables, non-conducting paints on some aircraft castings and anodic coating on aluminium alloy surfaces. Dimensions such as diameters of cylindrical specimens can also be determined. The materials can be automatically sorted in a production process. Since the method is adaptable to automation high speed inspection of small diameter tubing such as that used in steam generators, heat exchangers and as canning tubes for nuclear reactor fuel elements, is possible. Here the characteristics of tubing such as inner and outer diameters, eccentricity, wall thickness and the presence of defects are determined. It is also possible to inspect welded small bore piping. By using encircling type probes larger diameter pipes can be inspected. Similarly long bars and wires can be speedily inspected. In tube testing the eddy current method also allows high speed detection of intergranular corrosion on the inside surface. In some applications round metallic spheres and balls are inspected by eddy currents.

1.1.5.3. Range and limitations of eddy current testing

Eddy current testing can be carried out on all materials which conduct electricity. Both ferromagnetic and non-ferromagnetic materials can be tested. The method has the advantage that contact with the test specimen is not necessary. No couplant is therefore needed. The probe coils can be made with very small diameters and thus can detect the presence of very small flaws. The sensitivity of the coils can be increased by the insertion of high permeability cores such as ferrite rods which produce very sensitive focused coils. Long wires, tubes, rods etc can be tested by feeding them through the coils at a constant speed. Since the technique is susceptible to automation, fast scanning up to say 300m/min is possible and it allows rapid 100% inspection of production items. The relative cost of inspection is therefore low. Under certain circumstances the indications produced are proportional to the actual size of the defect. Thus the tests can be useful for grading and classifying.

Due to the skin effect the depth of penetration into the test specimen is limited and therefore the application of the technique is limited to detection of surface and close-to-surface defects. Also because of this the measurement of wall thicknesses is limited to thin wall tubing and to smaller thicknesses of materials. The lift-off effect is undesirable in most testing cases. The technique is limited to inspecting materials which are good conductors of electricity. It presents some difficulties when attempts to make absolute measurements are made. For manual testing there is a need to have properly trained, qualified and experienced operators.

1.1.6. **Ultrasonic Testing**

1.1.6.1. Nature and Type of Ultrasonic Waves

Ultrasonic inspection is a nondestructive method in which high frequency sound waves are introduced into the material being inspected. Most ultrasonic inspection is done at frequencies between 0.5 and 25MHz well above the range of human hearing, which is about 20 Hz to 20KHz. Ultrasonic waves are mechanical vibrations of the particles of the medium in which they travel and are in general represented by the equation,

$$A = A_0 \sin 2\pi f(t - x/v)$$

where A = the displacement of a particle of the medium in which the mechanical wave is travelling at a time t and distance x from the first excited particle

A_0 = amplitude of the wave which is the same as that of the amplitude of vibration of the particles of the medium

v = velocity of propagation of the wave

f = frequency of the wave

There are different types of ultrasonic waves. These are classified on the basis of the mode of vibration of the particles of the medium with respect to the direction of propagation of the waves.

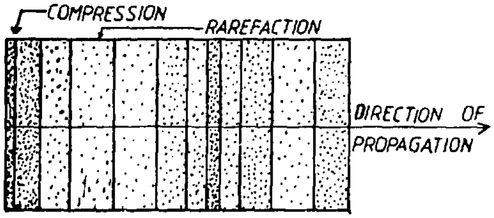


Figure 1.11 Longitudinal wave consisting of alternate rarefactions and compressions along the direction of propagation.

Longitudinal waves or Compression waves are those in which alternate compression and rarefaction zones are produced by the vibration of the particles. The direction of oscillation of the particles is parallel to the direction of propagation of the waves (Figure 1.11). Because of its easy generation and detection , this type of ultrasonic wave is most widely used in ultrasonic testing. Almost all of the ultrasonic energy used for the testing of materials originates in this mode and then is converted to other modes for special test applications. This type of wave can propagate in solids, liquids and gases.

In Transverse or Shear waves the direction of particle displacement is at right angles to the direction of propagation as shown in Figure 1.12.

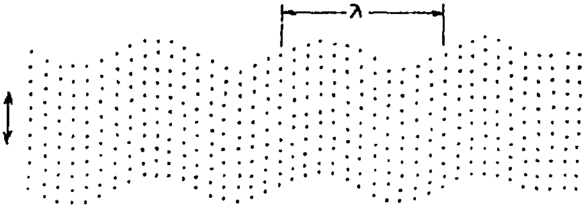


Figure 1.12 Schematic representation of a transverse wave.

For all practical purposes , transverse waves can only propagate in solids. This is because the distance between molecules or atoms, the mean free path, is so great in liquids and gases that the attraction between them is not sufficient to allow one of them to move the other more than a fraction of its own movement and so the waves are rapidly attenuated.

Another type of sound wave is called the Surface or Raleigh wave. These waves can only travel along a surface bounded on one side by the nearly nonexistent elastic forces between gas molecules. Surface waves , therefore, are essentially nonexistent in a solid immersed in a liquid, unless the liquid covers the solid surface only as a very thin layer. In surface waves , particle vibration generally follows an elliptical orbit, as shown schematically in Figure 1.13.

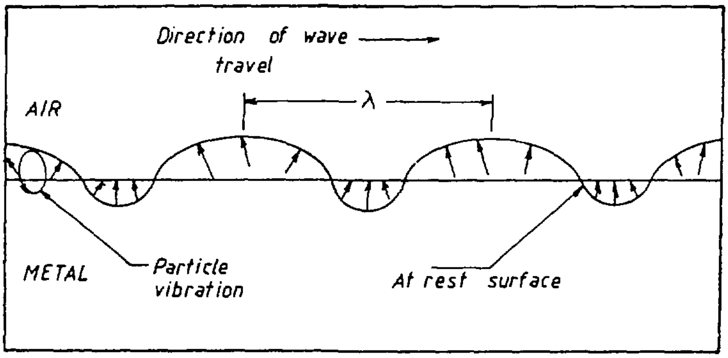


Figure 1.13 Diagram of surface wave propagating at the surface of a metal along a metal - air interface.

Surface waves are useful for testing purposes because the attenuation they suffer for a given material is lower than an equivalent shear or longitudinal wave and because they can flow around corners and thus can be used for testing quite complicated shapes. Only surface or near surface cracks or defects can be detected of course. If a surface wave is introduced into a material that has a thickness equal to three wavelengths, or less, of the wave then a different kind of wave , known as a Plate wave, results. The material begins to vibrate as a plate i.e. the wave encompasses the entire thickness of the material. These waves are also called Lamb waves Unlike longitudinal, shear or surface waves , the velocities of these waves through a material are dependent not only on the type of material but also on the material thickness , the frequency and the type of wave. Plate or Lamb waves exist in several complex modes of particle movement.

1.1.6.2. Ultrasonic wave characteristics

1.1.6.2.1. Frequency

The number of cycles per second is called the frequency and it is measured in cycles per second (c/s) or Hertz (1 Hz = 1 c/s) The length of one complete cycle is the wavelength. The relationship between frequency and wavelength is given by

$$v = f\lambda$$

where

f is the frequency
λ is the wavelength and
v is the velocity of the wave.

Frequency and wavelength have important implications in ultrasonic testing as they determine the depth of penetration of ultrasound in the test material as well as the flaw sensitivity.

1.1.6.2.2 Wave velocity

Sound waves travel in different media with different velocities. In the same media the velocities of longitudinal and shear waves are also different. these differences arise from the fact that different materials have different elastic properties and consequently their abilities to support the stresses and strains differ. Velocity in a specific medium is given by

$$v = (q/\rho)^{1/2}$$

where

q is the constant of proportionality between stress and strain in Hooke's Law
and ρ is the density of the material.

Velocities of longitudinal and shear waves in some common materials are summarized in TABLE I.I

TABLE I.I VELOCITIES OF SOUND IN SOME COMMON MATERIALS($cm^{-1}x10^5$)

	Longitudinal	Transverse
Aluminium	6.32	3.13
Brass	4.28	2.03
Copper	4.66	2.26
Gold	3.24	1.20
Iron	5.90	3.23
Lead	2.16	0.70
Steel	5.89	3.24
Perspex	2.70	1.40
Water	1.43	-
Oil (transformer)	1.39	-
Air	0.33	-

Since shear waves can only be generated and sustained in materials having some value of modulus of rigidity the velocity for shear waves is given by

$$v_T = (G/\rho)^{1/2}$$

This explains why the velocity is lesser in water than in steel because although the density for steel is higher than that for water , the elasticity of steel is much higher than that of water and this outclasses the density factor.

$v_T \approx 0.5\ v_L$ and
$v_s = 0.9\ v_T$

The velocity of propagation of Lamb waves , as mentioned earlier, depends not only on the material density but also on the type of wave itself and on the frequency of the wave.

1.1.6.2.3. Acoustic pressure

The material carrying the sound wave is subjected to a pressure or stress called acoustic pressure given by

$$P = P_o \sin w (t - x/v)$$

where

P is the acoustic pressure amplitude.

The acoustic pressure is positive for a compression and negative for an expansion.

1.1.6.2.4. Characteristic acoustic impedance

Characteristic acoustic impedance Z of a material , may be imagined as the resistance offered by the material to the passage of sound through it. It depends on the physical properties of the material and is given by

$$Z = \rho\ v$$

1.1.6.2.5. Acoustic intensity

Acoustic Intensity I is defined as the rate of flow of sound energy through unit area of an imaginary plane surface drawn about the point in question and oriented at right angles to the direction of wave motion. Intensity is given by

$$I = P_o^2/2\ \rho v$$

Intensity I may be expressed in relation to a reference intensity I_o by a logarithm scale called the decibel scale. This intensity level $= 10 \log_{10} I/I_o$ dB

1.1.6.2.6. Reflection and transmission of sound waves

Sound energy may be reflected , refracted, scattered, absorbed or transmitted while interacting with a material. Reflection takes place in the same way as for light i.e. angle of incidence equals angle of reflection. At any interface between two media of differing acoustic impedance a mismatch occurs causing the major percentage of the wave to be reflected back, the remainder being transmitted. There are two main cases.

1.1.6.2.6.1 Reflection and transmission at normal incidence

The percentage of incident energy reflected from the interface between two materials depends on the ratio of acoustic impedances of the two materials and the angle of incidence. When the angle of incidence is 0° (normal incidence), the reflection coefficient

(R), which is the ratio of the reflected beam intensity I_r to the incident beam intensity I_i, is given by

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

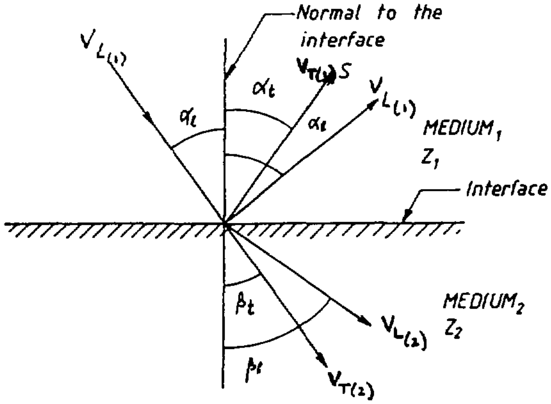
where

Z_1 is the acoustic impedance of medium 1, and
Z_2 is the acoustic impedance of medium 2.

The remainder of the energy is transmitted across the interface into the second material.

1.1.6.2.6.2 Reflection and transmission at oblique incidence

When an ultrasonic wave is incident on the boundary of two materials at an angle other than normal, then the phenomenon of mode conversion (a change in the nature of the wave motion i.e. longitudinal to transverse and vice versa) and refraction (a change in direction of wave propagation) must be considered. All possible ultrasonic waves leaving the point of impingement are shown for an incident longitudinal ultrasonic wave in Figure 1.14. Mode conversion can also take place on the reflection side of the interface if material 1 is solid.



$v_{L(1)}$ and $v_{L(2)}$ = velocities of longitudinal waves in material 1 and 2 respectively.
$v_{T(1)}$ and $v_{T(2)}$ = velocities of transverse waves in material 1 and 2 respectively.
α_L and α_T = angles of reflection of longitudinal wave and transverse wave respectively in material 1.
α_L = angle of incidence of longitudinal wave.
β_L and β_T = angles of refraction of longitudinal wave and transverse wave respectively in material 2.

Figure 1.14 Phenomena of reflection,refraction and mode conversion for an incident wave.

1.1.6.2.7. Snell's Law

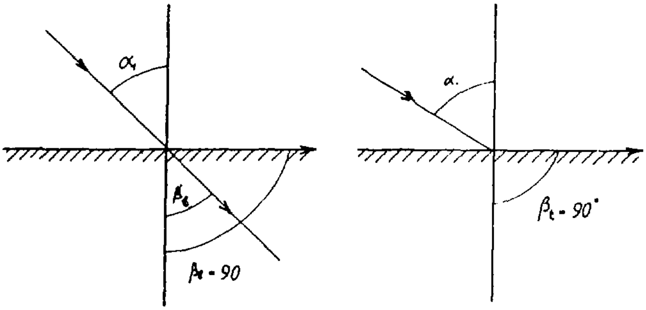
The general law that describes wave behaviour at an interface is known as Snell's Law. According to Snell's Law the ratio of the sine of the angle of incidence to the sine of the angle of reflection or refraction equals the ratio of the corresponding velocities. Mathematically Snell's Law can be expressed as

$$\sin \alpha / \sin \beta = v_1/v_2$$

where
α is the angle of incidence,
β is the angle of reflection or refraction, and
v_1 and v_2 are the respective velocities of the incident and reflected or refracted waves.

1.1.6.2.8 First and Second Critical Angles

If the angle of incidence α_1 is small (Figure 1.15), ultrasonic waves travelling in a medium undergo the phenomena of mode conversion and refraction on encountering a boundary with another medium. This results in the simultaneous propagation of longitudinal and transverse waves at different angles of refraction in the second medium As the angle of incidence is increased , the angle of refraction also increases. When the refraction angle of a longitudinal wave reaches 90° the wave emerges from the second medium and travels parallel to the boundary (Figure 1.15a). The angle of incidence at which the refracted longitudinal wave emerges is called the first critical angle. If the angle of incidence α_1 is further increased the angle of refraction for the transverse wave also approaches 90°. The value of α_1 (Figure 1.15b) for which the angle of refraction of the transverse wave is exactly 90° is called the second critical angle. At the second critical angle the refracted transverse wave emerges from the medium and travels parallel to the boundary. The transverse wave has become a surface or Raleigh wave.



a) First critical angle

b) Second critical angle

Figure 1.15 First and Second Critical Angles

1.1.6.3 Equipment for ultrasonic testing

1.1.6.3.1 Flaw detector

A general purpose ultrasonic test unit (Figure 1.16) comprises the following essential modules.

i) A pulsed oscillator which, when electrically triggered generates a burst of alternating voltage. The principal frequency of the burst, its duration, the profile of the envelope of the burst and the burst repetition rate may be either fixed or adjustable depending on the flexibility of the unit.

ii) A sending transducer (probe) to which the voltage burst is applied and which mechanically vibrates in more or less faithful compliance with the applied alternating voltage. When appropriately coupled to an elastic medium, the transducer thus serves to launch ultrasonic waves into the medium.

iii) A receiving transducer (probe) which serves to convert ultrasonic waves that impinge upon it in to corresponding alternating voltages. In the pitch - catch mode, the sending and receiving transducers are separate units, in the pulse echo mode , a single transducer alternately serves both functions.

iv) A receiver that amplifies and (if desired) demodulates the received signal.

v) A display oscilloscope with which the user can observe the wave form of signal voltages.

vi) An electronic clock or timer which serves as a source of logic pulses and reference voltage wave forms. The timer governs the internal operation of the system as a whole.

The unit also includes a power supply. Additional features which are often included in test units are electronic compensation for loss of signal amplitude caused by attenuation of the ultrasonic pulse in the medium under test and electronic gates which monitor the return signal for pulses of selected amplitude and which occur within a selected time delay range (corresponding to defects of a certain size at a prescribed depth). Other refinements are available especially in the areas of signal processing and automatic interpretation and in the interfacing of the unit with mechanical scanning systems.

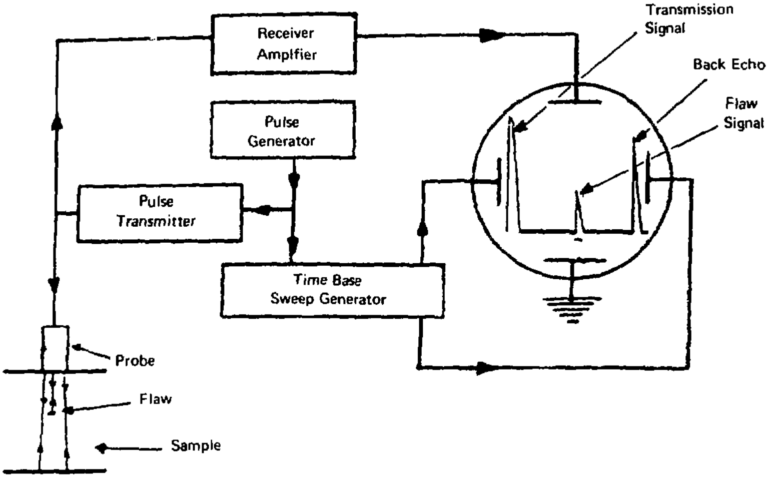


Figure 1.16 A typical ultrasonic test unit

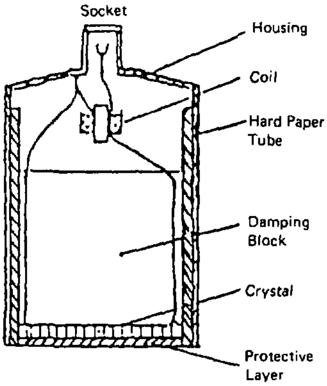


Figure 1.17 A typical normal beam single crystal ultrasonic probe

1.1.6.3.2. Transducers

Certain natural and artificially made crystals show the effect of piezoelectricity i.e. they produce electric charges on being subjected to mechanical stresses and vice versa. Thus on the application of electric pulses of appropriate frequency these crystals produce ultrasonic pulses which are mechanical vibrations. The most commonly used materials are quartz, lithium sulphate, barium titanate and lead meta-niobate. The properly cut crystal is contained in a housing , the whole assembly being termed an ultrasonic probe. The two faces of the crystal are provided with electrical connections. On the front face of the crystal (the face which comes in contact with the test specimen) a perspex piece is provided to avoid wear and tear of the crystal. At the rear of the crystal there is damping material such as a spring or tungsten araldite. This damping material is necessary to reduce the vibration of the crystal after transmitting the ultrasonic pulse so that the crystal can be more efficient as a receiver of sound energy. Damping is necessary therefore to improve the resolution of the probe. A typical probe is shown in Figure 1.17.

1.1.6.3.2.1. Fundamental Resonant Frequency

The fundamental resonant frequency is the vibrating frequency of the crystal and is given by $F_f = v/2t$ where v is the frequency of sound in m/sec in the crystal material and t is the thickness of the crystal in meters. The frequency F_f is in Hertz.

1.1.6.3.2.2. Near and Far Zones

The ultrasonic beam from a transducer looks like the one shown in Figure 1.18.

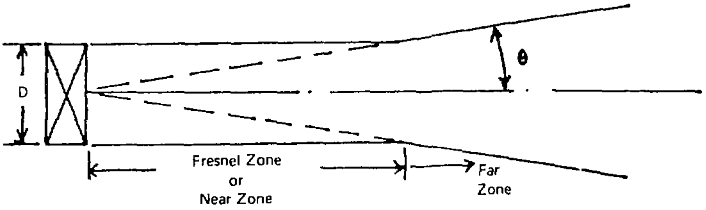


Figure 1.18 Ultrasonic beam from a transducer showing the near and far fields(simplified)

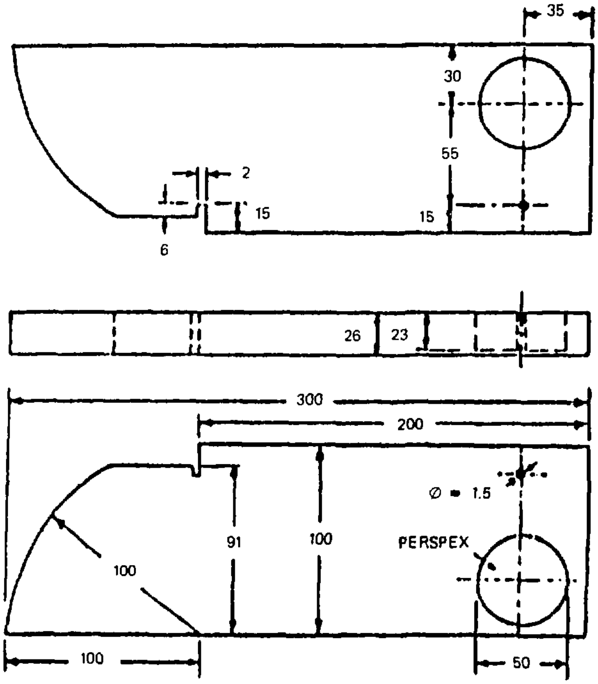


Figure 1.19 I.I.W test block

In the near field the ultrasonic beam within the material under test remains parallel and has the same diameter as that of the transducer. The extent of the near field, which is also known as the Fresnel zone, in front of the crystal is given by $D^2/4\lambda$ where D is the crystal

diameter and λ the wavelength in the material under test. In the near field the intensity of the ultrasonic beam fluctuates through successive maxima and minima due to interference effects. This part of the beam is generally not used to test materials.
In the far field the intensity of sound falls obeying an inverse square law and the beam diverges at an angle Θ given by $\sin(\Theta/2) = Kv/fD$ where K is a factor which increases from the beam axis to the edge of the beam. Most testing is carried out in the far field of the beam.

1.1.6.4. Ultrasonic Test Blocks

There are a number of test blocks used in the ultrasonic testing of materials. They help in the calibration of the flaw detector - probe system and also provide a means of comparing test results with standardised and known ultrasonic reflectors. Some of the commonly used test blocks are described.

1.1.6.4.1. I.I.W test block

The I.I.W test block, shown in Figure 1.19, can be used to set test sensitivity,time base calibration, determination of shear wave probe index, determination of shear wave probe angle, checking the amplifier linearity and checking the flaw detector - probe resolving power. The block is sometimes referred to as the V1 block.

1.1.6.4.2. V2 test block

This test block is mainly used with the miniature angle probes to calibrate the CRT screen. The block is shown in Figure 1.20 along with the CRT screen appearance when the probe is placed in two different positions on the block.

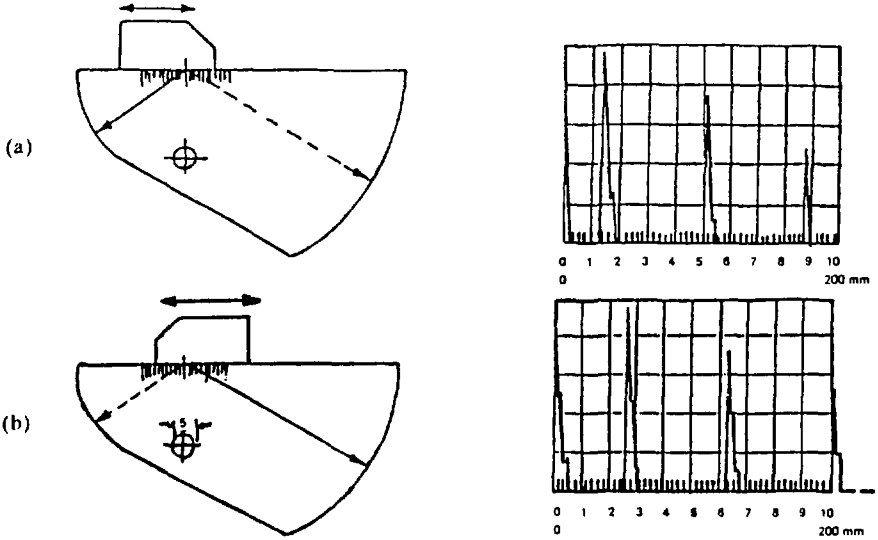


Figure 1.20 V2 test block (a) with the probe index at the zero point and directed to the 25mm radius, (b) with the probe index at the zero point and directed to the 50mm radius.

1.1.6.4.3. Flat bottom hole (FBH) test blocks

These types of test block are made from a plate of the same material as the material under test. The ASTM Area - Amplitude blocks and Distance - Amplitude blocks are examples of this type of block, Figure 1.21.

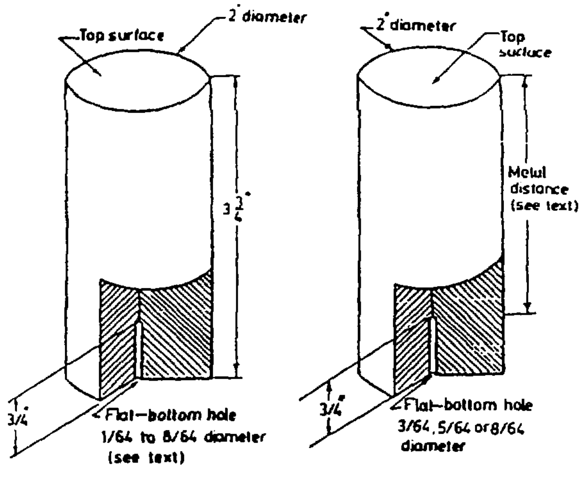


Figure 1.21 Flat bottom hole type test block

These blocks provide known reflectors area which can be compared to reflections from unknown reflectors. It also enables reproducible levels of sensitivity to be set and therefore to approximate the magnitude of flaws in terms of reflectivity.

1.1.6.4.4. General

In addition to the standard test blocks there are a number of other test blocks available. In general a test block is made to meet the inspection requirements of the job. Essentially a test block should simulate the physical and metallurgical properties of the specimen under test. The variety of test blocks available can be found by consulting the various national standards e.g. ASME, ASTM, BS, DIN, JIS etc.

1.1.6.5. Methods of Ultrasonic Testing

1.1.6.5.1. Direct or through transmission method

In this method two ultrasonic probes are used. One is the transmitter probe and the other the receiver probe which is situated on the opposite side of the specimen to the transmitter probe., Figure 1.22

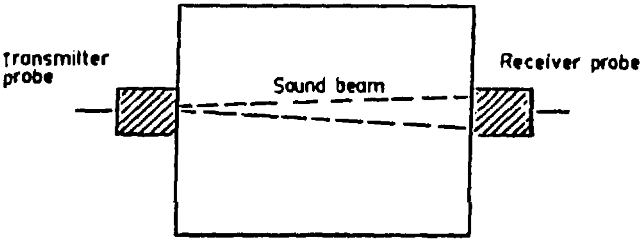


Figure 1.22 Position of transmitter probe and receiver probe in the direct transmission method of ultrasonic testing.

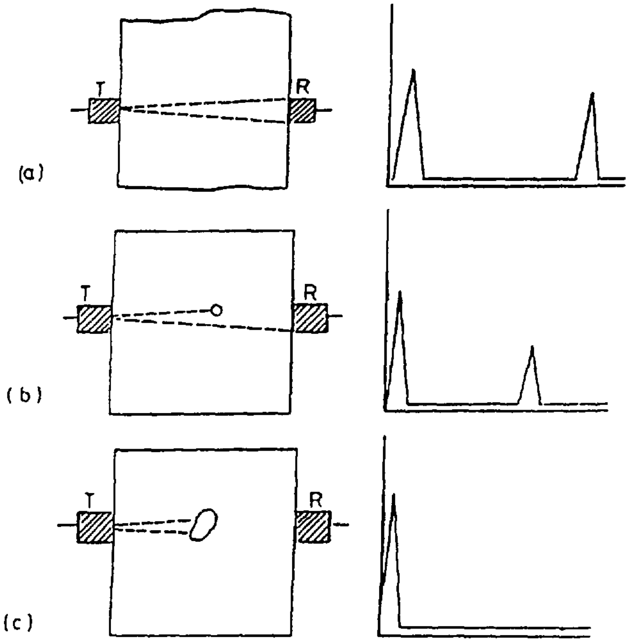


Figure 1.23 (a) Defect free specimen, (b) Specimen with a small defect, (c) Specimen with a large defect.

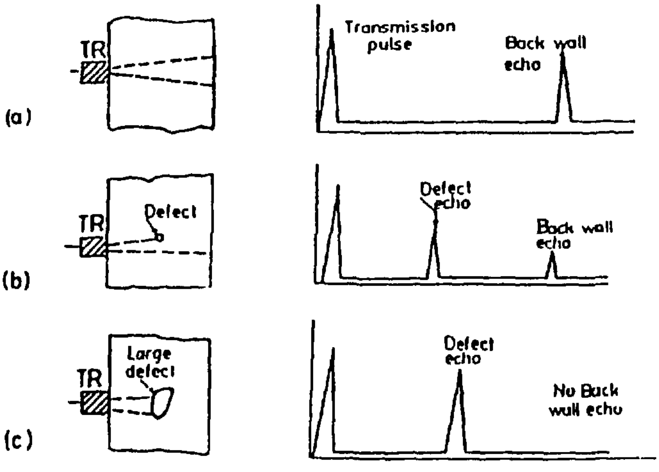


Figure 1.24 Principle of pulse echo method of ultrasonic testing. (a) defect free specimen (b) specimen with small defect (c) specimen with large defect.

In this case the presence of an internal defect is indicated by a reduction in amplitude or,in the case of gross defects, by complete loss of the transmitted signal. The appearance of the CRT screen in such cases is illustrated in Figures 1.23 (a), (b) and (c).This method is normally used to inspect large ingots and castings which can have gross defects. The method does not give the defect size and position. In addition a good method of mechanical coupling is essential to properly align the probes.

1.1.6.5.2 Pulse-echo or reflection method

This is the method most commonly utilised in the ultrasonic testing of materials. The transmitter and receiving probes are on the same side of the specimen and the presence of a defect is indicated by the reception of an echo before that of the boundary or backwall signal. The CRT screen shows the separation between the time of arrival of the defect echo compared to that of the natural boundary of the specimen, therefore, location of the defect can be assessed accurately. Usually one probe acts simultaneously as a transmitter and then as a receiver and is referred to as a TR probe. The principle of the pulse echo method is illustrated in Figure 1.24.

The time base of the CRT can be calibrated either in units of time or,if the velocity of sound in the material is known, in units of distance. If " l " is the distance from the transducer to the defect and " t " the time taken for waves to travel this distance in both directions then, $l = vt/2$ where v is the sound velocity in the material.

1.1.6.5.3 Resonance method

A condition of resonance exists whenever the thickness of a material equals half the wavelength of sound or any multiple thereof in that material. Control of wavelength in ultrasonics is achieved by control of frequency. If we have a transmitter with variable frequency control, it can be tuned to create a condition of resonance for the thickness of plate under test. This condition of resonance is easily recognised by the increase of received pulse amplitude. Knowing the resonance or fundamental frequency "f" and velocity "v" of ultrasound in the specimen the thickness "t" of the specimen under test can be calculated from the equation :-

$$t = v/2f$$

Since it is difficult to recognise the fundamental mode of vibration, the fundamental frequency is usually calculated from the difference of two adjacent harmonics which are depicted by two adjacent rises in the pulse amplitude. Therefore :-

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

where

f_n = frequency at nth harmonic.
f_{n-1} = frequency at (n-1) th harmonic.

The resonance method of ultrasonics was at one time specially suited to the measurement of thickness of thin specimens such as the cladding tubes for reactor fuel elements. The method has now be largely superseded by the pulse echo method because of improved transducer design.

1.1.6.6 Recommended procedures for ultrasonic testing

The choice of method and procedure to conduct an ultrasonic test is influenced by a number of factors. Also the nature of test problems in industry varies over a wide range. Therefore it is difficult to define a method which is versatile enough to work in all situations. However it is possible to outline a general procedure which will facilitate the inspection by ultrasonics in most cases. Some of the important steps involved in the inspection procedure are discussed in the following sections.

1.1.6.6.1. The test specimen

Specimen characteristics such as the condition and type of surface , the geometry and the microstructure are important. Very rough surfaces may have to be made smooth by grinding etc. Grease , dirt and loose scale or paint should be removed. The geometry of the specimen should be known since this has a bearing on the reflection of sound inside the specimen. Some reflections due to a complex geometry may be confused with those from genuine defects. The material microstructure or grain structure affects the degree of penetration of sound through it. For a fixed frequency the penetration is more in fine grained materials than in coarse grained materials.

1.1.6.6.2. Types of probes and equipment

The quality of ultrasonic trace depends on the probes and equipment which in turn determine the resolving power, the dead zone and the amount of sound penetration. It is difficult to construct a probe which will provide good detection and resolving qualities and at the same time provide deep penetration. For this reason , a variety of probes exist some of which are designed for special purposes. For the examination of large surface areas it is best to use probes with large transducers in order to reduce the time taken for the test. However the wide beam from such a probe will not detect a given size of flaw as easily as a narrower one. The probability of detecting flaws close to the surface depends on the type of equipment and probes used. The dead zone can be decreased in size by suitably designing the probe and also shortening the pulse length.

The selection of the test frequency must depend upon previous experience or on preliminary experimental tests or on code requirements. The finer the grain structure is , the greater is the homogeneity of the material and the higher is the frequency which can be applied. The smaller the defects being looked for the higher the frequency used. Low frequencies are selected for coarse grained materials such as castings etc.

After the selection of the probe and the equipment has been finalised , its characteristics are checked with the help of test blocks.

1.1.6.6.3. Nature of defects

Defect characteristics which include the type, size and location, differ in different types of materials. They are a function of the manufacturing process and the service conditions of the material.

The detection and evaluation of large defects is not normally a difficult problem. The outline of a defect can be obtained approximately by moving the probe over the surface of the test specimen. The flaw echo increases from zero to a maximum value as the probe is moved from a region free from defects to a point where it is closest to a defect. Information as to the character of a defect can be obtained from the shape of the defect echo. For small defects , the size of the defect is estimated by comparing the flaw reflectivity with the reflectivity of standard reflectors. If the standard reflector is of the same shape and size as the unknown flaw, the reflectivity will be the same at the same beam path length. Unfortunately this is seldom the case since reference reflectors are generally flat bottomed holes or side drilled holes and have no real equivalence to real flaws. Theoretically it is possible under favourable conditions to detect flaws having dimensions of the order of half a wavelength.

Indications obtained with an ultrasonic flaw detector depend to a great extent on the orientation of the defect in the material. Using the single probe method the largest echoes are obtained when the beam strikes the surface of the specimen at right angles. On a properly calibrated time base the position of the echo from a defect indicates its location within the specimen. The determination of the type, size and location of defects which are not at right angles to the sound beam is complicated and needs deep understanding and considerable experience.

1.1.6.6.4. Selection of couplant

The couplant provides impedance matching between the probe and the test specimen. The degree of acoustic coupling depends on the roughness of the surface and the type of couplant used. In general the smoother the surface the better the conditions for the penetration of ultrasonic waves into the material under test. Commonly used couplants are water, oils of varying degrees of viscosity, grease, glycerin and a mixture of 1 part glycerin to 2 parts water. Special pastes such as Polycell mixed with water are also used.

1.1.6.6.5. Test standards

Standards are used to check the performance of the flaw detector - probe system. There are mainly two types of these standards. The first type of standard is used to control. such parameters as amplifier gain, pulse power and time base marking and to ensure that they remain constant for the whole of the test. They are also used to verify the angle of incidence and to find the point where the beam emerges in angle probes. Another purpose of this group of standards is to calibrate the time base of the oscilloscope.

The second group of standards contains those used for special purposes. They are normally used for tests which are largely dependent on the properties of the examined material and , if possible , they are made of the same materials and have the same shapes as the examined objects. These standards allow for the setting of the minimum permissible defect as well as the location of defects.

1.1.6.6.6. Scanning procedure

Before undertaking an ultrasonic examination , the scanning procedure should be laid down. For longitudinal probes this is simple but care must be taken with angle or shear wave probes. For instance in the inspection of welds using an angle probe scanning begins with the probe at either the half skip or full skip positions and continues with the probe being moved in a zigzag manner between the half skip and full skip positions. There are in general four scanuing movements in manual scanning, rotational, orbital, lateral and traversing. The half skip position is recommended for critical flaw assessment and size estimation whenever possible. In the gap scanning method, an irrigated probe is held slightly away from the material surface by housing it in a recess made in a contact scanning head. Probe wear can be avoided by interposing a free running endless belt of plastic ribbon between the probe and the test surface. Acoustical coupling is obtained by enclosing the probe in an oil filled rotating cylinder in which case only the surface requires irrigation.

Immersion scanning which is most commonly used in automatic inspection is done by holding the probe under water in a mechanical or electronic manipulator, the movement of which controls the movement of the probe.

1.1.6.6.7. Defect sizing

The commonly used methods for flaw sizing in ultrasonic testing are :

i. 6 dB drop method.
ii. 20 dB drop method.
iii. Maximum amplitude method.
iv. DGS diagram method.

1.1.6.6.7.1. 6 dB Drop Method

The basic assumption in this method is that the echo height displayed when the probe is positioned for maximum response from the flaw will fall by one half (i.e. by 6 dB and hence the name) when the axis of the beam is brought in to line with the edge of the flaw

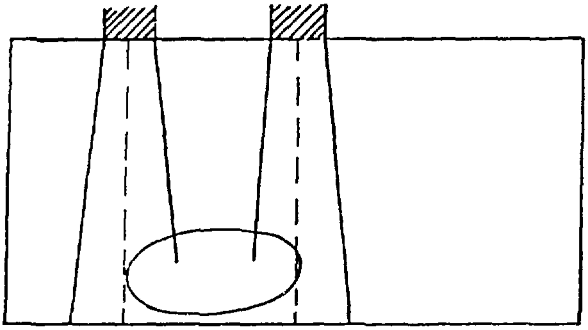


Figure 1.25 Defect sizing using the 6 dB drop method

as illustrated in Figure 1.25. The method only works if the ultrasonic response from the flaw is essentially uniform over the whole reflecting surface.

The procedure to determine the dimension of a flaw parallel to the probe movement ie. the flaw length is as follows :

i. Position the probe to get maximum echo from the flaw.
ii. Adjust the height of the echo to some convenient scale on the CRT screen by using the gain control of the flaw detector.
iii. Move the probe across the flaw in one direction until the echo height falls to one half of the height adjusted in (ii).
iv. Mark the centre of the probe on the surface of the test specimen for this probe position.
v. Now move the probe in the opposite direction through the maximised echo position to the position when the echo height again falls to one half of the height adjusted in (ii).
vi. Mark the probe centre at this position as well.
vii. The distance between the two marks gives the dimension of the defect parallel to the probe movement.If the reflectivity of the flaw varies considerably the probe is moved until the last significant echo peak is observed just before the echo drops off rapidly. This peak is brought to full screen height and then the probe is moved as in iii. A similar procedure is followed for the other end of the flaw.

The 6 dB drop method is suitable for the sizing of flaws which have sizes of the same order or greater than that of the ultrasonic beam width but will give inaccurate results with flaws of smaller sizes than the ultrasonic beam. It is therefore generally used to determine flaw length but not flaw height.

1.1.6.6.7.2. 20 dB Drop Method

This method utilises for the determination of flaw size, the edge of the ultrasonic beam where the intensity falls to 10% (i.e. 20 dB) of the intensity at the central axis of the beam.

The procedure to determine the size of the flaw with the 20 dB drop method is as follows :

i. Position the probe to get a maximum echo amplitude from the flaw.
ii. Adjust the echo amplitude to some convenient scale on the CRT screen using the gain control of the flaw detector.
iii. Move the probe first across the flaw in one direction until the echo amplitude falls to 1/10th of its original height (i.e.by 20 dB).
iv. Mark the position of the probe index on the surface of the test specimen at this position.
v. Now move the probe in the opposite direction through the maximised echo position until the echo amplitude again falls to 1/10th of its original height.

vi. Mark the position of the probe index on the surface at this position.
vii. Measure the distance between the two markings.
viii. Determine the beam width W at the depth, d, of the flaw from the beam profile diagram or from the equation.

$$W = D + 2(d - X_0)\tan\phi$$

where

W = beam width,
d = defect depth,
X_0 = near field length,
D = probe diameter,
ϕ = angle of beam spread.

ix. (vii) minus (viii), as illustrated in Figure 1.26 will thus give the dimension of the flaw parallel to the movement of the ultrasonic beam.

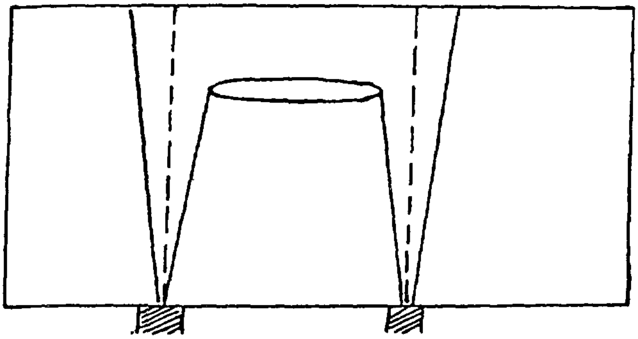


Figure 1.26 20 dB method of defect sizing

As for the 6dB drop method if the echo amplitude varies as the probe is traversed across the flaw the 20dB drop should be carried out from the last significant echo peak. The 20 dB drop method gives more accurate results than the 6 dB drop method because of the greater control one has on the manipulation of the ultrasonic beam. However size estimation using either the 6 dB or 20 dB drop methods have inherent difficulties which must be considered. The main problem is that the amplitude may drop for reasons other than the beam scanning past the end of the defect :

1. The defect may taper in section giving a reduction in cross sectional area within the beam. If this is enough to drop the signal 20 dB or 6 dB the defect may be reported as finished while it in fact continues for an additional distance.

2. The orientation of the defect may change so that the probe angle is no longer giving maximum response - another probe may have to be used.

3. The defect may change its direction.

4. The probe may be twisted inadvertently.

5. The surface roughness may change.

1.1.6.6.7.3. Maximum amplitude technique

This method takes in to account that fact that most defects which occur do not present a single, polished reflecting surface, but in fact take a rather ragged path through the material with some facets of the defect surface suitably oriented to the beam and some unfavorably oriented. Figure 1.27 illustrates this, showing a crack propagating in a weld.

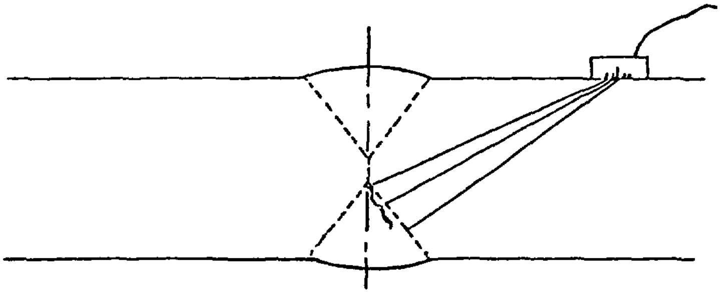


Figure 1.27 Illustration of ragged weld crack

Each of the reflecting facets will be at a slightly different range, and although they may be too close together to resolve as separate echoes, the echo envelope can nevertheless be regarded as a series of overlapping separate echoes. In fact the envelope may look like Figure 1.28 a, b, or c depending on the degree of range variation from the different facets and on the resolution of the equipment. As the beam is scanned across the surface of the defect, the beam centre will sweep each facet in turn. As it does, the echo from that facet will reach a maximum and then begin to fall, even though the main envelope may at any instant, be rising or falling in echo amplitude. The stand-off and range of the maximum echo of each facet is noted and plotted on the flaw location slide. This results in a series of points which trace out the extent of the defect. The gain is increased to follow the series of maximum echoes until the beam sweeps the last facet.

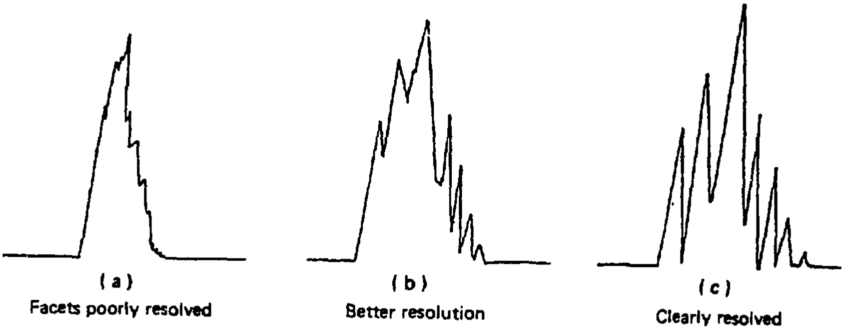


Figure 1.28 Response from weld crack

1.1.6.6.7.4. DGS Diagram Method

This method makes use of the so called DGS diagram, developed by Krautkramer in 1958 by comparing the echoes from small reflectors, namely different diameter flat bottomed holes located at various distances from the probe, with the echo of a large reflector, a back wall reflector, also at different distances from the probe. The difference in the amplitude of echoes of the flat bottomed holes and the back wall reflector is determined in decibels i.e. dB. The universal DGS diagram for normal beam probes, which can be used for any normal beam probe irrespective of the size and frequency of the probe, is shown in Figure 1.29.

This diagram relates the distance D from the probe (i.e along the beam) in near field units ,thus compensating for probes of different size and frequency ,to the gain G in dB for a flat bottomed hole (f.b.h.) compared to a particular back wall reflector and the size S of the flat bottom hole as a proportion of the probe crystal diameter.

Since in the case of angle beam probes some of the near field length is contained within the perspex path length and this varies for different designs and sizes of probe, individual

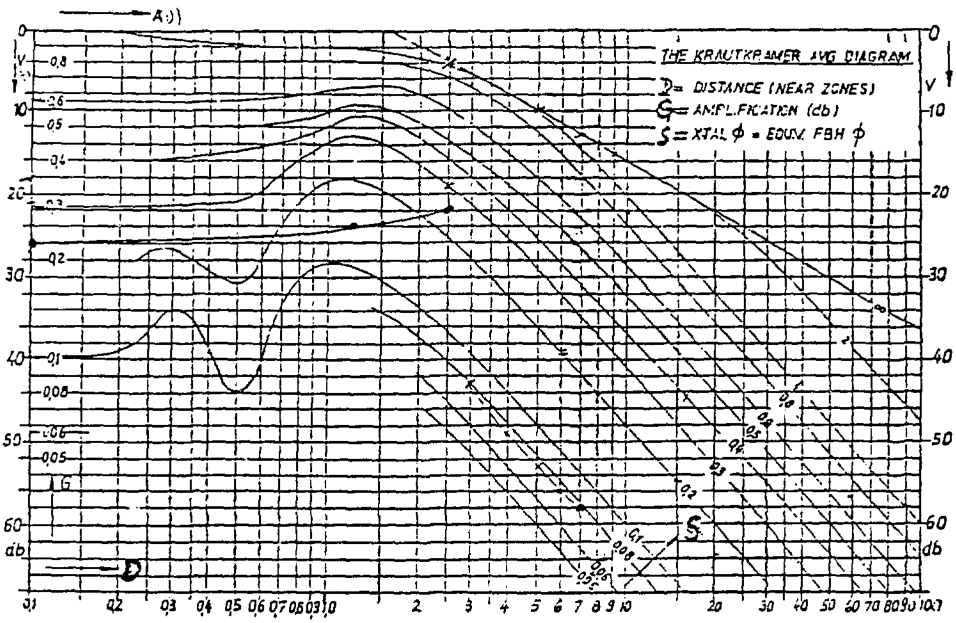


Figure 1.29 Universal DGS diagram.

DGS diagrams are drawn for each design size and frequency of angle beam probe. For this reason the scale used in the angle beam probe DGS diagrams is simplified: the D-scale is calibrated in beam path lengths,the G-scale in decibels as before and the S-scale representing flat bottom hole or disc shaped reflector diameters in mm. Figure 1.30 shows a typical DGS diagram for a particular angle beam probe.

1.1.6.6.8 Test Report

In order that the results of the ultrasonic examination may be fully assessed it is necessary for the tester's findings to be systematically recorded. The report should contain details of the work under inspection, the code used, the equipment used and the calibration and scanning procedures. Also the probe angles, probe positions, flaw ranges and amplitude should be recorded in case the inspection needs to be repeated. The principle is that all the information necessary to duplicate the inspection has to be recorded.

1.1.6.7. Some applications of ultrasonics in the testing of materials

Because of the many applications which exist , the applications are only listed to show the wide applicability of the method.

1.1.6.7.1. Thickness measurements

Thickness measurements using ultrasonics can be applied using either the pulse or resonance techniques. Some typical applications are:

i) Wall thickness measurements in the shells of pressure vessels and other containers.
ii) Wall thickness measurement in pressure vessels, pipelines, gas holders, storage tanks for chemicals and other structures where it is necessary to have an accurate estimate of the effect of wear and corrosion without having to dismantle the plant.
iii) Measurement of the thickness of ship hulls for corrosion control.
iv) Control of machining operations, such as final grinding of hollow propellers and chemical machining.

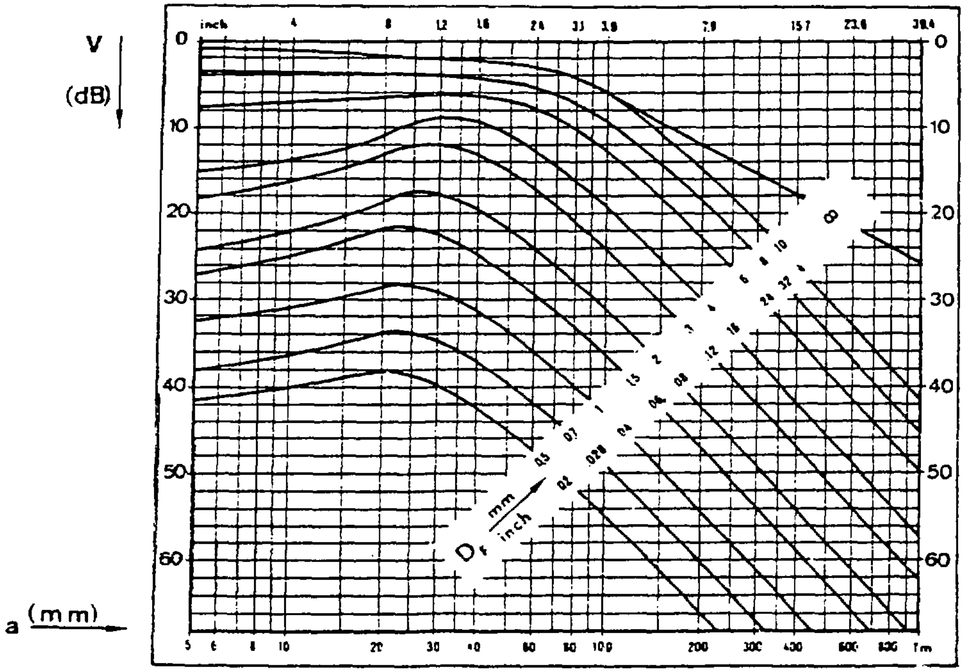


Figure 1.30. DGS diagram for an angle beam probe

v) Ultrasonic thickness gauging of materials during manufacture
vi) Measurement of wall thickness of hollow aluminium extrusions.
vii) Measurement of the thickness of lead sheath extruded over a core of wire and insulating material.
viii) Inspection of heat exchanger tubing in nuclear reactors.
ix) Measurement of the wall thickness of small bore tubing including the canning tubes for reactor fuel elements.

1.1.6.7.2. Flaw detection

Typical flaws encountered in industrial materials are cracks, porosity, laminations, inclusions, lack of root penetration, lack of fusion cavities, laps,seams corrosion etc. Some examples of the detection of these defects area as follows:

i) Examination of welded joints in pressure vessels, containers for industrial liquids and gases, steel bridges, steel or aluminium columns, frames and roofs.
ii) Inspection of plates for the welded shells of nuclear reactors.
iii) Inspection of steel, aluminium and other castings.
iv) Inspection of rolled billets, bars and sections.
v) Inspection of small bore tubes including the canning tubes for nuclear fuel elements.
vi) Ultrasonic testing of alloy steel forgings for large turbine rotors.
vii) Testing of turbine rotors and blades for aircraft engines.
viii) Early stage inspection in the production of steel and aluminium blocks and slabs, plates, bar sections, tubes , sheet and wire.
ix) Detection of unbonded surfaces in ceramics, refractories, rubber, plastics and laminates.
x) Detection of honeycomb bond in the aircraft industry
xi) Inspection of jet engine rotors.
xii) Detection of caustic embrittlement failure in riveted boiler drums in the power generation industry.

xiii) Detection of cracks in the fish plate holes in railway lines and in locomotive and bogey axles.
xiv) Detection of hydrogen cracks in roller bearings resulting from improper heat treatment.
xv) In service automatic monitoring of fatigue crack growth.
xvi) Detection of stress corrosion cracking.
xvii) Detection of fatigue cracks in parts working under fluctuating stress.
xviii) Inspection of fine quality wire.
xix) Testing of wooden components such as utility poles
xx) Application of ultrasonics to monitor material characteristics in the space environment.
xxi) Determination of lack of bonding in clad fuel elements.
xxii) Detection of flaws in grinding wheels.
xxiii) Varieties of glass which are not sufficiently transparent to allow optical inspection can be tested ultrasonically.
xxiv) Quality control in the manufacture of rubber tyres by locating voids etc.
xxv) Detection of small hydrogen flakes in gas carburised roller bearing forgings.
xxvi) Inspection of engine crankshafts.

1.1.6.7.3. Miscellaneous applications

As well as the applications already mentioned there are numerous others. Notable among these are those based on the measurement of acoustic velocity and the attenuation of acoustic energy in materials. Some of these applications are as follows:

i) Assessment of the density and tensile strength of ceramic products such as high tension porcelain insulators.
ii) Determination of the difference between various types of alloys.
iii) Detection of grain growth due to excessive heating.
iv) Estimation of the values of the elastic moduli of metals over a wide range of temperature and stress.
v) Tensile strength of high grade cast iron can be estimated by measuring its coefficient of acoustical damping.
vi) Crushing strength of concrete can be measured from the transit time of an ultrasonic pulse.
vii) Quarrying can be made more efficient by the measurement of pulse velocity or attenuation in rock strata.
viii) To find the nature of formations in geophysical surveys without having to undertake boring operations.
ix) Detection of bore hole eccentricity in the exploration for mineral ores and oil.
x) Study of press fits.
xi) Metallurgical structure analysis and control of case depth and hardness, precipitation of alloy constituents and grain refinement.
xii) Determination of intensity and direction of residual stresses in structural metal components.
xiii) Detection of honeycomb debonds and the regions in which the adhesive fails to develop its nominal strength in the aerospace industry.
xiv) Measurement of liquid level of industrial liquids in containers.

1.1.6.8 Comparison of ultrasonic testing with radiographic and other NDT methods

Advantages

The principal advantages of ultrasonic inspection as compared to other methods for nondestructive inspection of metal parts are:

i) Superior penetrating power, which allows the detection of flaws deep in the part. Ultrasonic inspection is done routinely to depths of about 20ft in the axial inspection of parts such as long steel shafts and rotor forgings.

ii) High sensitivity, permitting the detection of extremely small flaws.

iii) Greater accuracy than other nondestructive methods in determining the position of internal flaws, estimating their size and characterising their orientation, shape nature.

iv) Only one surface needs to be accessible.

v) Operation is electronic, which provides almost instantaneous indications of flaws. This makes the method suitable for immediate interpretation, automation, rapid scanning, on-line production monitoring and process control. With most systems, a permanent record of inspection results can be made for future reference.

vi) Volumetric scanning ability, enabling inspection of a volume of metal extending from the front surface to the back surface of a part.

vii)Is not hazardous to operators or to nearby personnel, and has no effect on equipment and materials in the vicinity.

viii) Portability.

Disadvantages

i) Manual operation requires careful attention by experienced technicians.

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

iii) Parts that are rough, irregular in shape, very small or thin, or not homogeneous are difficult to inspect.

iv) Discontinuities that are present in a shallow layer immediately beneath the surface may not be detectable.

v) Couplants are needed to provide effective transfer of ultrasonic wave energy between transducers and parts being inspected.

vi) Reference standards are needed, both for calibrating the equipment and for characterising flaws.

Government agencies and standards making organisations have issued inspection procedures, acceptance standards and related documentation. These documents are mainly concerned with the detection of flaws in specific manufactured products, but they also can serve as the basis for characterising flaws in many other applications. For successful application of ultrasonic inspection, the inspection system must be suitable for the type of inspection being done, and the operator must be sufficiently trained and experienced. If either of these prerequisites is not met, there is a high potential for gross error in inspection results. For instance, with inappropriate equipment or with a poorly trained operator, discontinuities having little or no bearing on product performance may be deemed serious, or damaging discontinuities may go undetected or be deemed unimportant. The fact that a part contains one or more flaws does not necessarily imply that the part is non-conforming to specification or unfit for use. It is important that standards be established so that decisions to accept or reject parts are based on the probable effect that a given flaw will have on service life or product safety. Once such standards are established, ultrasonic inspection can be used to characterise flaws in terms of a real effect rather than to characterise them on some arbitrary basis that may impose useless or redundant quality requirements.

1.2. MATERIALS AND DEFECTS

1.2.1. Structure of Metals and Alloys

The properties of metals can be explained in terms of the manner in which the atoms of a metal are bonded together. In this bond, called the "metallic bond", each atom of the metal is closely surrounded by many similar atoms, each with only a few electrons in its outer electron shell. In this situation the electron clouds overlap and the loosely held outer electrons are so completely shared as to be no longer associated with individual atoms. Leaving the metal atoms in place as ions, they form an electron gas, a pervasive glue that moves freely among the ions and binds them together, Figure 1.31. Because the electrons are free to move in an electric field, metals conduct electricity. Because free electrons absorb and then radiate back most of the light energy that falls on them, metals are opaque and lustrous. Because free electrons can transfer thermal energy, metals conduct heat effectively.

The metallic bond is nonspecific, which explains why different metals can be alloyed or joined one to another. It is also nondirectional, pulling equally hard in all directions. It therefore binds the metal atoms tightly, so that their cores (nuclei and inner-shell electrons) fit closely among one another. The close packing favoured by the metallic bond is best realised in certain regular crystalline structures. These structures, although resistant to tension, offer less resistance to shearing forces, and thus they explain the ductility of metals. They are by definition dense, and thus they explain the comparative heaviness of metals. The mechanical properties of metals, then, derive from their crystalline structure. That is the atoms in the solid state of a metal are arranged in definite three dimensional geometric patterns to form 'crystals' or 'grains' of the metal. The network formed by joining the centres of the atoms in a crystal is called the 'space lattice' or 'crystal lattice' of the metal. The smallest volume in a space lattice which properly represents the position of the atoms with respect to each other is known as the 'unit cell'. There are fourteen types of unit cells but the structures of most of the common and commercially important metals in the solid state are constructed from the following three types of unit cells:

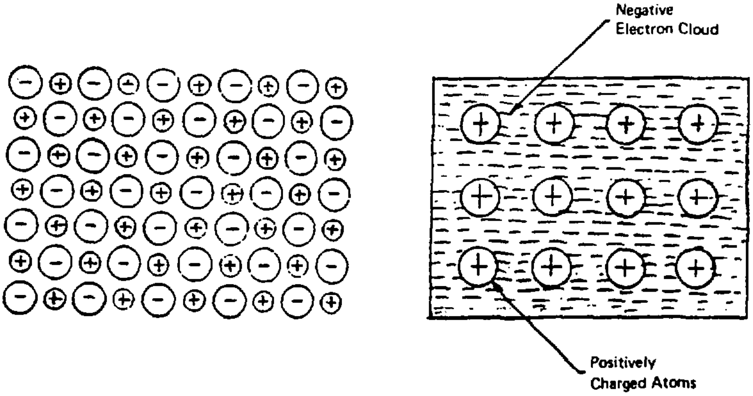


Figure: 1.31 Schematic illustration of a metallic bond

a) Body-centred cubic

The body-centred cubic cell is made up of nine atoms. Eight are located on the corners of the cube with the ninth positioned centrally between them (Figure 1.32a). The body-centred cubic is a strong structure, and in general, the metals that are hard and strong are in this form at normal temperatures. These metals include for example chromium, molybdenum, tantalum, tungsten, sodium and vanadium. Steel under 723°C also has this structure.

b) Face-centred cubic

Face-centred cubic cells consist of fourteen atoms with eight at the corners and the other six centred in the cube faces (Figure 1.32b). This structure is characteristic of ductile metals, which include aluminium, copper, gold, lead, nickel, platinum and silver. Iron, which is body-centred cubic at room temperature, is also of the face-centred structure in the temperature range from about 910° C to 1,400° C.

c) Hexagonal Close-packed

Seventeen atoms combine to make the hexagonal close-packed unit cell. Seven atoms are located in each hexagonal face with one at each corner and the seventh in the centre. The three remaining atoms take up a triangular position in the centre of the cell equidistant from the two faces (Figure 1.32c). The metals with this structure are quite susceptible to work-hardening. Some of the more commonly used metals that crystallise with this structure are cadmium, cobalt, magnesium, titanium, and zinc.

Tin is an exception to the other commonly used metals in that the atomic configuration is body-centred tetragonal, which is similar to the body-centred cubic but has wider atomic spacing and an elongated axis between two of the opposite faces (Figure 1 32b).

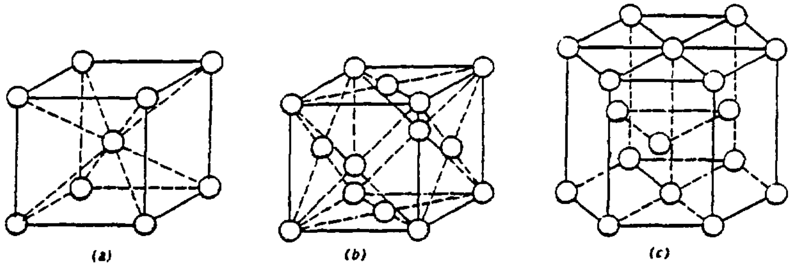


Figure 1.32 : Crystal types.

1.2.1.1. Grains (crystals) and grain boundary

When a metal is cooled from the liquid state to the solid state, because cooling cannot be exactly the same for every atom, certain atoms will be attracted to each other to form a unit cell ahead of others. This unit cell becomes the nucleus for crystal formation. As the cooling continues other atoms will take up their positions alongside this nucleus and the crystal, or as it is usually referred to for metals, the grain, will grow in size. This orderly growth of the grain continues in all directions until it runs into interference from other grains that are forming simultaneously about other nuclei. Figure 1.33 illustrates the process of the formation of grains and grain boundaries.

Although with some metals with special treatment it is possible to grow single crystals several inches in diameter, in most metals at the usual cooling rates, great numbers of crystals are nucleated and grow at one time with different orientations.
If two grains that have the same orientation meet, they will join to form a larger grain, but if they are forming about different axes, the last atoms to solidify between the growing grains will be attracted to each and must assume compromise positions in an attempt to satisfy a double desire to join with each. These misplaced atoms are in layers about the grains and are known as grain boundaries. They are interruptions in the orderly arrangement of the space lattices and offer resistance to deformation of the metal. A fine-grained metal with large numbers of interruptions, therefore, will be harder and stronger than a coarse-grained metal of the same composition and condition.

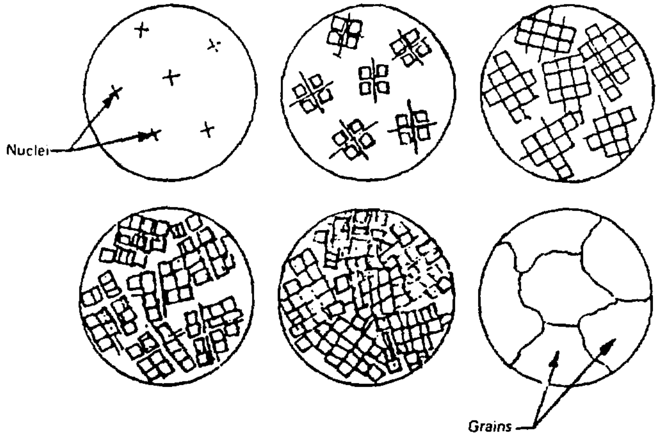


Figure 1.33 : Growth of crystals and grains during solidification.

1.2.1.2. Structure of alloys

Most commercially used metallic materials are not pure metals but alloys which consist of more than one element. Some of them may be non-metallic elements. Fundamentally, three modes of arrangement of atoms or phases exist in alloys. These three modes (phases) are; pure metal, solid solution and intermetallic compound. For simplicity of illustration, an alloy with two elements A and B, shall be considered in the following discussion.

a) Pure Metal

There exist no B-atoms in A-crystal grains and no A-atoms in B-grains i.e. mixture of pure A-and B-crystal grains. A and B metals are mutually insoluble. This complete lack of intersolubility is theoretically almost impossible. The solubility of one component in an other may be exceedingly small but hardly zero.

b) Solid Solution

There exist B-atoms (solute) in A-crystal grains (solvent). Solid solutions are of two types: substitutional solid solutions and interstitial solid solutions.

i. Substitutional solid solution

There exist B-atoms at the lattice points of A-crystals. For example, the lattice of nickel (A-crystal) can accommodate copper atoms (B-atoms) without loosing its f.c.c. structure (Structure of A-crystal).
In the Cu-Ni system the two elements can be substituted in all proportions and are said to be completely intersoluble. But commonly substitution of B-for A-atoms in limited, i.e., A and B are incompletely intersoluble.

ii. Interstitial solid solution

In the interstitial solid solution B-atoms are accommodated in the interstices of the lattice of A-crystal. Light atoms with small radii such as H, N, C and B tend to take up interstitial position in alloys. The solubility of solute atoms in solvent crystals in this type of solid solution is limited. Addition of B-atoms in solid solution may cause lattice expansion or contraction and metals are hardened (i.e. strengthened) by lattice distortion. The degree of hardening depends on the size and amount of B-atoms and the crystal structure of the A-and B-metals.

c) Intermetallic Compound

Elements A and B form an intermetallic compound A B. In contrast to a solid solution, the ratio of the number of A-atoms to B-atoms is fixed (m : n), and the crystal structure is quite different from both A-and B-metal crystals and usually very complicated. Almost all the intermetallic compounds are very hard and brittle due to their complicated crystal structure.

1.2.1. Allotropic Transformation

Many metals exist in more than one crystal structure. The transformation when a metal changes from one crystal arrangement to another is called an "allotropic transformation" or 'phase transformation'. In the iron-carbon alloy system such a transformation takes place between about 1300°F to 1600°F. The exact temperature is determined by the amount of carbon and other alloying elements in the metal. Iron transforms from a face-centred cubic (FCC) structure-called the gamma phase, or austenite, at high temperatures to a body-centred cubic (BCC) structure-alpha phase, or ferrite, at a lower temperature. In a bar of pure iron, this transformation is marked by a distinct increase in length as the metal cools below the critical temperature, because the body-centred lattice is less compact than the face centred lattice.The high-temperature austenite, or FCC structure, allows enough space for carbon to squeeze in between the iron atoms. Iron atoms maintain their place on the lattice and carbon atoms become "interstitials" . In the low-temperature ferrite, or BCC structure, however, there is no room for carbon atoms. What happens to these carbon atoms, determines many of the properties of iron and steel.

Finally, at about 1,350° F, the lower end of the transformation temperature range for 1020 steel, the last remaining austenite tries to transform in spite of the rich carbon concentrations. At this point, two things occur: The carbon bonds with available iron atoms to form Fe_3C, an intermetallic compound called cementite or iron carbide, and precipitates out as a discrete structure; and then the remaining austenite transforms to ferrite. The structure that results from this final transformation is a laminate consisting of alternating layers of ferrite and iron carbide. Of course, the portions of metal that transformed previously remain as large islands of pure ferrite. The laminated structure formed at the last moment is called pearlite. The combined structure of ferrite and pearlite is soft, ductile, and generally represents steel in its lowest strength condition. In contrast, when ferrous alloys are cooled rapidly, e.g. by quenching, expelled carbon atoms do not have time to move away from the iron as it transforms to ferrite. The steel becomes so rigid that, before the carbon atoms have a chance to move, they become trapped in the lattice as the iron atoms try to transform to the body-centred cubic structure. The result is a body-centred tetragonal structure in which the carbon atom is an interstitial member.

Steel that has undergone this type of transformation is called martensite. Naturally, martensite is in a state of unequilibrium, but owes much of its high strength and hardness (but lower ductility) to its distorted, stressed lattice structure. Figure 1.34 shows a typical phase diagram for steel.

1.2.2. Physical and Mechanical Properties of Metallic Materials

Mechanical properties are defined as the properties of a material that reveal its elastic and inelastic (Plastic) behaviour when force is applied, thereby indicating its suitability for mechanical applications; for example, modulus of elasticity, tensile strength, elongation, hardness, and fatigue limit. Other mechanical properties, not mentioned specifically above, are yield strength, yield point, impact strength, and reduction of area, to mention a few of the more common terms. In general, any property relating to the strength characteristics of metals is considered to be a mechanical property. Physical properties relate to the physics of a metal, such as density, electrical properties, thermal properties, magnetic properties and the like.

A brief mention has been made of some of the properties of metallic materials in the previous section. These and other properties will be described here in slightly more detail.

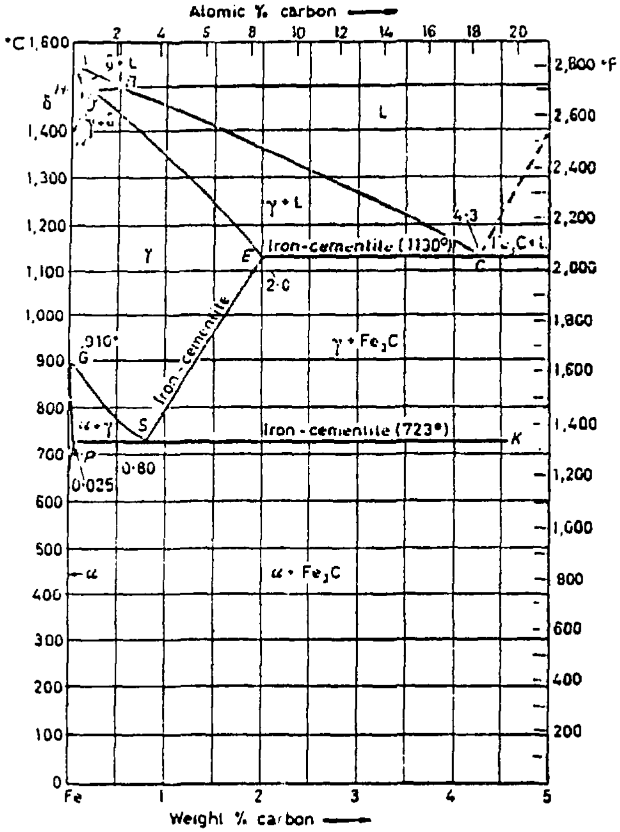


Figure 1.34 Equilibrium diagram for iron-carbon systems.

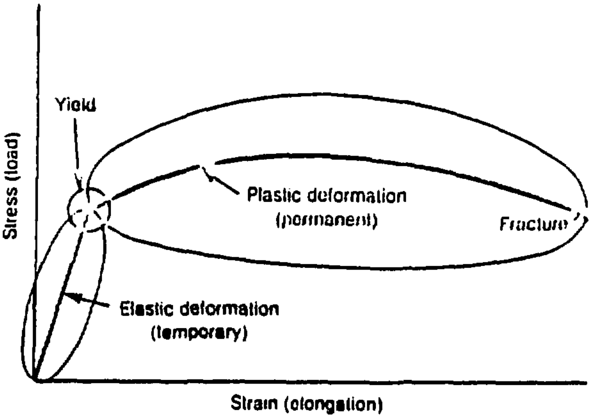


Figure 1.35: Stress-strain curve showing elastic and plastic portions of a typical curve.

1.2.2.1. Elasticity

When stress or force is applied to a metal, it changes shape. For example a metal under a compressive stress will shorten and metal in tension will lengthen. This change in shape is called strain. The ability of metal to strain under load and then return to its original size and shape when unloaded is called elasticity. The elastic limit (proportional limit) is the greatest load a material can withstand and still spring back into its original shape when the load is removed. Within the elastic range stress is proportional to strain and this is known as Hooke's law. The relationship between applied stress or load and the consequent strain or change in length is shown in Figure 1.35. The end of the straight line portion is known as the elastic limit. A point on the curve slightly higher than the elastic limit is known as the yield point or yield strength. The allowable or safe load for a metal in service should be well below the elastic limit. If higher loads are applied, however, the range of elasticity or elastic deformation is exceeded and the metal is now permanently deformed. Now it will not return to its original dimensions even when the load is removed. For this reason, the area of the stress-strain curve beyond the elastic limit is called the plastic range. It is this property that makes metals so useful. When enough force is applied by rolling, pressing or hammer blows, metals can be formed when hot or cold into useful shapes. If the application of load is increased in the plastic region a stage comes when the material fractures.

A very important feature of the stress-strain curve must be pointed out: the straight-line, or elastic, part of the stress-strain curve of a given metal has a constant slope. That is, it cannot be changed by changing the microstructure or heat treatment. This slope, called the modulus of elasticity, measures the stiffness of the metal in the elastic range; changing the hardness or strength does not change the stiffness of the metal. There is only one condition that changes the stiffness of any given metal. That is temperature. The stiffness of any metal varies inversely with its temperature: that is, as temperature increases, stiffness decreases, and vice versa.

The above comments on the elastic portions of the stress-strain curves apply to nearly all metals. However, there are a few metals that do not conform to Hooke's law. The reason in some cases e.g. gray cast iron, is the presence of graphite flakes embedded in the matrix of the metal. The flakes act as internal notches or stress concentrations and therefore give the metals unique and differert properties. Typical other examples of such metals are sintered metals and cold drawn steel bars.

1.2.2.2. Strength

The strength of a metal is its ability to resist changing its shape or size when external forces are applied. There are three basic types of stresses: tensile, compressive, and shear. When we consider strength, the type of stress to which the material will be subjected must be known. Steel has equal compressive and tensile strength, but cast iron has low tensile strength and high compressive strength. Shear strength is less than tensile strength in virtually all metals.

The tensile strength of a material in pounds per square inch(PSI), can be determined by dividing the maximum load (in pounds) by the original cross-sectional area (in square inches) before testing. Thus,

$$\text{Tensile strength (PSI)} = \frac{\text{Maximum load (lb)}}{\text{Original cross-sectional area (sq.in.)}}$$

To put it another way, the strength of materials is expressed in terms of pounds per square inch. This is called unit stress. The unit stress equals the load divided by the total area.

Metals are "pulled" on a machine called a tensile tester. A specimen of known dimensions is placed in the machine and loaded until it breaks. Instruments are sometimes used to make a continuous record of the load and the amount of strain. This information is put on a graph called a stress-strain diagram.

A stress-strain diagram can be made for any metal by preparing a specimen and by pulling it with a tensile testing machine. The cross-sectional area to be pulled is usually a standard diameter of which the area can be easily calculated in round numbers. The specimen is placed in the tensile testing machine and slowly pulled. If a strain gauge and an XY recorder are used, the diagram is automatically made.
If no recorder is available, the tensile testing machine may be stopped at intervals and the load, or stress, written down and the strain or distance between centre punched marks measured and copied down on the same line. With some equipment, readings may be taken without stopping the machine. Later, these stress-strain increments can be plotted on a graph to produce the stress-strain diagram for that particular metal.

1.2.2.3. Hardness

The hardness of a metal is its ability to resist being permanently deformed. There are three ways that hardness is measured; resistance to penetration, elastic hardness, and resistance to abrasion. Hardness varies considerably from material to material. This variation can be illustrated by making an indentation in a soft metal such as aluminium and then in a hard metal such as alloy tool steel. The indentation could be made with an ordinary centre punch and a hammer, giving a light blow of equal force on each of the two specimens. In this case just by visual observation you can tell which specimen is harder. Of course, this is not a reliable method of hardness testing, but it does show one of the principles of hardness testers; measuring penetration of the specimen by an indenter or penetrator, such as a steel ball or diamond point. Rockwell and Brinell hardness testers are the most commonly used types of hardness testers for industrial and metallurgical purposes. Heat treaters, inspectors, and many others in industry often use these machines. The Rockwell hardness test is made by applying two loads to a specimen and measuring the difference in depth of penetration in the specimen between the minor load and the major load. The minor load is used on the standard Rockwell tester to eliminate errors that could be caused by specimen surface irregularities. The major load is applied after the minor load has seated the indenter firmly in the work. The Rockwell hardness reading is based on the additional depth to which the penetrator is forced by the major load. The depth of penetration is indicated on the dial when the major load is removed. The amount of penetration decreases as the hardness of the specimen increases.

Generally the harder the material is, the greater its tensile strength will be, that is, its ability to resist deformation and rupture when a load is applied.

The Brinell hardness test is made by forcing a steel ball, usually 10 millimeters(mm) in diameter, into the test specimen by using a known load weight and measuring the diameter of the resulting impression. A small microscope is used to measure the diameter of the impressions. Various loads are used for testing different materials; 500 kilograms (kg) for soft materials such as copper and aluminium and 3000 kg for steels and cast irons.

1.2.2.4. Brittleness

A material that will not deform plastically under load is said to be brittle. Excessive cold-working causes brittleness and loss of ductility. Cast iron does not deform plastically under a breaking load and is therefore brittle.

A very sharp "notch" that concentrates the load in a small area can also reduce plasticity. Notches are common causes of premature failure in parts. Weld undercut, sharp shoulders on machined shafts, and sharp angles on forgings and castings are examples of unwanted notches (stress raisers).

1.2.2.5. Ductility

The property that allows a metal to deform permanently when loaded in tension is called ductility. Any metal that can be drawn into a wire is ductile. Steel, aluminium, gold, silver, and nickel are examples of ductile metals.The tensile test is used to measure ductility. Tensile specimens are measured for area and length between gauge marks before and after they are pulled. The percent of elongation (increase in length) and the percent of reduction in area (decrease of area at the narrowest point) are measures of ductility. A high percent elongation (about 70 percent) and reduction in area indicates a high ductility. A metal showing less than 20 percent elongation would have low ductility.

1.2.2.6. Malleability

The ability of a metal to deform permanently when loaded in compression is called malleability. Metals that can be hammered or rolled into sheets are malleable. Most ductile metals are also malleable, but some very malleable metals such as lead are not very ductile and cannot be drawn into wire easily. Metals with low ductility, such as lead, can be extruded or pushed out of a die to form wire and other shapes. Some very malleable metals are lead, tin, gold, silver, iron and copper.

1.2.2.7. Notch toughness

Notch toughness (impact strength) is the ability of a metal to resist rupture from impact loading when there is a notch or stress raiser present. A metal may show high ductility or strength when tensile tested or be hard or soft when hardness tested, but often the behaviour of metals under shock loads is not seemingly related to those properties. Of course, as a rule, a brittle metal such as gray cast iron will fail under low shock loads; that is, its shock resistance is low, and soft wrought iron or mild steel has a high shock resistance. But soft, coarse-grained metals will have lower shock resistance than fine-grained metals. A notch or groove in a part will lower the shock resistance of a metal, so a specific notch shape and dimension is machined on the test specimen in order to give uniform results.

In general, the tensile strength of a metal changes in proportion to hardness. However, this relationship does not always hold true at high hardness levels or with brittle materials because these materials are more sensitive to stress concentrations, or notches, and may fracture prematurely when stressed in tension.

The harder and stronger the metal, the more sensitive it is to stress concentrations. Therefore, high-hardness, high-strength metals must be treated carefully; virtually everything becomes critical because such metals cannot easily tolerate stress concentrations. They cannot flow, or deform plastically at the highly stressed regions of the stress concentrations as readily as more ductile metals of somewhat lower hardness. However ,high -hardness,high - strength metals are extremely useful when carefully used, because of their high static and fatigue strength as well as their high wear resistance.

1.2.2.8. Conductivity

Conductivity is a measure of the ability of a material to conduct electric current. It is the reciprocal of resistivity. Conductivity is commonly expressed as mhos per meter since the unit of resistivity is the ohm. The conductivity of metallic elements varies inversely with absolute temperature over the normal range of temperatures but at temperatures approaching absolute zero the imperfections and impurities in the lattice structure of a material make the relationship more complicated. Metals and materials exhibit a wide range of conductivities . Between the most conductive substances (silver and copper) and the most resistive (polystyrene for example) the difference amounts to 23 orders of magnitude.

The conductivity of materials can be explained as being due to the flow of loosely bound electrons which act as carriers and are free to wander through the solid. These electrons are mostly the valency electrons in the outer electronic shells of atoms. The difference between conductors and non-conductors can be explained in terms of the relative availability of carrier electrons. In the case of copper, a metal with a single valency electron, the electron is spread out in a cloud like orbit around the nucleus. In a crystal of copper in which the atoms are tightly packed together the electrons spread themselves throughout the entire lattice. They find this energetically favourable because according to the uncertainty principle their delocalisation lowers their kinetic energy. It is this effect that causes the atoms in the crystal to stick together. Such delocalised electrons are ready candidates for acceleration in an electric field. In contrast to copper the atoms of the semiconductor germanium are cemented together more favourably by forming covalent bonds. In the resulting diamond like structure the electrons are not free to wander through the crystal or act as electrical carriers. Accordingly at absolute zero germanium would be an insulator.. If however sufficient energy (in the form of heat or light) is supplied to break some of the chemical bonds and so release electrons germanium becomes a conductor.

1.3. BASIC METALLURGICAL PROCESSES AND DEFECTS

Although it is not generally considered to be a part of nondestructive testing, a reasonable working knowledge of methods of fabrication is necessary for the NDT person to appreciate the types and likely locations of faults when a particular form of fabrication is used. It is, perhaps, as important for the designer to understand the possibilities and limitations of NDT and for both parties to be involved in the early design stages of a project to ensure that the final result can be inspected satisfactorily.

1.3.1. **Welding Processes**

Welding can be defined as the metallurgical method of joining, applied to the general problem of construction and fabrication. It consists of joining two pieces of metal by establishing a metallurgical atom-to-atom bond, as distinguished from a joint held together by friction or mechanical interlocking. This metallurgical atom-to-atom bond is achieved by the application of heat and sometimes pressure.

Welding processes may be classified according to the source of energy employed for heating the metals and the state of metal at the place being welded. A rational classification of the numerous welding processes can be made on several basis. If the process is classified on the basis of heat source, which is the usual practice, the main headings would be the 'electric arc' 'electrical resistance' and 'organic fuel'. The metallurgist classifies welding processes on another basis. In making a joint two parts of the same chemical composition may be welded together using no added metal to accomplish the joint. This might be termed as 'autogenous' welding.

A metal which is of the same composition as the parts being joined may be added, in which event, the process would come under the general heading 'homogenous' welding. Finally, an alloy quite different form that of which the parts are made may be used or alternatively the parts themselves may differ significantly in composition. Then this process is called 'heterogeneous' welding. This approach to classification is most useful in studying the properties of welded joints but is not so advantageous as the preceding one in studying the processes themselves. Since it is of interest to study the processes rather than the properties of the joints the classification based on the heat source employed for welding will be adhered to. Figure 1.36 outlines the various welding processes. Some of the most commonly used of these processes are described here in some detail.

1.3.1.1. <u>Oxy-fuel gas welding</u>

Gas welding is a chemical process of welding in which the required heat is produced by the combustion of a mixture of two gases. The two gases are mixed in proper proportions in a welding blow pipe or torch which is designed so that the operator has complete control of the welding flame.

Common mixtures of gases are oxygen and acetylene, oxygen and hydrogen, and other fuel gases like, butane, propane etc. and air and acetylene.

The oxygen acetylene mixture is used to a much greater extent than the others and has a prominent place in the welding industry. It is designated by the term oxy-acetylene welding.

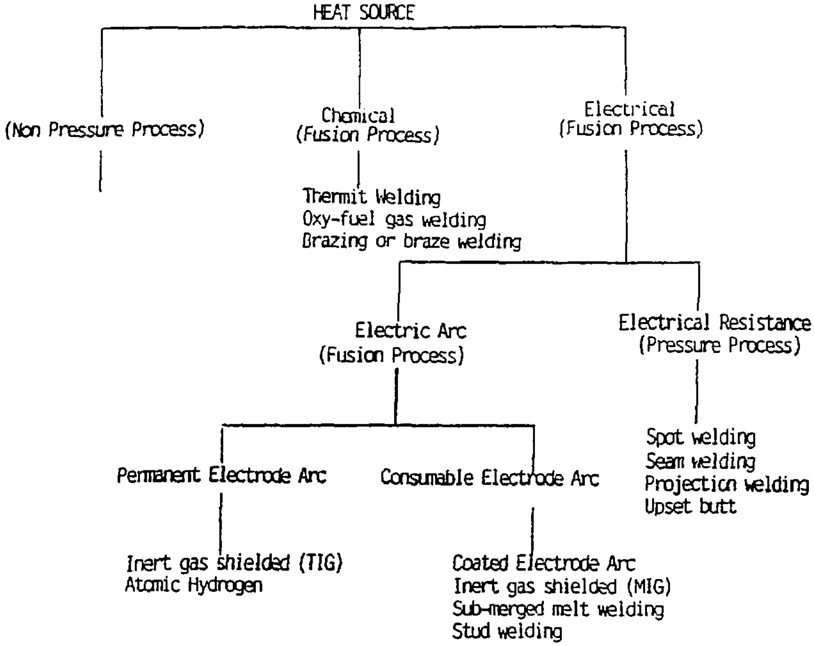


Figure 1.36 : *Different processes of welding*

Oxy-acetylene welding is a form of fusion welding wherein the heat required is supplied by the oxyacetylene flame. Usually in the fusion process of welding a filler metal is added in the form of a welding rod to form the welded joint, although joints in some instances are formed in oxy-acetylene welding merely by fusing together the parts to be joined without the addition of the welding rod. Flux is employed in the welding of some metals as a means of floating out impurities or as an aid in obtaining a satisfactory bond.

The oxyacetylene welding process is used in practically all the metal working industries. It is widely employed in such fabricating industries as sheet metal, tubing, aircraft, industrial piping and automotive, in laying pipelines, in shipyards, and for maintenance and repair purposes.

1.3.1.2. Electric arc welding

The electrical source of energy is used for heating the parts to be joined. This heat is produced by an electric arc between the metal pieces and an electrode of consumable or nonconsumable nature. The heat liberated at the arc terminals and in the arc stream is used to melt the metals to be welded at the point of contact, so that they will flow together and form a solid integral mass. Thus, different parts may be joined, or material may be added to the surface of a metal.

The arc welding processes fall naturally into two groups. Those in which the electrode melts and becomes a part of the weld and those in which the electrode is permanent. Hundreds of different alloys are suitable for the manufacture of consumable electrodes, but only tungsten and graphite meet the requirements for non-consumable or permanent electrodes, and that is why consumable arc processes are by far the more important industrially.

An example of the permanent electrode arc welding process is inert gas shielded tungsten arc (TIG) welding. In TIG welding a tungsten electrode is used because of its lower burn off rate. The arc is struck between the tungsten electrode and the work. The atmosphere is either argon or helium. A filler rod may or may not be required, but usually it is needed while welding heavier sections. The inert gas, argon or helium, prevents oxidation of the molten metal by excluding oxygen from it.

The gas is fed through a nozzle surrounding the electrode in the head of a suitably designed electrode holder. The flowing inert gas completely envelops the lower end of the electrode and the work to exclude or physically displace the atmosphere from the molten metal. The total shielding of the system from air contamination prevents the formation of oxides, nitrides, and other compounds which tend to reduce the strength of the welded joint.

Among the consumable electrode processes are 'coated electrode welding' 'inert gas shielded metal arc (MIG) welding; 'submerged metal arc welding' and 'stud welding'. Since molten steel has an affinity for oxygen and nitrogen, when it is exposed to the air, it enters into chemical combination with the oxygen and nitrogen of the air to form oxides and nitrides in the steel. These impurities weaken and embrittle the steel and lessen its resistance to corrosion. To avoid these impurities in the weld the joint is shielded by a suitable shielding material. This may be a gas, a flux or some shielding material coated on the electrode. The electrode used in this process serves as a filler rod and is consumed by melting into the weld along with the flux which has been provided as a coating. The coating also helps to form and raise the slag to the top of the weld.

The basic principle of MIG welding is the same as that of coated electrode welding except that shielding in this case is provided by an inert gas, mostly helium or argon. The electrode is melted like the base metal by the intense heat of the arc produced between the filler metal (electrode) and base metal (work). Inert gas is supplied from an independent source, and is guided around the weld joint and the lower end of the electrode.

In the submerged arc welding process the welding area is shielded by a blanket of granular fusible material on the work. The granular material is usually called the melt or the flux. The filler metal is the current carrying conductor. It is usually a bare or coated wire. The flux is spread over the area to be welded, is melted with the melting of the electrode and the work piece directly under it. The molten filler metal displaces this fluid flux and forms the weld. The fused flux floats to the top of the deposited metal and solidifies in the form of a brittle slag, which contracts upon cooling and is readily removable from the weld surface.

Stud welding is an arc welding process which in many respects resembles manual metal arc welding. The weld is effected by first drawing an electric arc between a stud (electrode) and the base material (work) to which it is to be welded and then bringing the two pieces in intimate contact when the proper temperature has been reached. The establishment of the arc, the determination of the welding time and the final plunging of the stud on to the work to complete the weld can be controlled automatically. Ordinarily in stud welding no shield of the weld zone is provided as in the case of inert gas shielded arc welding. However, the granular flux attached to the end of the welding stud does set up a reducing or protective atmosphere under nearly all welding conditions. Added protection is obtained from the porcelain or ceramic ferrule which surrounds the stud and the weld area and restricts the access of air to the weld zone. As a result of the combined shielding action, stud welding may be classified as a shielded arc-welding process.

1.3.1.3. Electrical resistance welding

Resistance welding is a process wherein two or more parts are welded together by the combined use of heat and pressure, and that is why this is classified as a pressure process of welding. The heat is generated by a relatively short-time flow of low voltage high density electric current across the intended joint location, and the pressure being supplied by contacting electrodes. These same electrodes also carry the current to the workpieces. Both electric current and pressure are closely regulated and controlled all the time.

Some of the sub-classifications of electrical resistance welding include 'spot welding', 'seam welding', and 'butt welding'. Spot welding' is a resistance process of welding in which coalescence is produced by the heat obtained from resistance to the flow of an electric current through the workpieces pressed together by pointed electrodes. The electrodes are brought to and removed from the workpieces at predetermined times and rates, and a clamping force is applied through the electrodes by some suitable means. The most widely used electrode material is pure copper, as it gives optimum results .

However in general, relatively high conductivity electrodes should be used to weld low conductivity materials and low conductivity electrodes should be used on high conductivity materials. Moreover it should have enough compressive strength to withstand the applied welding pressures. In seam welding, electrodes in the form of rolls are used to transmit pressure and to send current through the overlapping sheet being moved between them. Interrupted current control is usually necessary since it provides better control of the heat, allows each successive increment in the seam to cool under pressure, and minimises distortion, flashes and burns. Butt welding is used to join lengths of rods and wires. The ends are pressed together and an electric current passed through the work so that the ends are heated to a plastic state due to higher electrical resistance existing at the point of contact. The pressure is sufficient to form a weld. Some of the sub-classifications of electrical resistance welding include 'spot welding', 'seam welding', and 'butt welding'. Spot welding' is a resistance process of welding in which coalescence is produced by the heat obtained from resistance to the flow of an electric current through the workpieces pressed together by pointed electrodes. The electrodes are brought to and removed from the workpieces at predetermined times and rates, and a clamping force is applied through the electrodes by some suitable means. The most widely used electrode material is pure copper, as it gives optimum results.

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1.3.2. Weld Defects

During the process of welding, defects of various types may occur. Some defects. such as those dealing with the quality and hardness of the weld metal, are subjects for the chemist and research worker, while others may be due to lack of skill and knowledge of the welder. These of course can be overcome by correct training of the welding operator. This latter field of defects is of concern here and will be discussed. The most common defects occurring in welds are given in the following.

1.3.2.1. Porosity

Molten weld metal has a considerable capacity for dissolving gases which come into contact with it, such as hydrogen, oxygen and nitrogen. As the metal cools its ability to retain the gases diminishes. For instance, in steel the oxygen reacts with the carbon to form carbon monoxide, which is given off as a gas. With the change from the liquid to the solid state, there is reduced solubility with falling temperature. This causes an additional volume of gas to be evolved at a time when the metal is becoming mushy and therefore incapable of permitting the gas to escape freely. Entrapment of the gas causes gas pockets and porosity in the final weld. The porosity can be of three types namely 'fine porosity', 'blow holes' and 'piping'. Fine porosity consists of small bubbles of gas usually of diameter less than 1.6mm. Blow holes are usually gas pores larger in dimension while 'piping' is an elongated or tubular cavity. Piping is usually almost perpendicular to the weld surface. It can result form the use of wet powdered flux or from inadequate regulation of the welding current. Another typical form of pipes has the appearance of a branch of a tree.

Porosity may be scattered uniformly throughout the weld, isolated in small groups or concentrated at the root of the weld. Various causes of porosity may include excessive moisture content of the electrode covering, incorrect electrode current, defective gas shielding, contamination of joint surface or filler wire, rapid cooling of the weld metal or the composition of the parent metal or electrode core wire.

1.3.2.2. Non-Metallic inclusions

These may be the result of weld-metal contamination by sub substances on the surface of the joint or by the atmosphere. But the usual source is the slag formed by the electrode covering or flux used in the welding process. Some slag may be trapped in the deposited metal during its solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multi-pass welding, insufficient cleaning between weld passes can leave a portion of the slag coating in place to be covered by subsequent passes. A particular characteristic of slag inclusions is the 'slag line', intermittent or continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal. In general, inclusions may be due to any one of several reasons which include failure to clean the surface of the joint, failure to remove slag from a previous deposit, incorrect edge preparation, incorrect manipulation of the electrode and insufficient arc shielding.

1.3.2.3. Tungsten inclusions

Tungsten inclusions are particles of metallic tungsten embedded in the weld metal which originate from the tungsten electrode used in tungsten arc welding. Causes are excessive welding current allowing the melting and deposition of tungsten in the weld and incorrect polarity of electrode using a d.c. source. Tungsten inclusions can also be caused from dipping the electrode into the molten weld metal or by touching the filler rod to the electrode during welding. Tungsten inclusions frequently occur at the start of welds when the electrode may be cold. Small globular and widely scattered tungsten inclusions are sometimes permissible, but sharp edged inclusions are dangerous.

1.3.2.4. Lack of fusion

This is due to the lack of union in a weld between the weld metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Consequently the lack of fusion can be of three types namely lack of side fusion, lack of root fusion and lack of inter-run fusion. The defect results mainly from the presence of slag, oxides, scale, or other nonmetallic substances, too low a welding current or incorrect edge preparation. Incomplete fusion can also arise from too high a welding current when the high melt rate encourages the welder to use excessive welding speed, The defect reduces considerably the strength of a joint subjected to static loading, and under cyclic or shock loading it is quite serious.

1.3.2.5. Incomplete root penetration

In butt welding, a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. Therefore there can be a lack of fusion in the root of the weld or a gap left by the failure of the weld metal to fill the root of a butt weld. It is caused by the electrode held at an incorrect angle, an electrode too large in diameter, a rate of travel too fast, an insufficient welding current, or an improper joint preparation (e.g. joint misalignment).

1.3.2.6. Cracks

Cracks can be defined as a discontinuity produced either by tearing of the metal while in a plastic condition (hot crack) or by fracture when cold (cold crack). Cracks can occur in either the weld metal or parent metal. In the former they are classified as longitudinal, transverse, crater, and hairline cracks. In the latter it is cracking in the parent plate with the origin in the heat-affected zone of the weld, The strength of a welded joint under any conditions of loading will be seriously reduced by the presence of a crack. Weld metal cracks are caused by high localised stresses in the joint arising from the shrinkage of weld metal, by resistance of movement of the parts or by vibration of the structure during welding. Therefore it is important that each weld run is strong enough to withstand the shrinkage and to allow as much freedom of movement as possible. Longitudinal weld cracks usually occur in the root run and, if left, will eventually propagate through subsequent runs. Incorrect finishing of a weld run can form a crater and possibly lead to a crater crack.

Parent metal cracking is associated with the welding of medium carbon and alloy steels. A considerable amount of research has gone into the techniques for welding these steels and it is most important that instructions regarding type and condition of electrode, the degree and extent of preheat and the restrictions on size of single pass welds are strictly observed to avoid this form of cracking.

1.3.2.7. Undercut

During the final or cover pass the exposed upper edges of the weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement.

1.3.2.8. Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip.

1.3.2.9. Excessive penetration

In welds molten metal sometimes runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of excess metal.

1.3.2.10. Overlap

Overlap is an imperfection at the toe or root of a weld caused by an overflow of weld metal on to the surface of the parent metal, without fusing with the later. It is caused when the welding rod has been used at an incorrect angle, the electrode has travelled too slowly, or the current was too low.

1.3.3. Casting Processes

A commonly used method of forming metal objects of complex shape is by pouring molten metal into a mould in which it sets to the required shape. The mould is then broken away to expose the casting, or the design of the mould is such that it can be separated without damage and re-used. The moulds are usually formed from patterns which can be used many times over, if necessary, and their design is critical in that 'feed' and 'vent' holes must be carefully positioned in the mould to permit the metal to flow freely into all parts. Problems that can occur are interaction on cooling. It is also unlikely that the crystal structure of a casting will be optimum in all parts so that its strength may be less than with other methods of fabrication. Various casting processes include 'sand die casting', 'permanent mould casting','centrifugal casting', and 'shell mould casting'.

Since the casting process is complex and a large number of variables need to be controlled to get a good quality product and since it is not possible to give all the details here, only the principles and salient features of the above mentioned processes of casting are briefly presented.

1.3.3.1. Sand die casting

In this case a sand mould is used for casting the desired shape of the required alloy. A sand mould may be defined as a preformed sand container into which molten metal is poured and allowed to solidify. In general sand moulds are destroyed as the casting is removed from them. Sand moulds make it possible to cast complex shapes that might not be possible otherwise.

Different types of sand moulds can be made to make different castings. Green sand moulds are made from moist sand and are used for practically all ferrous and non-ferrous castings.

They have the disadvantage of not being very strong as well as requiring moisture during manufacture which may cause certain defects in the casting, Green sand moulds may be provided with a dry sand on the surface to give 'skin-dry moulds'. Purely 'dry-sand moulds' can also be made by adding to the sand a 'binder' instead of moisture.Its main advantages include a greater resistance to metal erosion, increased strength and a lessening of the tendency in the casting to acquire moisture related defects. In some cases silica sand bonded with portland cement may be used to make the moulds. Methods of preparing sand moulds include 'bench moulding', 'machine moulding', 'floor moulding' and 'pit moulding'. 'Bench moulding' is used for small castings. This is usually a slow and laborious process since hand ramming with a loose pattern, is usually used. Small and medium moulds may be made even with the aid of a variety of 'machines' which is usually faster and more uniform than bench moulding. Medium to large moulds are made directly on the foundry floor. Very large moulds made in a pit constructed for the purpose are called 'pit moulds'.

The sands most commonly used in 'sand die casting' contain silica sand which is usually from 5O to 95% of the total material in any moulding sand, zirconate and olivine etc. The most important properties and characteristics of such sands are 'permeability','cohesiveness' and 'refractoriness'. Permeability is a condition of porosity and is related to the passage of gaseous material through the sand as well as to the density of sand grains. Cohesiveness can be defined as the holding together of sand grains or strength of moulding sand and depends upon the size and shape of the sand grains. The property of cohesiveness may be improved by adding to the sand some 'binders' such as clay, resins and gums and drying oil. The third important characteristic of the moulding sand is 'refractoriness' which is its ability to withstand a high temperature without fusing. Pure silica sand can withstand a temperature as high as 3148°F. The property of 'refractoriness' can be affected by impurities like metallic oxides. Mould cavities may be produced by packing the moulding material around what are called 'patterns'. The 'patterns' may be made from wood, metal or other suitable materials. There are a variety of these patterns used in the manufacture of castings. Another important part of the casting process is the 'core box' which is a structure made of wood, metal or other suitable material, containing a cavity with the shape of a desired core. Making a sand mould involves the proper packing of moulding sand around a pattern. After the pattern is removed from the sand and the gating arrangement completed, the mould cavity is filled with molten metal to form the casting.

1.3.3.2. Permanent mould casting

A casting made by pouring molten metal into a mould made of some metallic alloy or other material of permanence is known as a permanent mould casting. Gray cast iron and Meehanite with large graphite flakes are the most commonly used materials in the construction of permanent moulds. This common use is partly due to the ease with which they may be machined. Certain steels, particularly special alloy steel that are heat-treated, often have especially good resistance to erosion. They have excellent refractory properties. Some aluminium alloys on which the surface has been anodised, are also used a moulding materials. Anodising produces $Al_2 2O_3$ which is very refractory and resistant to abrasion. These alloys are very easy to machine and possess a good chilling capacity. The mould is not destroyed on removing the casting and therefore can be reused many times.

The advantages of 'permanent mould casting' are that the casting process requires less skill , needs less floor space, better tolerances can be maintained, surface finish is improved, casting is not susceptible to the typical sand casting defects and production costs can be reduced by increasing the lot sizes, The disadvantages include the higher cost of mould production in the case of small production lots, the limited number of metals that are suitable to make moulds, the creation of undesirable stress problems due to the chilling effect of metallic moulds and the difficulty of casting ejection due to the rigid nature of the mould.

1.3.3.3. Centrifugal casting

Any process in which molten metal is poured and allowed to solidify while the mould is revolving, is a centrifugal casting process. Castings produced under this centrifugal force are called centrifugal castings. There are three recognised centrifugal processes namely 'true centrifugal casting','semicentrifugal casting' or 'profiled-centrifugal casting' and 'centrifuged or pressure casting'. 'True centrifugal casting' is that in which castings are made in a hollow, cylindrical mould rotated about an axis common to both casting and mould. Cast-iron pipe is commonly made by this method. In this process the axis of spin may be horizontal, inclined, or vertical. In the true centrifugal casting process the inside circumference is always circular. When the mould is rotated on a horizontal axis, a true cylindrical inside surface is produced. True centrifugal casting is used only on symmetrically shaped objects. 'Semicentrifugal or profiled centrifugal casting' is similar to the true centrifugal method except that a central core is used to form the inner surface or surfaces. The casting is not dependent upon centrifugal force for its shape. A good example of semicentrifugal work is a cast wheel-like casting. The axis of spin in the semicentrifugal process is always vertical. Although the yield is better than with static casting, it is not as high as in true centrifugal casting. With this process also only symmetrically shaped objects can be cast. Centrifuged or pressure casting is applied for nonsymmetrical castings. The mould cavity is not rotated about its own axis but about the axis of a central down sprue common to the axis of spin, which feeds metal into the mould cavity under centrifugal force. This process of centrifuging can be done only about a vertical axis. Centrifugal force provides a high pressure to force the metal alloy into the mould cavity.

Centrifugal casting processes can be used to produce parts made of both the ferrous and non ferrous alloy groups. Cast-iron pipe, gun barrels, automotive cylinder walls, jet engine rings, piston rings and brake drums are common parts centrifugally cast. Advantages include the elimination of foreign inclusions and the production of sounder castings. The chief disadvantages are the shape and size limitations.

1.3.3.4. Investment casting

This process involves making a one-piece mould from which the pattern is removed by a procedure which melts the pattern. The moulds used in this process are single purpose moulds. The elimination of all parting planes provides improved dimensional tolerances. Since the pattern is removed by melting or burning out, casting precision is increased through eliminating drift, rapping, and shifts. Various other names are given to this process. It is also called ' precision-investment casting ', ' precision casting ' or the ' lost-wax process '. Various types and grades of wax are the common materials for pattern making for investment casting. Certain plastics that burn without residue are also used as pattern materials. Some low melting point metallic alloys can also be used as pattern materials. In this process of casting the patterns are formed afresh each time by casting or forging the pattern material in dies made of metal, plastic, rubber or wood. There are a number of materials applicable as investment material. These are actually the moulding materials, but due to the process used they are called investment material. Fine grained silica sand with a suitable binder is often used. Plaster of paris and other gypsum products serve well as a binder for investment moulds used in the casting of non ferrous alloys. Other binders may include sodium silicate and various organic or inorganic chemical substances which satisfy specific applications. The investment materials are usually mixed into a fairly fluid slurry which is poured into place and vibrated to promote uniform packing and removal of air bubbles.

Patterns are first made of wax or other pattern materials by melting it and then injecting it into a metallic or non metallic die. Then the patterns are welded or joined to gates and runners, which are also of the same material as the pattern. By this welding or joining of the pattern to gates and runners a treelike pattern is prepared. This tree is now dipped into a refractory sand, placed in a metal flask and sealed to the pallet. Then the investment or moulding material, in viscous slurry form, is poured around the pre-coated tree. When the investment has set, the mould is heated by putting it in an oven at 200°F. By this heating the mould is dried and baked and the pattern is melted and the molten pattern material is taken out of the mould. Now as a final touch to the mould before casting the mould is placed in a furnace and is heated to a temperature of 1300 - 1900°F. This removes all the wax residue if any sticking to the investment mould. The mould is then heated to the casting temperature.

In general investment castings have high precision and extremely smooth surfaces and are easily produced. The process also makes possible the elimination of most machining operations and provides for an increased yield. Investment casting is adaptable to more complex and smaller designs in both limited as well as production lots. All metallic alloys can be cast with this process of casting. On the other hand the process is often more costly since materials as well as moulds are single purpose. Casting large objects is impracticable, the operators need to be more skilled and more technically trained and the production cycle is a relatively slow one.

1.3.3.5. <u>Shell moulding process</u>

This process involves making a mould that has two or more thin, shell-like parts consisting of thermosetting resin-bonded sand. These shells are single purpose in application and are hard and easily handled and stored. Shells are made so that the matching parts fit together easily, held with clamps or adhesives and poured in either a vertical or horizontal position. These moulds may be supported in racks or in a mass of bulky permeable material like sand, steel shot or gravel.

Metallic patterns are used for the production of shells, as they are subjected to heating temperatures approaching 1000°F. The pattern must have some provision,in the form of ejector pins, for the removal of shells from the surface of the pattern. Clean dry silica sand is the bulk material used in the making of shell moulds. Grain size and distribution can vary with use. Thermosetting synthetic resins are used as binders for sand. The resins include the phenolformal-dehydes, urea formaldehydes, and others.

The sand and resin mix or coated sand is caused to fall against or is blown against, a heated metal pattern or core box. The temperature of the pattern ranges from 350 to 600°F . Contact of the thermosetting resin with the hot pattern causes an initial set and thus an adhering layer of bonded sand is formed within 5 to 20 seconds. The pattern with this adhering layer of bonded sand is placed in a furnace and is cured by heating to the proper temperature for from one to three minutes. The curing time depends on the shell thickness and the resin type. The assembly is then removed from the furnace and the shell is stripped from the pattern by ejector devices. This stripping is sometimes a problem and can be overcome by using a silicon parting agent.

The main advantages of this process are that the shell cast parts have generally a smooth surface and thereby reduce machining costs. These techniques are readily adaptable to mass production by using automatic equipment. The disadvantages can be the initial cost of metal patterns, the higher cost of resin binders and a general size limitation.

1.3.4. **Casting Defects**

Casting defects may be defined as those characteristics which create a deficiency or imperfection exceeding quality limits imposed by design and service requirements. There are in general three broad categories of these defects. First are the major or most severe defects which result in scraping or rejection of the casting. The second category is of intermediate defects which permit salvaging of the casting through necessary repair. The third category defects are minor ones which can be easily repaired. The elimination and control of casting defects is a problem that the foundry engineer may approach in several ways. The common procedure is to rely on salvaging techniques that appear to provide immediate savings. Remedial procedures in the moulding, coremaking, melting or pouring areas of the foundry are frequently neglected but highly desirable to be controlled to avoid defects. Some of the defects which usually occur in castings are given here.

1.3.4.1. Porosity

Gas holes are spherical holes of varying size, with bright walls, usually fairly evenly distributed and formed by gas in the metal. The larger holes tend to be found in the heavier section (i.e last to solidify). If the metal is correct prior to casting, the pinhole type of porosity is probably due to absorption of hydrogen from steam in the mould. The gas in the molten metal is removed by a gas scavenging technique and by keeping casting ladles and moulds dry.

1.3.4.2. Blowholes

Blowholes are mainly found in three forms. Elongated cavities with smooth walls, found on or just below the surface of the topmost part of a casting. These are caused by entrapped air and repetition can be avoided by venting the mould and increasing its permeability. Rounded shape cavities with smooth bright walls are caused by mould or core gases, coupled with insufficient permeability, or venting. They can be avoided by using less oil binder in the mould and ensuring that cores are dry and properly baked and that the sand is properly mixed. Small cavities immediately below the skin of the casting surface are formed by the reaction of the molten metal with moisture in the moulding sand. This can be avoided by reducing the volatile content in mould cores and mould dressing, by ensuring that metal is deoxidised, by using more permeable sands, by ensuring that moulds and cores are properly vented and by reducing pouring temperature.

1.3.4.3. Piping

When this term is used in the foundry it refers to the defects encountered in risers or within the casting proper.

1.3.4.4. Inclusions

These are material discontinuities formed by the inclusion of oxides, dross, and slag in a casting. They are due to careless skimming and pouring, to the use of a dirty ladle and to turbulence due to improper gating methods when casting alloys, such as aluminium bronze, that are subject to surface oxide-skin formation. Faulty closing of moulds can cause 'crush' and loose pieces of sand becoming incorporated in the casting. The occurrence of inclusions can be avoided by proper use of equipment and foundry practice.

1.3.4.5. Sponginess

A defect that occurs during the early stages of solidification of a casting and has the appearance, as the name would imply, of a sponge; it may be local or general in extent. The major cause is failure to obtain directional solidification of the casting toward the desired heat centres, such as risers and ingates; insufficiently high pouring temperature, and placing of ingates adjacent to heavy sections.

1.3.4.6. Shrinkage

A casting defect that occurs during the middle and later stages of solidification of the cast metal. It has a branching formation, is readily distinguishable from that of sponginess, and is a form of void. The defect can be avoided by paying particular attention to the direction of solidification and ensuring adequate risers, or other feeding aids, on the heavier sections of a casting. Modification of casting design, i.e. to make cast sections more uniform for the flow and solidification of the metal is helpful in avoiding shrinkage. Moulds and cores are sometimes made too strong and greatly resist the contraction of the cast metal and, in this way, will cause a breakdown in the homogeneity of the metal.

1.3.4 7. Hot tears

These are discontinuities that result from stresses developed close to the solidification temperature when the metal is still weak. These again are attributed to resistance of the mould and core, which hinder contraction of the casting, causing thermal stress. Hot tears resemble ragged cracks. They can be avoided by making cores and moulds more collapsible, avoiding abrupt changes in section and preventing the formation of intense hot spots by designing with more uniform sections.

1.3.4.8. Crack

Well defined and normally straight, they are formed after the metal has become completely solid. Quite large stresses are required to cause fracture, and the walls of such cracks are discoloured according to the temperature of the casting when the cracks formed. Bad casting design coupled with restriction of contraction by the mould, core, or box bars contribute to cracking, and avoidance of these, together with the easing of mould or cores as soon as possible after solidification, will help to prevent build-up of stresses.

1.3.4.9. Cold shuts

These are discontinuities (a form of lack of fusion) caused by the failure of a stream of molten metal to unite with another stream of metal, or with a solid metal section such as a chaplet. They are linear in appearance, with perhaps a curling effect at the ends. A cold shut is caused by the fluidity of the metal being too low (i.e. surfaces too cold) or perhaps unsatisfactory methods of feeding in the molten metal.

Cold shuts can often be avoided by raising the pouring temperature or pouring rate or both and reviewing the position, size, and number of ingates and the arrangements for venting the mould.

1.3.4.10. Unfused chaplet

A chaplet is often used to support a section of a mould or a core within a mould and when the molten metal is poured in,the chaplets should fuse into the casting. When unfused the chaplet will cause a discontinuity in the casting. Design of chaplet and type of chaplet should be reviewed in overcoming this defect.

1.3.4.11. Misplaced core

An irregularity of wall thickness, e.g. one wall thicker than the other, can be detected by a double wall technique radiograph. It is caused by core out- of-alignment, careless coring-up and closing of mould, or rough handling after the mould is closed.

1.3.4.12. Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy. The segregation can be 'general' extending over a considerable part of a casting, 'local' when only the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point or 'banded' which is mainly associated with centrifugal castings but can also occasionally occur in static castings.

1.3.5. Forging Processes

Forging is the working of metal into a useful shape by hammering or pressing and is the oldest of the metal forming processes. Most forging operations are carried out hot, although some metals are cold-forged. The hot working of metals in the forging process results in an improvement in the mechanical properties. This method of shaping is therefore used in the manufacture of parts requiring good mechanical properties.

Improvement in the mechanical properties results from a general consolidation of the metal and closing of gas and contraction cavities by means of mechanical pressure, a refinement of the crystal structur., a destruction of the continuity of intergranular concentrations of impurities and inclusions.

Forging is done on either a hammer or a press. A horizontal press (forging machine) is used in certain instances for forging small parts; otherwise forging machines are vertical, the lower die of which is fixed while the upper die is movable, being carried on a vertical ram. In the case of hammers the die is raised mechanically and the blow is struck by the die falling freely. With presses, force is used to raise and lower the die and the metal is worked by slow, steady pressure. Forging is not only employed to produce parts of a shape that cannot be rolled but also for parts of simple uniform shape, round or rectangular, when these are large or when the quantity required is too small to warrant a roll set-up. Tool steels are often forged with a view to improving their properties.

Forging may be considered under two categories. First where the working surface of the dies is flat or of uniform curved contour and shaping is done by manipulation using tools of simple shape. This is called 'open-die' forging. The second is where impression dies are used and the metal is shaped by being forced into the die impressions. This is called closed-die forging. In the first category are forgings of simple, round or rectangular cross-section and forgings of more complicated shape which are so large that 'sinking' of closed dies would be impractical or too costly. Small forgings of complicated final shape may be rough forged on simple dies and then machined to final form if the number required is too small to justify the cost of an impression die. In this category also are hollow forged parts. For these, the centre metal of the rough piece of proper size is either machined out cold (trepanned), or is punched out hot using suitable dies on a press. The part is then forged on a mandrel passing through the centre hole and supported at both ends so that the mandrel acts as the bottom die. In closed die forging on a hammer or vertical press, the lower die has an impression corresponding to one half of the part to be made while the upper die has an impression corresponding to the other half. For relatively simple shapes the dies may have only one impression but more commonly they incorporate a series of impressions in which the part is successively shaped to the final form. Closed die forging is commonly known as 'drop forging'. Around the impressions the dies are shaped to provide space for the excess stock, as it is not practical to have exactly the amount of metal required to fill the impressions. The excess metal that is forced into this space is referred to as 'flashing' or 'flash'. After forging this is trimmed off in suitable dies. The closed die forging business is so competitive that the losses in trim scrap provide one of the most important areas for economy.

The hot forging process whereby bolts, for example, are headed is referred to as 'hot upset forging' or 'hot heading'. In this process, a bar of uniform cross section is gripped between grooved dies and pressure is applied on the end in the direction of the axis of the bar by means of a heading tool. The metal flows under the applied pressure and fills the cavity between the dies.

1.3.6. Rolling processes

The flattening of metal between rollers is used for the production of strip, sheet, plate, bar and sections. Since the metal is formed by a squeezing action, rolling can be considered as a continuous forging process with the rolls acting as hammers and the metal being drawn down. Rolling may be performed above the temperature of recrystallisation (hot rolling) or below the temperature of re-crystallisation (cold rolling). Hot rolling is always used for the initial rolling of the cast ingot. Not only is it easier to break down the ingot to size quickly when it is hot and plastic, but the hot-rolling process closes any casting discontinuities and forge welds their surfaces together. This prevents any faults, which could lead to lamination, being carried forward into subsequent rolling operations. In hot rolling the coarse grains are first elongated and distorted and then formed into equi-axed crystals due to recrystallisation. The crystals elongated and distorted by cold rolling do not recrystallise and the metal therefore remains work-hardened. Rolling mills are described according to the arrangement of the rolls. The simplest is the two-high reversing mill. In this the metal is passed through from one side, the rolls are then lowered and their direction of rotation is reversed, and the metal is passed back through them. This cycle is repeated until the metal is of the required thickness. In the three-high mill the rolls rotate continuously in one direction. The roller beds rise and fall to pass the metal between the lower two rolls first and then back again between the upper two rolls. The cycle is repeated until the metal is the required thickness. In the four-high mill and the cluster mill the additional rolls 'back-up' the working rolls and allow them to apply water pressure on the metal being rolled without deflection. Four-high and cluster mills operate in the same manner as the two-high reversing mill, and are widely used for cold rolling bright finished strip. Some typical rolling-mill processes are slabbing, cogging and re-rolling. Slabbing is the process of breaking down the ingot into slabs ready for re-rolling into strip, sheet and plate. The process is carried out at 1300°C and casting discontinuities in the ingot are welded by the process thus making the slab homogeneous. Cogging is similar to slabbing except that the ingot is rolled into 'blooms' ready for re-rolling into bars and sections. Two-high and four-high reversing mills are usually used for rolling both slabs and blooms. The re-rolling of slabs into strip is usually performed in a continuous strip mill. The slab is reheated to 1300°C and passed through a water spray and scale-breaking rolls to remove the scale left on the surface of the slab from previous processing. It is then roughed down, and finally passed to the finishing 'train' of rolls. The strip is finally coiled ready for further processing. The re-rolling of sections and bars is usually performed in two-high reversing mills fitted with grooved rolls. Some modern plants handling large quantities of standard section beams and joints are often laid out to provide a continuous train.

Whilst materials that are forged into wire and tube require the property of malleability, materials that are drawn into wire and tube require the property of ductility, combined with a relatively high tensile strength and a low work-hardening capacity as the process is performed cold. The reduction in size of the drawn section is provided by the material being pulled through a die. Rods and bars are drawn using draw-benches.Fine wire, especially the copper wire used for electrical conductors, is drawn on multiple-die machines. A capstan block pulls the wire through each die and passes it on to the next stage in the machine. As the wire becomes finer its length increases and the speed of the last capstan has to be very much higher than the first.

Tube drawing is similar to rod drawing using a draw bench. However, the billet is pierced to start the hole and the tube is drawn over a mandrel. Where longer lengths of tube are required, the stock and the drawn tube have to be coiled. This prohibits the use of a fixed mandrel, and a floating mandrel or plug is used.

Another process which is similar to rolling is extrusion. In principle, extrusion is similar to squeezing toothpaste from a toothpaste tube. The raw material is a heated cast billet of the required metal.

Usually this is either a copper alloy, an aluminium alloy or lead. The pressure necessary to force the metal through the die is provided by the hydraulic ram. Since the billet is reduced to the size of the finished section in one pass through the die, extrusion is a highly productive process. However, the plant is extremely costly and so is its operation and maintenance. Like most hot processes the finish and dimensional accuracy of the section is lower than that associated with cold drawing. Therefore, where greater accuracy is required, the extruded section is given a light draw to strengthen the section, improve its finish, and improve its dimensional accuracy.

1.3.7. Forging and rolling defects

Discontinuities in forgings may originate in the slab or billet and be modified by the rolling and forging of the material, or may result from the forging process itself. Some of the defects that can occur in forgings are similar to those in castings since most forgings originate from some form of cast ingot. Given below are some of the more specific defects.

1.3.7.1. Laminations

Large porosity, pipe and nonmetallic inclusions in slabs or billets are flattened and spread out during the rolling and forging processes. These flattened discontinuities are known as laminations.

1.3.7.2. Seams

Surface irregularities, such as cracks, on the slab or billet are stretched out and lengthened during rolling and are then called seams. Seams may also be caused by folding of the metal due to improper rolling. Seams are surface discontinuities and on finished bars will appear as either continuous or broken straight lines. On round bar stock they will appear as straight or slightly spiral lines, either continuous or broken.

1.3.7.3. Forging laps

Forging laps are the discontinuities caused by the folding of metal in a thin plate on the surface of the forging. They are irregular in contour.

1.3.7.4. Centre bursts

Ruptures that occur in the central region of a forging are called centre bursts.. They can arise because of an incorrect forging procedure (e.g. too low a temperature or too drastic a reduction) or from the presence of segregation or brittle phase in the metal being forged.

1.3.7.5. Clinks (Thermal Cracks)

Clinks are cracks due to stresses arising from excessively high temperature gradients within the material. Cracks formed during too rapid cooling originate at the surface and extend into the body of the forging; those formed during too rapid heating occur internally and can be opened up to become diamond-shaped cavities, during subsequent forging.

1.3.7.6. Hairline cracks (Flakes)

Flakes are very fine internal cracks of circular shape that develop and extend with time and are associated with the presence of hydrogen in steel. There is greater susceptibility in larger forgings than in smaller and in certain grades of alloy steel than in carbon steel; they can be avoided by correct treatment.

1.3.7.7. Hot tears

Surface defects due to metal being ruptured and pulled apart during forging. They may be associated with the presence of local segregation, seams, or brittle phases.

1.3.7.8. Stringers

Nonmetallic inclusions in slabs or billets, that are thinned and lengthened in the direction of rolling by the rolling process, are called stringers.

1.3.7.9. Overheating

Normally identified by the facets seen on the fractured surfaces of a test-piece, but in extreme cases can manifest itself as a severely broken-up surface.

1.3.7.10. Pipe

If there has been insufficient discard from the original ingot, remnant primary pipe will normally show up axially. Secondary pipe that has never been exposed to the atmosphere will have welded-up if there has been sufficient forging.

1.4. MATERIALS IN SERVICE

1.4.1. Behaviour of materials in service

Materials have to operate and perform in widely varied environments and situations. The requirements of safety and reliability demand that the materials and components should perform well in their environments and situations without premature failure. There are a number of factors and processes which can cause the failure of materials. As premature failure of critical components can be disastrous in many situations apart from being a cause for lost production and bad reputation, it is essential to understand and control these causes of failure.

1.4.2 Conditions leading to defects and failure

Due to advances in technology and in the understanding of materials and their design, and due to sophisticated inspection and testing methods, such as the non-destructive testing methods, metal failures occur only in an extremely low percentage of the millions of tons of metals fabricated every year. Those that do occur fall mainly into three categories. Operational failures can be caused by overload, wear, corrosion and stress corrosion , brittle fracture and metal fatigue. In the second category fall the failures due to improper design. In this it is necessary to consider whether sharp corners or high stress areas exist in the design, has sufficient safety stress factor been considered and whether the material selected is suitable for a particular application. The third type of failure is caused by thermal treatments such as forging, hardening, tempering and welding, and by surface cracks caused by the heat of grinding. These aspects and especially those related to operational or in-service conditions will be described here in more detail.

1.4.2.1. Corrosion

With the exception of some noble metals, all metals are subject to the deterioration caused by ordinary corrosion. Iron, for example, tends to revert back to its natural state of iron oxide. Other metals revert to sulfides and oxides or carbonates. Buildings, ships, machines and automobiles are all subject to attack by the environment. The corrosion that results often renders them useless and they have to be scrapped. Billions of dollars a year are lost as a result of corrosion. Corrosion can also cause dangerous conditions to prevail, such as on bridges, where the supporting structures have been eaten away, or in aircraft in which an insidious corrosion called intergranular corrosion can weaken the structural members of the aircraft and cause a sudden failure.

Corrosion in metals is the result of their desire to unite with oxygen in the atmosphere or in other environments to return to a more stable compound, usually called ore. Iron ore, for example, is in some cases simply iron rust. Corrosion may be classified by the two different processes by which it can take place;

direct oxidation corrosion, which usually happens at high temperatures, and galvanic corrosion, which takes place at normal temperatures in the presence of moisture or an electrolyte. Direct oxidation corrosion is often seen in the scaling that takes place when a piece of metal is left in a furnace for a length of time. The black scale is actually a form of iron oxide, called magnetite (Fe_3O_4). Galvanic corrosion is essentially an electrochemical process that causes a deterioration of metals by a very slow but persistent action. In this process, part or all of the metal becomes transformed from the metallic state to the ionic state and often forms a chemical compound in the electrolyte. On the surface of some metals such as copper or aluminium, the corrosion product sometimes exists as a thin film that resists further corrosion. In other metals such as iron, the film of oxide that forms is so porous that it does not resist further corrosive action, and corrosion continues until the whole piece has been converted to the oxide.

It is familiarly known that atoms having positive or negative charges are called ions and these are formed either by accepting or donating electrons in the outermost orbit. Metallic atoms form positive ions while non-metals form negative ones. Ions having opposite charges can often combine to form compounds. An electrolyte is any solution that conducts electric current and contains negative or positive ions. Corrosion requires the presence of an electrolyte to allow metal ions to go into solution. The electrolyte may be fresh or salt water and acid or alkaline solutions of any concentration. Even a fingerprint on metal can form an electrolyte and produce corrosion. When corrosion of a metal occurs, positively charged atoms are released or detached from the solid surface and enter into solution as metallic ions while the corresponding negative charges in the form of electrons are left behind in the metal. The detached positive ions bear one or more positive charges. In the corrosion of iron, each ion atom releases two electrons and then becomes a ferrous iron carrying two positive charges. Two electrons must then pass through a conductor to the cathode area. The electrons reach the surface of the cathode material and neutralise positively charged hydrogen ions that have become attached to the cathode surface. Two of these ions will now become neutral atoms and are released generally in the form of hydrogen gas. This release of the positively charged hydrogen ions leaves an accumulation and a concentration of OH negative ions that increases the alkalinity at the cathode.

When this process is taking place, it can be observed that hydrogen bubbles are forming at the cathode only. When cathodes and anodes are formed on a single piece of metal, their particular locations are determined by, for example, the lack of homogeneity in the metal, surface imperfections, stresses, inclusions in the metal, or any thing that can form a crevice such as a washer. Corrosion can also take the form of erosion in which the protective film, usually an oxide film, is removed by a rapidly moving atmosphere or medium. Depolarisation can also take place, for example, on the propellers of ships because of the movement through the water, which is the electrolyte. This causes an increased corrosion rate of the anodic steel ship's hull. Impellers of pumps are often corroded by this form of erosion corrosion in which metal ions are rapidly removed at the periphery of the impeller but are concentrated near the centre where the velocity is lower. Another form of corrosion is intergranular corrosion. This takes place internally. Often the grain boundaries form anodes and the grains themselves form cathodes, causing a complete deterioration of the metal in which it simply crumbles when it fails. This often occurs in stainless steels in which chromium carbides precipitate at the grain boundaries. This lowers the chromium content adjacent to the grain boundaries, thus creating a galvanic cell. Differences in environment can cause a high concentration of oxygen ions. This is called cell concentration corrosion. Pitting corrosion is localised and results in small holes on the surface of a metal caused by a concentration cell at that point. When high stresses are applied to metals in a corrosive environment, cracking can also be accelerated in the form of stress corrosion fatigue. It is a very localised phenomenon and results in a cracking type of failure.
Cathodic protection is often used to protect steel ships hulls and buried steel pipelines. This is done by using zinc and magnesium sacrificial anodes that are bolted to the ship's hull or buried in the ground at intervals and electrically connected to the metal to be protected. In the case of the ship, the bronze propeller acts as a cathode, the steel hull as an anode, and the seawater as an electrolyte. Severe corrosion can occur on the hull as a result of galvanic action. The sacrificial anodes are very near the anodic end of the galvanic series and there is therefore a large potential difference between both the steel ship's hull and the bronze propeller. Both the hull and propeller become cathodic and consequently do not deteriorate. The zinc or magnesium anodes are replaced from time to time. Selection of materials is of foremost importance.

Even though a material may be normally resistant to corrosion, it may fail in a particular environment or if coupled with a more cathodic metal.Coatings are extensively used to prevent corrosion. There are different types of such coatings, for example: anodic coatings, cathodic coatings,organic and inorganic coatings, inhibitive coatings etc.

1.4.2.2. Fatigue

When metal parts are subjected to repeated loading and unloading over prolonged periods they may fail at stresses far below their yield strength with no sign of plastic deformation. This is called a fatigue failure. When designing machine parts that are subject to vibration or cyclic loads, fatigue strength may be more important than ultimate tensile or yield strength. Fatigue is a universal phenomenon observed in most solids. Cyclic loading leads to a continuous accumulation of damage which, as in the case of static fracture, eventually results in rupture. The Fatigue Limit, or Endurance Limit, is the maximum load that can be applied an infinite number of times without causing failure. But 10 million loading cycles are usually considered enough to establish fatigue limits. The number of cycles leading to fracture at a given stress is often referred to as the fatigue strength or endurance. This phenomenon of failure of a material when subjected to a number of varying stress cycles is known as fatigue since it was once thought that fracture occurred due to the metal weakening or becoming tired.

Failures caused by fatigue are found in many of the materials of industry. Some plastics and most metals are subject to fatigue in varying degrees as these are widely used in dynamically loaded structures and machines. It has been estimated that at least 75% of all machine and structure failures were caused by some form of fatigue. Fatigue is caused by a crack that is initiated by notch, bend, or scratch that continues to grow gradually as a result of stress reversals on the part. The crack growth continues until the cross-sectional area of the part is reduced sufficiently to weaken the part to the point of failure. Even welding spatter on a sensitive surface such as a steel spring can initiate fatigue failure. Fatigue is greatly influenced by the kind of material, grain structure and the kind of loading. Some metals are more sensitive to sharp changes in section (notch sensitive) than others.

There are various types of fatigue failure. In the case of one -way bending load, a small elliptical shaped fatigue crack usually starts at a surface flaw such as a scratch or tool mark.

The crack tends to flatten out as it grows. It is caused by the stress at the base of the crack being lower because of the decrease in distance from the edge of the crack to the neutral axis. If a distinct stress raiser such as a notch is present, the stress at the base of the crack would be high, causing the crack to progress rapidly near the surface, and the crack tends to flatten out sooner. In a two-way bending load cracks start almost simultaneously at opposite surfaces when the surfaces are equally stressed. The cracks proceed toward the centre at similar rates and result in a fracture that is rather symmetrical.

In the early stages of fatigue testing, specimens will generally evolve an appreciable amount of heat. Later fissures develop at the surface eventually leading to failure. The surface of the specimen is a preferential seat of damage initiation. Corrosive effects may also assist in degradation of the structure at the surface. Corrosion is essentially a process of oxidation and under static conditions a protective oxide film is formed which tends to retard further corrosion attack. In the presence of cyclic stress the situation is quite different, since the partly protective oxide film is ruptured in every cycle allowing further attack. It is a rather simplified explanation that the microstructure at the surface of the metal is attacked by the corrosive environment causing an easier and more rapid initiation of cracks. One of the important aspects of corrosion fatigue is that a metal having a fatigue limit in air no longer possesses one in the corrosive environment and therefore fracture can occur at relatively very low stress levels.

In commercial alloys the technical fatigue limit generally lies between 0.3 and 0.5 of the ultimate tensile stress. The fatigue strength of metals can often be enhanced by treatments which render the surface more resistant to deformation. Fracture then tends to start at the interface between the hard surface layer and the softer core. Stress raisers, such as sharp notches, corners, key ways, rivet holes and scratches, can lead to an appreciable lowering of the fatigue strength of metal components. Good surface finish and corrosion protection are desirable to enhance fatigue resistance. Fatigue is basically a low temperature problem and at temperatures relatively high with respect to the melting point, fracture and hence specimen life are governed by creep.

Fractured surfaces of fatigued metals generally show a smooth and lustrous region due to the polishing effects arising from attrition at fissures. The remaining parts of the fracture surface, over which failure occurred through weakening of the specimen by the reduction of its load bearing cross-section by surface cracks and fissures, may look duller and coarser, as it is essentially caused by static fracture.

1.4.2.3. Wear

Wear may be defined as undesired removal of material from contacting surfaces by mechanical action. Excessive wear can be caused by continuous overload, but wear is ordinarily a slow process that is related to the friction between two surfaces. Rapid wear can often be attributed to lack of lubrication or the improper selection of material for the wear surface. Some wear is to be expected, however, and could be called normal wear. Wear is one of the most frequent causes of failure. We find normal wear in machine tooling such as carbide and high-speed tools that wear and have to be replaced or resharpened. Parts of automobiles ultimately wear until an overhaul is required. Machines are regularly inspected for worn parts, which when found are replaced; this is called preventive maintenance. Often normal wear cannot be prevented; it is simply accepted, but it can be *kept* to a *minimum* by the proper use of lubricants. Rapid wear can occur if the load distribution is concentrated in a small area because of the part design or shape. This can be altered by redesign to offer more wear surface. Speeds that are too high can increase friction considerably and cause rapid wear.

Metallic wear is a surface phenomenon which is caused by the displacement and detachment of surface particles. All surfaces subjected to either rolling or sliding contact show some wear. In some severe cases the wear surface can become cold welded to the other surface. In fact, some metals are pressure welded together in machines, taking advantage of their tendency to be cold welded. This happens when tiny projections of metal make a direct contact on the other surface and produce friction and heat, causing them to be welded to the opposite surface if the material is soft. Metal is torn off if the material is brittle. Insufficient lubrication is usually the cause of this problem. High pressure lubricants are often used while pressing two parts together in order to prevent this sort of welding. Two steel parts such as a steel shaft and a steel bore in a gear or sprocket, if pressed together dry, will virtually always seize or weld and cause the two parts to be ruined for further use. In general, soft metals, when forced together, have a greater tendency to cold weld than harder metals. Two extremely hard metals, even when dry, will have very little tendency to weld together. For this reason, hardened steel bushings and hardened pins, are often used in earth moving machinery to avoid wear. Some soft metals when used together for bearing surfaces (for example aluminium to aluminium) have a very great tendency to weld or seize. Among these metals there are aluminium, copper, and austenitic stainless steel.

Cast iron is used on the sliding surfaces in machine tools e.g. on the ways of lathes or milling machine tables. It has less tendency than soft metals to seize because the metal contains graphite flakes that provide some lubrication, although additional lubrication is still necessary. As a general rule, however, it is not good practice to use the same metal for two bearing surfaces that are in contact. However, if a soft steel pin is used in a soft steel link or arm, it should have a sufficiently loose fit to avoid seizing. In this application it is better practice to use a bronze bushing or other bearing material in the hole than a steel pin because the steel pin is harder than the bronze and when a heavy load is applied, the small projections of bronze are flattened instead of torn out. Also the bronze will wear more than the steel and usually only the bushing will need replacing when a repair is needed.

Different types of wear include abrasive wear, erosive wear, corrosive wear and surface fatigue. In abrasive wear small particles are torn off the surface of the metal, creating friction. Friction involving abrasive wear is sometimes used or even required in a mechanism such as on the brakes of an automobile. The materials are designed to minimize wear with the greatest amount of friction in this case. Where friction is not desired, a lubricant is normally used to provide a barrier between the two surfaces. This can be done by heavy lubricating films or lighter boundary lubrication in which there is a residual film. Erosive wear is often found in areas that are subjected to a flow of particles or gases that impinge on the metal at high velocities. Sand blasting, which is sometimes used to clean parts, utilizes his principle. Corrosive wear takes place as a result of an acid, caustic, or other corrosive medium in contact with metal parts. When lubricants become contaminated with corrosive materials, pitting can occur in such areas as machine bearings. Surface fatigue is often found on roll or ball bearing or sleeve bearings where excessive side thrust has been applied to the bearing. It is seen as a fine crack or as small pieces falling out of the surface.

Various methods are used to limit the amount of wear in the part. One of the most commonly used methods is simply to harden the part. Also, the part can be surface hardened by diffusion of a material, such as carbon or chrome, into the surface of the part. Parts can also be metallized, hard faced, or heat treated. Other methods of limiting wear are electroplating (especially the use of hard industrial chromium) and anodizing of aluminium. Some nickel plate is used, as well as rhodium, which is very hard and has a high heat resistance. The oxide coating that is formed by anodizing on certain metals such as magnesium, zinc, aluminium and their alloys, is very hard and wear resistant. These oxides are porous enough to form a base for paint or stain to give it further resistance to corrosion. Some of the types of diffusion surfacing are carburizing, carbo-nitriding, cyaniding, nitriding, chromizing, and siliconizing. Chromizing consists of the introduction of chromium into the surface layers of the base metal. This is sometimes done by the use of chromium powder and lead baths in which the part is immersed at a relatively high temperature. This, of course, produces a stainless steel on the surface of low carbon steel or an iron base metal, but it may also be applied to nonferrous materials such as tungsten, molybdenum, cobalt, or nickel to improve corrosion and wear resistance. The fusion of silicon, which is called ihrigizing, consists of impregnating an iron base material with silicon. This also greatly increases wear resistance. Hard facing is put on a metal by the use of several types of welding operations, and it is simply a hard type of metal alloy such as alloying cobalt and tungsten or tungsten carbide that produces an extremely hard surface that is very wear resistant. Metal spraying is used for the purpose of making hard wear resistant surfaces and for repairing worn surfaces.

1.4.2.4. Overload

Overload failures are usually attributed to faulty design, extra loads applied, or an unforeseen machine movement. Shock loads or loads applied above the design limit are quite often the cause of the breakdown of machinery. Although mechanical engineers always plan for a high safety factor in designs (for instance, the 10 to 1 safety factor above the yield strength that is sometimes used in fasteners), the operators of machinery often tend to use machines above their design limit. Of course, this kind of overstress is due to operator error. Inadequate design can sometimes play a part in overload failures. Improper material selection in the design of the part or improper heat treatment can cause some failures when overload is a factor. Often a machinist or welder will select a metal bar or piece for a job based upon its ultimate tensile strength rather than upon its yield point. In effect this is a design error and can ultimately result in breakdown.

Basically there are only two modes or ways in which metals can fracture under single or monotonic loads. These two modes are shear and cleavage and they differ primarily in the way the basic metal crystal structure behaves under load. Almost all commercial solid metals are polycrystalline. Each individual crystal or grain is a structure composed of a very large number of atoms of the constituent elements. These atoms are arranged in cells within each crystal in a regular, repetitive, three-dimensional pattern. Adjacent cells share the corner atoms and their positions are balanced by electrical forces of attraction and repulsion. Applied forces can cause distortion of the cells. Shear deformation represents a sliding action on planes of atoms in crystals. In a polycrystalline metal, slight deformation causes no permanent change in shape. It is called elastic deformation. That is the metal returns to its original size and shape, like a spring, after being unloaded. If a greater load is imposed, permanent or plastic deformation occurs because of irreversible slip between certain planes of atoms that make up the crystal structure. If the applied load or force is continued, the shear deformation causes tiny microvoids to form in the most highly stressed region. These tiny voids soon interconnect and form fracture surfaces. The cleavage mode of separation of the cell is different. In this case separation occurs suddenly between one face of the cell and the mating face of the adjacent cell without any deformation being present.

Fracture will originate whenever the local stress i.e. load per unit cross-sectional area, first exceeds the local strength. This location will vary depending upon the strength of the metal and the applied stress. When a shaft or similar shape is pulled by tensile force it becomes longer and narrower. For ductile metals the shear strength is the weak link and these metals fail through the shear mode. These metals fail when shear stress exceeds the shear strength. In the case of brittle metals, these fail because the tensile stress exceeds the tensile strength. Brittle metals always have a fracture that is perpendicular to the tensile stress and little or no deformation because fracture takes place before the metal can deform plastically as ductile metals do.

When a cylinder is loaded in axial compression, a ductile metal becomes shorter and thicker. In short it bulges when squeezed by the compressive force and there is no fracture. A brittle metal in pure compression will fracture parallel to the length of the cylinder.

1.4.2.5. Brittle and ductile fracture

Fracture preceded by a significant amount of plastic deformation is known as ductile fracture, otherwise it is brittle fracture. Brittle fracture occurs, when plastic flow is inhibited either by the effective locking of atomic dislocations by precipitates or elements or by the pre-existence or formation of cracks and imperfections acting as local stress raisers in the material. All materials can be embrittled if the temperature is lowered sufficiently. Glass, sealing wax, germanium, silicon and other materials though ductile at temperatures close to their melting point are brittle at ordinary temperatures. In most materials the brittle strength, defined as the maximum tensile stress withstood without the occurrence of brittle fracture,is low compared with the ideal strength the fault-free material would be expected to exhibit. The source of brittle fracture is therefore to be sought in the presence of structural defects.

As has already been mentioned brittle metals always have a fracture that is perpendicular to the tensile stress and have little or no deformation because fracture takes place before the metal can deform plastically. Thus a tensile fracture of a brittle metal has a fracture plane that is essentially straight across. It also usually has a characteristic bright sparkling appearance when freshly fractured.

The pattern of a break can often reveal how the failure was precipitated. For example, if the break was caused by a sudden shock load such as an explosion, there are usually chevron-shaped formations present that point to the origin of fracture. When a stress concentration is present, such as a weld on a structure that is subject to a sudden overload, the fracture is usually brittle across the entire break, showing crystals, striations, and wave fronts. Brittle fractures are often intergranular (along the grain boundaries); this gives the fracture surface a rock candy appearance at high magnification. When grain boundaries are weakened by corrosion, hydrogen, heat damage, or impurities, the brittle fracture may be intergranular. Brittle failures can also be transgranular (through the grains). This is called cleavage.

Cleavage fracture is confined to certain crystallographic planes that are found in body-centered cubic or hexagonal close-packed crystal structures. For the most part, metals having other crystalline unit structures do not fail by cleavage unless it is by stress corrosion cracking or by corrosion fatigue. Cleavage should normally leave a flat, smooth surface; however, because metals are polycrystalline with the fracture path randomly oriented through the grains and because of certain imperfections, certain patterns are formed on the surface.

Small quantities of hydrogen have a great effect on the ductility of some metals. Hydrogen can get into steels when they are heated in an atmosphere or a material containing hydrogen, such as during pickling or cleaning operations, electroplating, cold working, welding in the presence of hydrogen-bearing compounds, or the steel-making process itself. There is a noticeable embrittling effect in steels containing hydrogen. This can be detected in tensile tests and seen in the plastic region of the stress-strain diagram showing a loss in ductility. Electroplating of many parts is required because of their service environment to prevent corrosion failure. Steel may be contaminated by electroplating materials that are commonly used for cleaning or pickling operations. These materials cause hydrogen embrittlement by charging the material with hydrogen. Monatomic hydrogen is produced by most pickling or plating operations at the metal-liquid interface, and it seems that single hydrogen atoms can readily diffuse into the metal. Preventive measures can be taken to reduce this accumulation of hydrogen gas on the surface of the metal. A frequent source of hydrogen embrittlement is found inthe welding process. Welding operations in which hydrogen-bearing compounds such as oil, grease, paint, or water are present, are capable of infusing hydrogen into the molten metal, thus embrittling the weld zone. Special shielding methods are often used that help to reduce the amount of hydrogen absorption. One effective method of removing hydrogen is a "baking" treatment in which the part, or in some cases the welding rod, is heated for long periods of time at temperatures of 121 to 204°C. This treatment promotes the escape of hydrogen from the metal and restores the ductility.

Stress raisers such as notches on the surface of a material have a weakening effect and cause embrittlement. A classical example is provided by the internal notches due to graphite flakes in cast irons. The flakes embrittle the irons in tension. Therefore in structural applications cast irons are more usefully employed under compressive loads. Their brittle strength and toughness can, however, be increased appreciably if the graphite is allowed to form in spheroidal rather than flaky form. This can be done by alloying the melt, for example, with magnesium.

1.5. SURFACE FINISHING

Products that have been completed to their proper shape and size frequently require some type of surface finishing to enable them to satisfactorily fulfill their function. In some cases, it is necessary to improve the physical properties of the surface material for resistance to penetration or abrasion. n many manufacturing processes , the product surface is left with dirt, metal chips, grease or other harmful material on it. Assemblies that are made of different materials or from the same materials processed in different manners, may require some special surface treatment to provide uniformity of appearance.

Surface finishing may sometimes become an intermediate step in processing. For instance, cleaning and polishing are usually essential before any kind of plating process. Some of the cleaning procedures are also used for improving surface smoothness on mating parts and for removing burrs and sharp corners. which might be harmful in later use. Another important need for surface finishing is for corrosion protection in a variety of environments. The type of protection provided will depend largely upon the anticipated exposure, with due consideration to the material being protected and the economic factors involved.

Satisfying the above objectives necessitates the use of many surface finishing methods that involve chemical change of the surface, mechanical work affecting surface properties, cleaning by a variety of methods and the application of protective coatings, organic and metallic.

1.5.1. Casehardening of steels

Casehardening results in a hard , shell like surface. Some product applications require surface properties of hardness and strength to resist penetration under high pressure and to provide maximum wear properties. Where through hardness and the maximum strength associated with it are not necessary, it may be more economical to gain the needed surface properties by a casehardening process. Casehardening involves a change of surface properties to produce a hard, wear resistant shell with a tough fracture resistant core. This is usually accomplished by a change of surface material chemistry. With some materials, a similar condition can be produced by a phase change of the material already present.

Casehardening may be more satisfactory than through hardening in those cases where a low cost, low carbon steel with a hard shell can be used instead of a higher cost , high carbon or alloy steel which would be needed for through hardening. The process is much less likely to cause warping or cracking and the product, because of its soft, ductile core, is less subject to brittle failure than a through hardened product. Case hardening is often suitable for heavy sections that would require very special high alloy steels for through hardening to be effective.

Case depth measurement is sometimes checked by destructive methods, cutting the object , etching the cut surface and checking the cut depth with a measuring microscope. A faster a more usable method when knowledge is needed directly for service parts is to use eddy current tests.

1.5.2. Carburizing

Casehardening of steel may be accomplished by a number of methods. The choice between them is dependent on the material to be treated, the application and the desired properties. One of the more common methods is carburizing which consists of an increase or addition of carbon to the surface of the part. Carburizing is usually performed on a low alloy or plain low carbon steel . If an alloy steel is used , it usually contains small quantities of nickel or some other elements that act as grain growth retarder during the heating cycle. Low carbon steels are commonly used to minimize the effect of subsequent heat treatment on the core material. It is possible to carburize any steel containing less than the 0.7% to 1.2% carbon that is produced in the surface material.

Carbon is caused to diffuse into the steel by heating the material above its critical temperature and holding it in the presence of excess carbon. The temperatures used are usually between 850°C and 930°C with the choice most dependent on the desired rate of penetration, the desired surface carbon content and the permitted grain growth in the material. Penetration is dependent upon both the temperature and time, with variations of case depth from 0.25 to 1.0 millimeter (0.010 to 0.040 inch) possible in the first 2 hours by varying the temperature between the two extremes. The rate of penetration slows down as the depth increases, as shown in Figure 1.37 , so that for large depths, relatively long periods of time are necessary.

The excess carbon for diffusion is supplied from a carbon rich environment in solid, liquid , or gas form. Parts to be carburized may be packed in carbon or other carbonaceous material in boxes that are sealed to exclude air and then heated in a furnace for the required length of time in a process sometimes called pack carburizing. The liquid method makes use of molten sodium cyanide in which the parts are suspended to take on carbon. The cyanide method is usually limited to shallow case depths of about 0.25mm (0.010in) maximum. The third method often the most simple for production operations requiring a thick case depth supplies gaseous hydrocarbons from an unburnt gas or oil fuel source to the furnace retort in which the product is heated. The product is usually suspended on wires or rolled about so that all surfaces are exposed uniformly.

Carburizing steels containing grain growth inhibitors may be quenched directly from the carburizing furnace to harden the outside shell, but plain carbon steels must be cooled and reheated through the critical range to reduce grain size. Even the alloy steels will have better properties if treated in this manner. Quenching from above the critical temperature will produce a hard martensitic structure in the high carbon surface material but will have little or no effect on the low carbon core. As in the case of most through hardened steels, tempering is usually required to toughen the outside shell. The complete cycle for casehardening by carburizing is illustrated in Figure 1.38.

1.5.1.3 Flame hardening

Another case hardening process that does not require a change of composition in the surface material is flame hardening. This method can be used only on steels that contain sufficient carbon to be hardenable by standard heat treating procedures. The case is

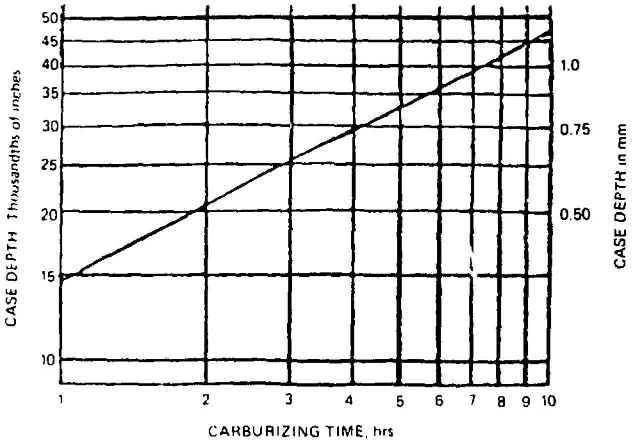


Figure 1.37 Typical carburizing case depth - time relationship.

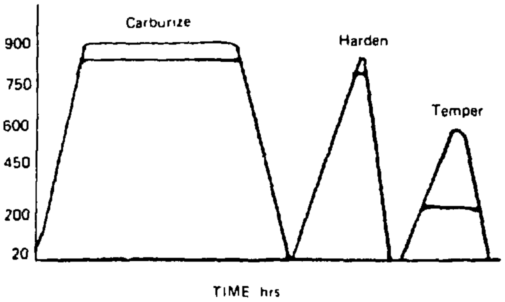


Figure 1.38 Typical heat treatment cycle for carburizing

produced by selectively heating part or all of the surface with special high capacity gas burners or oxy acetylene torches at a rate sufficiently high that only a small depth from the surface goes above the critical temperature. Following immediately behind the torch is a water quenching head that floods the surface to reduce the temperature fast enough to produce a martensitic structure. As in the case of carburizing, the surface may be then reheated to temper it for toughness improvement. The depth of hardness is controlled by the temperature to which the metal is raised , by the rate of heating, and by the time that passes before quenching.

1.5.2 Cleaning

Few if any shaping and sizing processes produce products that are suitable without some type of cleaning unless special precautions are taken. Hot working, heat treating, and welding cause oxidation and scale formation in the presence of oxygen. For the same reason , castings are usually coated with oxide scale.. If they are made in sand moulds they may have sand grains fused or adhering to the surface. Residue from coolants, lubricants and other processing materials is common on many manufactured parts. In addition to greasy films from processing, protective coatings of greases, oils, or waxes are frequently used intentionally to prevent rust or corrosion on parts that are stored for some period of time before being put to use. Even if parts are clean at the completion of manufacturing, they seldom remain that way for long. After only short storage periods , corrosion and dust from atmospheric exposure necessitate cleaning particularly if further processing is required.When using NDT methods such as penetrant testing and ultrasonic testing good precleaning may be necessary to get accurate results and postcleaning is often needed to leave the surface in a suitable condition. In some applications such as on stainless steels and nickel based alloys, ultrasonic couplants and penetrant materials must be made of only certain material so that they do not cause stress corrosion failure.Cleaning sometimes has finish improvement associated with it. Some shape producing methods produce unsatisfactory surface characteristics such as sharp corners, burrs and tool marks which may affect the function, handling ease, and appearance of the product. Some cleaning processes at least partially blend together surface irregularities to produce uniform light reflection. Improvement of surface qualities may be accomplished by removal of high spots by cutting or by plastic flow as cleaning is performed.

TABLE 1.2 CLEANING METHODS

CLEANING		
CHEMICAL	MECHANICAL	ELECTROCHEMICAL
VAPOUR BATH	BLAST	REVERSE PLATE
SPRAY	TUMBLE	
BRUSH	VIBRATE	
DIP	BRUSH	
BLAST	BELT GRIND	
	POLISH	
	BUFF	
	BURNISH	

1.5.2.1 **Choice of cleaning method**

As indicated by Table 1.2 , many different cleaning methods are available The one most suitable for any particular situation is dependent upon a number of factors. Cost is ,of course, always a strong consideration, but the reason for cleaning is bound to affect the choice. Convenience in handling, improvement in appearance, elimination of foreign material that may affect function, or establishment of a chemically clean surface as an intermediate step in processing might all call for different methods. Consideration must be given to the starting conditions and to the degree of improvement desired or required. Methods suitable for some materials are not at all satisfactory for use on other kinds of material.

Some cleaning methods provide multiple benefits. As pointed out previously, cleaning and finish improvement are often combined. Probably of even greater importance is the combination of corrosion protection with finish improvement, although corrosion protection is more often a second step that involves coating an already cleaned surface with some other material.

1.5.2.2 **Liquid and vapour baths**

The most widely used cleaning methods make use of a cleaning medium in liquid or vapour form. These methods depend on a solvent or chemical action between the surface contaminant to be removed , the importance and degree of cleanliness , and the quantity to be treated. Among the more common cleaning jobs required is the removal of grease and oil deposited during manufacturing or intentionally coated on the work to provide protection. One of the most efficient ways to remove this material is by use of solvents that dissolve the grease and oil but have no effect on the base metal. Petroleum derivatives such as Stoddart solvent and kerosene are common for this purpose, but as they introduce some danger of fire, chlorinated solvents, such as trichloroethylene, that are free of this fault are sometimes substituted. One of the most economical cleaning materials is water. However, it is seldom used alone even if the contaminant is fully water soluble because the impurity of the water itself may contaminate the work surface. Depending on its use , water is treated with various acids and alkalis to suit the job being performed. Water containing sulfuric acid in a concentration from about 10% to 25% and at a temperature approximately 65° is commonly used in a process called pickling for removal of surface oxides or scale on iron and steel. The work is immersed in the solution contained in large tanks for a predetermined period of time after which it is rinsed to stop the chemical action. Improper control. of the timing , temperature , or concentration in the pickling baths is likely to result in pitting of the surface because of uneven chemical reaction. Most pickling baths are treated with chemical inhibitors that decrease the chemical effect of the acid on the base metal but have little effect on the rate at which the oxides are attacked. Many of the common cleaning liquids are made up of approximately 95% water containing alkaline cleaners such as caustic soda, sodium carbonate, silicates, phosphates, and borates. The proportions are varied for different purposes and are available under different brand names for particular applications.

Liquid cleaners may be applied in a number of ways. Degreasing, particularly on small parts, is frequently done with a vapor-bath. This does an excellent job of removing the grease but has the disadvantage of not being able to remove chips and other kinds of dirt that might be present. Vapor degreasing is usually done in a special tank that is cooled at the top to condense the solvent. Cold work suspended in the vapor causes condensation of the solvent, which dissolves the grease and drips back into the bottom of the tank. The difference in volatility between the solvent and the grease permits the vapor to remain unchanged and to do a uniform cleaning job.

Spraying, brushing and dipping methods are also used with liquid cleaners. In nearly all cases, mechanical work to cause surface film breakdown and particle movement is combined with chemical and solvent action. The mechanical work may be agitation of the product as in dipping movement of the cleaning agent as in spraying, or use of a third element as in rubbing or brushing. In some applications, sonic or ultrasonic vibrations are applied to either the solution or the workpiece to speed the cleaning action. Chemical activity is increased with higher temperatures and optimum concentration of the cleaning agent, both of which must in some cases be controlled closely for efficient action.

Washing and rinsing away the cleaning liquid is usually necessary to prevent films and spots. Fast drying of water solutions on iron and steel products is sometimes needed to prevent the formation of rust. If the product mass is large enough, heat picked up from the cleaning bath may be sufficient to cause fast drying; otherwise, air blasts or external heat sources may be required.

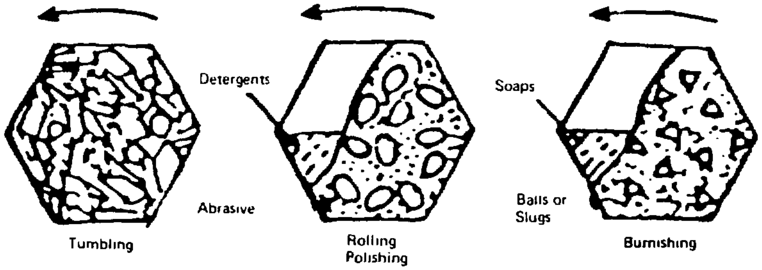
1.5.2.3 **Blasting**

The term blasting is used to refer to all of those cleaning methods in which the cleaning medium is accelerated to high velocity and impinged against the surface to be cleaned. The high-velocity may be provided by air or water directed through a nozzle or by mechanical means with a revolving slinger. The cleaning agent may be either dry or wet solid-media such as sand, abrasive, steel grit, or shot, or may be liquid or vapor solvents combined with abrasive material. The solid media are used for the removal of brittle surface contamination such as the heat treat scale found on forgings and castings. Steel grit has replaced sand and other refractory type abrasives to some extent because of the reduced health hazard (silicosis) and a reduced tendency for pulverization. Sand, however, can be used without danger to the operator when parts are small enough to be handled by hand inside a properly designed chamber fitted with a dust collector. In addition to cleaning, solid particles can improve finish and surface properties of the material on which they are used. Blasting tends to increase the surface area and thus set up compressive stresses that may cause a warping of thin sections but in other cases, it may be very beneficial by reducing the likelihood of fatigue failure. When used for this latter purpose, the process is more commonly known as "shotpeening".

Liquid or vaporized solvents may by themselves be blasted against a surface for high speed cleaning of oil and grease film with both chemical and mechanical action. Water containing rust-inhibiting chemical may carry, in suspension, fine abrasive particles that provide a grinding cutting type action for finish improvement along with cleaning. The blasting method using this medium is commonly known as "liquid honing".

1.5.2.4 Abrasive barrel finishing

A Low Cost Cleaning and Finishing Method. When large numbers of small parts that do not need to have sharp detail or accurate dimensions require cleaning, the rotating barrel method may be very economical. Names used are: Barrel-finishing; rolling, tumbling and rattling. They are all similar but various media may be combined with the work as indicated in Figure 1.39. High polish may be produced by tumbling with pieces of leather to wipe the surfaces smooth as in a strop honing operation. In some cases a number of hours may be required to produce the desired results but since the finishing machines do not have to be tended by operators, the unit cost may be extremely low. Machines with a vibratory motion and loaded with abrasive media are also used for similar type cleaning and finishing work.



Barrel finishing

Figure 1.39

1.5.2.5 Wire brushing

A number of cleaning operations can be quickly and easily performed by use of a high speed rotating wire brush. In addition to cleaning, the contact and rubbing of the wire ends across the work surface produces surface improvement by a brushing-type action. Sharp edges and burrs can be removed. Scratches, rough spots, and similar mechanical imperfections can be improved primarily by plastic flow which also tends to work harden the surface material. Most wire brushing is done under manual control, but where the surfaces can be made accessible and the quantity to be treated is sufficiently large for economic feasibility, machines for automatic brushing can be set up.

Common applications of wire brushing are the cleaning of spatter and slag from weldments; and the removal of rust, corrosion, and paint from any object whose base material is strong enough to withstand the brushing. Wire brushing produces a distinctive pattern on the surface and in addition to cleaning it sometimes is used to produce a decorative surface.

A precaution regarding surface defect detection should be kept in mind. Any method of surface cleaning involving abrasion or rubbing may smear the surface material in such a way as to disguise or cover over surface defects and prevent their detection by usual methods. Careful selection of a method may be necessary, or in some cases, such drastic methods as etching may be needed. Machining, including fine grinding, also has similar effects to a lesser degree but should be remembered when small defects could be serious regarding service life of the part under consideration. Penetrant tests are most severely affected and can be rendered practically useless if defect openings have been smeared.

1.5.2.6 Polishing

The term polishing may be interpreted to mean any nonprecision procedure providing a glossy surface but is most commonly used to refer to a surface-finishing process using a flexible abrasive wheel. The wheels may be constructed of felt or rubber with an abrasive band, of multiple coated abrasive discs, of leaves of coated abrasive, of felt or fabric to which loose abrasive is added as needed, or of abrasives in a rubber matrix. These wheels differ from grinding wheels only by being flexible, which enables them to apply uniform pressure to the work surface and permits them to conform to the surface shape. Polishing is usually done manually except where the quantity is large. The process may have several objectives. Interest may be only in finish improvement for appearance. The surface finish may be important as an underlay for plating, which has only limited ability to improve surface quality over that of the surface on which it is placed. Polishing may also be important as a means of improving fatigue resistance for products subject to this kind of failure.

1.5.2.7 Buffing

About the only difference between buffing and polishing is that, for buffing, a fine abrasive carried in wax or a similar substance is charged on the surface of a flexible wheel. The objectives are similar. With finer abrasive, buffing produces higher quality finish and luster but removes only minor amounts of metal. With both polishing and buffing particularly of the softer metals, plastic flow permits filling of pores, scratches and other surface flaws to improve both appearance and resistance to corrosion.

1.5.2.8 Electropolishing

If a workpiece is suspended in an electrolyte and connected to the anode in an electrical circuit, it will supply metal to the electrolyte in a reverse plating process. Material will be removed faster from the high spots of the surface than from the depressions and will thereby increase the average smoothness. The cost of the process is prohibitive for very rough surfaces because larger amounts of metal must be removed to improve surface finish than would be necessary for the same degree of improvement by mechanical polishing. Electropolishing is economical only for improving a surface that is already good, or for polishing complex and irregular shapes, the surfaces of which are not accessible to mechanical polishing and buffing equipment.

1.5.3. Coatings

Many products, in particular those exposed to view and those subject to change by the environment with which they are in contact, need some type of coating for improved appearance or for protection from chemical attack. All newly created surfaces are subject to corrosion, although the rate of occurrence varies greatly with the material, the environment, and the conditions. For all practical purposes, some materials are highly corrosion resistant because the products of corrosion resist further corrosion. For example, a newly machined surface on an aluminium alloy will immediately be attacked by oxygen in the air. The initial aluminum oxide coating protects the remaining metal and practically stops corrosion unless an environmental change occurs. Corrosion rates are closely dependent on environment. Rates increase with rise of temperature and greater concentration of the attacking chemical. The need for corrosion protection for maintenance of appearance is obvious. Unless protected, an object made of bright steel will begin to show rust in a few hours of exposure to ordinary atmosphere. In addition to change of appearance , loss of actual material, change of dimensions, and decrease of strength, corrosion may be the cause of eventual loss of service or failure of a product. Material that must carry loads in structural applications, especially when the loads are cyclic in nature , may fail with fatigue if corrosion is allowed to take place. Corrosion occurs more readily in highly stressed material where it attacks grain boundaries in such a way as to form points of stress concentrations that may be nuclei for fatigue failure.

The correction for corrosion problems include choice of materials that resist attack from the environment to which they are exposed, selection or control of the environment to minimize corrosion effects and the use of selective corrosion by placing materials with greater susceptibility to corrosion near to those to be protected. The latter is illustrated by the use of magnesium rods in hot water tanks. The magnesium is the target for corrosion , as long as it is present, corrosion of the steel walls of the tank is insignificant. Another correction for corrosion, when the others are impractical, is the coating of the surfaces needing protection with a material that resists the environmental elements that are harmful. Thickness of coating may be important for many reasons. If the objective is improvement of appearance , uniformity of coating may be required, or lacking that , some minimum value may have to be surpassed to provide the appearance of uniformity. Life of a coating is usually also closely associated with uniformity and depth of coating layer. Many coatings are inherently porous to some degree and resistance to corrosion is likely to require thickness sufficient to resist penetration of liquids and gases. For those reasons manufacturing specifications frequently list minimum thickness for coatings and an NDT measurement is usually the only way to know when that specification is being met. Although other methods are possible, gaging with eddy current methods is common.

In addition to stabilizing appearance by resisting corrosion, coatings are often very valuable for providing colour control, changing appearance and providing variety which may be important in enhancing sales appeal. Some coatings such as fillers, paint and others with substantial body, improve surface smoothness by filling pores and cavities. Some coating materials can provide uniform appearance for products made as assemblies of different materials. Coating of various types may be used to change or improve surface properties. Case hardening of steel has been discussed earlier and although it is a surface property-changing method, in most of its forms, casehardening does not consist of the addition of a coating. Hardness and wear resistance can, however, be provided on a surface by plating with hard metals. Chromium plating of gages subject to abrasion is frequently used to increase their wear life. Coatings of plastic materials and asphaltic mixture are sometimes placed on surfaces to provide sound deadening. The additional benefit of protection from corrosion is usually acquired at the same time. Frictional characteristics of a surface can be varied in either direction by application of a coating. Rubber and some other plastic materials may be applied for increase of friction. An example would be the special compounds applied to the floorboards or bottom of small boats to decrease the chance of slipping. Other plastic materials, the fluorocarbons being good examples, are applied to surfaces where slipping is required because they provide a very low co-efficient of friction.

1.5.3.1 Preparation for coatings

The ability of an organic film to adhere to a metal surface (adhesion) is dependent to a large degree on the cleanliness of the metal surface. However, some materials hold together tighter on a surface that has been slightly roughened by some process such as sand blasting, while others may require chemical treatment of the base metal for formation of an anode or phosphate film for satisfactory adhesion. Cleaning by one or more of the methods discussed earlier in this chapter is usually essential before any kind of coating should be applied. Practically in every case a clean dry surface is necessary for coating adhesion. Whether or not a combination of cleaning and smoothing operation should be used depends somewhat on the previous processing as well as on the desired final finish. Some coatings, such as the heavier plastics, can hide large faults and surface imperfections, but others, such as finishing lacquers and metallic platings, improve finish quality to only a very small degree. With the latter, scratches, surface faults, and even tool marks can continue to show on the final surface although the coating tends to blend and soften their appearance.

1.5.3.2 Paints,varnishes and enamels

Painting is a generic term that has come to mean the application of almost any kind of organic coating by any method.

Paint: As originally defined and as used mostly at present, paint is a mixture of pigment in a drying oil. Color and opacity are supplied by the pigment. The oil serves as a carrier for the pigment and in addition creates a tough continuous film as it dries.

Varnish: Varnish is a combination of natural or synthetic resins and drying oil, sometimes containing volatile solvents as well. The material dries by a chemical reaction in the drying oil to a clear or slightly amber coloured film. A solution of resin in a volatile solvent without the drying oil is called spirit, or shellac, varnish.

Enamel: Enamel is a mixture of pigment in varnish. The resins in the varnish cause the material to dry to a smoother, harder,and glossier surface than produced by ordinary paints. Some enamels are made with thermosetting resins that must be baked for complete dryness. These baking enamels provide a toughness and durability not usually available with the ordinary paints and enamels.

1.5.3.3 Lacquers

The term ' lacquer ' is used to refer to finishes consisting of thermoplastic materials dissolved in fast drying solvents. One common combination is cellulose nitrate dissolved in butyl acetate. Present day lacquers are strictly air drying and form films very quickly after being applied, usually by spraying. No chemical change occurs during the hardening of lacquers consequently, the dry film can be redissolved in the thinner. Cellulose acetate is used in place of cellulose nitrate in some lacquers because it is nonflammable. Vinyls, chlorinate hydrocarbons, acrylics, and other synthetic thermoplastic resins are also used in the manufacture of lacquers. Clear lacquers are used to some extent as protective films on such materials as polished brass, but the majority are pigmented and used as color coats. The pigmented lacquers are sometimes called lacquer enamels. Lacquers are widely used for coating manufactured products because of their ease of application and speed of drying.

1.5.3.4 Organic coating applications

Dipping Dipping is common for applying protective coatings to forgings and castings to prevent rust during storage and processing and to serve as primers for final finish. Many other products made in large quantities also are finished by dipping. Dip application is limited to parts that do not have recesses, pockets, or shapes that will hold the liquid paint or prevent its flowing to an even coat.

Brushing: Brush painting is slow and used little in manufacturing work except on large, heavy or odd shaped parts that cannot be moved or manipulated in a spray paint area. Brushing and rolling are commonly used for coating structural surfaces such as walls and ceilings of buildings. Brushing does provide efficient , use of coating material, as practically none is wasted and the mechanical rubbing of a brush or roller provides some cleaning action that may provide better adhesion.

Spraying: By far the greatest amount of organic coatings are applied industrially by spraying. This method is used most with lacquers and fast drying enamels. The short drying time causes parts to become dust free very quickly so that they can be moved away from the spray area and advantage can be taken of this fast application method. Spraying is done in booths designed for this purpose where adequate ventilation carries fumes and spray particles away from the operator. Spray painting of automobile bodies and other large objects that are conveyorized is often done automatically with a number of spray heads, some stationary and some movable, adjusted to spray a uniform layer over the entire object. In many cases spray application of penetrant materials is the fastest and best way of obtaining uniform coverage. Spraying aids particularly on parts cont 'ning recesses and corners difficult to contact with a brush.

Electrostatic spraying: For electrostatic spraying the paint particles are sprayed through a high voltage electrostatic field. Each paint particle takes on an electric charge from the field and is attracted towards the grounded article to be painted. This method provides better efficiency of paint use than ordinary spraying, but even more important, causes the coating to distribute itself more evenly over the entire object. Electrostatic force can also be used to pull off drips or tears that form by gravity along the bottom edges of newly painted objects.

As indicated previously, organic coating is often done in free air. Some solvents and vehicles are so volatile that drying is accomplished almost immediately. Others require several days for drying, and still others require elevated temperatures for necessary polymerization to take place. Heat for drying and speeding chemical reaction may be provided by various types of ovens. Some ovens are batch types in which racks of parts are placed for specific periods of time. Others are continuous types built over conveyer systems that regulate the time of exposure by the length of oven and the speed of conveyer operation.

1.5.3.5 Vitreous enamels

Vitreous, or porcelain, enamel is actually a thin layer of glass fused onto the surface of a metal, usually steel or iron. Shattered glass, ballmilled to a fine particle size, is called frit. Frit is mixed with clay, water and metal oxides, which produce the desired color, to form a thin slurry called slip. This is applied to the prepared metal surface by dipping or spraying and, after drying, is fired at approximately 800°C to fuse the material to the metal surface. For high quality coating, more than one layer is applied to guard against pinhole porosity. Glass applied in this way has high strength and is usually flexible enough to withstand bending of the steel within the elastic limits of the base metal. The coatings have excellent resistance to atmospheric corrosion and to most acids. Vitreous enamels can be made suitable for use over a wide range of temperatures. Some special types have been used for corrosion protection on exhaust stacks for aircraft engines. Considering their high quality protection, vitreous enamels are relatively inexpensive and find many uses.

The advent of rockets and missiles has introduced , an entirely new field in which high temperature corrosion protection is essential. Porcelain enamel has been satisfactory in some of these applications, but ceramic coatings with better refractory characteristics are more commonly used. Some are applied in the same way as porcelain enamel. Others are fused to the metal surfaces with the intense heat of a plasma jet.

Porosity of porcelain or ceramic coatings can be checked with penetrants and coating thickness determined by use of eddy current methods.

1.5.4 Metallizing

Metal spraying, or metallizing, is a process in which metal wire or powder is fed in to an oxyacetylene heating flame and the same after melting, is carried by high velocity air to be impinged against the work surface. The small droplets adhere to the surface and bond together to build up a coating. The nature of the bond is dependent largely on the materials. The droplets are relatively cool when they make contact and in fact can be sprayed on wood, leather, and other flammable materials. Little, if any, liquid flow aids the bonding action. If, however, sufficient affinity exists between the metals, a type of weld involving atomic bonds may be established. The bond is largely mechanical in most cases and metal spraying is usually done on surfaces that have been intentionally roughened to aid the mechanical attachment. Zinc, aluminium, and cadmium, which are anodic to steel and therefore provide preferential corrosion protection, are usually sprayed in thin layers, averaging about 0.25 millimeter (0.010 inch) in thickness, as protective coatings. Because sprayed coatings tend to be porous, coatings of two or more times this thickness are used for cathodic materials such as tin, lead, and nickel. The cathodic materials protect only by isolating the base material from its environment.

Another important application for metal spraying is in salvage operations for which a wide variety of metals and alloys may be used. Surfaces, usually after first being roughened, are built up to oversized dimensions with metal spray. The excess material is then machined away to the desired dimension. Expensive parts with worn bearing surfaces or new parts that have been machined to undersize can sometimes be salvaged by this relatively cheap procedure.

1.5.4.1 Vacuum metallizing

Some metals can be deposited in very thin films, usually for reflective or decorative purposes, as a vapor deposit. The metal is vaporized in a high vacuum chamber containing the parts to be coated. The metal vapor condenses on the exposed surfaces in a thin film that follows the surface pattern. The process is cheap for coating small parts, considering the time element only, but the cost of special equipment needed is relatively high. Aluminium is the most used metal for deposit by this method and is used frequently for decorating or producing a mirror surface on plastics. The thin films usually require mechanical protection by covering with lacquer or some other coating material.

1.5.4.2 Hot dip plating

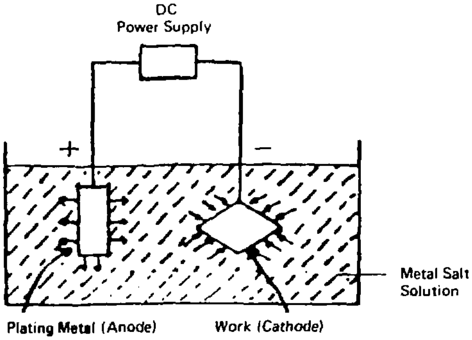
Several metals, mainly zinc, tin, and lead, are applied to steel for corrosion protection by a hot dip process. Steel in sheet, rod, pipe, or fabricated form, properly cleansed and fluxed, is immersed in molten plating metal. As the work is withdrawn, the molten metal that adheres solidifies to form a protective coat. In some of the large mills, the application is made continuously to coil stock that is fed through the necessary baths and even finally inspected before being recoiled or cut into sheets. Zinc is one of the most common materials applied to steel in this manner. In addition to protection by exclusion, electro-chemical protection (the source of the term galvanized iron) occurs when exposed steel and adjacent zinc are connected by conducting moisture. Zinc is one of the most favoured coating for corrosion protection of steel because of its low cost and ease of application. In addition to hot dipping, zinc can also be applied by electroplating, spraying, and sherodizing. Sherodizing is a process by which steel, heated in the presence of zinc dust, becomes coated with zinc. Tin plating and terne plating, the latter using a mixture of approximately four parts lead to one part tin, are also done by hot dipping.

1.5.4.3 Electroplating

Coating of many metals can be deposited on other metals, and on non-metals by electroplating, when suitably prepared. The objectives of plating are to provide protection against corrosion, to improve appearance, to establish wear and abrasion resistant surfaces, to add material for dimensional increase, and to serve as an intermediate step to multiple coating. Some of the most common metals deposited in this way are copper, nickel, chromium, cadmium, zinc, tin, silver and gold. The majority are used to provide some kind of corrosion protection, but appearance also plays a strong part in their use. Figure 1.40 is a schematic diagram of a simple plating set up. When direct-current power of high enough voltage is applied to two electrodes immersed in a water solution of metallic salt, current will flow through the circuit causing changes at the electrodes. At the negative electrode, or cathode (the work), excess electrons supplied from the power source neutralize positively charged metallic ions in the salt solution to cause dissolved metal to be deposited in the solid state. At the positive electrode, or anode (plating metal), metal goes into solution to replace that removed at the other electrode. The rate of deposition and the properties of the plated material are dependent on the metals being worked with, the current density, the solution temperature, and other factors. Thickness of plating is usually low, in the range of 2.5 microns to O.025 millimeter (0.0001 to 0.001 inch). Chromium applied for appearance only may be used in a thickness of only about one-tenth these amounts, but when used to provide wear resistance and to build up dimensions as on gages, may be applied in thicknesses of as much as 0.25 millimeter (0.010 inch).

When plating thickness is a critical consideration, measurement and control may be established with NDT. Both eddy current methods and radiation back scatter are useful.

Layers of different metals are sometimes plated for maximum properties. For example, an object such as a steel bumper for an automobile may first be copper plated to provide good adhesion and coverage of the steel and to facilitate buffing to a smooth surface necessary



Electroplating

Figure 1.40

for high quality final finish. Nickel is then plated over the copper to serve as the principal corrosion protection. Finally, chromium is plated over the nickel to serve as a hard, wear-resistant, bright blue-white color coating over the softer tarnishable nickel.

Some problems exist with electroplating. Deposit on irregular shapes may vary widely in thickness. Projections and exposed surfaces may plate readily but recesses, corners and holes can sometimes be coated only by using specially located electrodes or electrodes shaped to conform to the workpiece shape. Electroplating can be costly because it involves payment for considerable electric power and the metal plated and lost. Because plating thicknesses are usually very small, the coating has little hiding power.

1.5.5 **Chemical conversions**

A relatively simple and often fully satisfactory method for protection from corrosion is by conversion of some of the surface material to a chemical composition that resists attack from the environment. These converted metal surfaces consist of relatively thin (seldom more than 0.025 millimeter, or 0.001 inch thick) inorganic films that are formed by chemical reaction with the base material. One important feature of the conversion process is that the coatings have little effect on the product dimensions. However, when severe conditions are to be encountered, the converted surface may give only partial protection, and coatings of entirely different types may be applied over them.

1.5.5.1 **Anodizing**

Aluminium, magnesium, and zinc can be treated electrically in a suitable electrolyte to produce a corrosion-resistant oxide coating. The metal being treated is connected to the anode in the circuit, which provides the name anodizing for the process. Aluminium is commonly treated by anodizing that produces an oxide film thicker than, but similar to that formed naturally with exposure to air. Anodizing of zinc has very limited use. The coating produced on magnesium is not as protective as that formed on aluminium but does provide some protective value and substantially increases protection when used in combination with paint coatings. Because of their greater thickness and abrasion resistance anodic films offer much better protection against corrosion and mechanical injury than do the thin natural films. Aluminium is usually treated in a sulfuric acid electrolyte that slowly dissolves the outside and at the same time it is converting the base metal to produce a porous coating. The coating can be impregnated with various materials to improve corrosion resistance. It also serves as a good paint base and can be colored by use of dyes.

The usual commercial anodizing methods used on aluminium cause formation of billions per square inch of aluminium oxide cells which grow above the original metal surface and at the same time extend below the original surface. Each of these cells has a pore in its centre that extends to a solid barrier layer near the bottom of the cell. These numerous pores permit impregnation of the surface with various desirable materials but they are also a source of problems for penetrant testing of anodized aluminium surfaces. The penetrant can enter the pores to such an extent that an extremely high background is produced. Special care in the interpretation of results is therefore be necessary. Checking for cracks is often called for because aluminium oxide is brittle and subject to cracking particularly if deformation of the material occurs after anodizing.

1.5.5.2 Chromate coatings

Zinc usually has a relatively good corrosion resistance. This is true when the exposure is to normal out door atmosphere where a relatively thick corrosion film forms. Contact with either highly aerated water films or immersion in stagnant water containing little oxygen causes uneven corrosion and pitting. The corrosion products of zinc are less dense than the base material so that heavy corrosion not only destroys the product appearance but also may cause malfunctions by binding moving parts.

Corrosion of zinc can be substantially slowed by the production of chromium salts on its surface. The corrosion resistance of magnesium alloys can be increased by conversion. Treatment of both zinc and magnesium improves corrosion resistance but is used also to improve adhesion of paint.

1.5.5.3 Phosphate coatings

Phosphate coatings, used mostly on steel, results from a chemical reaction of phosphoric acid with the metal to form a non-metallic coating that is essentially phosphate salts. The coating is produced by immersing small items or spraying large items with the phosphating solution. Phosphated surfaces may be used alone for corrosion resistance, but their most common application is as a base for paint coatings. Two of the most common application methods are called parkerizing and bonderizing.

1.5.5.4 Chemical oxide coatings

A number of proprietary blackening processes, used mainly on steel, produce attractive black oxide coatings. Most of the processes involve the immersing of steel in a caustic soda solution heated to about 150°C(300°F) and made strongly oxidizing by the addition of nitrites or nitrates. Corrosion resistance is rather poor unless improved by application of oil, lacquer, or wax. As in the case of most of the other chemical conversion procedures, this procedure also finds use as a base for paint finishes.

1.6 METROLOGY

1.6.1 Units and standards of measurement

From earliest history nations have had standards for length, volume and mass. These have differed from country to country and even from time to time, so that a large number of units for mass, length volume and area were in wide spread use by the 18th century.

In 1773 the French Government adopted the decimal/metric system wherein the basic unit of length was defined as one ten-millionth of Earth's polar quadrant (as determined from latitude surveys), to be called the meter. The basic unit of mass was defined as the mass of one cubic decimeter of water, to be called the kilogram. For working standards a platinum bar was marked with fine lines one meter apart and a platinum iridium cylinder was constructed equal in mass to a cubic decimeter of water. When later refinements in measurement showed that neither of these standards exactly realized the units as originally defined , the discrepancies were eliminated by redefining the units in terms of the materials from which they had been constructed.

The United States in 1866 legalized the use of the metric system without making its use mandatory and in 1875 signed a treaty with 18 other countries providing for international standards of measurement. An international committee on Weights and Measures and a laboratory were established near Paris , known as the International Bureau of Weights and Measures (BIPM). In 1893 the United States received prototypes of international standards of the meter and kilogram. In 1975 the United States adopted the Metric Conversion Act to increase the use of the metric system in the United States.

The British Government in 1965 announced a policy of moving towards full metric usage in industry and trade, hoping that this could be generally accomplished within 10 years. By 1980, many major industries had successfully adopted metric conversion and encouraging progress was being made in the remaining areas , but total conversion had not been attained.

English Units have become almost universal in some world wide industries, e.g. the dimensions of oil drilling equipment or altitude measurement in aviation or the size of a football field. The wide spread practice in aviation control is to separate aircraft flying in various directions by 500, 1000,or 2000 feet in altitude. Altimeter pointers making one revolution for each 1000 feet provide a conveniently readable index. To adopt a metric conversion it was thought 300 meters or even 500 meters would result in reading inconvenience and some change in flight safety. The unit for speed in air navigation (as in marine navigation) is the knot, defined as 1 nautical mile (1 minute of arc of the earth's surface) per hour. These have been temporarily permitted for use with the International System. Thus it is likely that there will always be exceptions to uniformity, requiring knowledge of special units for at least some people even if the whole world goes metric in principle.

1.6.2 **International System of Units (SI)**

At present the International System of units (abbreviated to SI from the French terminology of System International d'Unites) is constructed from seven base units for independent quantities and two supplementary units for plane angle and solid angle as shown in TABLE 1.3. Units for all other quantities are derived from these nine units.

TABLE 1.3 SI BASE AND SUPPLEMENTARY UNITS

Quantity	Unit Name	Unit symbol
Base Units		
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	Ampere	A
Thermodynamic temperature	Kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
Supplementary Units		
Plane angle	radian	rad
Solid angle	steradian	sr

In TABLE 1.4 are listed 19 SI derived units with special names.

TABLE 1.4 SI DERIVED UNITS WITH SPECIAL NAMES

	SI unit			
Quantity	Name	Symbol	Expression in terms of other units	Expression in terms of SI units
Frequency	Hertz	Hz		s-1
Force	Newton	N		$m.kg.s^{-2}$
Pressure stress	Pascal	Pa	N/m^2	$m^{-1}.kg.s^{-2}$
Energy,work quantity of heat	Joule	J	N.m	$m^2.kg.s^{-2}$
Power,radiant flux	Watt	W	J/s	$m^2.kg.s^{-3}$
Quantity of electricity, electric charge	Coulomb	C	A.s	s.A
Electric potential P.D.,E.M.F.	Volt	V	W/A	$m^2.kg.s^{-3}A^{-1}$
Capacitance	Farad	F	C/V	$m^{-2}.kg^{-1}.s^4.A^{-2}$
Electric resistance	Ohm	Ω	V/A	$m^2.kg.s^{-3}.A^{-2}$
Conductance	Siemens	S	A/V	$m^{-2}.kg^{-1}.s^3A^2$
Magnetic flux	Weber	Wb	V.s	$m^2.kg.s^{-2}A^{-1}$
Magnetic flux density	Tesla	T	Wb/m2	$kg.s^{-2}A^{-1}$
Inductance	Henry	H	Wb/A	$m^2.kg.s^{-2}A^{-1}$
Celsius temperature	degree celsius	^0C		K
Luminous flux	Lumen	lm		Cd.Sr
Illuminance	Lux	lm/m^2		$m^{-2}cd.sr$
Activity (of a radio nuclide)	Becqueral	Bq		s^{-1}
Absorbed dose, specific energy imparted,kerma, absorbed dose index	Gray	Gy	J/kg	m^2s^{-2}
Dose equivalent dose equivalent index	sievert	Sr	J/kg	m^2s^{-2}

Some more SI derived units are given in TABLE 1.5.

TABLE 1.5 DERIVED UNITS OF THE INTERNATIONAL SYSTEM

Quantity	Name of unit	Unit symbol where differing from basic form	Unit expressed in terms of base or supplementary units*
area	square meter		m^2
volume	cubic meter		m^3
frequency	hertz	Hz	s^{-1}
density	kilogram per cubic meter		kg/m^3
velocity	meters per second		m/s
angular velocity	radian per second		rad/s
acceleration	meter per second squared		m/s^2
angular acceleration	radian per second squared		rad/s^2
volumetric flow rate	cubic meter per second		m^3/s
force	newton	N	$kg.m/s^2$
surface tension	newton per meter, Joule per square meter	$N/m, J/m^2$	kg/s^2
pressure	newton per square meter, pascal	N/m^2, Pa	$kg/m.s^2$
viscosity dynamic	newton-second per square meter, pascal second	$N.s/m^2$, Pa.s	kg/m.s
viscosity kinematic	meter squared per second		m^2/s
work, torque, energy, quantity of heat	joule, newton-meter watt-second	J, N.m, W.s	$kg.m^2/s^2$
power, heat flux	watt, joule per second	W, J/s	$kg.m^2/s^2$
heat flux density	watt per square meter	W/m^2	kg/s^2
volumetric heat release rate	watt per cubic meter	W/m^3	$kg/m.s^3$
heat transfer coefficient	watt per square meter Kelvin	$W/m^2.K$	$kg/s^3.K$
heat capacity (specific)	joule per kilogram Kelvin	J/kg.K	$m^2/s^2.K$
capacity rate	watt per Kelvin	W/K	$kg.m^2/s^2.K$
thermal conductivity	watt per meter Kelvin	$W/m.K, J.m/s.m^2.K$	$kg.m/s^3$
quantity of electricity	coulomb	C	A.s
electromotive force	Volt	V, W/A	$kg.m^2/A.s^3$
electric field strength	Volt per meter	V/m	$kg.m/A.s^3$
electric resistance	Ohm	Ω, V/A	$kg.m^2/A.s^3$

TABLE 1.5 (cont.)

Quantity	Name of unit	Unit symbol where differing from basic form	Unit expressed in terms of base or supplementary units*
electric conductivity	ampere per volt meter	A/V.m	$A.s^2/kg.m^2$
electric capacitance	farad	F,A.s/V	$A^3s^4/kg.m^2$
magnetic flux	weber	Wb,V.s	$kg.m^2/A.s^2$
inductance	henry	H,V.s/A	$kg.m^2/A^2.s^2$
magnetic permeability	henry per meter	H/m	$Kg.m/A^2.s^2$
magnetic flux density	tesla,weber per square meter	$T,Wb/m^2$	$kg/A.s^2$
magnetic field strength	ampere per meter		A/m
magnetomotive force	ampere		A
luminous flux	lumen	lm	cd.sr
luminance	candela per square meter		cd/m^2
illumination	lux,lumen per square meter	$lx, lm/m^2$	$cd.sr/m^2$
activity(of radionuclides)	becquerel	Bq	s^{-1}
absorbed dose	gray	Gy, J/kg	$m^2.s^{-2}$
dose equivalent	sievert	Sv	$m^2.s^{-2}$

* supplementary units are : plane angle, radian(rad), solid angle, steradian(sr).

The set of 16 prefixes to be used with the SI units for forming multiples and sub multiples of these units are given in TABLE 1.6.

TABLE 1.6 PREFIXES FOR UNITS IN THE SI

Prefix	Symbol	Power	Example
exa	E	10^{18}	
peta	P	10^{15}	
tera	T	10^{12}	
giga	G	10^{9}	
mega	M	10^{6}	megahertz
kilo	K	10^{3}	kilometer
hecto	h	10^{2}	
deca	da	10^{1}	
deci	d	10^{-1}	
centi	c	10^{-2}	
milli	m	10^{-3}	milligram (mg)
micro	μ	10^{-6}	microgram (ug)
nano	n	10^{-9}	nanosecond (ns)
pico	p	10^{-12}	picofarad (pf)
femto	f	10^{-15}	
atto	a	10^{-18}	

For mass it must be noted that the prefixes are to be applied to the gram instead of the SI unit, the kilogram.

1.6.2.1. Natural units

In some cases quantities are commonly expressed in terms of fundamental constants of nature and use of these constants or natural units is acceptable. Typical examples of natural units with their symbols are as follows:

Elementary charge	e
Electron mass	me
Proton mass	m
Bohr radius	a^P
Electron radius	r^o
Compton wavelength of electron	e_c
Bohr magneton	P_b
nuclear magneton	n
speed of light	c
Plank's constant	h

1.6.2.2. Units acceptable for use with SI

Certain units which are not part of the SI are used so widely that it is impractical to abandon them. The units that are accepted for continued use with the International System are listed in TABLE 1.7.

TABLE 1.7 UNITS ACCEPTED FOR USE WITH THE SI

Name	Symbol	Value in SI unit
minute	min	1 min = 60s
hour	h	1 h = 60 min = 3600s
day	d	1 d = 24 h = 86400s
degree	°	$1^\circ = (\pi/180)$rad
minute	'	$1' = (1/60)^\circ = (\pi/10800)$rad
second	"	$1'' = (1/60)' = (\pi/64800)$rad
liter	L*	$1L = 1dm^3 = 10^{-3}m^3$
metric ton	t	$1t = 10^3kg$
hectare	ha	$1ha = 10^4m^2$

It is likewise necessary to recognize outside the International System the following units which are used in specialized fields.

electron volt	ev
unified atomic mass unit	u
astronomical unit	AU
parsec	pc

TABLE 1.8 gives examples of conversion factors from non-SI units.

TABLE 1.8 SOME COMMON UNITS DEFINED IN TERMS OF SI units

Quantity	Name of unit	Symbol	Definition of unit
length	inch	in.	2.54 x 10^{-2}m
mass	pound(avoirdupois)	lb	0.45359237 kg
force	kilogram-force	kgf	9.80665 N
pressure	atmosphere	atm	101325 Pa
pressure	torr	torr	(101325/760) Pa
pressure	conventional -millimeter of mercury	mmHg	13.5951x980.665 x10^{-2} Pa
energy	kilowatt-hour	kWh	3.6x10^6 J
energy	thermochemical calorie	cal	4.184 J
energy	international steam table calorie	cal_{IT}	4.1868 J
thermodynamic temperature(T)	degree Rankine	°R	(5/9)K
customary temperature(t)	degree Celsius	°C	t(°C) = T(°K)-273.15
customary temperature(t)	degree Fahrenheit	°F	t(°F) = T(°R)-459.67
radioactivity	curie	Ci	3.7x10^{10}Bq
energy#	electron volt	eV	eV ≈ 1.60219x10^{-19}J
mass#	*unified atomic mass unit*	u	u ≈ 1.66057x10^{-27}kg

* The conventional millimeter of mercury ,symbol mmHg (not mm Hg) is the pressure exerted by a column exactly 1 mm high of a fluid of density exactly 13.5951 $g.cm^{-3}$ in a place where the gravitational acceleration is exactly 980.665 $cm.s^{2}$. The mmHg differs from the torr by less than 2x10^{7} torr.

These units defined in terms of the best available experimental values of certain physical constants may be converted to SI units. The factors for conversion of these units are subject to change in the light of new experimental measurements of the constants involved.

1.6.3. Internationally accepted definitions

The internationally accepted definitions for some of the base and derived units are as follows.

1.6.3.1. Mass

The kilogram (kg) is equal to the mass of the international Prototype kilogram. The international Prototype is a platinum-iridium cylinder preserved at the International Bureau of Weights and Measures at Sevres, France.

Prototype No 20 is kept at the U.S. National Bureau of Standards. Equivalent prototypes are kept by other countries. Mass is the only one of the base quantities for which the standard is an arbitrarily defined object. No basic property of matter involving mass can be measured with more precision than is possible in comparing kilogram masses by weighting, about 1 part in 10^8.

1.6.3.2. Time interval

The second is the duration of 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

1.6.3.3. Length units

The meter(m) is the SI unit of length. The use of special names for decimal submultiples of the meter should be avoided, and units formed by attaching appropriate SI prefixes to the meter should be used instead. Thus the micron (u) which was defined as 10^{-6}m should be replaced by the micrometer (um) which has the same value: and the millimicron (mu) which was defined as 10^{-9} m should be replaced by the nanometer (n). The fermi which was defined as 10^{-15} and was used to measure nuclear distances should be replaced by the femtometer (fm) which has the same value. The Angstrom (A) is equal to 10^{-10}m. Although it has been accepted for temporary use with the SI it is preferable to replace this unit with the nanometer, using the relation 1A = 0.1nm.

The nautical mile (nmi) equal to 1852 m has been accepted for temporary use with the SI in navigation.

The foot (ft) is the unit of length in the British system of units and it is also in common use in the United States. Since 1959 the foot has been defined as exactly 0.3048m. The yard (yd) is defined as exactly 3 ft or 0.9144m.

Relative measurements of x-ray wavelengths can be made to a higher accuracy than absolute measurements. That is, the ratio of two x-ray wavelengths can be determined with a higher accuracy than the ratio of either of them to the meter. The same situation holds for dimensions of crystal lattices which are derived from x-ray wavelengths by x-ray diffraction experiments. For this reason, x-ray wavelengths and dimensions of crystal lattices have been expressed in units that are defined in terms of a standard wavelength or crystal lattice dimension.

Before 1965 most x-ray wavelengths were expressed in terms of the x-unit which is approximately 10^{-13}m.The grating constant of calcite was defined to be exactly 3029.04 x-units. Subsequent absolute measurements of the x- ray wavelengths with ruled gratings indicated that the x-unit exceeds 10^{-13} by about 2 parts per thousand. Furthermore, in practice, workers in the field began using definitions of the x-unit based on various x-ray wavelengths instead of the calcite grating definition and subsequent precise measurements indicated that these wavelength standards differed from each other and from the calcite grating by as much as 20 parts per million.

The x-unit has been superseded by the A* unit introduced by J.A. Bearden in 1965. This is based on the tungsten ka line as a standard. The peak of this line is defined as exactly 0.2090100 A*. X -ray wavelength tables have been published in terms of this unit. At the time the A* unit was defined it was thought to be equal to 10^{-10}m (the angstrom unit, A) within 5 parts per million but the A* unit is now believed to be 20 ± per million larger than 10^{-10}m.

1.6.3.4. Units used in astronomy

Special units whose values are obtained experimentally are used in astronomy. The astronomical unit and parsec are accepted for use with the SI. The parsec rather than the light-year is used in technical literature.

1.6.3.5. Area units

The square meter (m^2), the SI unit of area, is the area of a square with sides of length 1. Other area units are defined by forming squares of various length units in the same manner. The hectare (ha) is equal to 1 square hectometer (1 hm^2) or equivalent to 10^4 m^2. Its use with the SI is permitted for expressing land or water areas.

Cross sections which measure the probability of interaction between an atomic nucleus, atom or molecule and an incident particle have the dimensions of area and the appropriate SI unit for expressing them is therefore the square meter. The barn (b) a unit of cross section equal to 10^{-28} m^2 has been accepted for temporary use with the SI. Typical nuclear reactions have cross sections ranging from millibarns to several thousand barns. A related quantity which is connected with the probability that a reaction will emit radiation in a particular direction is the differential cross section which has the dimensions of barns per sterdian.

1.6.3.6. Time units

The second (s) is the SI base unit of time. However other units of time in customary use , such as the minute (1min = 60s), hour (1h = 60min) and the day (1d = 24hr) are used in the SI.

1.6.3.7. Frequency units

The hertz(Hz), the SI unit of frequency, is equal to 1 cycle per second. A periodic oscillation has a frequency of n hertz if it goes through n cycles in 1 s. Other units of frequency are defined by forming reciprocals of time units in the same manner.

1.6.3.8. Speed and velocity units

The meter per second (m/s) , the SI unit of speed or velocity, is the magnitude of the constant velocity at which a body traverses 1 m in 1 s. Other speed and velocity units are defined by dividing a unit of length by a unit of time in the same manner.

The knot (kn) is equal to 1 nautical mile per hour (1nmi/h). It has been accepted for temporary use with the SI.

1.6.3.9. Pressure and stress units

The pascal (Pa) , the SI unit of pressure and stress, is the pressure or stress of 1 newton per square meter (N/m^2). This a rather small unit for most practical purposes. For example, atmospheric pressure is approximately 10^5 Pa. Thus most pressures are most readily expressed in decimal multiples of the Pascal formed by attaching the appropriate SI prefix.

Pressure has been frequently expressed in terms of the bar and its decimal submultiples, where 1 bar = 10^6dynes/cm^2 = 10^6 Pa. A reference level of 1 microbar (1ubar = 10^{-6} bar = 1 dyne/cm^2 = 0.1 Pa) is commonly used in the calibration of microphones, hydrophones and loud speakers. The millibar (1mbar = 10^{-3} = 10^{-2} dynes/cm^2 = 10^3 = 0.1 kPa) is commonly used in metrology. The temporary use of the millibar within the SI has been allowed in order to permit metrologists to communicate easily within their profession but the kilopascal should be used in presenting metrological data to the public.

Two other units which have been frequently used for measuring pressure are the standard atmosphere and the torr. The standard atmosphere (atm) is exactly 101,325 Pa, which is approximately the average value of atmospheric pressure at sea level. The torr is exactly 1/760 atmosphere, or approximately 133.322 Pa to within 1 part per million. It is equal to the pressure of a column of mercury of height 1 millimeter (1 mmHg) at a temperature of 0° C when the acceleration due to gravity has the standard value g = 9.80665 m/s.

1.6.3.10. Power units

The watt (W), the SI unit of power, ie the power which gives rise to the production of energy at the rate of 1 joule per second (1 j/s). Other units of power can be defined by forming the ratio of a unit of energy to a unit of time in the same manner. The horse-power (hp) is equal to exactly 550 ft.lb/s or approximately 745.700 W. It has been employed frequently to express the power generated by engines and machinery.

1.6.3.11. Electrical units

A full coverage of electrical units has to cover the SI or mks system, the three cgs systems(the electrostatic system of units- esu, the electromagnetic system of units - emu and the gaussian system as well as definitions of the SI units ampere(A), volt (V), ohm (Ω), coulomb (C), farad (F), henry (H), weber (Wb) and tesla (T). The relationship between the various units is shown in TABLE 1.4. This section discusses some additional SI units and some units in the cgs electromagnetic system which are frequently encountered in scientific literature in spite of the fact that their use has been discouraged.

(i) Siemens

The siemens (S), the SI unit of electrical conductance, is the electrical conductance of a conductor in which a current of 1 ampere is produced by an electrical potential difference of 1 volt. The conductance G is defined by the equation $I = GV$, where I is the current in amperes, V is the potential difference in volts and G the conductance in siemens. The conductance of an electrical conductor in siemens is the reciprocal of its resistance in ohms. The siemens was formerly called the mho (μ) to illustrate the fact that the unit is the reciprocal of its resistance in ohms.

(ii) Maxwell

The maxwell (Mx) , the cgs electromagnetic unit of magnetic flux, is the magnetic flux which linking a circuit of 1 turn produces in it an electromotive force of 1 abV as it is reduced to zero in 1 s. Then 1 maxwell = 10^{-8} weber, as can be seen from the following equation,

$$1 \text{ Mx} = 1 \text{ abVs} = 10^{-8} \text{ Vs} = 10^{-8} \text{ wb}.$$

1.6.3.12. Photometric units

Photometric units involves a new base quantity, luminous intensity. For the definition of the candela (cd), the SI unit of luminous intensity and for discussion of photometric units, including units of illuminance(illumination),luminance and in particular the Si units lux (lx) and candela per square meter (cd/m^2) refer to a text book such as McGraw - Hill encyclopedia of physics. This section will only give an explicit definition of the lumen and discuss units of luminous energy.

(i) Lumen

The lumen (lm), the SI unit of luminous flux, is the luminous flux emitted within a unit solid angle (1 sterdian) by a point source having a uniform intensity of 1 candela. It follows therefore that a light source having an intensity of 1 candela in every direction will be emitting a total luminous flux of 4 lumens. The lumen is also equal to the luminous flux received on a unit surface, all points of which are at a unit distance from a point source having a uniform intensity of 1 candela.

The output of light sources is given in lumens.

(ii) Luminous energy units

The lumen-second (lm.s) , the SI unit of luminous energy (also called quantity of light), is the luminous energy radiated or received over a period of 1 second by a luminous flux of 1 lumen. This unit is also called the talbot.

1.6.3.13. Bel

The bel is a logarithmic unit expressing the ratios of power, voltage, current or sound intensity. The number of bels separating two power readings is the logarithm to the base 10 of their ratio (for example, two powers differ by 1 bel when their actual ratio is 10:1.), while the number of bels separating two current readings or the sound pressures of an acoustical signal is twice the logarithm of the ratio of the currents. It is convenient in acoustics to express sound intensity in logarithmic units because of the wide range of pressures to which the ear is sensitive. The strength of a sound is usually specified as the square root of the mean of the squares of the instantaneous pressures measured over a period of time. The sound intensity is proportional to the square of the sound pressure. The measure of the level in bels of a sound is $\log(I/I_R)$, where I is the intensity of the sound and I_R is a specified reference intensity. A smaller unit called the decibel, equal to 1/10 bel, is more commonly used.

1.6.3.14. Decibel

The decibel is a logarithmic unit used to express the magnitude of a change in the level of power, voltage, current or sound intensity. A decibel is 1/10 bel. In acoustics a step of 1 bel is too large for most uses. It is therefore the practice to express sound intensity in decibels. The level of a sound of intensity I in decibels relative to a reference intensity I_R is given by,

$$10 \log_{10} I/I_R$$

Because sound intensity is proportional to the square of sound pressure P, the level in decibels is given by,

$$10 \log_{10} P^2/P^2_R = 20 \log_{10} P/P_R$$

The reference pressure is usually taken as 0.0002dynes/cm^2 or 0.0002 microbar (The pressure of the Earth's atmosphere at sea level is approx. 1 bar) A sinusoidal cyclic change in pressure at a frequency of 1000 Hz is barely audible to the average person when it has a root mean square sound pressure of 0.0002 microbar. By this definition such a tone has a sound pressure level of 0 dB. The neper is similar to the decibel but is based upon natural (Napierian) logarithms. One neper is equal to 8.686 dB.

1.6.4. Some rules when applying SI units

In connection with Si units , some rules of style, abbreviations, writing and drafting practices are applied.

(i) No dots, commas etc. are used after SI symbols except at the end of sentences. For example 32 meters is written as 32 m and not as 32 m..
(ii) Plurals are never used in connection with SI unit symbols. For example 32 meters is written as 32 m and not as 32 ms which would mean 32 milli seconds.
(iii) Decimal fractions are always started with 0. For example a half meter is written as 0.5 m and not as .5 m.
(iv) Multiplication or times sign is "." This is used for the purpose of clarity between the numbers to be multiplied and between unit symbols in derived units where two unit symbols adjoin. e.g. the unit of torque may be written as Nm (Newton-meter) which if written as mN can be misunderstood as millinewton.
(v) All symbols and prefixes are lower-case letters, except symbols derived from proper names, such as W for watt and M, G and T for the largest three power of 10 prefixes. All symbols should be used as they are to avoid any confusion.
(vi)No degree mark (o) is used with kelvin, the unit of temperature. A temperature interval can also be expressed in degree celsius.
(vii) Double prefixes should not be used e.g. one kilomega watt may not be written as kMW, but as GW.
(viii) The expression "per"in symbols of derived units is always indicated by a fraction line as m/s but the word "per" should not be used for this purpose.
(ix) Only the numerator should be multiplied by powers of 10 in compound derived units and the denominator should always remain the base unit.
(x) Numbers may be grouped in clusters of three in both directions from the decimal mark and a gap may be given for clarity. A comma should not be used in the gap.

e.g. 153297.3 m may be written as 153 297.3 m and not as 153,297.3 m.

(xi)Units with names of scientists should not be capitalized when written in full.

(xii) According to SI recommendations litre is a special name given to cubic decimeters and the word litre should not be used for expressing results of high precision volume measurements.

(xiii) Some units which though strictly incompatible with SI units have been allowed initially, e.g. km/hr, rev/min.

2. PHYSICAL PRINCIPLES OF RADIOGRAPHY

2.1. FUNDAMENTALS OF X-RAYS AND GAMMA RAYS

2.1.1. X-Rays and Radiography

In 1895 Roentgen discovered X-rays while studying the phenomenon of electrical discharge through gases. In the course of his investigations on these new and mysterious rays, Roentgen made shadow pictures of various objects including a box of weights and a shot gun. These pictures marked the birth of radiography. Within a year of Roentgen's discovery of X-rays a weld had been radiographically examined. In 1913 Coolidge designed the new X-ray tube. This enabled the production of X-rays of higher intensity and greater penetrating power. In 1917 Department of Radiological Research was established at the Royal Arsenal at Woolwich. The next important development came in 1930 when the U.S. Navy agreed to get fusion welded boiler drums radiographed. Within a few years this step led to universal acceptance of radiography for class I fusion welded pressure vessels and X-rays made a steady progress as a tool for testing of welding and casting. With the outbreak of the 2nd World War X-ray radiography saw a spectacular success. The value of radiography was very apparent in the aircraft industry but then it also spread to other fields like welds in power plants, refineries, ships structures and fighting vehicles. This laid the basic for continued expansion of the radiographic inspection technique.

2.1.2. Nature of X-rays

X-rays are electromagnetic radiation just like light. The only difference between X-rays and ordinary light is that X-rays have several thousand times smaller wavelengths. X-rays usually used for radiography have wavelengths in the range 0.0001 A° to 10 A° where 1A° $= 10^{-8}$ cm.

2.1.3. Fundamentals of Gamma Rays

2.1.3.1. Radioisotopes

An atom consists of a nucleus and electrons revolve around the nucleus. The nucleus contains protons having positive charge and neutrons with no charge. The number of protons represents the atomic number Z, and the total number of nucleons i.e. protons plus neutrons, determines the mass number or atomic weight A. Atoms having the same Z but different A are known as isotopes of an element. Some isotopes are stable while some are unstable. Those which are unstable, tend to become stable by emitting radiation and are known as radioisotopes. The process which is followed by the emission of radiation is commonly known as disintegration.

Some of the naturally occurring isotopes are Radium, Radon and Uranium. Stable isotopes may be made radioactive by the bombardment of neutrons and these types of radioisotopes are known as artificial radioisotopes such as Cobalt, Thulium, and Iridium. In radiography artificial radioisotopes are more commonly used.

Radioisotopes emit alpha, beta and gamma radiation. In industrial radiography gamma emitting radioisotopes are used.

2.1.3.2. Gamma rays

Gamma rays are electromagnetic waves like X-rays but usually have shorter wave length and are more penetrating than the X-rays produced by the commonly used industrial X-ray units. Some gamma rays can penetrate a thickness as great as 10cm of lead. Gamma rays originate from the atomic nucleus unlike X-rays which are generated outside the nucleus.

The wavelength of electromagnetic radiation is expressed in meters, centimetres, millimetres, micrometers, nanometres and in Angstrom units where $1A^0 = 10^{-8}$ cm. Figure 2.1 shows the position of X-rays and gamma rays in the spectrum of electromagnetic radiation.

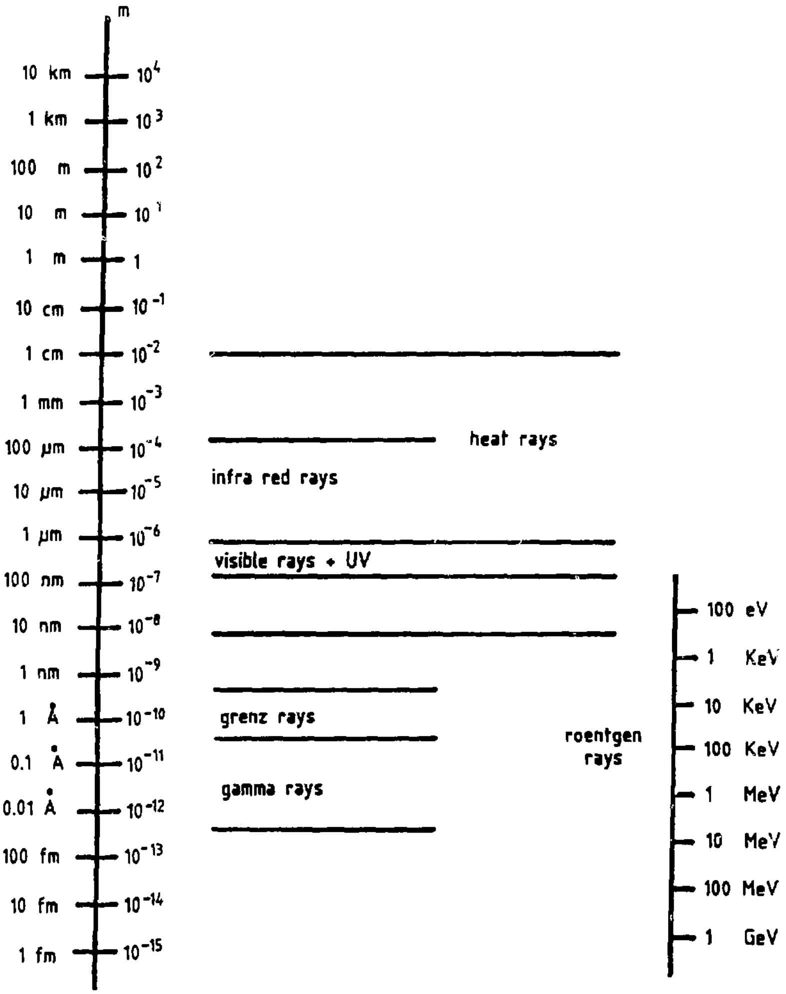


Figure 2.1 Electromagnetic radiation spectra

2.1.4. X-ray and gamma ray spectra

The basic fact is that x-rays are produced when electrons decelerate. When the speeding electrons pass near the nucleus (which has a net positive charge) they experience a force of attraction and are slowed down. In this process of slowing down or deceleration they lose a part of their initial kinetic energy which is converted into x-rays. So we can say that x-rays are emitted as a consequence of the deflection of cathode electrons by the strong fields surrounding the nucleus of the target atoms. Sometimes the electrons are stopped instantaneously then all their energy is transformed into the maximum radiation energy with minimum wave length.

But there actually is a whole spectrum of longer wave lengths or low frequencies emitted by electrons which lose only a part of their energy in a single encounter with a nucleus and experience many collisions with target atoms before being brought to rest. The X-ray spectrum is therefore continuous with a definite minimum wavelength λ_{min}. We have $E = hf$, where h = Plank's Constant, and f = frequency.

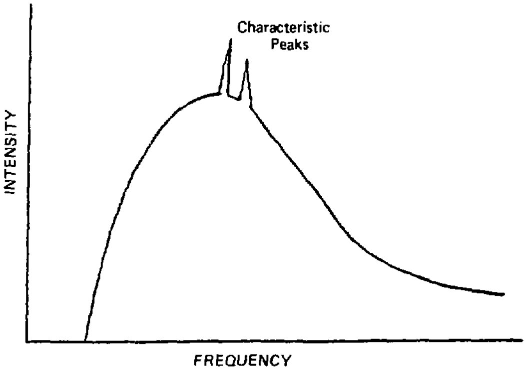


Figure 2.2 Characteristic x-ray spectrum

The energy of an electron of charge (e) in falling through a potential difference V is eV and on complete absorption (or being completely stopped) this energy appears as a quantum of X-rays of energy $hf = hc/\lambda = eV$ which gives $\lambda_{min} = hc/eV = 12.4/V$

where,

c is the velocity of light and
V is the voltage applied to the X-ray tube.

Characteristic X-rays are produced in quite a different way. Sometimes the impinging electrons can make a direct impact upon one of the inner electrons in an atom of the target, and, if the energy is great enough, can knock it right out of the atom. The atom is then unstable, and another electron in the same atom will drop into the space vacated. In so doing it loses energy and a quantum of radiation is emitted. If E is the energy lost then

$$E = hf = hc/\lambda$$

which gives $$\lambda = hc/E$$

E is a definite quantity associated with the particular energy change in the atom and so the wave lengths concerned are specific. Several wave lengths are possible and they constitute the characteristic spectrum, Figure 2.2. The process is similar to the production of light, but for light the outer electrons only are involved. For X-rays the tightly bound inner shells K,L,M are concerned. If a K electron is dislodged and an electron falls from the L shell to the K shell, the K X-ray line is produced, if an M shell electron falls to the K shell then the weaker K line is produced. The letter K shows the shell into which the electron falls.

The characteristic X-ray spectrum for copper will look like the continuous line in Figure 2.3. It has, superimposed on a white spectrum, two peaks characteristic of copper i.e. K_{Cu} & K_{Cu}. Their wave lengths are 1.40 Å and 1.54 Å respectively. Copper has an atomic number of 29. If we now change the target from copper to nickel then the new spectrum will be as shown in the dotted line. It can be seen that by changing the target from a high to low atomic no. (Ni has at.no. 28) the characteristic spectrum becomes softer (higher λ) whereas there is not any appreciable change in the continuous spectrum. The characteristic radiation cannot be produced below a certain critical voltage because lower voltages cannot knock out electrons. If the voltage is raised beyond this critical voltage the intensity of the characteristic radiation changes but not their wave length.

In contrast to the continuous spectrum of X-rays, the gamma-ray spectrum is discrete. The actual values of wave lengths depend on the emitting nucleus i.e. the radioactive source. Radioisotopes emit one or more wave lengths. For example caesium-137 emits only one

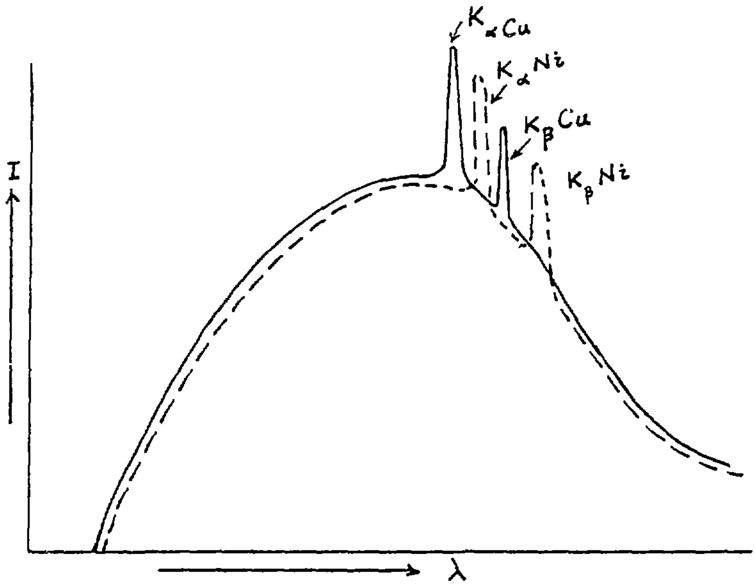


Figure 2.3 Characteristic X-ray spectra for Cu and Ni

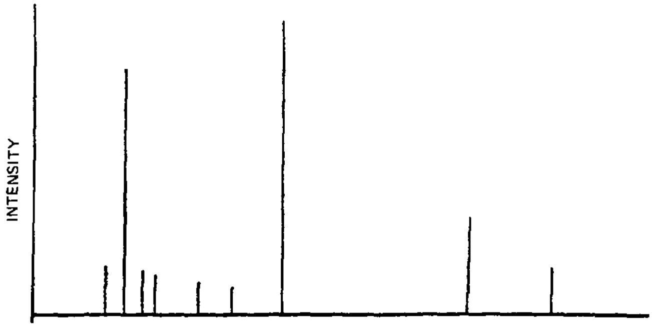


Figure 2.4. Line spectrum of gamma ray source

wavelength, cobalt-60 emits two and iridium-192 emits five prominent wavelengths. All gamma ray sources have a line spectrum (discrete energies) unlike the continuous spectrum of X-rays, Figure 2.4.

In literature it is more customary to describe a particular gamma ray by its photon energy rather than by giving its wavelength. The photon energy is expressed in electron volts and is usually of the order of a million electron volts, MeV. Caesium-137 gamma photons have an energy of 0.667 MeV and those of cobalt-60 have 1.17 MeV and 1.33 MeV energies.

2.1.5. Properties of X-ray and gamma rays

Being the same in nature, X-ray and gamma rays show similar properties. In brief these are :-

i. They are invisible

ii. They cannot be felt by human senses

iii. They cause materials to fluoresce. The fluorescent materials are zinc sulfide, calcium tungstate, diamond, barium platinocyanide, naphthalene, anthracene, stilbene, thallium activated sodium iodide, etc.

iv. They travel at the speed of light i.e. 3×10^{10}cm/sec

v. They are harmful to living cells.

vi. They can cause ionisation. They can detach electrons from the atoms of a gas, producing positive and negative ions.

vii. They travel in straight line. Being electromagnetic waves, X-rays can also be reflected, refracted and diffracted.

viii. They obey the inverse square law according to which intensity of X-rays at a point is inversely proportional to the square of the distance between the source and the point.

Mathematically $I \alpha 1/r^2$ where I is the intensity at a point distant r from the source of radiation.

ix. They can penetrate even the materials through which light cannot. Penetration depends upon the energy of the rays, the density and thickness of the material. A monoenergetic beam of X-rays obeys the well known absorption law,

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

where,

I_0 = the incident intensity of X-rays and
I = the intensity of X-rays transmitted through a thickness x of material having absorption coefficient μ .

x. They affect photographic emulsions.

xi. While passing through a material they are either absorbed or scattered.

Properties (vii), (viii), (ix), (x), (xi), are mostly used in industrial radiography.

2.1.6. Inverse Square Law

The intensity of radiation reaching a point is governed by its distance from the source. The intensity varies inversely with the square of this distance. This principle is illustrated in Figure 2.5. In this example, it is assumed that the intensity of the rays emitted at the source remains constant and that the radiation passing through the aperture B covers an area of 4 square centimetres on reaching the recording surface C_1 at 12 centimetres from the source. If the recording surface is moved to 24cm from the source at C_2 , the X-ray beam will cover 16 square centimetres, an area 4 times as large as that at C_1 . It follows therefore, that the radiation per square cm on the surface at C_2 is only one-quarter of that at C_1.

This is known as the inverse square law of radiation.

The inverse square law has important implications in practical radiography. The film should receive a certain amount of radiation dose or exposure to produce a radiograph of a particular radiographic density. If due to some reason the distance between the source and the film has to be altered then the exposure should be modified in accordance with the inverse square law.

Thus the exposure that would be adequate at C_1 must be increased four times in order to produce at C_2 a radiograph of equal density. In practice this may be done by increasing

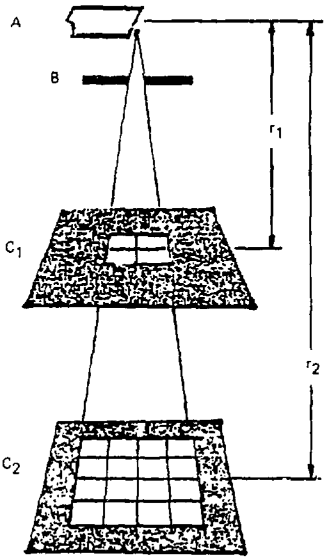


Figure 2.5 Schematic diagram illustrating the inverse square law

either the exposure time or the radiation intensity since radiographic exposure is the product of radiation intensity and time.

This inverse square law may be stated algebraically as follows:-

$$\frac{I_1 \text{ (intensity at } C_1 \text{)}}{I_2 \text{ (intensity at } C_2 \text{)}} = \frac{(r_2)^2}{(r_1)^2}$$

where r_1, and r_2 are respectively the distances of C_1 and C_2 from the source.

Since $I_1 x I/E_1$ and $I_2 x 1/E_2$,
therefore $E_2/E_1 = (r_2/r_1)^2$

where,

E_1 = exposure at r_1 and
E_2 is exposure at r_2.

The inverse square law may also be stated in another way which is helpful in the area of radiation safety and protection. In this form

$$D_1/D_2 = (r_2/r_1)^2 .$$

Here D_1 & D_2 are radiation dose rates at distances r_1 and r_2 from the source. D_1 and D_2 have the same units and r_1 and r_2 also are in the same units. This means that the radiation hazard (dose rate) decreases rapidly as we move away from the radiation source. As an example, the dose rate due to a radiation source at a distance of 10 meter from the source would be only one hundredth ($1/100 = 1/10^2$) of the dose rate due to the same source at 1 meter. This is the simplest practical way in which a person working with external radiation sources can keep his radiation dose down.

2.2. RADIOACTIVITY

It has already been stated in 2.1.3.1. that some of the isotopes of an element are stable while others may be unstable. The unstable atoms may become stable by emitting radiation. The process which is followed by the emission of radiation is commonly known as disintegration and this phenomenon of disintegration of atoms of (naturally occurring or artificially produced) elements is called radioactivity. Materials exhibiting this phenomenon are termed radioactive materials, or radioisotopes. Curie (Ci) is the unit of radioactivity and is equal to the disintegration rate of 3.7×10^{10}d.p.s. Smaller units of radioactivity are millicurie and microcurie which are one thousandth and one millionth part of a curie respectively. The internationally agreed system of coherent unit for radioactivity that is now in use for all scientific and technological purposes in many countries is the bacquerel (Bq). The bacquerel is defined as one disintegration per second. The relationship between curie and bacquerel is 1 curie = 3.7×10^{10} bacquerel.

2.2.1. Radioactive decay

The activity of any radioactive material depends on the concentration of radioactive atoms in it. This process of radioactive decay is according to an exponential law, known as the radioactive decay law. Mathematically it may be stated as $N = N_0 e^{-\lambda t}$ where N_0 is the number of radioactive atoms present at some reference time $t = 0$; N is the number of radioactive atoms left after time t has passed and is called the disintegration constant. λ is a characteristic of the radioactive material. Materials with higher values of λ decay or disintegrate rapidly and vice versa. In actual practice, the decay of a radioactive isotope is usually given in terms of its half life denoted by $T_{1/2}$. This is defined as the time required for one-half of the atoms originally present to decay. It simply means that after a half life the number of radioactive atoms or activity is reduced by a factor of 2 as compared with its number or activity at any earlier reference time t_0 . The half life is a characteristic of a particular radioisotope and is essentially different for different radioisotopes. It varies from a fraction of a second to millions of years. In radiography we use isotopes with half life varying from a couple of days to a few years. Sources with shorter half life die out quickly. Substituting $N = N_0/2$ and $t = T_{1/2}$ the decay equation may be modified as

$$N_0/2 = N_0 e^{-\lambda T_{1/2}} \text{ which gives } T_{1/2} = 0.693/\lambda$$

The decay equation shows that theoretically it requires an infinite time for the complete decay of a radioactive sample. When plotted graphically the decay equation results in what is known as a decay curve such as the one shown in Figure 2.6.

2.2.2. Radiation intensity and specific emission

The intensity may be defined as the number of rays per second falling perpendicularly over a unit area. The radiation output of a given source is measured in terms of roentgens per hour at a distance of 1 meter from the source. This is known as the RHM value of the source. The roentgen itself may be defined as that amount of X or gamma radiation which when it passes through 1 cm of dry air at N.T.P. (weighing 0.00129 gm) produces ions equivalent to one e.s.u. of charge of either sign. Roentgen is also equivalent to an energy absorption of 87.7 ergs/gm of the exposed material. A particular radioactive source has a specific RHM value per curie. The number of roentgens per hour at 1 cm from a 1 mC source of a gamma-ray emitter is called the K-factor of the specific gamma ray emission. The intensity of radiation obeys the inverse square law i.e. when the distance from the source is doubled, the intensity is reduced four times.

The specific activity of a radioisotope source , usually measured in curies per gram, is of importance in radiography. A higher specific activity means that a source of a given strength can be produced in a smaller physical size, which is of great importance from the point of view of radiographic definition. Also a small dimensioned source has less self absorption of radiation and so a greater effective output. The specific activity depends on the nuclear reactor and the time for which the material is irradiated, as well as on the

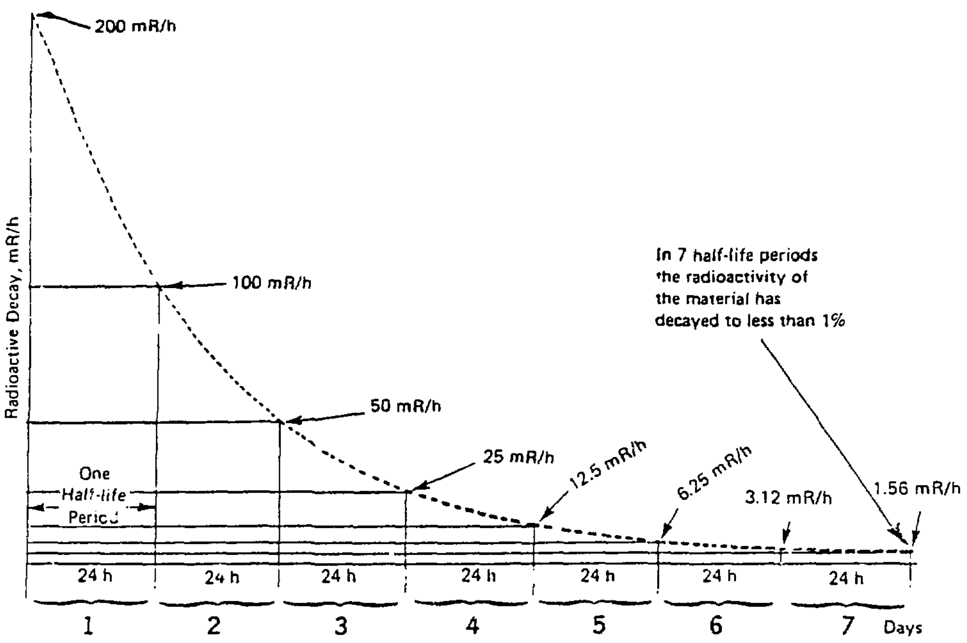


Figure 2.6 Decay of radioactive material with a 24 h half-life

Typical decay curves for Iridium-192 are shown in Figure 2.7 and 2.8 while those for cobalt-60 and other radioisotopes of interest can be easily drawn knowing their half lives. (Figure 2.9)

characteristics of the irradiated material such as the atomic weight and the activation cross-section. Some elements can be activated to a very high specific activity while others are incapable of reaching high activities with available neutron fluxes.

2.2.3. Other radiations from radioisotopes

In addition to using X-and gamma radiation for radiography modern practice has seen the increasing use and testing by other types of penetrating radiation, whose attenuation behaviour is sometimes completely different. This different behaviour is also a means of detecting special properties. These other radiation types are without exception particles as opposed to electro-magnetic radiation (X-rays). In principle all radiation types have *only a limited penetration depth in material* and can thus be completely absorbed, absorption details depending on type, charge and kinetic energy of the particle. These other radiations are alpha particles, protons, beta particles and neutrons.

Whereas alpha radiation consists of relatively large and positively charged particles (helium nuclei: two protons plus two neutrons), its penetration is relatively low and is thus not particularly interesting for radiographic purposes. Beta radiation has a slightly larger penetrative power (obviously dependent on the particular particle energy). Its particles consist of electrons (negatively charged particles - which are, of course, also used when generating X-rays). In order to penetrate useful depths (e.g. in metals) one requires very high energies of radiation, such that their use is for the most part limited to thin specimens. Similar conditions apply to proton radiation (positively charged particles).

Neutron radiography has a special place since the neutrons are electrically neutral and are thus not subject to any attracting or repelling forces. They are only weakened by direct hits

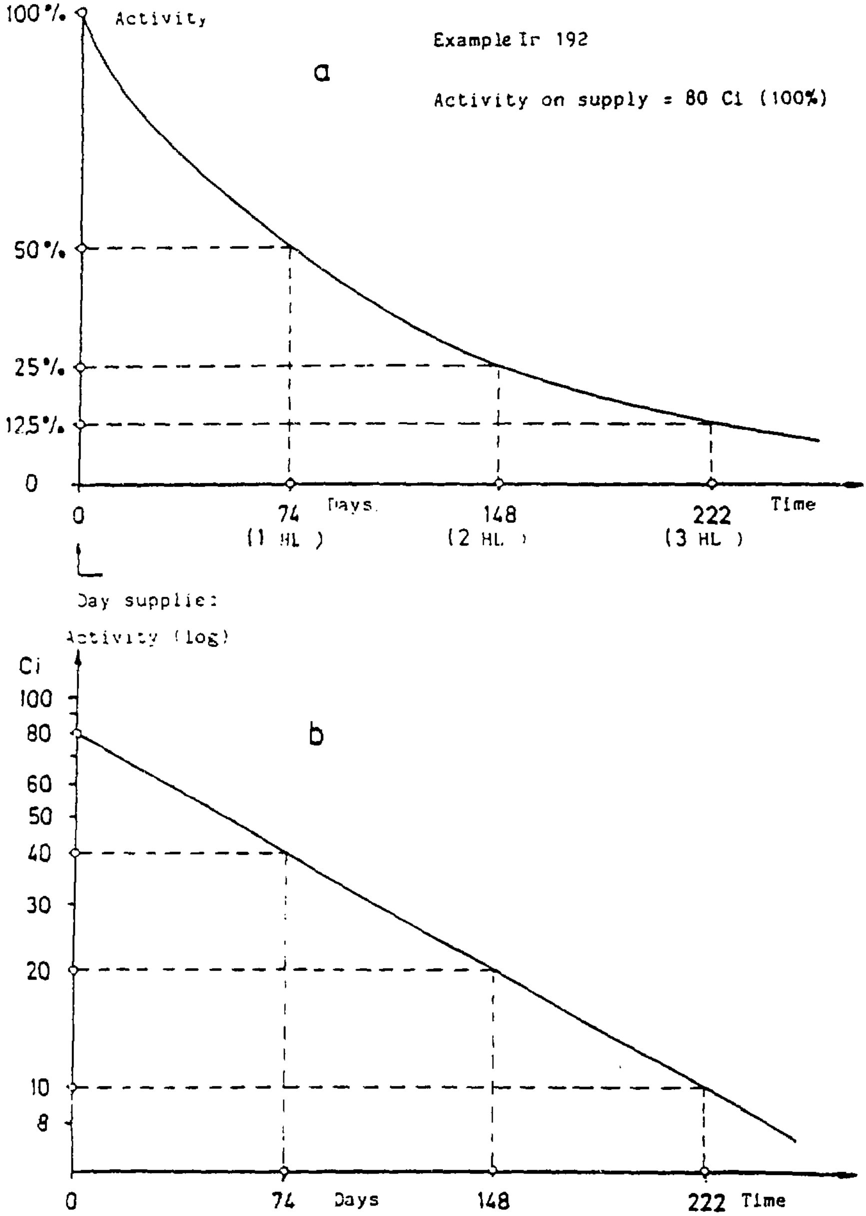


Figure 2.7 : Decay curves of radioactive source, eg. Ir-192 (a) Fall in activity over time. (b)Fall in activity using logarithmic activity scale.

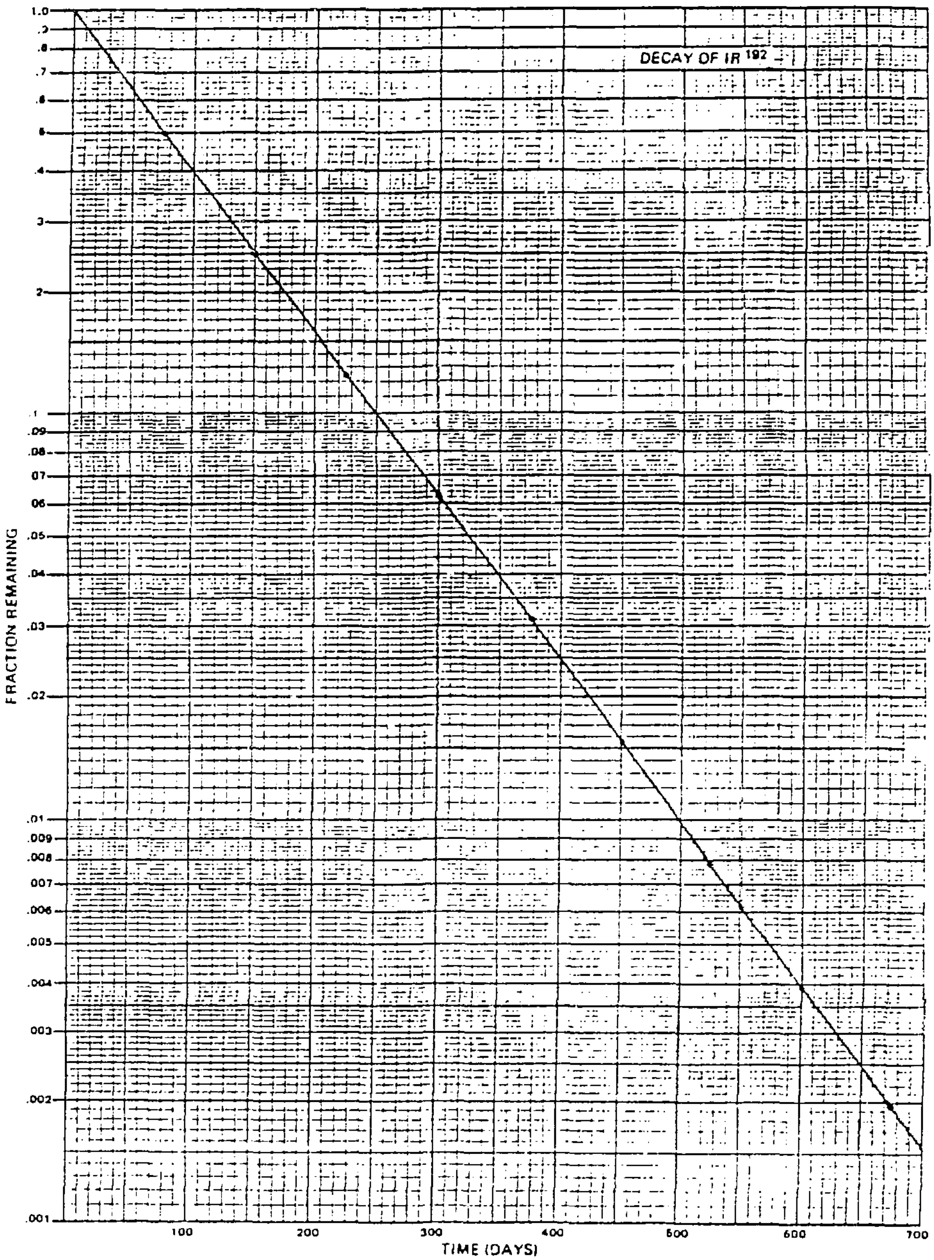


Figure 2.8. Decay of Ir^{192}

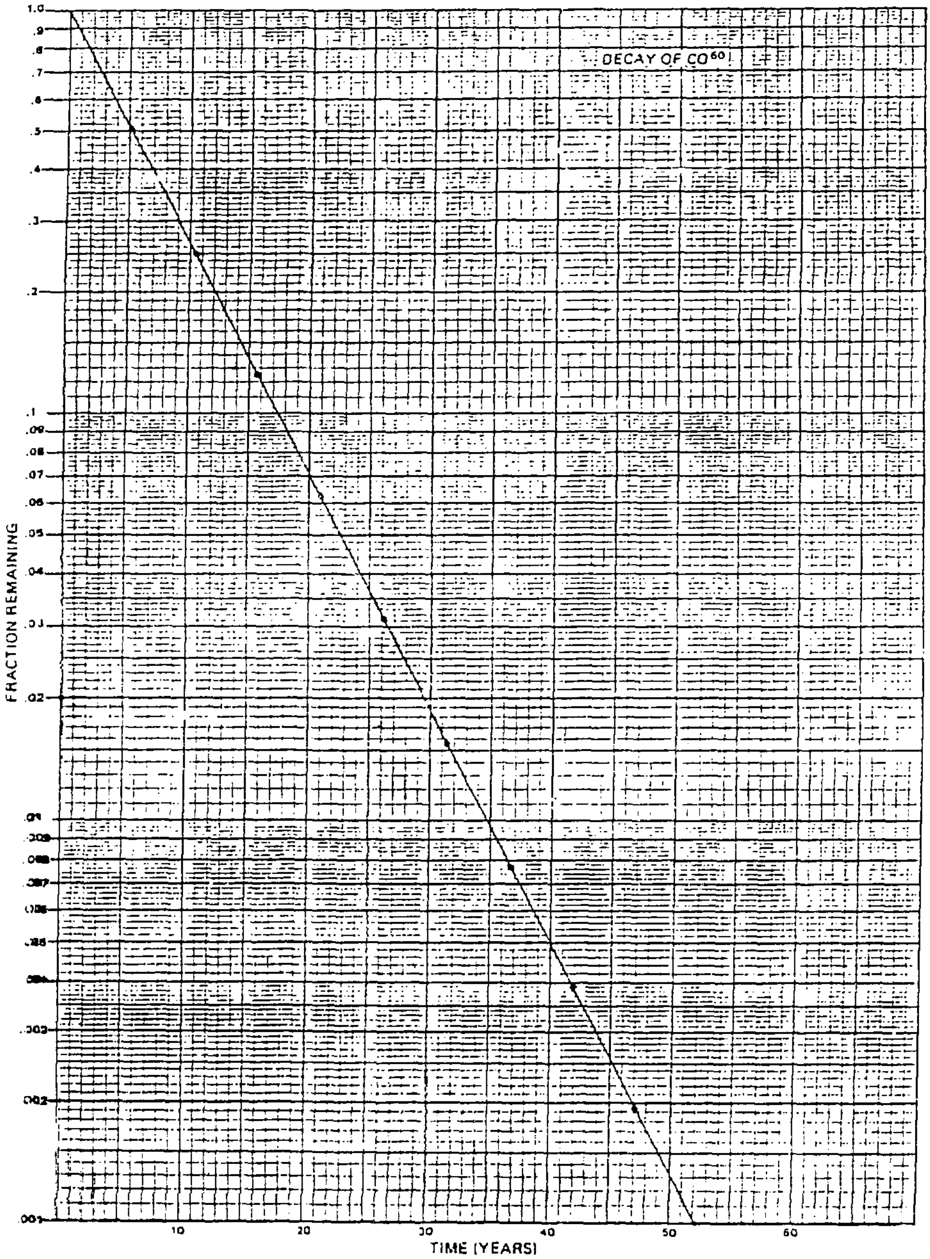


Figure 2.9. Decay of Co^{60}

with atoms, and the smaller the difference in mass between the nucleus hit and the neutron the larger the energy loss (i.e. the attenuation). Thus the materials with small atomic nuclei, i.e. hydrogen and its chemical compounds e.g. water, organic substances and similar as well as other elements having light atomic weights, cause a much greater attenuation of neutron radiation than elements having larger atomic nuclei e.g. lead. This seemingly paradoxical attenuation behaviour has led to neutron radiography becoming fairly important in the present day.

2.3. INTERACTION OF RADIATION WITH MATTER

When a beam of X or gamma radiation falls on an object, some of it is transmitted through, some absorbed and some scattered in other directions. The knowledge of the phenomena involved is important for a radiographer and its various aspects are discussed below.

2.3.1. Absorption phenomenon

A beam of X or gamma rays, while passing through some material, suffers loss in intensity. This phenomenon is called absorption of X or gamma rays in matter. The amount of radiation lost depends on the quality of radiation, material/density of specimen and the thickness traversed. It is actually this property of X or gamma radiation which is utilised in industrial radiography. Defects in the internal structure of a specimen mean a change in thickness (e.g. a void) or change in density (e.g. inclusion of foreign material), the presence of which will cause corresponding changes in the transmitted beam intensity recorded in a radiograph. Due to its importance we shall consider this phenomenon in detail.

Consider a specimen slab of thickness 'X' on which monochromatic parallel beam of radiation is incident, Figure 2.10.

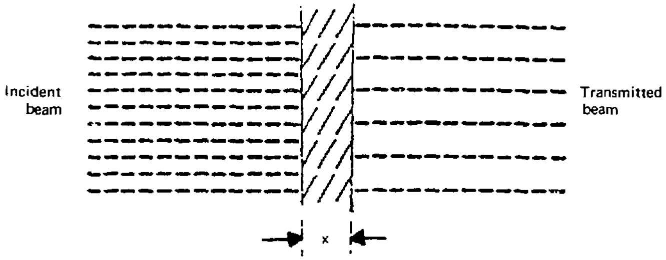


Figure 2.10. Absorption of radiation.

If the incident beam intensity is I_0, and I is the transmitted beam intensity then $I = I_0 \exp(-\mu x)$ where μ is called the linear absorption coefficient which depends on the incident radiation energy and the specimen material/density. The attenuation takes place through three principal effects: photoelectric absorption, Compton absorption and Compton scattering. A fourth mechanism, pair production, is operative above 1.02MeV and is of relatively lesser importance. Taking into account all these effects the value for μ can be written as $\mu = (\tau + \sigma + k)$ where μ is the total or linear attenuation coefficient, τ is the attenuation coefficient due to photoelectric absorption, σ is the scattering coefficient. σ has two components σ_a - Compton absorption coefficient and σ_r - Compton scattering coefficient and k is called the pair production coefficient.

2.3.1.1. Photoelectric absorption

In this process a photon gives up all its energy in ejecting an inner shell electron from the atom. The photon disappears in the process. The energy of the photon is used in knocking the electron out of the shell and giving it some kinetic energy.(Figure 2.11)

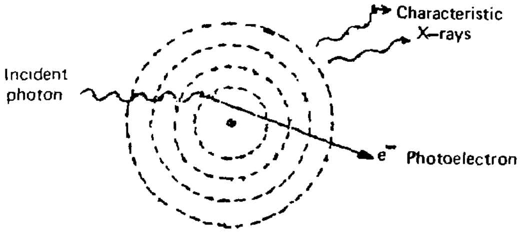


Figure 2.11 Photoelectric absorption

Photoelectric absorption process is most efficient when the interaction takes place with the most tightly bound electrons of an atom and cannot take place with free electrons as a third body is needed to share so as to conserve momentum. Therefore it is the K-shell electrons which are involved in this process. When the photon energy reaches the binding energy of a particular shell of electrons, there is an abrupt increase in the absorption. The energy at which this sharp change occurs for K electrons is called the K absorption edge and represents the situation where the kinetic energy of the ejected electron is zero. Further increase of photon energy causes the absorption to decrease with energy. The absorption edges occur at radiation energies lower than 115 keV. This process is accompanied by the emission of photo-electrons and characteristic X-rays.

Photoelectric absorption is most likely for photons of low energy(E) and elements of high atomic number (Z) because the electrons are more tightly bound to these atoms. The probability of photoelectric absorption roughly varies as $1/E^{3.5}$ and Z^5.

It is because of the latter fact that lead (Z=82) and uranium (Z=92) are very effective shields against X and gamma radiation.

2.3.1.2. Compton scattering

Upon increasing the photon energy beyond the K edge the main process of absorption changes from the photoelectric to Compton effect.

A photon, like a particle, can transfer some of its energy to an electron, causing it to be knocked off at speed, while the photon itself is scattered away at an angle and with reduced energy. Figure 2.12.

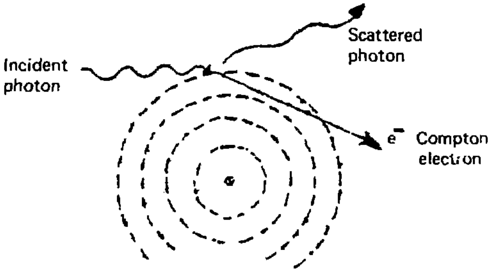


Figure 2.12 Compton scattering

Compton scattering takes place with free electrons and with loosely bound outer shell electrons of the atom because these electrons behave virtually free to high energy photons.

The probability of Compton interaction increases linearly with the atomic number of the scattering material and decreases slowly with increasing photon energy. For the radiation energies used in radiography, the intermediate energies, the Compton effect is the most important attenuation process. The practical effect of the scattered photon is that a great part of radiation reaching the film has a different direction from the primary beam. The primary radiation forms the radiographic image and the Compton scattered radiation tends to obscure the image. As the energy of the primary radiation increases a greater percentage of the Compton scattering is in the forward direction (closer to the primary beam).

If a photon being scattered does not change its energy, then this process is called coherent scattering (or Rayleigh scattering).

2.3.1.3. Pair production

When a photon has sufficient energy ($\geq$ 1.02MeV) to create two electrons it can materialise into a positive and a negative electron in the electric field of the nucleus. The uncharged photon disappears in this process and electrons of equal and opposite charges are created, Figure 2.13.

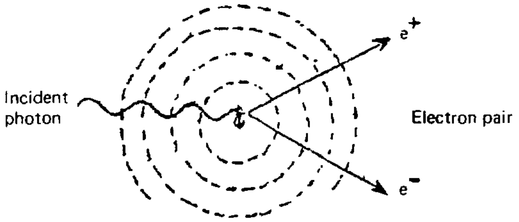


Figure 2.13 Pair production

Unlike Compton and photoelectric processes, pair production does not result in ionisation of the atom struck, but the nucleus does have to take some of the momentum. Pair production dominates other modes of interaction for photons of higher energies. The probability of this process increases rapidly with photon energies.

2.3.2. Absorption coefficient

In the equation for absorption μ is known as the linear absorption coefficient. The linear absorption coefficient is the fractional reduction in intensity that is produced by unit thickness of the absorber. As the thickness is normally measured in centimetres and as μ_x must be dimensionless, μ will have dimensions of cm^{-1}.

The distance $1/\mu$ is sometimes known as the mean free path of the photon and for calculations of the depth of penetration the depth is often expressed in relaxation length and where $x = 1/\mu$, $\mu_x = 1$ is called one relaxation length.

The value of $\mu = K\lambda^3 z^3$ which shows that μ depends upon the wavelength of the primary radiation and therefore soft or lower energy rays will be absorbed to a greater degree. μ also depends on the atomic number Z of the absorber material and increases with Z. High atomic number materials will therefore absorb more radiation as compared to the low atomic number materials. In the equation for μ , k is a constant which depends on the physical density of the absorber material.

As explained earlier absorption of radiation in matter is the net effect of different processes of interaction of the radiation with the atoms of the absorber material. These processes of interaction of the radiation with the atoms of the absorber material are the photoelectric effect, Compton scattering and pair production. Consequently the total attenuation coefficient is the sum of the attenuation coefficient due to photoelectric absorption(τ), the Compton scattering coefficient (σ) and the pair production coefficient (k). If the attenuation coefficient is plotted against the energy of the radiation under consideration, curves such as those shown in Figure 2.15 and 2.16 are obtained. Figure 2.15 shows the curves for different components of μ for lead while, Figure 2.16 shows the variation of μ for aluminium,lead and iron.

The absorption equation can be graphically presented as in Figure 2.14. In a linear scale this curve is shown on Figure 2.14 a. In a semilogarithmic scale the curve is a straight line and its slope gives the attenuation coefficient.

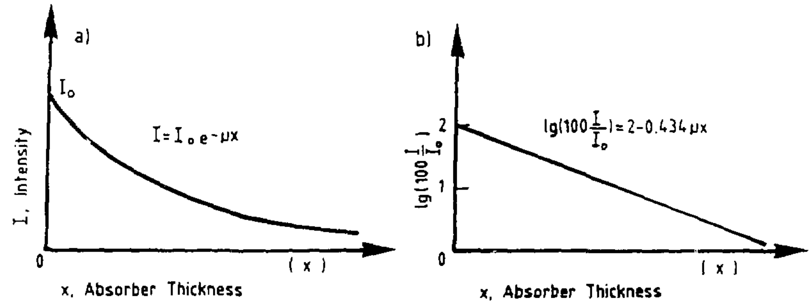


Figure 2.14 : Attenuation curve (a) in linear (b)in semilogarithmic scale

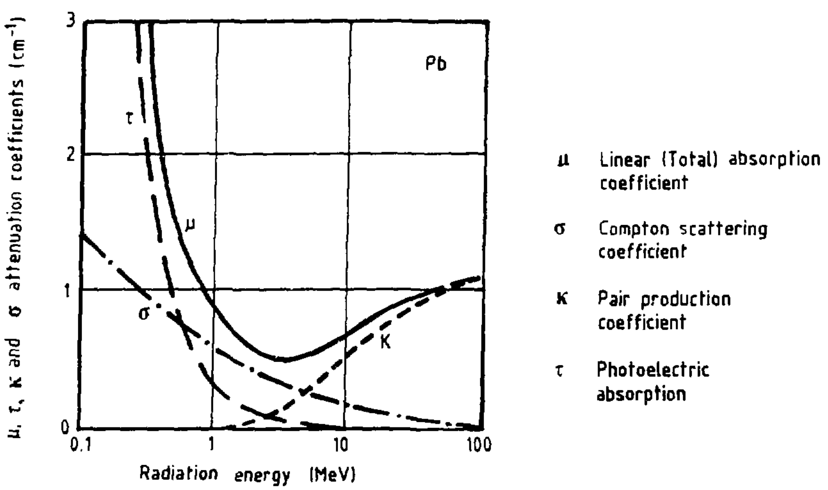


Figure 2.15 Energy dependence of attenuation coefficient and its various components

The equations and curves given relate only to *monochromatic radiation*. If a radiation spectrum is composed of more than one spectral line (radioisotopes) or is a continuous spectrum (Bremsstrahlung) then for each radiation energy a different attenuation coefficient applies. For heterogeneous radiation an equivalent attenuation coefficient can be applied, which will change with the thickness of the attenuating material. This can be illustrated by Figure 2.17 where attenuation curves are given for a radiation beam composed of two different energies and corresponding attenuation coefficient $\mu_1 = 0.7cm^{-1}$ and $\mu_2 = 3.5cm^{-1}$.

Attenuation curves for those monochromatic radiations are straight lines, whereas the resultant curve is no longer straight. The equivalent attenuation coefficient can be derived from the slope of the attenuation curve. As can be seen the attenuation curve of a heterogeneous radiation approaches a straight line as the thickness of attenuating material increases. This is true for all kinds of heterogeneous radiation (X-or gamma). This is due to the fact that radiation components of lower energy (with higher attenuation coefficients) are more effectively absorbed and through thicker layers of the absorber practically only the radiation with higher energy is able to penetrate. The values of linear absorption coefficient for some materials of interest are given in Table 2.1.

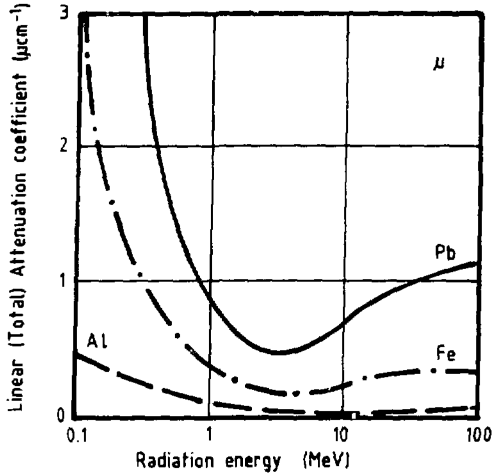


Figure 2.16 Variation of attenuation coefficients of μ. Al, Pb and Fe with radiation energy

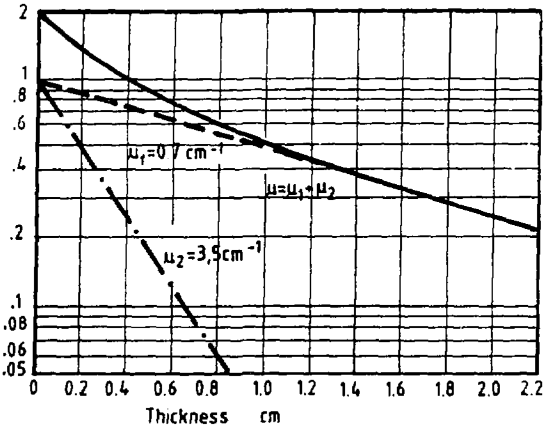


Figure 2.17. Attenuation of a radiation beam composed of two different energies

TABLE 2.1 LINEAR ABSORPTION COEFFICIENT

Radiation Energy E (MeV).	Absorption Coefficients (cm^{-1})			
	Pb	Fe	Al	H_2O
0.2	5.0	1.06	0.33	0.14
0.5	1.7	0.63	0.23	0.090
1.0	0.77	0.44	0.16	0.067
1.5	0.57	0.40	0.14	0.057
2.0	0.51	0.33	0.12	0.048
2.5	0.48	0.31	0.10	0.042
3.0	0.47	0.30	0.090	0.038
4.0	0.48	0.27	0.082	0.033
5.0	0.48	0.24	0.074	0.030

Sometimes it is convenient to use μ_m (= μ / ρ) instead of μ , where ρ is the density of the shield material. μ_m is called mass attenuation coefficient and is expressed in cm^2/gm. In most of the literature, the values quoted are in μ_m and when using these values from the literature in the equation $I = I_o e^{-\mu x}$, μ should be calculated by multiplying μ_m with the respective ρ of the material.

2.3.2.1. Build-up Factor

The simple absorption equation is based upon the assumption that scattered radiation is completely removed from the beam. However, in reality, this is not the case especially in a thick material. For a thin shield, the above equation is valid because the probability that scattered radiation will reach the observation point (or detector) after a single collision is small. On the other hand, for thick material some of the scattered radiation finally emerges together with the unattenuated radiation. As a result of this, the measured intensity of radiation after passing a shield will be significantly higher than that calculated using the simple absorption equation.

The above phenomena is well known as build up radiation due to multiple scattering. Thus, in practice, the absorption equation is modified by introducing another quantity known as build-up factor, which is a function of the shield material, the thickness, x, and the energy of radiation. The absorption equation now becomes,

$$I = I_o B.e^{-\mu x}$$

where B is the build-up factor. Thus the build up factor B can be defined as the ratio of the actual radiation flux to that which would be calculated by the use of the narrow beam coefficient.

i.e. B = (True flux/calculated flux) = $I/I_o e^{-\mu x}$.

With the introduction of the build-up factor into the absorption equation, it will be observed that the actual dose is significantly higher than that calculated using the simple exponential law. This is of considerable importance in the calculation of radiographic sensitivity. By definition the direct intensity has been taken to be the component of the radiation intensity reaching the film by travelling in a direct line from the source to the film; this radiation therefore forms the image of defects in the specimen. The scattered radiation component reaches a point on the film from any direction other than direct. It cannot therefore form an image of a defect at the correct position on the film and as its effect at any one point on the film must be integrated over a large angle, its effect is to produce an overall 'fogging' of the film image. Such radiation is therefore non-image forming and its effect is to reduce the contrast of the image on the film. The proportion of (non-image forming)/(image forming) radiation reaching the film is therefore a useful ιantity to be able to control since if it is reduced in intensity it will lead to a better thickness sensitivity.

2.3.3. Half-value thickness

The radiation quality can be characterised by the so-called half value layer (HVL). A HVL is that thickness of a given material which will reduce to one half the intensity of radiation (of a given energy) passing through it. Substituting $I = I_o/2$ in the absorption equation we get $HVL = 0.693/\mu$. Radiographic half value layers may be defined as the thickness of test specimen through which the attenuated radiation will produce the same photographic density on a film as that produced by the unattenuated beam with half the exposure. In shielding the HVL will be the thickness of a shielding material required to reduce the radiation dose by a factor of 2.

Sometimes a term Tenth Value Layer (TVL) is also used and is defined as the thickness of the shield material to reduce the radiation intensity or dose by a factor of 10. Thus substituting $I = I_o/10$ in the absorption equation we get $TVL = 2.30/\mu$.

An idea of the scattered radiation from various materials of interest in radiography while using a primary radiation beam of 400 keV and 1.5mm beryllium filter can be had from Table 2.2.

TABLE 2.2 SCATTERED RADIATION USING 400 kV AND A 1.5 mm BERYLLIUM FILTER

Scatter body	Scattered radiation Equivalent rated voltage (kV_{equiv})	Attenuation in Air	
		Air HVL (m)	Air TVL (m)
Lead	125	1.5	4.8
Paraffin	150	1.6	5.2
Baryt-concrete	175	1.7	5.6
Aluminium	210	1.8	5.9
Concrete	210	1.8	5.9
Steel	225	2.0	6.5

2.4. IONISATION

Atoms and molecules are generally electrically neutral. If by any process the electrons are removed from these neutral bodies then a net positive charge remains on them. Atoms, molecules and various subatomic particles which carry either a positive or negative electrical charge are called ions. Free electrons, not attached to any parent atom, are negative ions and free particles carrying positive charges are positive ions. Any action which disturbs the electrical balance of the atoms which make up matter is referred to as ionisation. Radiation, either particle or electromagnetic, has the ability to ionise. A high speed particle or a photon of energy which passes through matter will disrupt the atomic arrangement of the matter. For example, an alpha particle may strike an orbital electron in an atom and cause the electron to leave its orbit. The electron may attach itself to an atom. The first atom then has a positive charge and the latter atom a negative charge, and these are referred to as positive and negative ions or an ion pair.

By the process of ionisation, the number of orbital electrons may be changed but not the nucleus. The nucleus remains as an atom of the same element as it was originally. Gamma and X-rays have no mass and no weight. They travel at the speed of light and do not produce ionisation directly by collision. In passing through matter, gamma and X-rays lose their energy to atoms by the three ionisation processes described in 2.3, namely photoelectric absorption, Compton scattering and pair production.

Figure 2.18 shows an ion-chamber which forms an important part of a radiation detector utilising the phenomenon of ionisation. When a gas is bombarded by radiation, it ionises and becomes an electrical conductor. This is the underlying principle of all ionisation detectors. When the ionisation so produced is subjected to the action of an electrical field, the free charges can be collected and then related to the amount of incident radiation. If ionisation occurs within an electrical field, the ions, being charged particles, move towards the electrode of opposite polarity. An ionisation chamber is essentially a gas-filled region in an electrical field between electrodes across which a potential difference is applied.

The charged particles are collected at the plate of opposite polarity and their flow through the external circuit constitutes a current which can be measured and related to the intensity of the incident radiation.

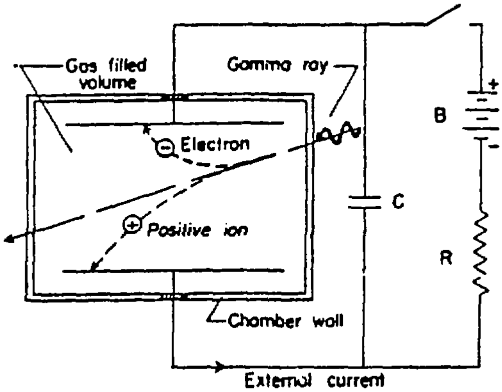


Figure 2.18 : Ionisation chamber

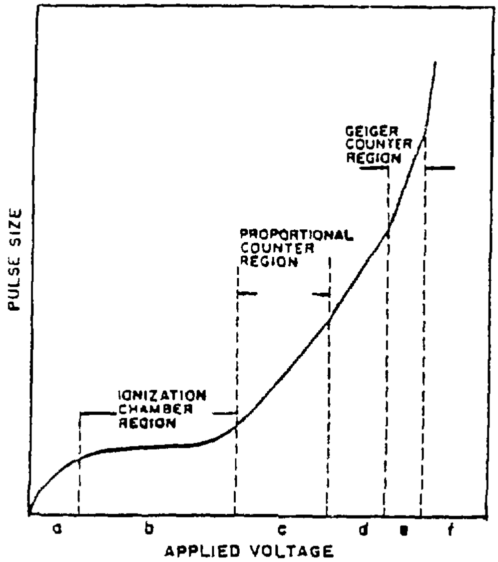


Figure 2.19 Pulse size as a function of applied voltage in gaseous ionisation chamber.

Various radiation detectors are based upon the principle of ionisation. The ionisation chambers are usually run on low voltages. There is an initial voltage on it and the radiation discharges it to an extent which depends on the amount of radiation. This drift in voltage is measured after sometime. The ionisation per unit volume of air is proportional to the amount of radiation absorbed in the process.

It is on this basis that the basic definition of a roentgen has been framed. One roentgen is defined as that amount of radiation which produces in unit volume of dry air at 0° C and 760 mm Hg pressure a charge of 1 e.s.u. of either sign. The pocket dosimeters which are used to measure radiation dose are a kind of ionisation chamber.

The number of ion-pairs produced in the ionisation process by the incident radiation depends on the applied voltage. This is shown in Figure 2.19.

The curve in Figure 2.19 shows various regions. In region 'a' some of the ions recombine. The ionisation is limited in the plane in which the ions are created. Pulse height is proportional to the energy of the quanta causing ionisation. In region 'b' the number of pulses received per second is constant. Every ion is collected at the electrodes before recombination takes place, if the voltage is high enough. The voltage which is just sufficient to collect every electron is known as the saturation voltage and beyond this voltage up to a certain extent the size of the pulse is independent of the voltage. This is the ionisation chamber region. As we increase the voltage further, we enter region 'c'. The speed of the electrons is now increased and they have sufficient energy to produce more electrons by further collision with gas atoms. Both the pulse height and the no. of pulses per sec. steadily increase with increasing voltage. For a given working voltage the pulse height is proportional both to the no. of ions produced by the initial event and to the gas amplification factor M i.e. the no. of electrons freed by the collision. M varies from unity in the ionisation region to about 10^4 at the upper end of the proportional region. The initial no. of ions produced depends on the type of radiation i.e. on the specific ionisation of the radiation. A proportional counter is therefore able to discriminate between different incoming events. Because of the higher ionisation currents involved, a proportional counter provides much stronger signals which require less external amplification. They are also faster than the ionisation chamber which means that higher counting rates are possible. This region is called the proportional counter region. In region 'd' the number of pulses per second continues to increase but proportionality between pulse height and amplification factor in no longer maintained. This is because the electrons previously produced have enough energy to ionise further atoms. The discharge tends to fill the tube with ions. Region 'e' is the Geiger Counter region. Because of the high voltage the discharge is no more confined to a small region of the gas but spreads to fill the whole volume between the electrodes. For a given voltage on the chamber, the pulse size is constant i.e. it is independent of the no. of ions produced by the initial event, though the absolute size of the pulse continues to increase with voltage, and it is only the total number of pulses that gives a measure of the radiant intensity. The output pulse is quite large and can be recorded with little or no amplification. The flat portion of the curve is called the plateau. Beyond the plateau the no. of pulses per second increases rapidly and the counter goes into a continuous discharge. Inside the G.M. tube, electrons because of their light mass are readily collected whereas positive ions move slowly towards the cathode. Thus there are two ions present in the active volume of the counter. If the velocity of these two ions is high enough they too can liberate electrons (secondary emission) on striking the cathode which also can lead the tube to continuous discharge. This tendency to continuous discharge must be prevented or quenched. Quenching is done in two ways (i) By employing an external circuit which, immediately after the pulse is recorded, lowers the voltage across the counter below that required for the positive ions to liberate electrons at the cathode, until all the ions are removed from the gas. (ii) By introducing a suitable polyatomic gas into the chamber. This is called self quenching. A common quenching gas is 10/90 percent alcohol/argon mixture at a total pressure of 10cm Hg. The halogen gases also have the self quenching property. While the positive ions are in the chamber the anode potential is reduced either by the cut off action of method (i) or by a sheath of +ve ions in a self quenching counter and for the duration of this time no further event can be detected. This is the dead time of the counter. After the dead time a small pulse is detected and then a large pulse can be detected. The total time interval between the production of full sized pulses is called the recovery time.

A typical value of dead time = 2×10^{-4} and of recovery time = 2.5 to 5×10^{-4} sec.

Ionisation chambers are used to measure the dose rates in mrem/hour and rem/hour and have a wide range from a fraction of mrem/hour to thousands of rem/hour. Such ionisation chamber detectors/ratemeters/survey-meters are both mains and battery operated and portable and non-portable. They are also used as personal dose rate alarms, personal dose rate threshold alarms and remote area/field monitors.

G.M. tubes are very sensitive and are particularly good for detecting small amounts of radioactivity e.g. a contamination survey. G.M.tubes are also used in dose-rate meters provided the instruments are properly designed. G.M. tubes come in many shapes and sizes. The thin walled tubes permit the passage of low energy beta particles. Very thin walled tubes are also available to detect even alpha particles and beta particles of very low penetrating power. Such tubes are usually built with fairly thick walls except for one end of the tube. In such cases only the thin end of the tube is used as a detector. Such tubes are called end window type G.M. tubes. As the voltage across a G.M. tube is very much higher than that in an ionisation chamber, the number of electrons produced due to direct (Primary) ionisation by the radiation gets amplified owing to the secondary ionisations produced by the primary electrons and this is the reason why G.M. tubes are more sensitive than ionisation chambers. The G. M. tube is connected to an electronic pulse counter which can detect and count the passage of an individual ionising particle by the current pulse it produces.

2.4.1. **Radiation exposure**

A radiation exposure or dose implies the total amount of radiation received by a body at a place. There are a number of factors involved in the estimation of exposure. The intensity of the radiation emitted by a source and its modification by distance and shielding materials is important. The second important factor is the time for which this intensity of radiation is present. Mathematically exposure or dose may be defined as $E = It$ where E is the exposure, I the radiation intensity and t the time for which the body has been exposed to the radiation. The exposure is measured in roentgens.

Roentgen has already been defined in a previous section but for convenience this definition is reproduced here. One roentgen is that amount of radiation which produces in unit volume of dry air at 0°C and 760mm Hg pressure a charge of 1 e.s.u. of either sign. Roentgen is applicable to X or gamma rays and for an air medium only. Roentgen Absorbed Dose (Rad) is defined as the amount of radiation which is equivalent to an energy absorption of 100 ergs/gm of the exposed material.

Relative Biological Effectiveness (R.B.E.) is the effectiveness of any radiation in causing biological damage as compared with the same amount of 250 KV X-rays.

$$\text{R.B.E.} = \frac{\text{Amount of 250 KV X-rays to produce a certain biological effect}}{\text{Amount of the radiation (whose R.B.E. is required) to produce the same biological effect}}$$

R.B.E. is also termed the quality factor and is denoted by Q.F.

The biological effect of a particular type of radiation depends, not only on the absorbed dose but also on the R.B.E. of the radiation. The unit which takes into account both absorbed dose and R.B.E. is the Roentgen Equivalent Man (Rem) and is defined as Dose in Rem = Dose in Rad x R.B.E. It is interesting to note that the same absorbed doses of different radiations amount to different doses in Rem, because of the difference in R.B.E. One Rad of alpha will be equal to 20Rad of gamma rays and both will be equal to 20 Rem. (R.B.E. for alpha rays = 20, R.B.E. of gamma rays = 1)

The S.I. unit for dose equivalent is sievert (Sv) defined as 1 rem = 10^{-2} Sv. The lower denominations of sievert are milli-sievert and micro-sievert. Roentgen Hour Meter (R.H.M) is the dose rate in roentgens/hour from one curie source at a distance of one meter from the effective centre of the source.

2.5. PRINCIPLES OF X AND GAMMA DETECTION

2.5.1. **Film**

Like visible light, X-rays and gamma-rays evoke photochemical changes in photographic emulsions, thus producing changes in density of x-ray films. The resulting film density depends both on the quantity and the quality of radiation reaching the film.

When radiation strikes a photographic emulsion a so-called latent image is formed. This occurs in the following way. The photographic emulsion contains small crystals of silver bromide. Under the action of a radiation photon of energy $h\gamma$ a negative ion Br^- releases its electron and passes to a neutral state.

i.e. $Br + h\gamma \rightarrow Br + e^-$.

The released electron neutralises the positive silver ion Ag^+ by the reaction

$Ag^+ + e^- \rightarrow Ag$.

The whole process can be presented as

$Ag^+ + Br^- + h\gamma \rightarrow Ag + Br$.

The neutral bromide atoms join together to form particles of Br and leave the Ag Br crystals, whereas the free silver atoms coagulate. During development the latent image becomes visible.

Film is the most commonly used means of detecting and recording X and gamma radiation in radiography. It is quite a sensitive method and beside many others has the advantage of providing a permanent record of the results. Various types of films and their properties will be described in detail in Section 4.

2.5.2. Fluorescence

Several substances such as cadmium sulphate, barium platinocyanide or calcium sulphate emit visible and ultraviolet light when irradiated with X-or gamma-rays. If the emission of light takes place only during the period of irradiation, this is called fluorescence. Fluorescence is used both in fluoroscopy (fluorescent screens on which a picture of the examined object can be observed) and in radiography, where fluorescent intensifying screens are used to increase the photochemical effect of radiation. The fluorometallic radiographic screens also employ this effect for image intensification. Using fluorescent screens either in fluoroscopy or radiography has some advantages that help reduce the time of inspection thereby making radiographic inspection more economical. The fluorescent or salt screens as they are generally called are specially suited to medical radiography where there is a requirement to get a proper radiograph with a minimum possible exposure to the patient. However, in fluoroscopy the technique is not quantitative and often cannot show serious defects. The quality of the image is generally poor. The screens tend to saturate with small amounts of radiation after which the glow remains constant, and the image contrast cannot be improved further.

2.5.3. Electronic detectors

Most electronic detectors employ scintillation detectors which are just another sophistication and extension of the fluoroscopic principle. A scintillation detector consists of a crystal and a photomultiplier tube. The crystal may consist of many different materials, some of which are, activated rhodium or lithium iodides. The crystal is usually coated with a thin layer of beryllium under which is a thin layer of aluminium. Beryllium is opaque to light but transparent to X-rays. The aluminium acts as a reflector for the light. Between the crystal and the photomultiplier tube is a material such as silicon which has a high transmission for the light scintillated in the crystal. In the photomultiplier tube a very large multiplication of the current of photoelectrons from the photo cathode of the tube can take place.

When a particle or photon strikes the scintillation crystal (NaI or LiI activated with thallium or germanium respectively) the photon can lose some or all of its energy by absorption and produce a scintillation of light within the crystal (in floresence this light is visually seen on the screen). The amount of light produced is a function of the energy of the particle falling on the crystal. The light is transmitted to the photo-cathode (a material which gives out electrons when bombarded by visible light) of the multiplier tube. The light causes the ejection of electrons from the cathode. These electrons are then permitted to strike the first diode of the photomultiplier tube. There is a multiplication at each diode and the resulting multiplication can reach well in excess of 10^9. These electrons are finally collected at the anode. The current pulse is amplified in a preamplifier and fed through an analyser or discriminator to a scaler or ratemeter.

3. RADIOGRAPHIC EQUIPMENT

3.1. X-RAY EQUIPMENT

Briefly, three basic requirements must be met to produce X-rays namely a source of electrons, i.e. a heated filament, a means of directing and accelerating the electrons i.e. a high voltage supply, and a target for the electrons to bombard i.e. a heavy metal. These requirements are fulfilled in an X-ray tube which consists of a glass envelope in which two electrodes are fitted: cathode and anode. The cathode serves as a source of electrons. The electrons are first accelerated by applying a high voltage across the cathode and the anode and then stopped suddenly by a solid target fitted in the anode. The sudden stoppage of the fast moving electrons results in the generation of X-rays.

Figure 3.1 shows the diagram of a typical tube, various parts of which are explained below.

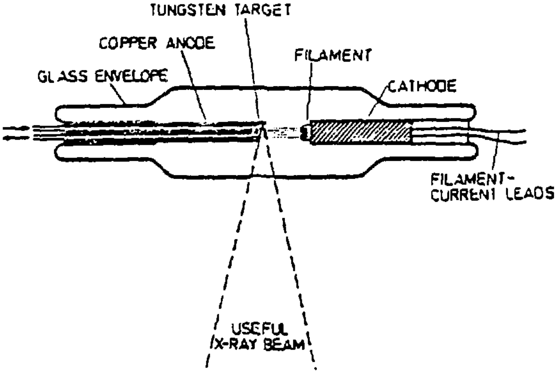


Figure 3.1 A typical X-ray tube

3.1.1. Electron source

When a suitable material is heated, some of the electrons in the material become agitated and escape from the material as free electrons. These free electrons will surround the material as an electron cloud. In an X-ray tube the source of electrons is known as the cathode. The cathode consists of a coil of wire (the filament) which functions as the electron emitter. When a voltage is applied across the filament, the resultant current flow heats it to electron emission temperatures. The filament is heated with an AC current of 1 to 5 amperes at 4 to 12 volts. The tube current between the cathode and the anode is approximately 0.1% of the heating or filament current. The tube current is of the order of milliamperes and can be directly measured. The filament is surrounded by a focusing cup usually made of very pure iron and nickel. This acts as an electrostatic lens and controls the shape of the electron beam.

3.1.2. Electron acceleration

The electrons emitted at the cathode of an X-ray tube are negatively charged. Following the fundamental laws of electrical behaviour they are repelled by negatively charged objects and attracted to positively charged ones. By placing a positive charge on the anode of an X-ray tube, and a negative charge on the cathode, free electrons are sped from the cathode to the anode. An arrangement is also made to focus the stream of electrons onto the anode. The collimated stream of electrons then strikes the target. For the radiation needed for industrial radiography the accelerating potentials range from about 30KV to 30MV. X-ray tubes are usually rated at up to 420KV while higher voltages are used in linear accelerators. The electrons acquire the energy equivalent to these voltages.

3.1.3. Target

X-rays are generated whenever high velocity electrons collide with any form of matter, whether it be solid, liquid or gas. The target material should have the following desirable properties: namely, high atomic number, high melting point and high thermal conductivity. The high atomic number gives the best efficiency of conversion of electron energy into X-rays. A high melting point allows high tube currents for a given size of focal spot thereby providing large X-ray output (i.e. intensity). High thermal conductivity reduces the amount of evaporation of target metal thereby increasing the life of the tube. Tungsten is the only metal which has all these properties so usually the target is made of tungsten. The target is fitted in a cup of copper which acts as an anode.

Taking away the heat generated due to the electron impacts is one of the major considerations in the design of X-ray tubes. The necessary cooling is done by liquid coolant such as oil or water. The tube target is usually vacuum-cast in a copper backing to provide thermal contact to conduct away the heat. The joint between the copper and tungsten must be good. The anode is usually hollow to allow the circulation of cooling fluids. In many modern X-ray tubes the anode is hooded. This hood consists of a metallic body over the anode with an aperture to permit the electron beam to reach the target and a second aperture for the X-ray beam. The hood also reduces the danger of electron back emission from the target if this gets overheated and limits the X-ray emission outside the useful beam by absorption. The part of the anode target on which the electrons impinge is called the focus of the X-ray tube.

To get sharp shadows, theoretically the focal spot must be as small as possible. But if the focal spot is actually made small, say 1 x 1 mm, the tube life is reduced due to the vaporisation of the target. If the area of the focal spot is extended to say 3 x 1 mm, the tube can run for about three times as long, but it will not give sharp shadows. To deal with this situation, the target is usually inclined at about 71° to the electron beam direction. The result is that the effective size of the focal spot reduces without reducing the actual size of the focal spot. This reduced focal spot is called the optical focal spot.

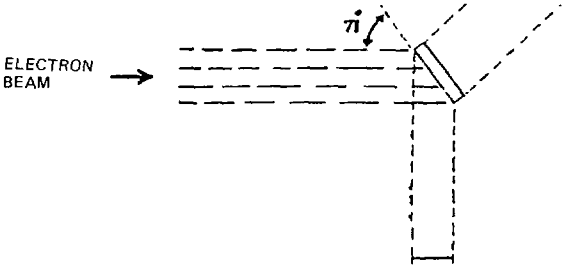


Figure 3.2 Actual Vs effective focal spot size

If the actual size is 3mm x 1mm, with an inclination of 71°, as shown in Figure 3.2, the effective size of the focal spot is,

$$3 \cos 71^\circ \times 1 \text{ mm} = 0.98 \times 1 \text{ mm} = 1 \times 1 \text{ mm}$$

Usually, therefore, industrial X-ray tubes have inclined targets.

Tubes with rotating targets have also been developed. Rotating targets make the running life of the tube longer, but such tubes are not used for industrial radiography because of relatively low tube currents.

3.1.4. Tube envelope

The tube envelope consists of a glass envelope in which two electrodes are fitted; cathode and anode. The filament portion of the cathode functions as a source of free electrons and the anode as the target upon which the electrons strike. The tube envelope is constructed of glass of the borosilicate type that has a high melting point because of the extreme heat generated at the anode. The envelope also has sufficient strength to resist the implosive force of the high vacuum interior. Inside the envelope there is a vacuum of the order of 10^{-6} mm Hg.

A high vacuum environment for the tube element is necessary to prevent oxidation of the electrode materials, to permit ready passage of the electron beam without ionisation of gas within the tube and to provide electrical insulation between the electrodes.

3.1.5. Tubeheads

The entire tube is enclosed in a metal casing lined with sufficient lead to restrict the radiation beam to the outlet port. Tubeheads usually contain the X-ray tube, high voltage and filament transformers and insulating oil or gas. In addition, the metal case is earthed to eliminate possible electrical hazards due to the high voltage used.

3.1.6. Tube window

The X-ray beam emerges from the tube through a port or window. The solid angle of the radiation cone is usually 40° - 50°. The window is usually made of a less radiation absorbent material such as a light metal of low atomic number (e.g. beryllium). Directly below the window in the useful beam area is the diaphragm, a shielded opening that permits changing of the useful beam size. In many machines a copper filter may be incorporated in or located close to the diaphragm. This copper filter shields out the low energy portion of the X-rays produced, making the useful beam that falls on the specimen more nearly uniform in energy.

3.1.7. Duty Cycle

The duty cycle is generally expressed as a percentage of exposure versus total time. For example a 100% duty cycle means that the tube can be operated continuously;50% means that it is necessary to provide equal rest time after each exposure and so on. The life of an average tube operating under conventional loads may be from several hundred to over one thousand hours. One major factor concerning the tube life is the effectiveness of its cooling. If it is overloaded, its life is considerably shortened, while its life is lengthened if the tube is under loaded. Also the tube life can be increased by preheating it (warm up) and controlling its operation every time it starts working again after an idle period.

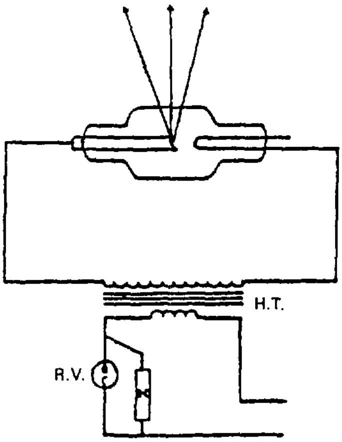
3.1.8. Electrical devices and circuits

In addition to the X-ray tube, other electrical equipment consists of:

(a) A high tension transformer to give the required high voltage.
(b) Gear to control the high voltage applied between the cathode and anode i.e. kV control knob.
(c) Gear to control the filament current i.e. mA control knob.
(d) Automatic trip system to protect the equipment from damaging itself due to overheating, overvoltage, overcurrent, etc.

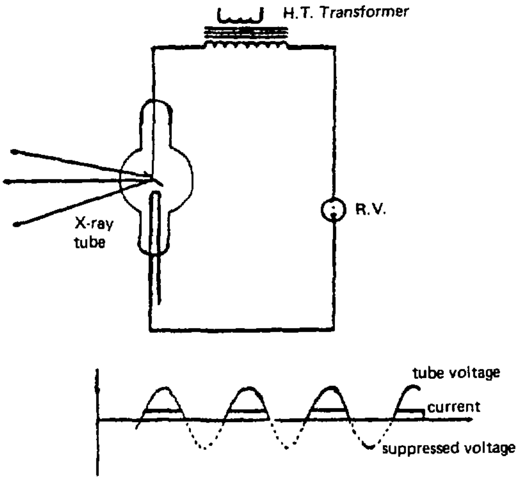
In portable X-ray units, a self rectifying circuit, Figure 3.3, is frequently used. In this circuit X-rays are only generated during one half-cycle of the applied voltage. Normally no electric current can travel from the anode of an X-ray tube towards the cathode; the negative half-cycles of an alternating current do not pass through the tube and only the positive half-cycles are used. For this circuit the tube current must be kept low, since if the anode becomes too hot it may emit electrons in the reverse direction (strike back), hence damaging the filament of the cathode.

In a single-valve circuit, Figure 3.4, there is no danger of a strike back and the tube can thus carry a heavier load.



Kearsley circuit

Figure 3.3. Self rectifying circuit



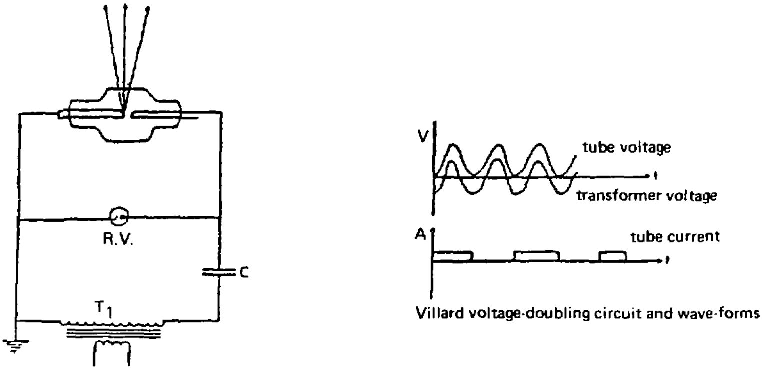
Half-wave rectification – circuit and wave-forms.

Figure 3.4 Single valve circuit

Figure 3.5. shows a circuit diagram for a Villard circuit. When the current flows in the direction shown by the broken line arrows, the two condensers are charged. When the current is in the opposite direction, it passes through the X-ray tube and is supplemented by the discharge from the condensers

Another type of circuit for X-ray machines is the Graetz circuit (Figure 3.6) During both the cycles of the voltage transformer, current passes through the X-ray tube in the same direction.

In the Greinacher circuit, Figure 3.7, the condenser C1 is charged during one half-cycle (solid-line arrows) while C2 is charged during the other half-cycle (broken-line arrows). The X-ray tube is connected in parallel to the two condensers, which are themselves connected in series; the result is a voltage which is doubled and which only fluctuates very slightly.



Villard voltage-doubling circuit and wave-forms

Figure 3.5. Villard voltage doubling circuit and wave forms

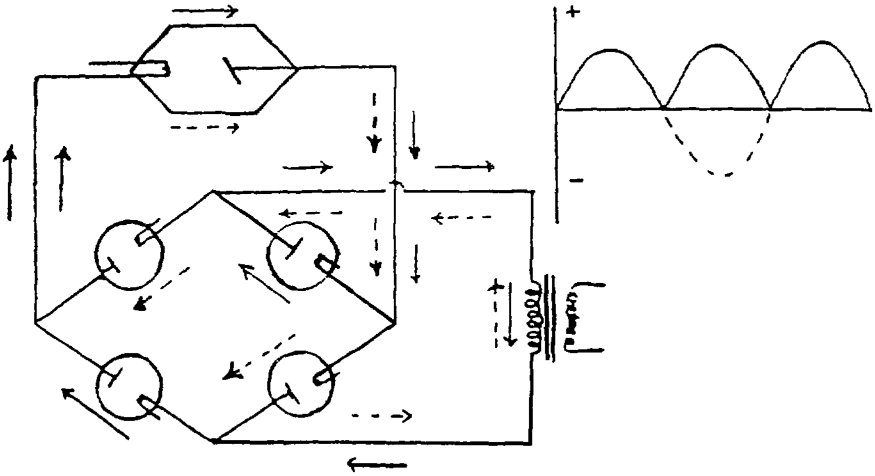


Figure 3.6. Graetz circuit

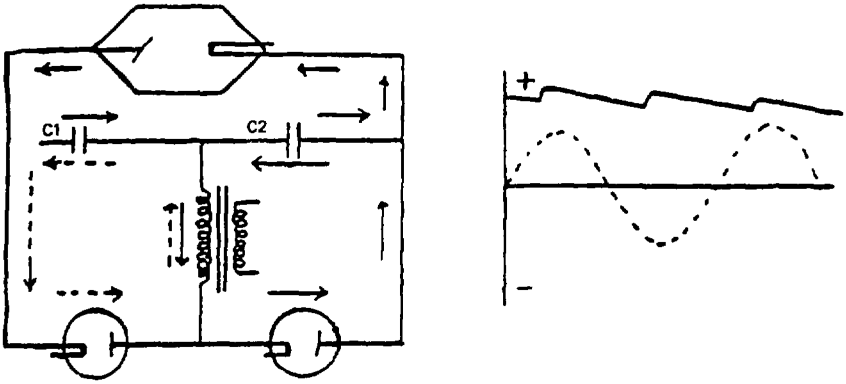


Figure 3.7. Greinacher circuit

3.1.9. Control consoles

Wherever a high voltage circuit is used, provision has to be made if possible for varying and measuring the high voltage applied to the X-ray tube and the current passing through the tube. The third variable that has to be controlled is the exposure. At a given kilovoltage the integrated output from a given equipment is proportional to the quantity of electricity passed through the tube, that is, the total number of milliampere seconds (mA.s). In some megavoltage machines such as linacs, a radiation-measuring chamber is built into the head of the machine close to the target which will measure both integrated dose and instantaneous dose rate and convert these to doses at the plane of the film, but such instruments are very rare on lower energy X-ray equipment. A direct method of measuring the total X-ray dose on the specimen or the film is rarely used but could be of considerable value. It could automatically compensate for slight variations in kilovoltage and tube current during the exposure time.

In most of the older X-ray machines the knobs for controlling the kilovoltage, milliamperage and time are present and have to be manually operated to select the given parameters. In the latest designs of x-rays machines, however, these controls are controlled through a microprocessor.

3.1.10. Quantity and quality of X-rays

Much of the energy of the impinging electrons is dissipated as heat. In very low voltage tubes 0.1% of the energy of the electron beam is converted into X- rays. At 100KV the X-ray generation efficiency increases to about 1%. At 2 million volts it approaches 10% and at 15 million volts it may be over 50%. The efficiency of conversion also depends upon the target material, being best for the high atomic number materials like tungsten, etc.

In brief the x-ray generation efficiency is given by $E = K.V.Z$ where V is the applied voltage, Z the atomic number of the target material and K is a constant having a value of 10^{-7} for tungsten.

The quantity or the intensity of X-rays produced depends on the number of electrons hitting the target i.e. tube current. The tube current, which is of the order of milliamperes, can be controlled by controlling the number of electrons emitted by the filament i.e. by controlling the heating current through the filament. Increasing the milliamperage increases the number of electrons that are available to strike the target. This is turn increases the quantity or the intensity of X-rays, Figure 3.8. Change in milliamperage causes no change in the wavelength of the X-rays produced.

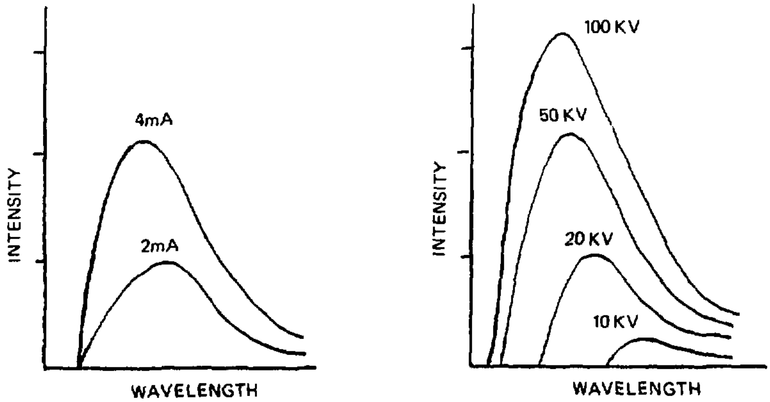


Figure 3.8 Effect of mA and KV on X-ray output

The quality or the energy of X-rays produced depends upon the energy of electrons striking the target. The energy of the striking electrons is controlled by the accelerating potential which is of the order of kilovolts (KV). An increase in KV results in the generation of more energetic (more penetrating) X-rays, Figure 3.8.

3.1.11. Modern X-ray equipment

A lot of development has occurred towards the production of versatile X-ray equipment. A wide range of sets is now commercially available that incorporates

(a) increased X-ray output with smaller size of focal spot
(b) availability of very low and very high energy x-rays with control of the emitted x-ray energy.
(c) portability/mobility of the units.
(d) directional and panoramic X-ray outputs.
(e) safe and simple operation of the equipment.

Equipment is manufactured by many firms and can be categorised as follows:-

i) Directional X-ray Units

Fully portable and mobile versions from 100 to 400 KV range are available. Kilovoltage can be varied continuously or in steps. The emergent beam angle is normally 40° but tubes with different beam angles are also available. Effective focal spot size normally varies from 0.5 x 0.5 to 4 x 4 mm. Tube currents range from 5 to 20 mA depending on the size of the focal spot. Normally the stability of the kilovoltage and output current is 1 % and 0.5% respectively.

Double focus X-ray tubes are also available with the provision to use a small focal spot at low tube currents and a large focal spot at high tube currents. Recently program controlled X-ray units have appeared commercially. Programming can be done by means of a program card. Automatic exposure devices can be used with these units and knowledge of specimen thickness and material is then not needed.

ii) Panoramic X-ray Units

Panoramic X-ray tubes up to 300KV are normally available with emergent beam angle of 360° x 30°. The focal spot is elliptical in shape and the effective focal spot sizes may be 4 x 1, 4.8 x 1, 5 x 1.5mm, etc. with tube current up to 15mA. These tubes are specially useful for the radiography of circumferential welds in large diameter pipes. A directional beam can also be obtained using protective collars generally provided with these tubes.

Panoramic X-ray tubes with rod anodes are also available. A directional beam with angles 90°, 120°, 180° and 360° (directed perpendicular to the anode) can be obtained by using diaphragm attachments provided with such tubes. Focal spot size may be 5mm dia. with 6mA tube current.

iii) Radiographic Linear Accelerators

For the radiography of thick samples, X-ray energy in the MeV range is required. This has now become possible with the availability of radiographic accelerators. The energy of the X-rays can be varied smoothly from 1MeV to 2.5MeV and is suitable for the thickness range of 2 to 20cm of steel. Focal spot size is 2.5 x 2.5mm and 10cm steel can be radiographed in one minute. Radiography at beam angles of 15°, 30°, 45° and 360° is possible. Electron beam current can be varied from 0.01 to 0.25 mA (giving maximum dose of 170 rads/min at 1 meter). Varian manufacture radiographic linear accelerators of 4MeV and 8 MeV suitable for radiography of up to 38cm of steel. The X ray beam is available in 15° and 40° cone angles. Max. focal spot diameter is 2mm. In their improved version (Linatron 2000) selection of either 5.5, 8 or 10MeV is possible from a switch on the control console. A dose output of 2000 rads per minute at one meter is achieved at 8MeV.

iv) Microfocus X-Ray System

Geometric sharpness (definition of radiograph) is badly affected in situations which do not permit large sfd (source to film distance) and small ofd (object to film distance). This can be overcome to a great extent by using tubes of very small focal spots. Magnaflux Corp. have developed a microfocus X-ray system. The small and light ceramic tube permits focal spots of variable size from 0.5 to 0.05mm. The electron beam is focused on to a tungsten target by the help of a focusing electrode. The size of the focal spot can be varied by varying the bias voltage on the focusing electrode. This new 100KV machine can be operated at a maximum of 1mA. The tube head can easily pass through an opening of 10cm diameter. The system is being used for the inspection of electron beam welds in the main engine mount of TFE31 jet engines.

v) Flash X-ray Tubes

An electron beam of very high intensity can be produced by field emission from a small radius metal cathode by the application of a high voltage pulse of very short duration. The pulse length must be of the order of a few microseconds and the pulses are generated with a capacitor, a pulse transformer and a high pressure spark gap, with a very low inductance circuit. This pulse of X-rays impinging on a target generates a very short but intense pulse of X-rays. Tube and generators have been built for this purpose to operate at 100-200kV to produce pulses up to 1R at 1m distance. The resulting apparatus is lightweight and portable and the tubes are said to have a life of 10^6 pulses.

Much larger 'flash X-ray' apparatus has also been built for special purposes such as ballistic studies. Some of it operates in the megavoltage region and uses 'one-shot' X-ray tubes. Voltage multiplication is accomplished by charging capacitors in parallel and discharging them in series. Spark gaps are used to switch from parallel to series operation. One or two of the gaps are triggered by a low voltage signal and the remainder are overloaded by the transient voltages within the generator. Capacitors, spark gaps and charging network are housed in an electrically grounded steel tank. The steel tank may be pressurised to improve insulation and control the breakdown voltage of the fixed spark gaps. Typical data on these generators are output voltage 250-600kV, peak current 10000A, pulse width 20ns, weight 300kg.

The electrode system used is the classical one for generation of fine-focus flash X-rays, consisting of a cone-shaped tungsten anode and a ring-shaped hollow stainless steel field emitter cathode. The tubes normally operate at a residual gas pressure below 10^{-6} torr.

vi) Betatron

The principle of this machine is to accelerate the electrons in a circular path by using an alternating magnetic field. The electrons are accelerated in a toroidal vacuum chamber or doughnut, which is placed between the poles of a powerful electromagnet. An alternating current is fed into the energising coils of the magnet and as the resultant magnetic flux passes through its zero value a short burst of electrons is injected into the tube. As the flux grows the electrons are accelerated and bent into a circular path. The magnetic field both accelerates the electrons and guides them into a suitable orbit and hence, in order to maintain a constant orbit, these two factors must be balanced so that the guiding field at the orbit grows at an appropriate rate. The acceleration continues as long as the magnetic flux is increasing, that is, until the peak of the wave is reached; at this point the electrons are moved out of orbit, either to the inner or outer circumference of the doughnut, by means of a d.c. pulse through a set of deflecting coils. The electrons then strike a suitable target. The electrons may make many thousands of orbits in the doughnut before striking the target, so that the path length is very great and the vacuum conditions required are in consequence very stringent. The radiation from betatrons is emitted in a series of short pulses. In order to increase the mean intensity, some machines operate at higher than mains frequency. Most betatrons designed for industrial use are in the energy range 15-31 MeV. Betatrons in general have a very small focal spot size typically about 0.2mm, but the X-ray output is low. Machines are built in the higher energy range in order to obtain a higher output, but this brings the disadvantages of a restricted X-ray field size.

vii) Microtron

A third alternative to the betatron and the linac for generating high energy electrons is the microtron. This is a form of circular orbit accelerator in which the electrons are accelerated by the field in a microwave resonator which is placed in a homogeneous magnetic field so that the electron orbits form a family of circles with their common tangent in the resonator. The electron gun is placed close to the entrance hole of the resonator and produces pulses of electrons. The magnetic field, the microwave frequency, and the energy gain per orbit, must be correctly related so that the electrons come back to the resonator in phase to acquire another acceleration. In a klystron-operated 8 MeV machine an output of 6000 R/min at 1m has been achieved, but although some microtrons were produced in the 1960's very few are in industrial use compared with the number of linacs.

3.1.12. Comparison of X-ray generators

Table 3.1 shows the specifications for some X-ray machines that are commercially available.

TABLE 3.1. PARAMETERS OF X-RAY GENERATORS

Unit Description	Max. kV	Weight of head in Kg	Current rating in mA	Focal spot in mm at 1m	Rad. output R/min.	Max.insp. thickness	
						Fe	Al
HT Cable	50	6	30	1.5x1.5	10	-	0.5
Light wt tank	80	9	2	1 x 1	-	0.3	3
Microtank (Philips)	100	45	5	3 x 1	32	0.4	3.5
Tank type (Andrex)	100	47	8	1 x1.5	20	0.5	4.0
Micro tank (Philips)	200	45	5	3 x 1	2.4	3.5	10.5
Tank type (Baymex)	250	454	10	5 x 5	20	6	17
Seifert (Ht Cable)	300	91	5	4 x 4	40	7.5	22
Laboratory (HT Cable)	400	350	10	4 x 4	50	10	25
G.E.Resonance Transformer	1000	1364	3	7 x 7	50	12	50
Van de-Graff	3000	3600	0.35	2.5x2.5	350	30	-
Linatron 400	4000	900	-	2	500	30	-
Linatron 2000A	3000	990	-	2	2000	38	-
Linatron 6000	15000	3900	-	3	6000	46	-
Betatron	18000	2000	-	0.2x0.2	100	50	-

3.1.13. Classification and Selection of X-ray Equipment

X-Ray equipment is usually classified by its voltage rating. As the energy or penetrating power is a function of the voltage, it therefore represents the equipment capacity. From a practical point of view the classification of X-ray equipment may be made as laboratory type, mobile type, portable type and enclosure type. Laboratory units are intended for permanent lead lined or concrete room installation. These are usually the constant potential type. Mobile equipment is designed to be moved within or between buildings. Portable equipment is designed to be transported to almost any location by any means. It is usually small and light weight. The tube head contains both the high tension transformer and the X-ray tube. Oil or gas insulation is used in the tube/transformer head and if oil is used it can also be pumped round the head to assist in cooling the tube. In most sets there is provision for additional cooling of the oil by an external water supply. Some sets have a limited duty cycle in that they cannot be operated continuously without this auxiliary cooling. Only a low voltage connection is required from the tube transformer tank to the control box and this cable can therefore be made of considerable length without difficulty. Enclosure type units consist of a lead-lined cabinet containing the X-ray tube and possibly a fluorescent screen for fluoroscopic work.

The selection of X-ray equipment will primarily be dictated by the type of applications for which it is intended. Some of the aspects that need to be kept in view while making this selection are briefly described here.

The quality of radiation emitted from the machine or the kV rating will determine its suitability for inspecting a material of a particular thickness. The intensity of radiation or mA rating will determine the length of exposure time needed to inspect the desired material. The focal spot size will indicate the capability of the machine to detect fine flaws for good quality radiography. The duty cycle and the type of cooling will determine the life and the productivity of the machine. The weight and dimensions of the machine and the shape of the emitted beam of radiation are other important factors to be considered. These will determine whether or not the machine can conveniently be put in the desired position for radiography. The beam spread will determine the area of the test specimen covered in one exposure. The cost of the equipment may be the final consideration for its selection.

3.2. GAMMA RAY SOURCES AND EQUIPMENT

The great penetrating power of gamma rays from most of the radioactive sources make them valuable specially when large thicknesses or high density specimens, beyond the range of generally available X-ray equipment, are involved. Gamma ray sources are not usually used for light alloys as the sensitivity required for a radiograph limits their use. Most of the concepts relating to radioisotopes, such as, what they are, how they are produced, radioactivity, radioactive decay, half life, specific activity of radioisotopes, the type of radiation emitted, the interaction and consequent absorption of these radiations by matter and the general properties of these radiations, have already been explained in chapter 2.

In this section the type of radioisotopes used in radiography and how they are used will be discussed.

3.2.1. Gamma-ray sources

The most commonly used radioisotopes are listed below along with their characteristics for ready reference. Approximate thickness ranges of materials that can be radiographed using a particular source are also given. Although greater thicknesses may be penetrated, exposure time would be very long.

3.2.1.1. Naturally occurring radioisotopes

Prior to the introduction of artificially-produced radioactive sources, radium was almost universally used for gamma-radiography. Its great merit was its very long half-life - 1590 years - and its relatively large radiation output. Today it has been completely ousted by the much less expensive artificial isotopes and for industrial use it is only of historical interest. However a radium source consists of about 200 to 250 mg of an element in the form of a salt of the metal and is sealed in a platinum capsule. Prominent energies emitted are 0.6, 1.12 and 1.76 MeV which are radiographically comparable to the X-rays from sets operating in the 1000 - 2000 KV range. The half life is 1590 years and the thickness range for which the source is used is 5 to 15cm of steel. One curie of the source gives 0.83 roentgens per hour at one meter.

3.2.1.2. Artificially produced radioisotopes

The radioisotopes that are most commonly used in radiography are the ones which are artificially produced. Some of these are produced by bombardment with neutrons in a nuclear reactor. The (n,γ) reaction is employed for the production of most gamma sources. This (n,γ) reaction is primarily a thermal neutron reaction.

The neutron is captured in the nucleus of the bombarded element and the material produced is a radioactive isotope of the original element. For example ,

$$ {}_{27}C^{59} + n^{1} \rightarrow {}_{27}Co^{60} + \gamma $$

Iridium - 192, Thulium -170 and Ytterbium - 169 are also produced in this way. The specific activity of isotopes produced by neutron bombardment can be calculated from

$$ a = \frac{0.6 \times \phi \times \sigma \times (1 - e^{-0.693\, t/T\, 1/2})}{3.7 \times 10^{10} \times A} $$

Where,

a is specific activity in Ci/g
ϕ is neutron flux of the reactor in n/cm^2
σ is activation cross section in barns (1barn = 10^{24} cm^2)
A is atomic weight of the irradiated element
t is irradiation time
$T_{1/2}$ is half life

Caesium - 137 is produced as a result of fission of uranium fuel in a nuclear reactor. Detailed descriptions of these radioisotope are given below.

3.2.1.2.1. Cobalt - 60

Cobalt is a hard metal of density 8.9 g/cm^3 and occurs naturally as a single stable isotope, cobalt-59. By the (n,γ) reaction this is activated to cobalt-60 which decays by emission of a 0.31 MeV beta-particle, followed by two gamma photons in cascade, of energy 1.17 and 1.33 MeV. The half-life is 5.3 years and the radiation output is 1.3RHM/Ci.Cobalt has a high slow-neutron capture cross-section and because of its neutron absorption characteristics it is usually produced in small pellets or thin discs rather than in single large sources. These pellets or discs are fabricated into sources, after activation, and are also sometimes nickel-plated for protection.

Because of their high energy cobalt-60 sources require considerable shielding. A container suitable for a 30Ci source is likely to weight at least 150kg. A few cobalt-60 sources of strengths 1000-3000 Ci are in use as static radiation machines; these are being used as alternatives to linacs and betatrons for the radiography of large thicknesses of steel, from 100-200mm. They are, of course, very much less expensive than megavoltage X-ray equipment in initial cost, but their radiation output is much smaller so that longer exposure times are needed than with X-ray machines. Also such high strength sources have considerable self- absorption of radiation.

3.2.1.2.2. Iridium - 192

Iridium is a very hard metal of the platinum family; its density is22.4 g/cm^3 and it occurs naturally as two isotopes, iridium - 191 (38%) and iridium - 193 (62%). Activation of natural iridium in the atomic pile is by the (n,) reaction and two radioactive isotopes are produced, iridium - 192 with a half-life of 74.4 days, and iridium - 194 with a half-life of 19h. It is usual to allow the activated source to decay for several days before measurement, so as to virtually eliminate the short-lived iridium-194. Iridium-192 decays chiefly by beta-emission to platinum-192 but there is also a second decay process, by electron capture to osmium-192; both these products are stable. The gamma-ray spectrum is complex, containing at least 24 spectrum lines with prominent lines of 0.13, 0.29, 0.58, 0.60 and 0.61 MeV. The source is radiographically comparable with X-rays from a unit operating at 500 KV. One curie of iridium source gives 0.50 roentgens per hour at a distance of one meter. The thickness range for which the source can be used is about 100mm steel. The sources are encapsulated in holders of aluminium alloy and are available in different sizes varying from 0.5 x 0.5mm to 6 x 6mm. The iridium - 192 sources used in industrial radiography are generally between 500 mCi and 50Ci in strength, but higher strengths up to 100 Ci are available and a 60Ci source can be as small as 2 x 2mm in size.

3.2.1.2.3. Caesium - 137

Caesium - 137 is one of the most abundant fission products of the atomic pile and can be extracted as the sulphate or chloride by a chemical precipitation method. The radioactive salt is compressed to a density of 3.5g/cm^3 and the specific activity is limited largely by the presence of other isotopes of caesium. Because caesium chloride is a soluble powder special double-encapsulation methods are used.

Caesium - 137 decays by beta - emission to an isomeric state of barium - 137(0.52MeV beta-92%,1 17MeV beta-8%) from which a 0.662MeV gamma-ray is emitted. The half-life is 30 years and the radiation output is 0.37RHM/Ci. Caesium-137 is used chiefly for the radiography of steel thicknesses between 40-100mm. For a given physical size of source it does not have the radiation output intensity of an iridium - 192 source and it is more expensive but its much longer half-life makes it attractive to the user who requires a gamma-ray source for occasional rather than continuous use.

3.2.1.2.4. Thulium - 170

The need for a radioisotope having a low-energy gamma-ray emission suitable for the radiography of thin steel specimens and for light alloys led to the introduction in 1953 of thulium - 170. Its half life is 127 days. Thulium is one of the rare earth elements and, as the metal is difficult to produce, it is generally used in the form of thulium oxide; as a powder this has a density of about 4g/cm^{3}and can be sintered into pellets of density 7g/cm^3. Thermal neutron capture converts the naturally occurring isotope thulium-169 into thulium-170. Decay is by emission of 0.968 and 0.884MeV beta-rays; the excited state of the nucleus is stabilised by emission of 0.084MeV gamma-ray photons or by internal conversion; only 3.1% of the disintegrations lead to the emission of gamma-rays. From internal conversion a 0.052MeV gamma-ray is emitted from 5% of the disintegrations. Only about 8% of the total number of disintegrations yield useful radiation from the point of view of radiography. Thulium - 170 gives 0.84MeV gamma rays which are comparable to X-rays from units operating at 120KV. Its RHM value is 0.0045. 0.2 to 1.2 cm thick aluminium samples and up to 0.5cm thick steel samples may be radiographed. The source is available in 2 x 3 mm and 3 x 3mm size pellets which are encapsulated in holders of aluminium alloy.

3.2.1.2.5. Ytterbium - 169

This is a much more recently available source. Ytterbium occurs as a mixture of several stable isotopes and on neutron activation in an atomic pile Yb-168 activates to Yb-169. The most abundant stable isotope Yb-174 activates to Yb-175. The latter has a low energy emission but a half-life of only 4.2 days, whereas the Yb-169 has a half life of 31 days. In a newly activated source, therefore, one has a mixture of two radioisotopes with different half-lives and different emission spectra and the relative proportions of the two will vary rapidly with time. After a relatively short time most of the Yb-175 will have decayed and the source will be mostly Yb-169.

TABLE 3.2 CHARACTERISTICS OF RADIOISOTOPES USED FOR INDUSTRIAL RADIOGRAPHY

Radioisotope	C0-60	Ir-192	Cs-137	Th-170	Yb-169
Half life	5.3Y	74d	30Y	127d	30d
Chemical form	Metallic	Metallic	Cs-Ce	Metallic or Tm_20_3	$Yb0_3$
Density(g/cm^3)	8.9	22.4	3.5	4	
Gamma ray energies (MeV)	1.17 1.33	0.31 0.47 0.64	0.66	0.87 0.052	0.17-0.2
Activation cross section in barns	36	370	-	130	5500
Ultimate specific activity(Ci/g)	1100	10000	25	6300	Depends upon the enrichment of Yb-168
Practical specific activity (Ci/g)	300	450	25	1500	2.5-3.5 Ci in 1 x 1mm size
RHM per curie	1.33	0.5	0.37	0.0025	0.125
Optimum thickness range (mm) of steel	50-150	10-70	20-100	2.5-12	3 - 12
Practical radiographic source activity (Ci)	100	50	75	50	2.5-3.5
Approx.diam(mm)	3	3	6	3	1
Shield weight (kg)	100	20	50	1	-
Half value layer(mm lead)	13	2.8	8.4	-	0.88

Ytterbium-169 has a gamma-ray spectrum consisting of several spectrum lines, the principal ones being 0.063, 0.198., 0.177 and 0.109MeV.

The radiation output is reported to be 0.125 RHM/Ci at a distance of 1m. Recently sources have been made from 24% enriched natural ytterbium which increases the proportion of Yb-169 in the activated source and so increases the activity which it is possible to obtain in a given physical size. With this enrichment it is possible to obtain about 1-3Ci in 0.6 x 0.6mm and 100-500 mCi in 0.3 x 0.3mm pellets. Higher percentage enrichments have also been reported.

Ytterbium is a very rare metal, is in short supply and the enrichment process is difficult so sources are relatively expensive. The supply situation appears to be the major problem with ytterbium sources at present. Experiments measuring the radiographic sensitivity attainable and the radiographic contrast show that radiographs taken with a Yb-169 source are roughly equivalent to radiographs taken with filtered X-rays between 250 and 350kV, depending on the specimen thickness.

For ready reference the main characteristics of the above mentioned radioisotopes are summed up in Table 3.2

3.2.2. Source Encapsulation

The source of radiation used in radiography is extremely small and enclosed in a sealed protective metal covering. Fig. 3.9 shows a typical source. Most isotopes used in radiography are right cylinders whose diameter and length are approximately equal. This source shape permits the use of any surface as the focal spot, since all surfaces as viewed from the specimen, are approximately equal in area.

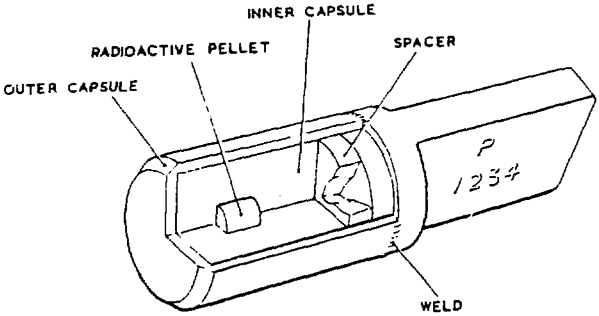


Figure 3.9 Cut away of a typical radiography source

The diameters of different cylindrical sources vary in the range from 0.5 to 20mm while their lengths may vary from 0.5 to 8 mm. The sources are also sometimes made in a spherical form. The diameters of the radioactive part may be between 6 and 20mm.

The sources may be supplied with or without tags. Cs-137 sources up to 3Ci contain the radioisotope as a bead of caesium glass. The larger sources contain compressed pellets of caesium chloride. They are available in plain cylindrical capsules or in capsules with a flat tag.

3.2.3. Gamma projectors

As gamma ray sources emit radiation at all times and in all directions, it is not safe to use them directly in the capsule form for radiography. They are enclosed in specially designed containers known as gamma projectors or gamma radiography cameras. The containers are generally made of good radiation-absorbent metals such as lead, tungsten or depleted uranium to reduce the emergent radiation intensity to a permissible level. The design of the container is such as to give ample protection when the source is not in use and to provide a beam of radiation when required. Gamma projectors are available in several designs suitable for various applications. One may choose one or other best suited to one's requirements.

The main points to be borne in mind in designing an exposing container are:

i) Provision must be made for loading and exchanging the source capsule easily and quickly.

ii) The container must be robust: if accidental damage prevents the container from being properly opened or closed the handling problem with a large source would become extremely serious. The effect of dirt and moisture on the mechanism must be considered under this heading.

iii) A fail-safe design is very desirable; i.e. if anything goes wrong, or is moved during exposure, the source returns to the safe position of the source.

iv) There should be a positive indication of the exact position of the source.

v) Except when the container is supported on a mechanised permanent mounting, size and weight are important factors.

vi) The containers should be designed so that the beam of radiation can be adjusted in direction; there should also be provision for making panoramic exposures.

vii) Scattered radiation, although less of a problem with gamma-rays than with X-rays, should still be kept to a minimum; it is desirable, therefore, to be able to adjust the beam width to suit the specimen and film size.

A few commonly used gamma projectors or cameras are briefly discussed below:

3.2.3.1. Removable plug type unit

Figure 3.10 shows one of the simplest projectors suitable for directional exposures. Units of this type up to 2Ci of Co 60 (100Ci of Ir 192) capacity are available. A conical stepped plug can be removed from the main body when a beam of radiation is required. The plug

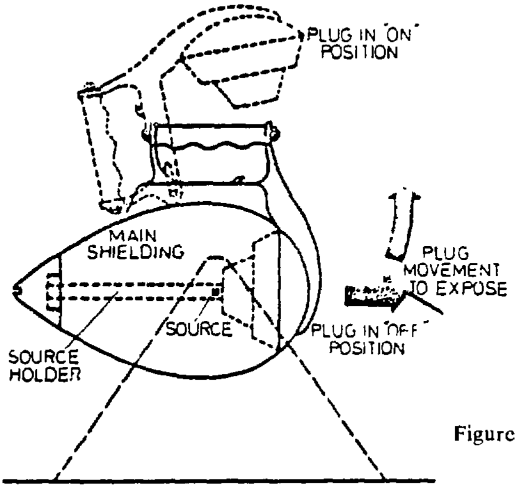


Figure 3.10 Removable plug type gamma projector

can be held at a position such that it does not obstruct the beam. The steps are made to avoid streaming. The unit can also be used for panoramic exposures by pushing the source out of the container with the help of a graduated rod.

3.2.3.2. D-type unit

Figure 3.11 shows a D-type gamma projector suitable for pipe radiography (double wall single image). Such units are available for up to 7.5 Ci Ir-192 or 1 Ci Cs-137. The unit can be clamped onto a pipe with the help of a chain and can also be rotated to a desired position when required. When the beam is required the inner source holding cylinder is rotated about its axis so that the source comes in front of the aperture in the outer shielding. The source is in the centre of the shielding when not in use.

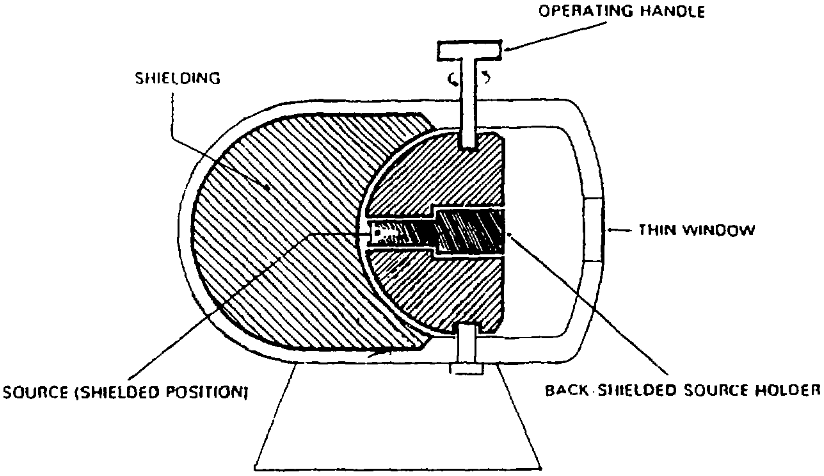


Figure 3.11 Rotating shutter type exposure container

3.2.3.3.Torch models

This type of equipment was originally developed for the testing of pipeline welds but adaptors are usually provided so that it can be used for other work as well. For pipe radiography, the torch is taken from the container and put into a shielding holder attached to the pipe. The shielding in the torch protects the operator while this is done. This model is illustrated in Figure. 3.12.

3.2.3.4. Remote control gamma radiography units

These units can be operated from a remote distance which makes them suitable when large activity sources are to be used. The source can be pushed out of its shielding to a desired position via guide tubes and brought back when the exposure is complete. Units that can hold very large Ir-192 sources and up to 500 curies Co-60 are available. There are two types of gamma radiography units which are commonly available.

(a) Clutch Wire Cable Type

It consists of a shielding container with all safety locks and devices etc. and a remote control system that controls the movement of the source with the help of a clutch wire cable (Figure 3.13). The source is pushed out of the container to an exposure site by rotating the handle of the operating device in one direction and pulled back into the container, at the termination of the exposure time, by rotating the handle in the opposite direction.

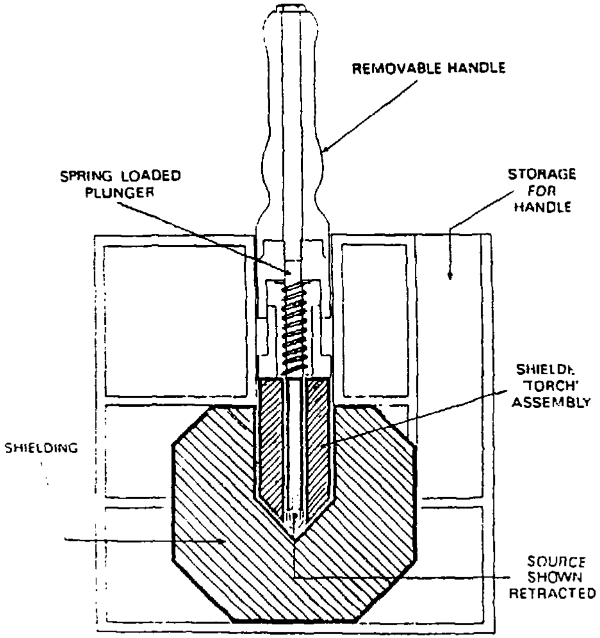


Figure 3.12 Torch type exposure container

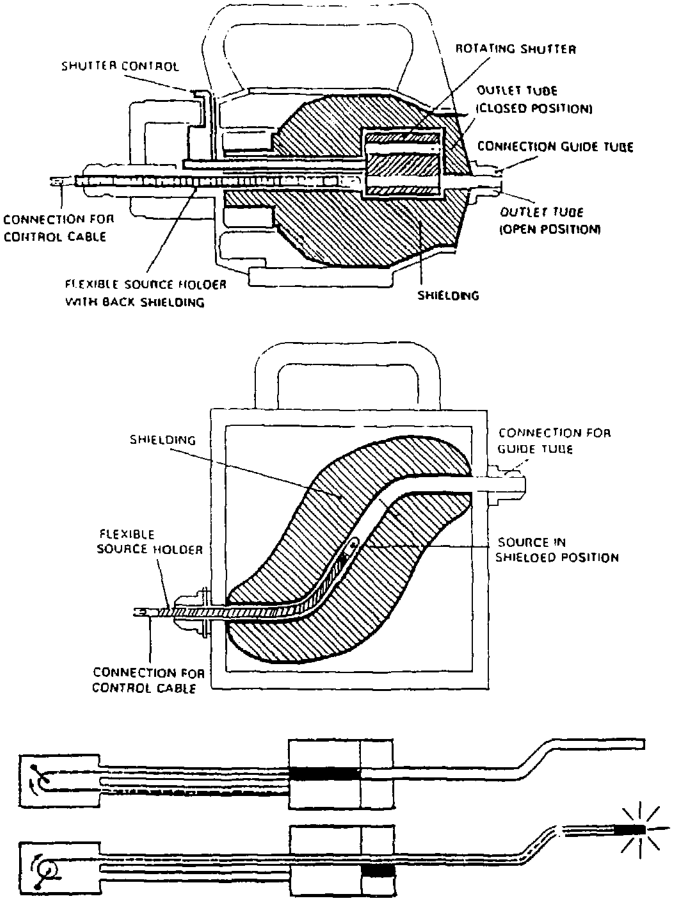


Figure 3.13 Principle of remote control gamma projector

TABLE 3.3: COMMERCIAL GAMMA PROJECTORS

Unit Description	Isotope	Capacity in Ci	Shielding	Weight in Kg	Rad.leakage
1	2	3	4	5	6
Tech/Ops Model 660	Ir-192	100	Depleted Uranium	20	Well below max.allowed by IAEA &USNRC
Iriditron (Sperry) Model - 520	Ir-192	100	-do-	18.18	50mR/hr at 6" from surface
Gammat Model TI	Ir-192	40	Metallic Uranium	12	200mR/hr at surface
Model TI-F	Ir-192	100	-do-	15	-do-
Gamma Indus. Model 35	Ir-192	35	Depleted Uranium	11.36	50mR/hr at 6" from surface
Pipeliner Model 1	Ir-192	100	-do-	14.5	-do-
Tech/Ops Model 684	Co-60	10	-do-	102.3	Well below max.allowed by IAEA & USNRC
Model 741	Co-60	30	-do-	136	-do-
Model 680 (Sperry)	Co-60	100	-do-	184	-do-
Unitron Model-110 AB	Co-60 or Ir-192	10 300	Lead	272.72	Less than 200 mR/hr at surface
Model151,161	Co-60	200	-do-	1363.63	-do-
Gammat Model TK 10	Co-60	10	Depleted Uranium	95	Less than 200 mR/hr at surface
Model TK 30	Co-60	30	-do-	120	-do-
Model TK 100	Co-60	100	-do-	140	-do-
Gamma Indust Gammatron Model 20A	Co-60	20	Depleted Uranium enclosed in polyurethane	136.36	-do-
Gammatron Model 50 A	Co-60	50	-do-	152.27	-do-
Gammatron Model 100 A	Co-60	100	-do-	204.54	-do-

b) Pneumatic Type

It consists of a shielding container and a pneumatic remote control system. The source is pushed out of the container to the exposure site by a compression stroke and sucked back into the container by a suction stroke.

Gamma projectors available commercially along with some of their important characteristics are summarised in Table 3.3.

3.2.4. Selection of a gamma ray source

To assess the usefulness of various sources for a particular job various characteristics must be considered. Brief guidelines are given below:-

3.2.4.1. Half life

The source should have a half life long enough to complete the job. If, however, due to other considerations a short lived source is selected, it should have high initial activity. For example, the Radon source has a half life of 3,825 days and will decay rapidly but a source of about 150mC initial activity will be radiographically useful for up to a fortnight.

3.2.4.2. Energy of gamma rays

The energy of gamma rays from the source must be sufficient to penetrate the thickness of the specimen to be radiographed. Useful thickness ranges of metals for various gamma ray sources are available in the literature. It is usual practice to restrict the thickness to specified ranges to minimise the loss of radiographic quality.

As the energy of radiation emitted is the characteristic of the source and cannot be altered, the only way to have radiation of different energy is to utilise a different source.

3.2.4.3. Size of the source

The size of the source should be small to minimise the penumbra which spoils the quality of the radiograph. In a pipe weld radiographic technique, for example, in which the source is placed inside the pipe and the film outside, a 30cm bore 1.2cm thick pipe may be examined using 2mm x 2mm source at the centre where as for a 5cm bore 0.5cm thick pipe a 1mm x 1mm source would be required to keep the penumbra within allowed limits.

3.2.4.4. High specific activity

To keep exposure times short it is necessary to have an adequate quantity of radiation (i.e. high activity). For optimum definition the source must have a high activity and be concentrated into a minimum volume. Its specific activity is expressed as activity per unit mass (Ci/g or Bq/g).

3.2.4.5. Availability

The source should be easily available and preferably of low cost. Finally, it is useful to note that Cobalt-60, Thulium-170 and Iridium-192 can be reactivated but Caesium-137 cannot.

3.2.5. Advantages and disadvantages in the use of isotopes

Advantages

(a) The cost of equipment and source is much less than that of an X-ray machine with a comparable energy range.

(b) The isotope equipment is more easily transported than X-ray equipment.

(c) The isotope source material itself is small enough to pass through small diameter openings.

(d) No external power supply is necessary therefore, tests can be performed in remote areas.

(e) The equipment is extremely rugged and simple to operate and maintain.

(f) Radiation from some radioisotopes has a very high penetrating power. This makes it possible to obtain satisfactory radiographs of very thick metal workpieces.

Disadvantages

(a) The first and most important from a safety viewpoint is that the radiation cannot be turned off.

(b) The radiographs generally have considerably less contrast than those exposed by X-radiation.

(c) Penetrating ability is solely dependent upon the particular isotope used and cannot be changed or varied without changing the isotope.

(d) Cost of replacing isotopes with short half-lives is high.

3.2.6. Exposure techniques with gamma rays

Many of the aspects of radiographic techniques with gamma-rays are exactly the same as with X-rays and these are discussed in detail in later chapters. Some special problems of technique arise with gamma-rays because one cannot control the gamma-ray energy in the way that the kilovoltage of an X-ray tube can be adjusted to match the specimen thickness. The only method of varying the gamma-ray energy is by choice of radioisotope.

The three most frequently used radioisotopes, Ir-192, Cs-137, and Co-60, all emit relatively high energy gamma-radiation. So that gamma-radiographs usually have a lower contrast than X-radiographs of the same specimens: this difference in contrast becomes less marked as the specimen thickness increases. Because of this a good gamma-ray technique attempts to compensate for the loss in radiation contrast by ensuring that as high a film contrast as possible is obtained.

Gamma-rays are used for much of site radiography, where an X-ray set requiring electricity and water supplies would be awkward or time consuming to manipulate. For steel specimens of thickness less than 50mm, and especially for those less than 25mm thick, the attainable sensitivity with any gamma-ray source is poorer than that on a good X-radiograph, and this loss of sensitivity must be balanced against the convenience of using gamma-rays. For pipe-weld inspection, for example, both X-rays and gamma-rays are employed and the choice is often governed by considerations of accessibility and working pressures: for high pressure pipework x-rays would be preferred if their use is possible, but for transmission pipelines, particularly over difficult terrain, gamma-ray inspection is accepted by many authorities. Figure 3.14 shows some examples of the use of radioisotopes for pipe inspection.

Gamma-rays are extensively used for both ferrous and copper-base casting inspection. The better sensitivity attainable with X-rays is rarely necessary for this type of work, and a medium-strength cobalt-60 source represents a much smaller outlay than a megavoltage X-ray unit for work of thickness beyond the capability of a small X-ray set. Exposure times are of course much longer than with X-rays and the volume of work which can be handled may be smaller, but this can sometimes be compensated by careful planning; if numbers of similar thickness castings have to be radiographed these can be oriented around a single gamma-ray source and left for an overnight exposure.

By using several tiers of castings a hundred or more radiographs may be exposed simultaneously in one overnight exposure; if these are set up in a locked room there need be no radiation hazard and no supervision. Consequently most of the day shift is spent on film processing, interpretation of the films and setting up the next series of castings. It is also possible to have a rotating turntable carrying a ring of specimens. The required exposure time is adjusted to be one rotation of the table. The specimens and the films can be changed at a fixed point from behind a shielding block. In a similar manner the whole circumference of a cylindrical vessel can be radiographed in one exposure with a source placed on the centre line.

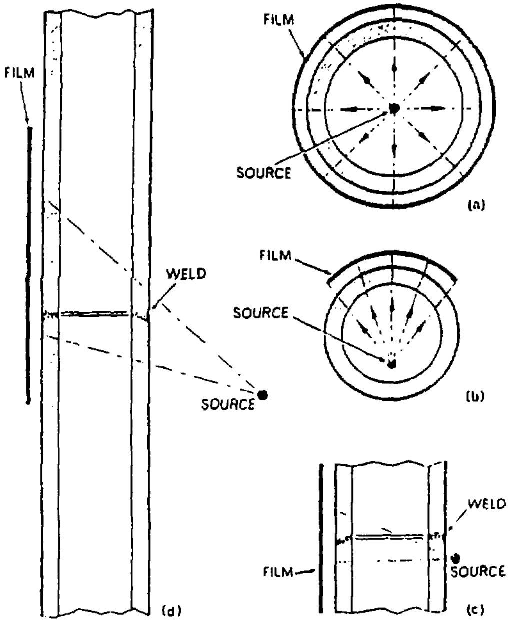


Figure 3.14 Techniques in gamma radiography of pipe welds

3.3. CHECKING AND MAINTAINING X AND GAMMA RAY DEVICES

The radiographic devices currently available are generally developed to the stage of allowing malfunction - free operation over long time periods. Despite this, however, damage or changes can occur making it seem sensible to subject x- and gamma ray equipment to regular maintenance and checking.

X-ray machines are for the most part liable to the following defects; burn out or loss of vacuum in tube, focal point changes, reduction of radiation efficiency, cable or connector faults, faults on controls, in HT generation and also cooling systems. Whereas most defects cause immediate system shut down, changes of for example focal length can only be established indirectly. The worst malfunction is generally regarded as tube failure caused by false operation, insufficient cooling or "aging". In the case of overloading or cooling failure, the anode is usually the first to be destroyed (plate on anode peels off, anode penetration), more rarely the heated coil can burn out. Since a replacement tube is extremely expensive (replacement costs approx. 30% of total system costs) it is worth while paying exact attention to the correct tube operating procedures. Overloading the tube is generally prevented by overvoltage, overcurrent and overtemperature limiting circuits, but the cooling conditions are not always completely measurable (e.g. bubble formation in anode area).

The manner in which a plant is operated has a great effect on its fatigue life. A major area is the start-up phase. In particular, after long operating breaks, the speed of build-up of voltage and current to operating levels (see operating manual) should not be exceeded. New tubes have to be "run in" The reason is that a drop in vacuum occurs over time which is only gradually compensated for after the tube is in operation. If, following an operating break, the tube is pushed up too quickly to its operating level it can lead to an internal tube overloading which shows fluctuations in the mA readings.

The most important checks are therefore checking the oil fill level (tube housing, high tension transformer) or the cooling water (not usually necessary in the case of one-tank devices), bleeding the cooling pipes or checking the gas pressure on pipes so insulated. An operating log book should also be kept. Defects and malfunctions are often due to relatively harmless causes. Should the power supply fail at the control panel, then one should check not only the power plug and cable but also the equipment fuses (installed in the control panel and often hard to find - see operating manual).

If power is present but the machine refuses to switch on this could be a fault in the cable to the tube, or one of the 2 sockets (most frequent). Checking the individual cables can quickly solve the mystery. High voltage cables must not be bent too much. It is recommended to have a spare cable available for the connecting cables of frequently used on-tank systems. Defects in the actual controls could also be the cause (regulators, instruments), which do however usually require expert checking.

Changes of the focal point or radiation efficiency (possible bremsspectrum changes, see energy distribution and total dose rate) are most difficult to detect. These can happen suddenly, e.g. through displacement of the cathode coil (impact, fall etc.). or gradually, e.g. through anode deterioration.

The form and largest diameter of a focus and its condition can be relatively simply carried out using a pinhole camera. This is particularly recommended for older tubes (it should not be forgotten that the focal point characteristics have a direct effect on the image quality).

The total dose rate (non-energy related) can be simply checked using a dose rate meter with separate probe (e.g. counter tube) which is placed into the line of the primary beam. Such a measurement is not absolute. It is affected by the energy dependence of the meter and the spectral and time dependent energy distribution, e.g. through self-filtering, circuit type, design etc.

One could also use a dose meter with suitably large measurement range (e.g. 20R or 50R rod dosimeter) assuming that the radiation conditions remain constant over the observed time period.

The energy distribution of the spectrum can be checked by taking radiographs of wedges, obviously under set conditions, in that one compares the contrast of the various steps with one another. This obviously only provides a relatively rough indication, i.e. for a possible tendency to e.g. "hardening".

Attention should also be paid to the still relatively frequently used hydraulically operated X-ray machine support mechanisms which tend to slowly sink. This can lead to movement unsharpness over longer exposure periods.

In the case of gamma devices the check and maintenance procedures are mainly limited to the remote handling systems and locks etc., and on the radiation protection provided (radiation protection measures are of course included in the X-ray machine test). Bowden cables, guide tubes, bearing surfaces etc. must be regularly cleaned and lubricated. It is often recommended to use graphite (or MoS_2) for lubrication since oil can tend towards resinification caused by the radiation. A frequent cause of malfunction are bowden cables (or guide tubes) being bent too sharply causing sticking of the source holder.

4. PHOTOGRAPHIC AND NON-PHOTOGRAPHIC RECORDING

4.1. CONSTRUCTION OF RADIOGRAPHIC FILMS

Radiographic films consist of a transparent, flexible base of clear cellulose derivative or like material. One or both sides of this base is coated with a light-sensitive emulsion of silver halide suspended in gelatine. The silver halide is distributed throughout the emulsion as minute crystals and exposure to radiation, such as X-rays, gamma rays or visible light, changes its physical structure. This change is of such a nature that it cannot be detected by ordinary physical methods, and is called the latent image. However, when the exposed film is treated with a chemical solution (called a developer) a reaction takes place causing the formation of tiny granules of black metallic silver. It is this silver, suspended in the gelatine on both sides of the base, that constitutes the image. Figure 4.1 is an expanded pictorial view of the general make-up of a film.

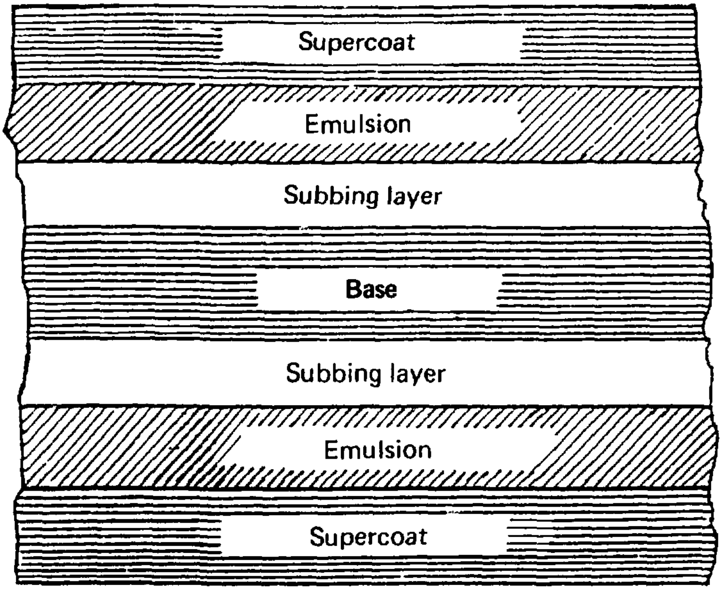


Figure 4.1 Construction of radiographic films.

The supercoat is a thin layer of clear hardened gelatine which protects the underlying emulsion from damage during normal handling. The emulsion is the most important layer of the film because it is sensitive to X-rays, gamma rays, light, heat, pressure and some chemicals. The emulsion consists of a large number of minute grains of silver bromide (silver halide) embedded in a supporting medium of gelatine, about 0.025mm thick. Modern films usually contain a small amount of silver iodide with the bromide as this increases sensitivity. When radiation strikes the emulsion a change takes place in the physical structure of the grains. This effect is called the 'latent image'. It cannot be detected by any normal physical means.The subbing layer consists of a mixture of gelatine and binding material. It ensures that the thin emulsion layer adheres firmly to the base during the stages of processing. This is particularly important in high temperature automatic processing techniques and processing under tropical conditions. The base is necessary because the sensitive emulsion is far too weak and flabby to be handled by itself and must therefore be centred on some firm support. The original supports were glass plates, but these were heavy and fragile and have been replaced by cellulose acetates. The majority of radiographic film emulsions used today are coated on cellulose triacetate or polyesters such as 'Estar' which forms a tough, transparent, but flexible base.

TABLE 4.1. CLASSIFICATION OF RADIOGRAPHIC FILMS

Film Characteristics	Speed*	Grain	Contrast *
TYPE I			
For critical inspection higher voltages and radiography of light metals and their alloys	very slow	extra fine	high
TYPE II			
For radiography of light metals at lower kilovoltages and heavier steel parts at 1000 at 2000 KV	slow	fine	high
TYPE III			
Highest available speed gamma rays or high-voltage X-rays are used direct or with lead-foil screens.	medium	medium	medium
TYPE IV			
Highest available speed and high contrast when used with fluorescent screens. Lower contrast when used direct or with lead-foil screens.	fast	medium	medium

* Note: These relative speeds and contrasts apply only to use of the film in direct exposures or with lead-foil screens.

4.2. CHARACTERISTICS OF RADIOGRAPHIC FILMS

Radiographic film is manufactured by the various film companies to meet a very wide diversified demand. Each type of film is designed to meet certain requirements and these are dictated by the circumstances of inspection, such as (a) the part, (b) the type of radiation used, (c) energy of radiation (d) intensity of the radiation and (e) the level of inspection required. No one film is capable of meeting all the demands. Therefore a number of different types of films are manufactured, all with different characteristics, the choice of which is dictated by what would be the most effective combination of radiographic technique and film to obtain the desired result.

The film factors that must be considered in choosing a film are speed, contrast, latitude and graininess. These four are closely related; that is, any one of them is roughly a function of the other three. Thus films with large grain size have higher speed than those with a relatively small grain size. Likewise, high contrast films are usually finer grained and slower than low contrast films. Graininess, it should be noted, influences definition of image detail. For the same contrast, a small grained film will be capable of resolving more detail than one having relatively large grains.

While an image may be formed by light and other forms of radiation as well as by gamma or X-rays, the properties of the latter two are of a distinct character and consequently the emulsions of films used with them are different from those used in other types of radiography. All radiographic films can be grouped according to the four factors already mentioned (speed, contrast, latitude and graininess).

4.3. RADIOGRAPHIC DENSITY AND METHODS OF MEASUREMENT

Qualitatively, radiographic density is defined as the degree of blackening obtained on a radiograph after processing. The blacker the radiograph the higher is said to be the density of the radiograph.

Quantitatively, it is defined by the following relation

$$\text{Density} = D = \log_{10} I_o / I_t$$

Where,

I_o = the intensity of light incident on the radiograph and,
I_t = the intensity of light transmitted through it.

The ratio I_o / I_t is known as the opacity of the radiograph, while the inverse of it i.e. I_t/I_o is called the transmittance of the radiograph.

TABLE 4.2. RELATIONSHIP OF RADIOGRAPHIC DENSITY TO OPACITY AND TRANSMITTANCE

DENSITY LOG (I_o/I_t)	OPACITY I_o/I_t	TRANSMITTANCE I_t/I_o
0	1	1.00
0.3	2	0.50
0.6	4	0.25
1.0	10	0.10
2.0	100	0.01
3.0	1000	0.001
4.00	10000	0.0001

Table 4.2 indicates that if the light transmitted through the film is half of the incident light (transmittance = 0.5), the density is only 0.3, and for a density of 1, only one-tenth of the incident light is transmitted. The density of a radiograph can be measured either by comparison with a film strip (density wedge) or by the use of instruments known as densitometers. The density wedge consists of a range of known densities and the density of a radiograph is measured by viewing it along side the radiograph under similar viewing conditions. This method is the least accurate of the available methods, since it is based upon a visual comparison of two pieces of film. This may be subjected to large errors of judgment on the part of the observer. The conditions in which the film strip and the radiograph are studied also exert a great influence on the result obtained.

If, for example, the area to be assessed lies in the centre of a large radiograph, it is not possible to place the film strip in close association with it without superimposing the strip upon another region of the radiograph. An accurate assessment can not be made under these conditions. Nevertheless, a calibrated film strip serves as a useful guide to density in many instances when a densitometer is not available.

Instruments known as densitometers are based on either optical or photoelectric principles and are used for a more accurate measurement of radiographic density. The optical densitometers incorporate a calibrated density wedge covering a suitable range of densities, e.g. 0.0 to 3.0, with which the radiograph to be measured may be compared.

The photoelectric densitometer utilises a photoelectric cell for the direct measurement of the light transmitted by the radiograph. The output from the cell is measured by a micro-ammeter having a scale calibrated in density units. This type of densitometer as compared to the optical densitometer gives a high degree of accuracy, is relatively free from operator error and usually covers a wide range of densities.

4.4. THE CHARACTERISTIC CURVE

The *characteristic curve*, sometimes referred to as sensitometric curve or the H and D curve (after Hurter and Driffield who, in 1890, first used it), expresses the relation between the exposure applied to a radiographic film and the resulting radiographic density after processing. Such a curve is obtained by giving a film a series of known exposures, determining the densities produced by these exposures and plotting density against the logarithm of relative exposure (For preparation of characteristic curve see section 6.5.2.1). Figures 4.2 and 4.3 show typical characteristic curves of direct type (non screen) and screen type films (For type of film see section 4.10).

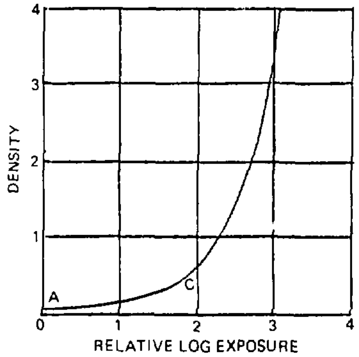


Figure 4.2 Characteristic curve of a typical direct-type X-ray film.

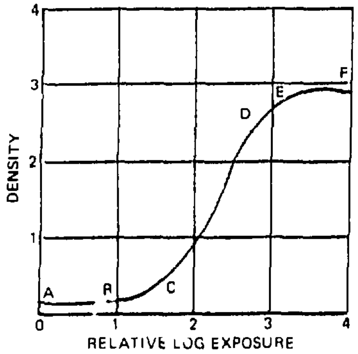


Figure 4.3 Characteristic curve of a typical salt-screen X-ray film.

Relative exposures are used because there are no convenient units suitable to all kilovoltages and scattering conditions, in which to express radiographic exposures. Hence, the exposures given to a film are expressed in terms of some particular exposure and thus a relative scale is obtained. The use of a logarithm of the relative exposure rather than the relative exposure itself has a number of advantages. It compresses an otherwise long scale; and in radiography ratios of exposures or intensities, which are determined by simply subtracting logarithms, are usually more significant than actual exposures or intensities.

The important features of a characteristic curve are that :

(i) it does not start from zero density i.e. even with no exposure, the film has some density upon developing.
(ii) it has a toe region, which curves upward.
(iii) it has an approximately straight-line portion.
(iv) it has a solarisation or shoulder region, where density decreases with increasing exposure. For direct type (non screen) films this region usually occurs at densities of about 10 or more, whereas for screen type films it occurs at densities between 2 and 3.

4.5. FOG DENSITY

With no exposure given to a radiographic film, the density obtained on the film after processing, is called the fog density or fog level of the film. Fog density is because of two reasons: one is the inherent density of the base of the film, since it is not fully transparent; and two is the chemical fog density, which is due to the fact that some grains are capable of being developed even without exposure. The actual fog density varies with the type and age of the radiographic film and with the conditions of development. Typical values of fog density for a radiographic film, for normal development, are between 0.2 and 0.3.

4.6. FILM SPEED

In absolute units, film speed is defined as the reciprocal of the total dose in roentgen of a particular radiation spectrum that produces a given density on the film. Methods to determine film speed are given in American Standard PH2. 8-1964, in International Institute of Welding document IIS/IIW-184-65 and British Standard BS 5230, 1975.

According to the American Standard method the film is exposed to densities (above fog) from approximately 0.20 to 3.0, by a well defined source of radiation. Each exposure is suitably measured in roentgens by means of an ionisation chamber. Densities are then plotted against the logarithm of the exposure and from such a characteristic curve the exposure required to produce a density 1.5 above fog level is determined. The speed of the film is taken to be the reciprocal of this exposure.

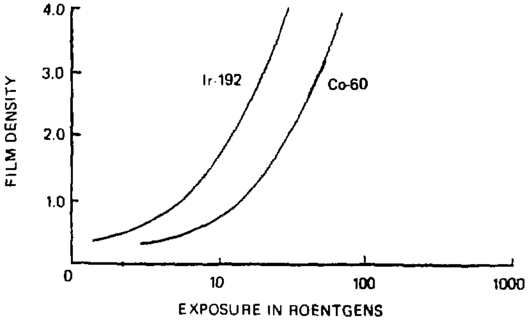


Figure 4.4 Effect of change of radiation quality on the characteristic curve of structurix D2 film.

The speed of a film, for normal development, depends upon the grain size and the energy of radiation. In general, the coarser the grain of the film, the faster is its speed. The decrease in film speed with increasing energy is illustrated in Figure 4.4.

Since it is difficult and cumbersome to make absolute measurements to determine film speed for most practical purposes, it is therefore convenient and effective to use relative speeds. The relative speed of film is assessed by the location of its characteristic curve along the log E axis relative to curves of other films.

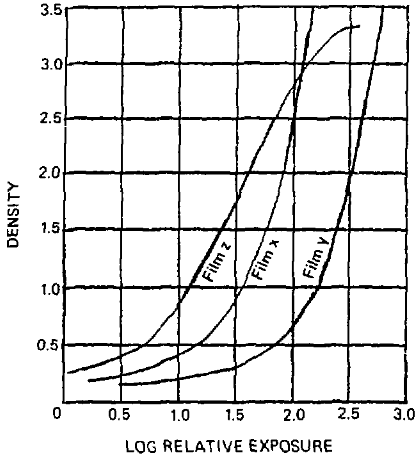


Figure 4.5 Characteristic curves of three typical industrial radiographic film

In Figure 4.5 the curves for various radiographic films are spaced along the log relative exposure axis. The spacing of the curve arises from the difference in relative speed - the curves for the faster films lying towards the left and those for the slower films towards the right. From these curves relative exposures to produce a fixed density can be read; the relative speeds are inversely proportional to these exposures.

The relative speeds are not necessarily the same at different densities because of the difference between one curve shape and another. Relative speeds also vary with quality of radiation. This is because different film types do not show similar response to radiation of different energies. Film manufacturers usually quote the speeds of their films relative to one of their films to which they assign an arbitrary speed value.

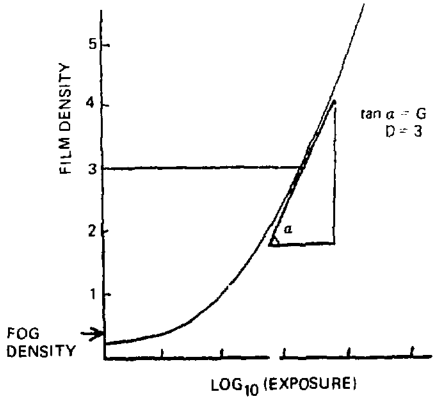


Figure 4.6 Typical characteristic curve for 'direct' x-ray film.

4.7. FILM CONTRAST

Film contrast or film gradient which is a factor in determining the radiographic contrast at a particular density is determined from the characteristic curve of the film by finding the slope of the curve at that density (Figure 4.6). Radiographic contrast is defined as the difference of densities of two adjacent portions of a radiograph.

Figures 4.7 and 4.8 illustrate the importance of film contrast.

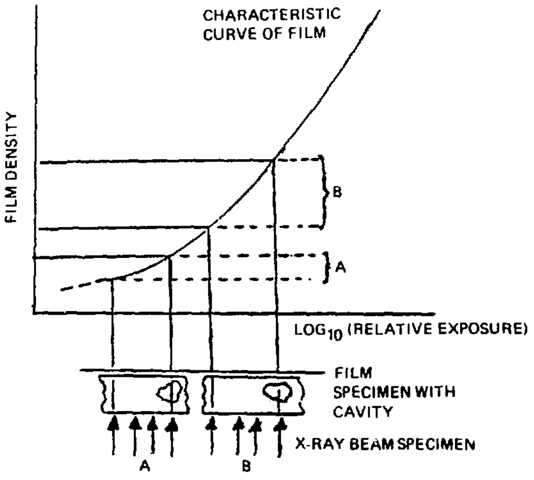


Figure 4.7 Diagram to illustrate the effect of using a higher working density on an radiographic film. A is the density difference in the image of the cavity after a short exposure. B is the density difference in the image of the cavity after a longer exposure.

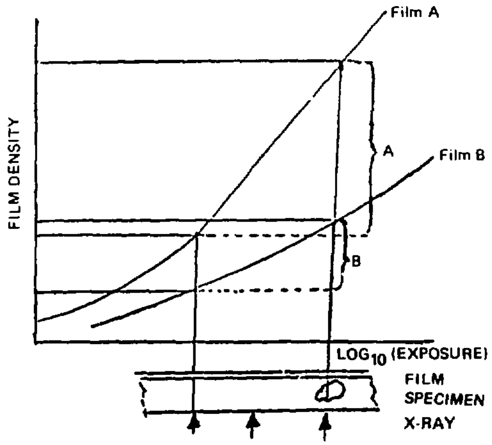


Figure 4.8 Diagram to illustrate the use of a greater film gradient at the working density on radiographic film. A is the density difference in the image on film A. B is the density difference in the image on film B.

In Figure 4.7 two exposures were made on the same type of film for the same specimen but one was given a longer exposure so that a region of the characteristic curve representing higher film densities is used-radio-graph B. Because of the shape of the characteristic curve, the same cavity in the specimen plate is recorded as a larger density difference on radiograph B than on radiograph A; that is it will be more clearly visible. Radiograph B is said to have higher contrast than radiograph A.

Figure 4.8 shows the effect of making the same exposure on two films having different characteristic curves. The specimen for both cases was the same. On film A with the steeper characteristic curve the density difference is greater than that obtained on film B, which means that contrast will be better for film A than film B.

As is clear from the example of Figure 4.7 it is better to work at densities which lie in the straight line portion of the characteristic curve. In the early days of film sensitometry with film exposed to light, the "straight-line" portion was thought to be truly straight and its slope (contrast) was called "gamma" and was constant. But more careful experiments have shown that with x-rays this "straight-line" portion curves gently upwards, and if the slope of the curve is measured, it has a rising value and this is why the slope of the "straight-line" portion of the characteristic curve is now called the film gradient and not gamma. By definition the slope of the characteristic curve is the film contrast, which means that film contrast increases with increasing density in the "straight-line" portion of the characteristic curve.

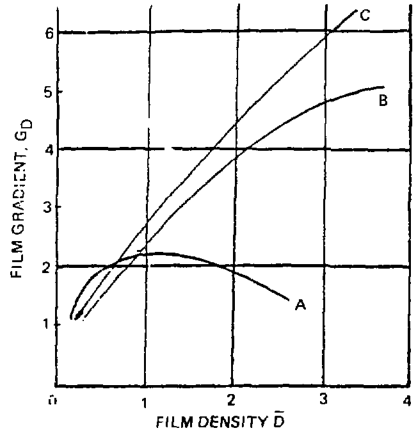


Figure 4.9 Film gradient against film density for various types of film. 'A' salt screen film used with salt screens. 'B' medium speed film used with metal screens or no screens. 'C' fine grain film used with metal screens or no screens.

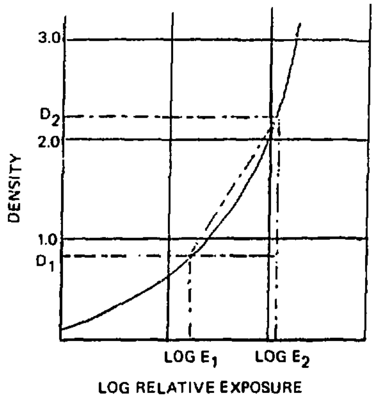


Figure 4.10 Measurement of slope (contrast) as an average between two densities.

The straight-line portion of the characteristic curves of direct or no-screen films extends to higher densities. The salt screen films used with salt screens show that an increase in contrast of these types of films is limited and that film contrast of such films shows a maximum at relatively lower densities (Figure 4.9).

From the above discussion it is obvious that for direct type films, working at higher densities is desirable, but using a density of about more than 3 would require higher illuminator brightness. Such illuminators require forced cooling and are, thus, costly. An optimum working density range of 1.7 to 3.0 is, therefore, recommended by most standards. For screen type films the recommended optimum working density range is 1.3 to 2.3.

Although film contrast (slope of the characteristic curve at any point on the curve) is useful, it is difficult to determine accurately. In practice the average contrast (or average gradient) is easier to determine because it is the slope of a line drawn between two specific points on the curve (Figure 4.10). The average contrast is calculated by dividing the density difference between the two specific densities by the difference between the two log relative exposures determined from the curve.

4.8. FILM DEFINITION

The degree of image sharpness that can be recorded on film will depend, among other things (see section 6.1), on the size and distribution of the developed silver grains in the emulsion. In general the smaller the grains, the finer are the details which can be resolved.

Two factors which influence film definition, are graininess and the effect of secondary electrons. Graininess is a subjective condition which is caused by the statistical fluctuation in the number of developed grains per unit area of the viewed film. Graininess depends upon:

(a)The type of film used : faster or coarse grain films give a greater impression of graininess than slow films;

(b) The quality of the exposing radiation; increase in the energy of radiation results in increase in graininess;

TABLE 4.3. FILM UNSHARPNESS AT DIFFERENT X AND GAMMA RAY ENERGIES

RADIATION (FILTERED)	U_f mm
50 KV X-ray	0.03
100 KV X-ray	0.05
200 KV X-ray	0.09
300 KV X-ray	0.12
400 KV X-ray	0.15
1000 KV X-ray (1MV)	0.24
2 MV X-ray	0.32
5.5 MV X-ray	0.46
8 MV X-ray	0.60
18 MV X-ray	0.80
31 MV X-rays	0.97
Iridium - 192 gamma rays	0.13
Caesium - 137 gamma rays	0.28
Cobalt - 60 gamma rays	0.35
Ytterbium - 169 gamma rays	0.07 - 0.10[a]

a: values depend on filter thickness

(c) Degree of development; longer development times result in increased graininess. The longer development times used to compensate for the temperature of the developer have virtually no effect on graininess and

(d) Screen type: the graininess of fluorescent screen radiographs increases significantly with increasing radiation energy. This limits the use of fluorescent screens to low energy radiation. Lead screens have little effect on the graininess of the image at any energy of radiation.

The effect of secondary electrons, released by the absorption of a quantum of x or gamma ray energy, is to expose emulsion grains adjacent to the grain which initially absorb the primary quantum. This diffusion of electrons, thus, causes a blurring of the image. This effect is usually known as film or inherent unsharpness, U_f. Increase in the energy of radiation increases the inherent unsharpness of a film by increasing the kinetic energies of the secondary electrons. Table 4.3 gives measured unsharpness values for direct type films for a range of radiation energies.

4.9. EFFECTS OF DEVELOPMENT ON THE CHARACTERISTICS OF RADIOGRAPHIC FILM

Figure 4.11 shows characteristic curves of a typical radiographic film constructed at different development times at 20°C in a typical developer.

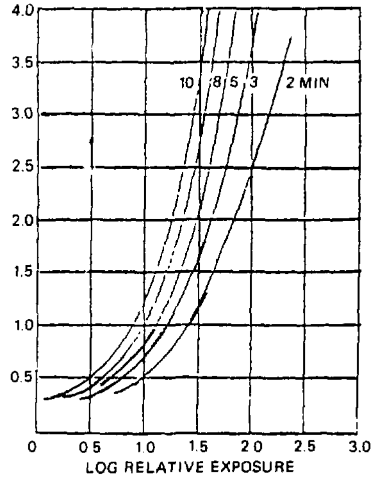


Figure 4.11. Characteristic curves of a typical industrial x-ray film, developed for 2,3,5,8 and 10 minutes.

From Figure 4.11 it is easy to see that :

i. Fog level of the film increases with increasing development time. The increase in fog level is as shown in Figure 4.12.

ii. Speed of the film (determined by the location of the characteristic curve along the log exposure axis) increases with increasing development time (Figure 4.12).

iii. Film contrast (determined by the slope of the characteristic curve) increases with the increasing development time. Figure 4.12 shows this effect.

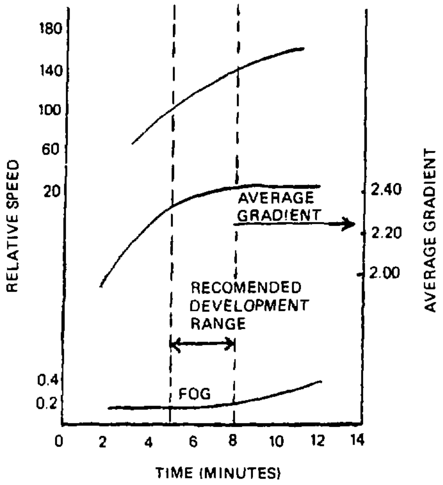


Figure 4.12 Dependence of the characteristics of a typical radiographic film on the development time

Another effect, not shown by Figure 4.11, is the increase of graininess of the radiograph with increasing development. Careful consideration of the above mentioned effects of development on the characteristics of film leads film manufacturers to recommend standard development times between 4 and 6 minutes at 20°C for various types of developers.

4.10. TYPE OF FILMS

Films used in industrial radiography are divided into two groups :

4.10.1. Salt screen type films

This type of film is used with salt intensifying screens (For screen types see Section 4.13) and is capable of producing radiographs with minimum exposure. They are rarely used in industry, but can be advantageous where a reduction in exposure is important.

TABLE 4.4. ASME (SE94) CLASSIFICATION OF RADIOGRAPHIC FILMS

Film Type	Film Characteristics		
	Speed	Contrast	Graininess
1	Low	Very high	Very fine
2	Medium	High	Fine
3	High	Medium	Coarse
4(a)	Very high(b) Medium(d)	Very high(b) Medium(d)	(c) Medium(d)

Notes: (a) Normally used with fluorescent screens.
(b) When used with fluorescent screens.
(c) Graininess is mainly a characteristic of the fluorescent screens.
(d) When used for direct exposure or with lead screens.

4.10.2. Direct type films

These are films which are intended for direct exposure to x-rays or gamma rays, or for exposure using lead screens. Some of these films may also be used with fluorometallic screens.

4.10.3. Films for fluorometallic screens

These films are specially designed to be used with fluorometallic screens. A screen type film can be used with metal foil screens instead of salt screens, but it usually yields lower contrast than non screen film with a similar speed.

Radiographic films are classified into different groups by various standards. Classification of films according to ASME (American Society for Mechanical Engineers) Standards, BS (British Standard) and DIN (German Standard) is given in Table 4.4, 4.5 and 4.6 respectively.

TABLE 4.5. BRITISH STANDARD (B.S.) CLASSIFICATION OF RADIOGRAPHIC FILMS

S.No.	Film Type
1	Ultra-fine-grain, high contrast
2	Fine-grain, high contrast
3	Medium speed

TABLE 4.6. DIN 54, 111 (GERMAN STANDARD) RADIOGRAPHIC FILM CLASSIFICATION

Film Class	Description
GI	Very fine grain
GII	Fine grain
GIII	Medium grain

Data about films manufactured by five of the most popular firms namely Agfa Gevaert, Kodak (U.K.), Kodak (U.S.A), Fuji and Dupont are given in Tables 4.7, 4.8, 4.9, 4.10 & 4.11 respectively.

The term exposure factor or film factor used in these tables is defined as the exposure required by a film, to have a certain density relative to the exposure required by a particular film to have the same density. For example, exposure factors of Agfa Gevaert films are given in terms of structurix D7. This means that if D7 requires 1mA-min to have a density of 2, for the same density structurix D4 would require an exposure of 3.3mA-min (reference Table 4.7).

TABLE 4.7. AGFA GAEVERT INDUSTRIAL RADIOGRAPHIC FILMS

USE	EXPOSURE FACTOR	CONTRAST (1)	GRAIN (2)	DIN CLASS	ASTM CLASS	FILM TYPE
	13.2	5.30	$0.23\mu_m$	I	special	D2
WITH OR	3.3	4.80	$0.55\mu_m$	II	1	D4
WITHOUT	1.8	4.65	$0.68\mu_m$	II	1-2	D5
LEAD	1	4.60	$0.88\mu_m$	III	2	D7
SCREENS	0.10-0.17	4.24	-	-	-	RCF

For the manufacturer's recommendations about the use of films, reference should be made to Section 7.

TABLE 4.8. KODAK(UK) INDUSTRIAL RADIOGRAPHIC FILMS

Film	Screens	Exposure Factor (relative to Industrex AX Film)			Classification	
		50KV to 150KV	150KV to Ir-192	Co-60 and high energy source	ASTM	British Standard
Industrex MX	With or without lead screens	220	230	400	1	ultrafine high contrast
AX		100	100	100	2	fine grain high contrast
CX		70	65	60	2	fine grain high contrast
Kodak No screen film		-	-	3	-	
Kodak OMAT film	X- Salt RP intensifying screens	-	-	-	-	

TABLE 4.9. KODAK (USA) INDUSTRIAL RADIOGRAPHIC FILMS

Film	Screens	Exposure Factor (relative to Industrex AA Film)				Classification
		100KV	200KV	Ir-192	Co-60	ASTM
Industrex R (single coat)	With or without lead screens	14	13	12	10	1
Industrex R (double coat)		16	15	14	12	1
Industrex M		50	45	35	30	1
Industrex TMX		60	60	55	50	1
Industrex T		80	70	65	55	1
Industrex AX		100	100	100	100	2
Industrex AA		100	100	100	100	2
Kodak No screen film						3
Kodak Blue Brand film	Salt screens	-	-	-	-	4

TABLE 4.10. FUJI INDUSTRIAL RADIOGRAPHY FILMS

Film	Screens	Relative speed (Type No 100 is taken as a standard				Class.
		X-rays	Co-60	X-rays with fluorometallic screens(SMP308)	fluorescent screens(KZ-S-F)	ASTM
#50	With or without screens	25	25	-	-	1
#80		5	50	25	-	1
#100		100	100	100	100	2
#150		180	180	-	-	3
#400	Fluorescent screens			1000	1000	4

TABLE 4.11. DUPONT CRONEX NDT INDUSTRIAL RADIOGRAPHIC FILMS

Film	Screens	Relative speed (at density of 2 exposed at 200KV with lead screens at standard processing times)	Classification	
			ASTM	DIN
NDT35	With or without lead screens	28	1	GI
NDT45		45	1	GI
NDT55		100	1	GII
NDT65		152	1-2	GII
NDT70		205	2	GIII
NDT75		266	2	GIII
NDT91	salt screens	-	-	-

4.11. FILM PACKAGING

Films are supplied in different types of packaging as follows: folder wrapped ;envelope packed ;bulk packed ; ready pack rolls.

4.11.1 **Folder wrapped (interleaved)**

These films are supplied in boxes of 100 sheets. Each sheet is separated by a single paper folder for protection. These films are not ' light tight ' and should not be removed from the box except in a darkroom. They can be used with or without lead screens. The paper folder must be removed before placing the film between the screens.

4.11.2 **Envelope packed**

These are supplied in boxes of 100 sheets. Each film is individually wrapped in a paper folder in a light tight envelope. The envelope can be removed from the box under normal lighting conditions. There is no need to remove the film from the envelope. Envelope packaging avoids the need to load cassettes.

4.11.3 **Ready pack rolls**

The film is sandwiched between two lengths of yellow and black duplex paper ,sealed along both edges and wound on a cardboard core. Rolls are also available with integral lead screens. Each loaded core is packed in a heat sealed foil bag inside a dispenser . Any desired length can be unrolled and cut from the dispenser . This can be done in white light if the film is folded and taped in a Z-pattern. If a straight cut and taping is carried out ,this must be done in a darkroom. Ready pack rolls are used for radiography of long welds.

4.11.4 **Bulk pack films**

This film is also available in roll form. It is sold without an envelope and must be cut to length and loaded into the user's own holders in a darkroom. These packs are useful in special circumstances, for example , for radiography of hot welds using special cassettes.

4.12 FILM STORAGE

The storage of unexposed X-ray film is most important. The storage area should be dry,free from contaminating chemicals, free from radiation, cool and the film boxes should be stored on end to avoid film sheets adhering to one another. In some cases necessity dictates that the storage area be close to a field of radiation . In this case the added precaution should be taken to have the storage area lined with lead, the thickness of which will depend upon the strength of the radiation field and the length of time the film is to be kept there. Films should be stored so that the oldest films are used first since all film will gradually deteriorate with age. It should be noted that the faster the film the shorter the storage life.

4.13 INTENSIFYING SCREENS

The degree of photographic effect of X-rays and gamma rays depends on the amount of radiation energy that is absorbed by the sensitised coating of the film. This is about 1 percent for radiation of medium penetrating power. The remaining 99 percent of radiation passes through the film and is not used. To overcome this the film may be sandwiched between two intensifying screens. Under the action of X-rays and gamma rays these screens either emit electrons (lead screens) or fluoresce (fluorescent screens).The result is an extra photographic effect on the film emulsion layers . Close contact between the film and the screens is essential to obtain sharp images. There are three main types of screens in general use : lead foil, salt or fluorescent and fluorometallic.

4.13.1. **Lead foil screens**

These are used extensively for industrial radiography. The intensifying effect is caused by the liberation of electrons from the lead foil under the excitation of radiation. With X-ray equipment ,the lead foil absorbs more scattered radiation than primary radiation and intensifies the primary more than the scattered radiation. The main advantages of lead foil screens are a reduction in exposure time above 120KV and a reduction in scattered radiation giving greater contrast . Lead screens are made up from thin sheets of lead foil which is specially uniform in structure and is stuck onto a thin base such as a stiff paper or card.

Normally two lead screens are used. The thickness of the front screen must be matched to the hardness of the radiation used. This is to allow the primary radiation to pass through while stopping as much of the secondary radiation scatter which has a longer wave length and is less penetrating. The front screen is usually 0.1mm (0.004in) thick and the rear screen about 0.15mm (0.006in) thick. It is however possible to use two screens of the same thickness. Flaws on screens such as scratches or cracks in the metal are visible on the radiographic image. Therefore damaged screens should not be used. Lead intensifying screens are not particularly effective with X-ray equipment below about 120KV.

4.13.2 Salt intensifying screens

These consist of a thin flexible base coated with a fluorescent layer made up of fine crystals of a suitable metallic salt - usually calcium tungstate. Two main types are used in industrial radiography:

(1) high definition (fine grain) screens made of small salt crystals
(2) screens giving high intensification (rapid or high speed screens) made of larger salt crystals.

Exposure to X-rays causes the salt crystals to glow with a blue light. This light affects the film and produces the main part of the latent film image . Salt screens reduce exposure time and allow a lower kilovoltage to be used. However, definition is affected by salt screens depending on the size of the salt crystals. Faster screens give the worst effect. The radiographic film is placed between two screens coated with these salts so that the salt coating is in contact with the film. The screens and the film are then placed in a metal or plastic cassette or film holder so that they are in intimate contact.

Salt screens should be examined frequently to ensure that they are free from dust and dirt. They can be cleaned with a slightly soapy sponge or wad of cotton wool applied gently until all traces of dirt have been removed. At no time should the sponge or cotton wool be wet enough to allow drops of water to fall on the screens. Wipe over once with a moistened damp cloth pad. Dry with a clean soft cloth free from loose fibres.

4.13.3. Fluorometallic screens

These screens are a combination of the lead screen and the salt screen giving the electron emission effect and the fluorescent effect.

They consist of pairs of screens made up of a flexible or card support, thin lead foil and a layer of fine grain fluorescent salt.

They are normally used with fine grain,high contrast direct type film giving an intensification which can reduce the exposure by as much as nine times ,yet without losing too much sensitivity of flaw detection. They are made in different grades to suit different X-ray and gamma energies. Their use is largely confined to routine inspection when speed of exposure is essential but where ordinary salt screens would give too great a loss in critical inspection.

4.13.4 Intensification factor

The intensification factor is expressed as the ratio of the exposure without using screens to that using screens as follows:

$$\text{Intensification Factor} = \frac{\text{Exposure without screens}}{\text{Exposure with screens}}$$

,and it varies with the kilovoltage and the circuitry of the X-ray set being used.

Figure 4.13 shows the intensification factor compared to the kilovoltage used for salt and lead screens. With lead screens the intensification effect is only obtained above 120Kv while with salt screens the maximum effect is obtained at about 200Kv. That is why salt screens are rarely used with gamma radiation.

4.14. Film cassettes

Film cassettes can be flexible or rigid. The flexible cassette is made from strong, black PVC and is used extensively for site radiography because it can be readily adapted to various shapes and sections such as pipework and circumferential welds. There are two designs:

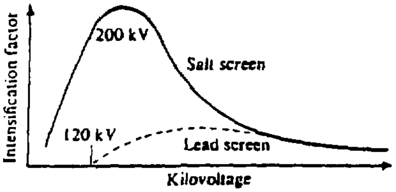


Figure 4.13 Variation of intensification factor with kilovoltage.

1) Double envelope cassettes - these have an inner and outer envelope. The outer envelope is closer to the film size than is possible with a rigid cassette. This makes accurate positioning of the film for exposure easier.
2) Single envelope cassettes - these have a nylon press down fastener which gives good light-tight sealing. It also enables the cassette to be opened or closed at a touch.

Rigid cassettes consist of a thin aluminium front with a felt pressure pad to keep the film and screen surfaces in intimate contact. It is therefore better to use a rigid cassette if an intensifying screen is required.

4.15. FILMLESS RADIOGRAPHY

Methods that do not use film to produce a radiographic image may be advantageous when speed of operation, observations in motion or magnification of the object are considered of primary importance. The filmless radiographic methods are usually much less expensive than film radiography and are used when rapid results are required. The filmless methods are limited by the size of the objects that can be examined. Production of permanent records after inspection is solved by photography.

4.15.1 Fluoroscopy

4.15.1.1. Generation of the image

Figures 4.14 and 4.15 illustrate two fluoroscopic arrangements - one with and one without the use of a mirror. The X-ray tube, the object and the fluorescent screen are encased in protective shielding and the object is placed between the tube and the fluorescent screen. The X-rays passing through the object excite the fluorescent material producing bright spots in the more heavily irradiated areas. Thus the fluorescent image is positive , whereas the developed film produces a negative image. The fluorescent screen may be viewed directly or by means of a mirror as shown in the illustrations. The mirror allows the viewer to see the image on the fluorescent screen without being in the direct line of radiation although the sensitivity thus obtained is usually somewhat inferior to that provided by direct viewing.

4.15.1.2. Fluorescent screens

Fluorescent screens give different image qualities depending on the grain of the fluorescent chemical,its nature and the applied radiation. Brightness is proportional to the intensity of radiation and therefore a compromise is necessary between screen brightness and the cost of protection from radiation. The brightness of each type of screen depends on kilovoltage. However each chemical offers its best brightness at different potentials and manufacturers of the screens supply data for the application ranges of their equipment.

4.15.1.3. Operational conditions

Viewing should be conducted in a room with very little light to enable the eye to adapt itself for the inspection. The operators should work for periods not exceeding one hour at the viewing window to avoid fatigue.

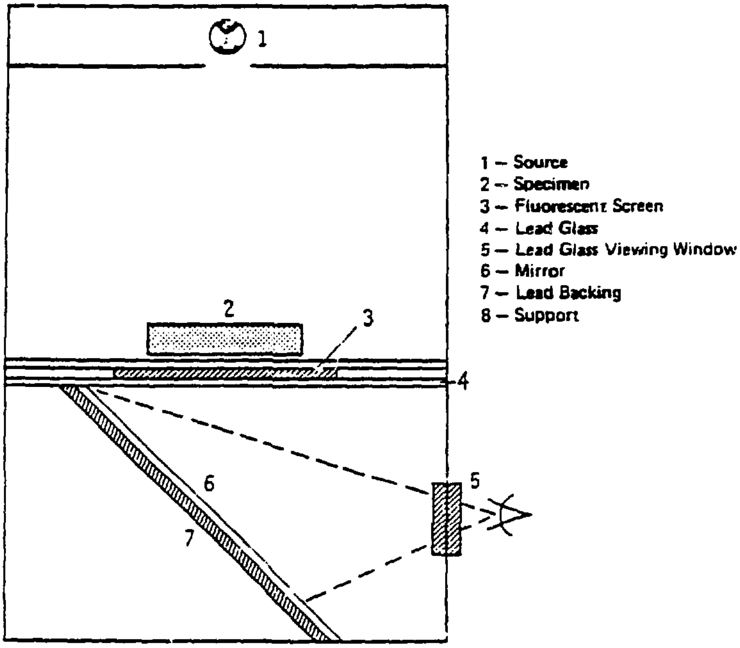


Figure 4.14 Fluoroscopic arrangement with mirror

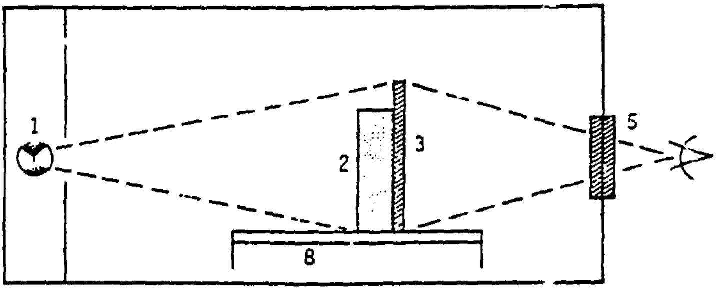


Figure 4.15 Fluoroscopic arrangement without mirror

The attention of the operator is stimulated by movement on the screen. This can be produced by adjusting the source - object distance , moving the stage or working on a conveyer. To increase the screen brightness it is advisable to maintain a short tube - screen distance. Screens that produce better brightness must have larger grain and therefore affect definition adversely. Scatter interferes with the image and the following measures should be used to reduce it:

(a) the fluoroscopic cabinet should be lined with lead.
(b) the cone of radiation should be restricted with masks and diaphragms to cover the specimen only.
(c) when a mirror is used for viewing it should be backed with lead.

A sensitivity of 3% may be obtained by fluoroscopy under ideal laboratory conditions, but in general the sensitivity seldom exceeds 5%.

4.15.1.4. Applications of fluoroscopy

In the metals field fluoroscopic inspection is carried out on light alloy castings up to 40mm in thickness. In many cases the castings are screened by this method and castings with obvious large defects are rejected before usual inspection using film radiography. The same practice may be applied to other thin metal parts, welded assemblies and coarse sandwich constructions.

Plastic parts may be checked for the presence of metal particles or cavities. Other applications include inspection of electrical equipment such as switches, fuses, resistors, capacitors, radio tubes, cables and cable splices in which breaks of metal conductors, short circuiting or wrong assembly may cause troublesome electrical testing. Ceramics, fire bricks and asbestos products lend themselves perfectly to fluoroscopy. Packaged and canned foods are examined for the amount of filling and for the presence of foreign objects.

4.15.2 Electronic fluoroscopy

Electronic methods may be applied to increase the brightness of the image,improve the definition and transmit the picture to a place remote from the radiation source. These systems are usually known as image intensifiers, image amplifiers or closed- circuit television systems. The latter may be based either on image transmission systems or on direct image generation without a fluorescent screen. The equipment is rather intricate and costly and its special area of operation is in the field of small objects. Although very useful for inspection of fused joints, the method can be expensive for testing large objects. Assessment of electronic components, particularly for miniaturised equipment, presents the most important field of application.

4.15.2.1. High brightness fluoroscopy

High image brightness is obtained by directing the X-rays through an object onto a fluorescent screen inside an instrument known as an image intensifier or image amplifier. The principle of the operation of this type of instrument is shown in Figure 4.16. The X-rays pass through the glass window of the intensifier tube and produce fluorescence in the fluorescent screen which is coupled to the photocathode. This in turn emits electrons in proportion to the intensity of fluorescence. The electrons are accelerated and directed by a high potential applied between the photocathode and the hollow anode to impinge upon the small observation screen. The resulting image is observed through a low magnification microscope. The brightness amplification is obtained by focusing the electron beam on the small screen thereby reducing the area of the image. By optical means the picture is magnified back to its original size. Amplification increases the eye's perception and helps to obtain a better contrast.

4.15.2.2. Closed-circuit television

This usually employs either an 'image orthicon' tube or 'Vidicon-type' tube. These tubes transform light or X-rays into electrical signals that may be converted into light in the picture tube of a television camera. The Vidicon system is in more general use than systems using an image orthicon tube. The image orthicon tube is however more light sensitive. A diagram of the Vidicon tube is shown in Figure 4.17 and an image orthicon tube in Figure

4.15.3. Summary of fluoroscopic methods

A summary of the fluoroscopic methods of most importance is shown diagrammatically in Figure 4.19 beginning with a direct viewing fluorescent screen.

(a) fluorescent screen
(b) solid state image intensifier
(c) electronic image intensifier in which a large light sensitive layer is in direct contact with the fluorescent screen in vacuum. The layer emits electrons which are accelerated and concentrated to achieve an image intensification.

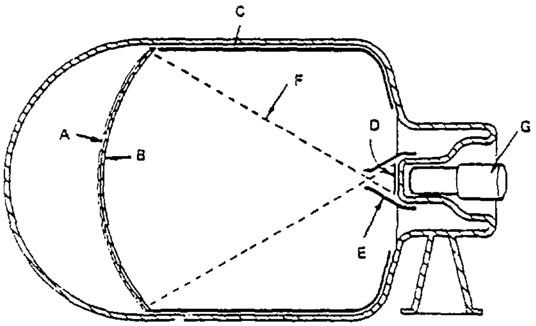


Figure 4.16 Norelco industrial image intensifier (A) Fluorescent screen (B) Photocathode (C) Conductive coating (D) Viewing screen (E) Anode (F) Electron paths (G) Optical system

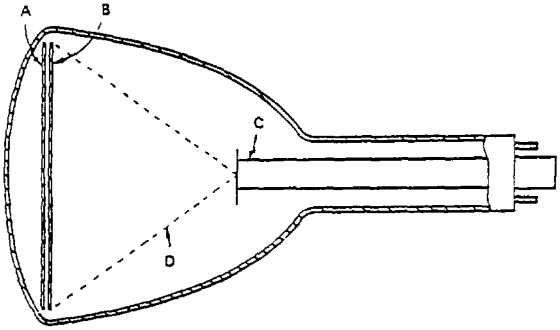


Figure 4.17 Photoconductive X-ray pick-up tube employed by Vidicon Television Systems. (A) X-ray sensitive plate (B) Screen grid (C) Electron gun (D) Electron beam

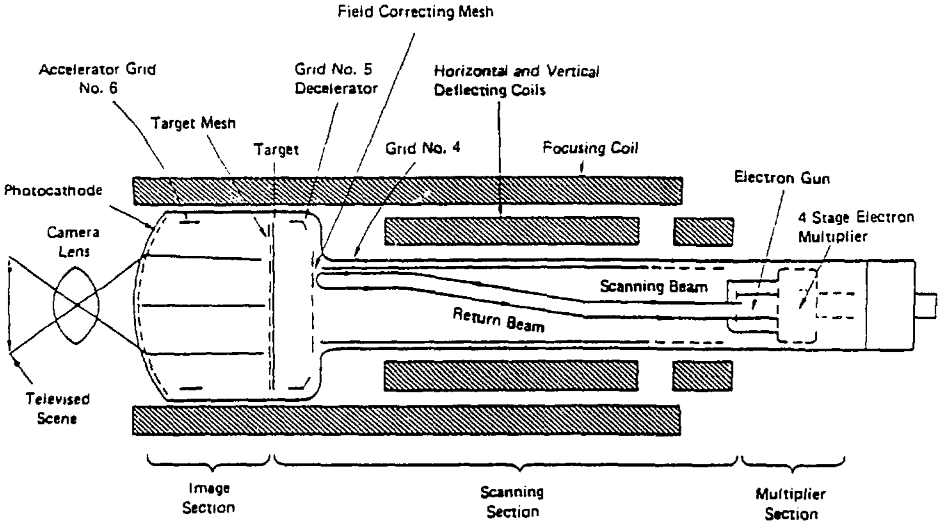


Figure 4.18 Image orthicon tube

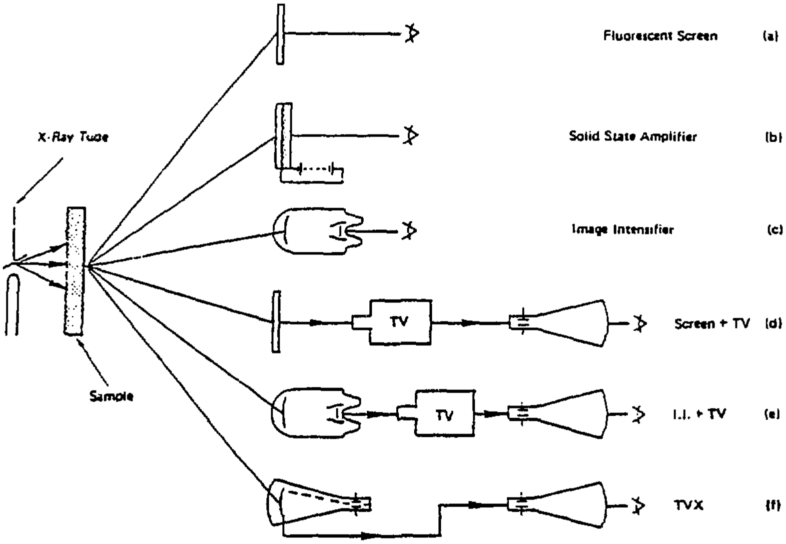


Figure 4.19 Summary of different fluoroscopic arrangements.

(d) Transmission and intensification of the fluorescent screen image with the aid of a highly sensitive television camera on to a television screen.
(e) transmission and intensification of the image on an electronic image intensifier with the aid of a television camera.
(f) X-ray television camera tube in which an X-ray sensitive layer is built into the television camera. The layer alters its conductivity under the influence of X-radiation and is directly scanned with the electronic beam. In this manner,a video signal is obtained which is taken directly to a television transmission system.

4.15.4. Xeroradiography

This is considered as a "dry" method of radiography in which a xerographic plate takes the place of the X-ray film. The plate is covered with a selenium powder and charged electrostatically in the dark room. Exposure to light or radiation causes the charge to decay in proportion to the amount of radiation received and a latent image is formed.

4.15.4.1. Xeroradiographic Plate

The selenium coated plate acts as a capacitor and is sensitised or charged by means of a corona discharge from a suitable electric apparatus. The charge may stay on the plate for more than 24h depending on the plate characteristics. The plate is in a cassette protected against light and is exposed to the radiation in the same way as a film with the selenium coated surface facing the exposed object. The radiation causes loss of charge proportional to the irradiation as shown in Figure 4.20. The preferential loss of charge causes differences in attraction of the 'developing powder' which produces an image on the plate. The powder may be stripped by contact with adhesive coated plastic and a permanent record obtained. After cleaning and recharging, the plate is ready for use again. The radiographic response of the plates depends on the thickness of the selenium layer. Careless handling or exposing the plates to high temperature gradients may cause permanent damage by separation or cracking of the dielectric. Ammonia fumes, alkaline liquids, sunlight,strong artificial light and high temperatures may damage the plates. The plates gradually deteriorate after repeated high charging and exposure to high kilovoltages. The image becomes darker and the contrast sensitivity is decreased. The plates should be stored in closed cassettes at a temperature not exceeding 20°C if the expected life of approximately 600 exposures is to be obtained.

4.15.4.2. Charging the plates

Sensitising is performed in a light tight cabinet in which one array of wires supplies a voltage of approximately 7KV while the other is held at a lower potential of several hundred volts to shield the plate from sparking. The metal plate is grounded and the corona effect from the high negative voltage of the wires above the selenium plate creates the charge. The cassette is inserted into the charger and the cover slide is removed. Charging is carried out and the cover reinserted before removing the cassette from the carrier. The cover is left on until the image is developed. It is preferable to process the plate immediately after charging but a few hours storage does not affect the performance to any great extent. Charged plates must not be exposed to any radiation during the period preceding their exposure and development.

4.15.4.3. Operation

The exposure of xeroradiographic plates is similar to that of films. The plates are more sensitive to soft radiation than most films and at high kilovoltages their speed equals that of Type II film. The sensitivity of the plates to low potential radiation requires care in reducing scatter by using diaphragms, backing the cassettes with lead, masking,etc. Xeroradiographic images have good three dimensional appearance and offer very good radiographic sensitivity on materials with low radiation absorption coefficients. Penetrameter sensitivity may be better than 2% up to 50mm of aluminium and 4% up to 40mm of steel.

The developing powder is sprayed on the plate in a light tight box. The particles are charged by friction while passing the spraying nozzle. White powders have best contrast with the black selenium surface but present problems in transferring the picture to paper. Coloured powders on transfer produce negative images while fluorescent powder gives the same picture as white powder and can be viewed under "black light" both before and after transfer.

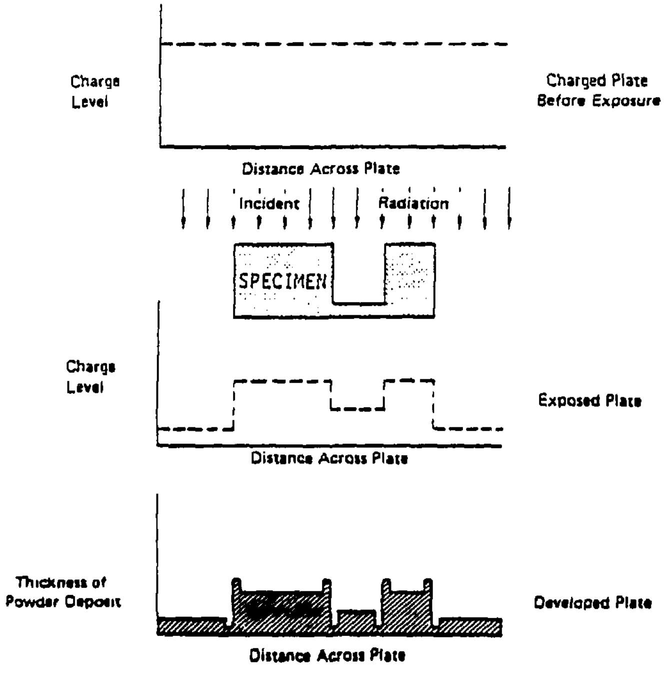


Figure 4.20 Diagrammatic representation of xeroradiography

5. PROCESSING OF RADIOGRAPHIC FILMS

5.1. INTRODUCTION

An X-ray film is composed of a transparent, cellulose base, both sides of which are coated with an emulsion of silver halide suspended in gelatine, the silver halide being distributed throughout the emulsion as minute crystals. When light, X-rays or gamma rays strike the silver halide crystals, a change takes place such that a latent image is formed in the crystals which is made visible and permanent by chemically processing the film.

The processing is carried out under subdued lighting of such a colour and intensity that it does not expose the film further. The colour and intensity of the safe light is recommended by the manufacturer of the film and these recommendations should be strictly followed. The processing solutions are normally contained in deep tanks so that films held in hangers may be suspended vertically in the solution.

5.2. SAFELIGHTS

Exposing films to white light affects the crystals; consequently X-ray films should only be handled under safe-light conditions. It should be remembered however, that even under safelight illumination it is not wise to allow undeveloped films to receive excessive exposure to safelight illumination as the film may become fogged. It should be noted that exposed film is more sensitive to light than unexposed film. The intensity and location of safelights must be carefully considered. Furthermore, the safelight intensity should be uniform throughout the darkroom. The "safeness" of such safelights is directly related to the correct wattage, type of filter and position (distance)of lamps in relation to the film. Hence it is quite important to guard films against direct safelight illumination when loading them on hangers preparatory to group development.

5.2.1 Test for safelight illumination

Tests should be carried out when a dark room is first used, safelight filters appear discoloured or when a film of a faster speed is going to be processed. Two simple and popular methods are as follows:

a) Place an uncovered, unexposed film flat down on the loading bench. Lay flat objects, such as a ruler, pencil,strip of metal,etc., on top of the film. Leave the film and objects under normal safelight illumination for one and a half to twice the time a film is normally left there. If no outline of the objects can be seen on the properly processed film then the safelight illumination can be considered of a low enough level.

b)Place an uncovered unexposed film flat down on the loading bench. Cover it completely except for a lengthwise strip about 25mm wide along one side. At a number of predetermined time intervals (e.g.5 min.) move the covering piece so that a new 25mm strip is exposed each time. After the desired number of time intervals have elapsed the film should be processed under normal conditions and examined when dry. The film can then be scanned across the strips with a densitometer for density variation(if any) for the different exposure times and an assessment made of the safelight illumination level.

5.3. FILM PROCESSING PROCEDURE

The essential stages in processing a radiographic film are as follows:

a) development
b) rinsing
c) fixing
d) washing
e) drying

5.3.1. Preparation prior to processing

The radiographer should always follow these important steps before beginning processing:

i) Stir all solutions before use. (Solutions tend to separate out when undisturbed)
ii) Check the temperature of the tank solutions. It is important that these be equalised as closely as the method of control permits and that the developer be brought as closely as possible to 20°C.
iii) Check the level of solutions in the tanks. The radiographer should maintain a careful watch over the level of the solutions in the tanks and wash water. The level should cover the cross bars of the hangers. Should the solution level be too low, the addition of replenishment solution will bring it to the proper level.
iv) Ensure there is an ample and steady flow of water in the rinsing and washing tanks.
v) Consult the table of development times and, when necessary, the time-temperature development chart that all manufacturers supply and set the timer accordingly.
vi) Clean all working surfaces and wash hands.
vii) Turn off all lights and proceed to work under safelight conditions only.

5.3.2 Developing

When the film is placed in the developer solution, the unexposed crystals are not affected or removed at this step, but the developer reacts on the exposed crystals latent image, freeing the silver from the compound and depositing it as tiny metallic grains of silver that form the black silver image. The higher the temperature , the quicker development is carried out. The best results, however, are obtained at a temperature of 20 C. A higher temperature results in a more intense chemical fog and in a more marked grain. Also,the developer will deteriorate sooner and faults due to a lack of freshness in the film and\or the baths or to insufficient washing after developing etc. will be more likely to occur. At high temperature the emulsion coating may be found to undergo reticulation, become detached or melt. On the other hand the further the temperature falls below 18° C the more the contrast producing element of the developer will be restrained.

5.3.2.1. Time-temperature relationship

When all other factors remain constant the amount or degree of development is a function of both time and temperature. By linking these two together in a time-temperature relationship it is possible to compensate for a change in one by changing the other. Thus within certain limits a change in the rate of development caused by an increase or decrease in temperature can be compensated for by adjusting the development time in accordance with the time - temperature relationship set up for that particular developing solution. All manufacturers of solutions provide time-temperature relationship data with their chemicals. Figure 5.1 illustrates a typical relationship in a chart form.

By using the afore mentioned relationship, positive control can be had over the developing procedure: errors in X-ray technique can then be recognised easily and not confused with development problems. Sight development, even at best, is an inexact method because it depends on the technician's judgment, which in turn depends upon numerous factors, such as fatigue and length of time in the dark room.

5.3.2.2. Agitation

Film agitation is the movement of film in the various processing solutions in such a manner that fresh solution is brought to the surface of the film so that the proper reaction occurs between the film emulsion and solution. Agitation is most important during the development cycle. If a film is placed in the developing solution and allowed to develop without any movement, the reaction products of development will flow down the surface of the film thus keeping fresh solution away from the film's surface. The greater the film density the greater the flow downward causing uneven development in the areas below. This may show up in the form of streaks.

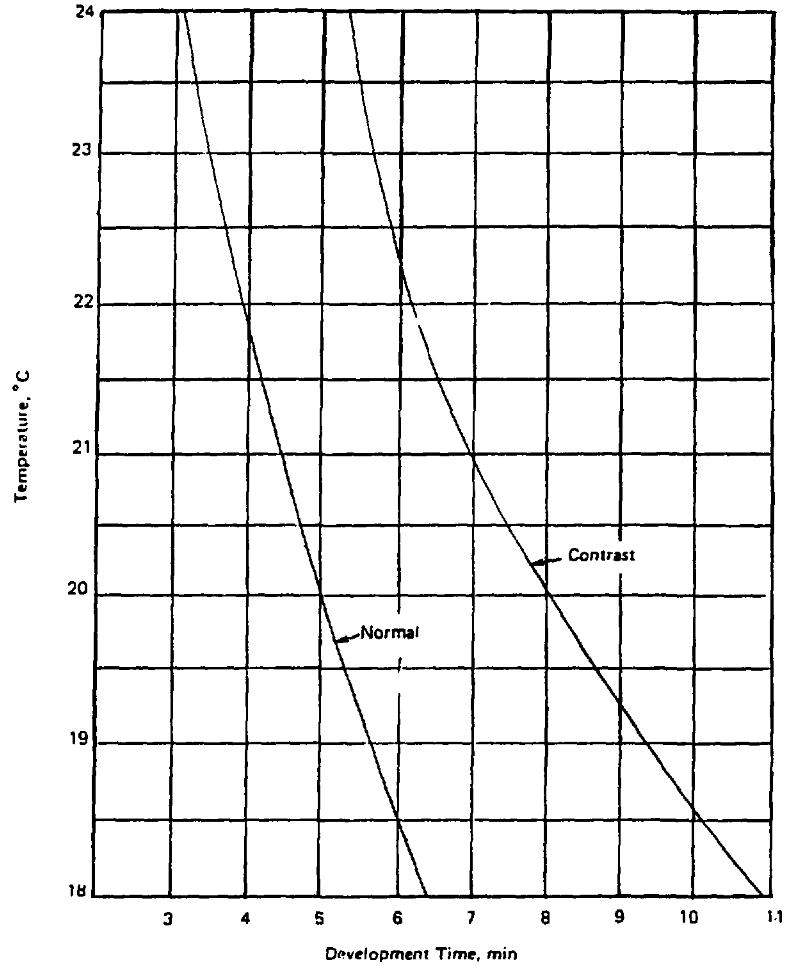


Figure 5.1 Time-temperature relationship for the development of a radiographic film.

In manual processing, agitation is done by hand. Stirrers or circulating pumps are generally discouraged because preferential flows are usually set up in the solution when these mechanical devices are used and worse conditions of uneven development can occur than with no agitation at all. Acceptable agitation is provided when films are shaken vertically and horizontally and moved from side to side in the tank for a few seconds every minute during developing. More satisfactory renewal is obtained by lifting the film clear of the developer, allowing it to drain from one corner for 1-2 seconds, then re-inserting it into the developer and then repeating the procedure with drainage from the other corner. This is repeated at one minute intervals during the development cycle.

5.3.3. Rinsing

After development, the film is rinsed in the stop bath for about 30 to 60 seconds. The stop bath consists of a 2.5% solution of glacial acetic acid i.e. 2.5mL of glacial acetic acid per litre of water. The acid is used to stop the action of the developer on the film. It also inhibits the transfer of the developer into the fixing bath which would be spoiled otherwise. If glacial acetic acid is not available, the film can be immersed in clean running water for at least 1-2 minutes.

5.3.4. Fixing

The functions of the fixing or "hypo" bath are:

(a) to stop further development
(b) to remove from the emulsion all undeveloped silver salts thereby leaving the developed silver as a permanent image.
(c) to harden the gelatine of the emulsion so that it will be more stable during subsequent washing, drying and handling operations.

The interval between the placing of the film in the fixer solution and the disappearance of the original, diffused, yellow milkiness is known as the clearing time. This is when the fixer dissolves the undeveloped silver halides. An equal amount of time is required for the dissolved silver halides to diffuse out of the emulsion and for the gelatine to harden adequately. Thus total fixing time should be at least twice the clearing time. Films should be agitated vigorously when first placed in the fixer, in the same way as carried out in the developing procedure. Fixer should be maintained at the same temperature as the developer and stop bath (between 18-24°C).

5.3.5. Washing

The emulsion of the film carries over some of the fixing bath chemicals from the fixing bath to the wash water. If these chemicals were allowed to remain on the film, they would cause the radiograph to become discoloured and fade after a storage period. To prevent this the film should be washed under conditions that are most suitable for the removal of these chemicals. The following are the most important practices to follow when washing a radiographic film :-

(a) use clean running water that is so circulated that the entire emulsion area will receive frequent changes.
(b) ensure that the bar and clips of the film hangers are immersed.
(c) wash for at least 20min.
(d) water temperature should not exceed about 25°C so that emulsion does not soften and wash away.
(e) water temperature should not go below 15° C because below this temperature hypo solution will not dissolve well.
(f) water flow should be such that the volume of the tank is replaced four to eight times per hour.

5.3.5.1. Methods of washing

(a) Single Tank with Running Water (Figure 5.2) The first films should be placed at the inlet side of the tank and moved progressively towards the outlet end of the tank as more films are added to the tank.

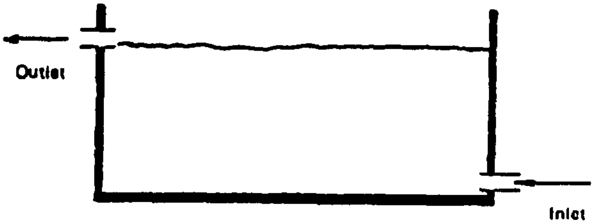


Figure 5.2 Single tank with running water.

(b) Cascade Washing (Figure 5.3) The cascade method of washing is the most economical of water and gives better washing for the same period of time. In this method the washing compartment is divided into two sections. The films are taken from the fixer solution and placed in compartment A. After they have been partially washed they are moved to compartment B, leaving compartment A ready to receive more films from the fixer.

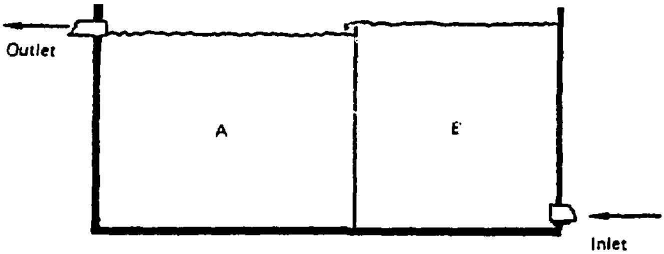


Figure 5.3 Cascade washing tanks

(c) Multiple Tank (Where no running water is available or a small supply of fresh water is available). This method consists of placing the films successively in four different tanks each of which is filled with standing water. The advantage of this method compared with that of placing films in one tank of standing water is that, as the films are placed successively in each of the four tanks, a decrease in the fixer content is obtained.

5.3.5.2. Drying

Drying has an important bearing on the quality of the finished radiograph. It should be done without causing any damage to the emulsion or marks from uneven drying, and without exposing the damp emulsion to dust or lint. To avoid drying marks and to speed the rate of drying, the film is immersed in a "drying" solution that is commercially available, for about 15-30 s. This bath overcomes the surface tension of the water, thus preventing the formation of water droplets. If a drying solution is not used then the film can be wiped down with a sponge. The films are usually dried in cabinets by circulating temperature controlled air. The temperature should be such that it does not cause the film to buckle or dry unevenly. Care should be taken that films do not touch one another in the cabinet.

5.4. MAINTENANCE OF PROCESSING TANKS

5.4.1. Developer Tank

As a developer is used, its developing power decreases, partly because the developing agent deteriorates through use, partly because of the restraining effect of accumulated reaction products of development, and to a small extent, aerial (or atmospheric) oxidation of the developing agent, even when not in use. An accurate way to check developer activity is to test it at regular intervals with film strips that have been exposed under standard conditions. One procedure is to expose a film through a step block without screens of any kind: then cut standard size strips to serve as standards when a new tank of developer is put into use. After that, develop individual strips at pre-determined intervals and compare the densities with those of the standard strip. When the developer replenisher system is used in processing radiographic film, replenishment is carried out for two reasons :

(a) to maintain the level of the solutions in the tanks so that they cover both film and film hangers.
(b) to maintain the activity of the solutions so that the results obtained are consistent. Replenishment solutions are made up according to manufacturer's instructions and can be the same as the solution replenished or of a less dilute nature. A practice often carried out in a laboratory darkroom is just to maintain the level of solution in the tanks by the addition of replenisher and this system can be adequate. More precise replenishment is attained however, by following the manufacturer's recommended practice of solution replacement to the required tank level as dictated by the volume of films processed.

5.4.2. Fixer tank

The life of a fixing solution depends on its ability to neutralise the alkali on the films. The time required to clear a film is a good gauge of fixer exhaustion. When it exceeds approximately 8min, the bath should be replenished. This prolongs the life of the fixer and maintains a rapid fixing time. When exhausted solutions are used, the emulsion is not sufficiently hardened. In addition, the radiographs may have a brown stain that is seen by reflected light but is not noticeable by transmitted light.

5.5. CHEMISTRY OF PROCESSING

5.5.1. Developer

All X-ray developers essentially have the following five constituents:-

(i) Developing Agent

It is basically a mild organic reducing agent which reduces only exposed silver. The most commonly used developing agents are :

(a) Monomethyl *paraminophenol* sulphate
(b) Hydroquinone

In X-ray developers, both of these are used at the same time. A latent image developed in monomethyl paraminophenol sulphate comes up very quickly but gains density very slowly, while with hydroquinone the image comes up very slowly but gains density rapidly.

(i) Accelerator

Its function is to accelerate the action of the developer. It is basically an alkali. Sodium carbonate and sodium hydroxide are the ones commonly used as accelerators.

(ii) Preservative

Developer gets oxidised due to contact with air and thus loses its developing properties to some extent. A preservative when added to the developer prevents this oxidation. Usually sodium sulphite is used as preservative.

(iii) Restrainer

It controls the activity of the developer and allows it to reduce only the exposed silver halide to black metallic silver. Potassium bromide is the one used as restrainer.

A typical X-ray developer formula is as follows :

Monomethyl paraminophenol sulphate	2.3 gm
Sodium sulphite (anhydrous)	72 gm
Hydroquinone	8.8 gm
Sodium carbonate (anhydrous)	48 gm
Potassium bromide	4 gm
Water to make	1000 cc

To make the solution, dissolve the constituents in distilled water at 32°C (90°F) in the order given and develop the film for 5 minutes at 20° C (68°F).

5.5.2. Replenisher

The level and activity of the developer are lowered with use. So it should be replenished properly to keep up the level and activity of the developing bath. A typical formula for a Replenisher is as follows :

Monomethyl paraminophenol sulphate	4 gm
Sodium sulphite (anhydrous)	72 gm
Hydroquinone	16 gm

Sodium carbonate (anhydrous)	48 gm
Sodium hydroxide (caustic soda)	7.5 gm
Water to make	1000 cc

Dissolve the ingredients (in the order given) in distilled water at 32°C (90°F) to make the solution.

5.5.3.Fixer

The essential ingredients of X-ray fixer are given below :-

(i) Hypo .

It dissolves the undeveloped silver halide crystals only and thus removes them from the film which otherwise will obscure the desired image by getting darkened as a result of light action. The commonly used fixing agents (also called hypo) are sodium thiosulphate and ammonium thiosulphate.

(ii) Developer Neutraliser

It neutralises the developer carried with the film after development. It is acetic acid (glacial) which is added to the fixer as developer neutraliser.

(iii) Preservative

It prevents the decomposition of thiosulphate by the acetic acid. Sodium sulphite added to the fixer serves as preservative.

(iv) Hardener

It hardens the gelatine of the emulsion lest it should swell or soften during washing and drying. Besides, the hardened film dries more quickly than otherwise. Potash alum is commonly used as hardener.

A typical formula for an X-ray fixer is given below :-

Sodium thiosulphate (hypo)	300 gm
Sodium sulphite (anhydrous)	5 gm
Acetic acid (glacial)	10 cc
Boric acid crystals	5 gm
Potash alum	10 gm
Water to make	1000 cc

To make solution, dissolve the constituents simultaneously in distilled or tap water. For standard processing the developer and the fixer as recommended by the manufacturer of the films should be used.

5.6. PROCESSING UNITS

There are three types of processing units which can be used to process X-ray films and X-ray instant paper. They are discussed below.

5.6.1. Manual processing unit

It consists of a developing bath, a stop bath, two fixing baths, a washing bath and a photoflo bath and all these baths are contained in a big tank (Figure 5.4). It is also equipped with a thermostatic temperature control to keep the processing solutions at a constant temperature. Though it offers a slow processing yet it is used where there is less work load. It is preferably used for training purposes. It is a must for learners, because it provides a thorough understanding of all the stages of processing an X-ray film.

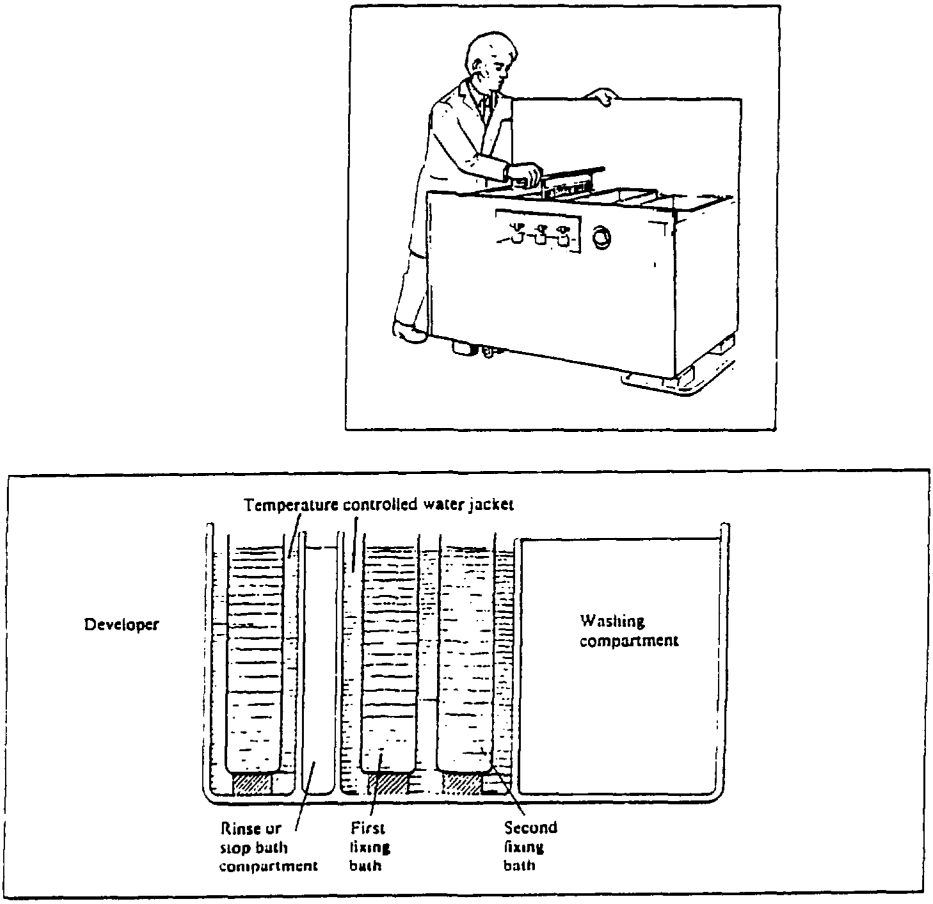


Figure 5.4 Manual processing tanks

5.6.2. Automatic procedures

Automatic film processors are available that greatly speed up the processing of films and minimise manual processing of film artefacts. With an automatic film processing unit, the radiographer needs only to remove the exposed film from the cassette, and feed it into the processing unit. The unit then takes over and, in about 15 min, the film is ready for viewing. The advantages of course, are that the output is increased and the film quality is improved. The automatic method is achieved by the roller transport principle (Figure 5.5)

A series of small driven rollers arranged in offset positions transport each film independently through the solutions. The rolling action creates a vigorous and uniform surface agitation and, together with proper operating temperatures and solution recirculation, achieves a reduction in processing time. Consequently, efficiency and uniformity of processing are achieved. Because of the intimate relationship between the chemical and mechanical requirements of the system, special chemicals have been developed for use with the automatic processing system. These chemicals both control and maintain the physical and chemical characteristics of the film within the required tolerances of the roller transport system. Furthermore, the solutions function under rigid 'time temperature conditions. The reason for this is that, since surface liquids are removed by roller squeeze action as each film passes from one solution to the next, the solutions are

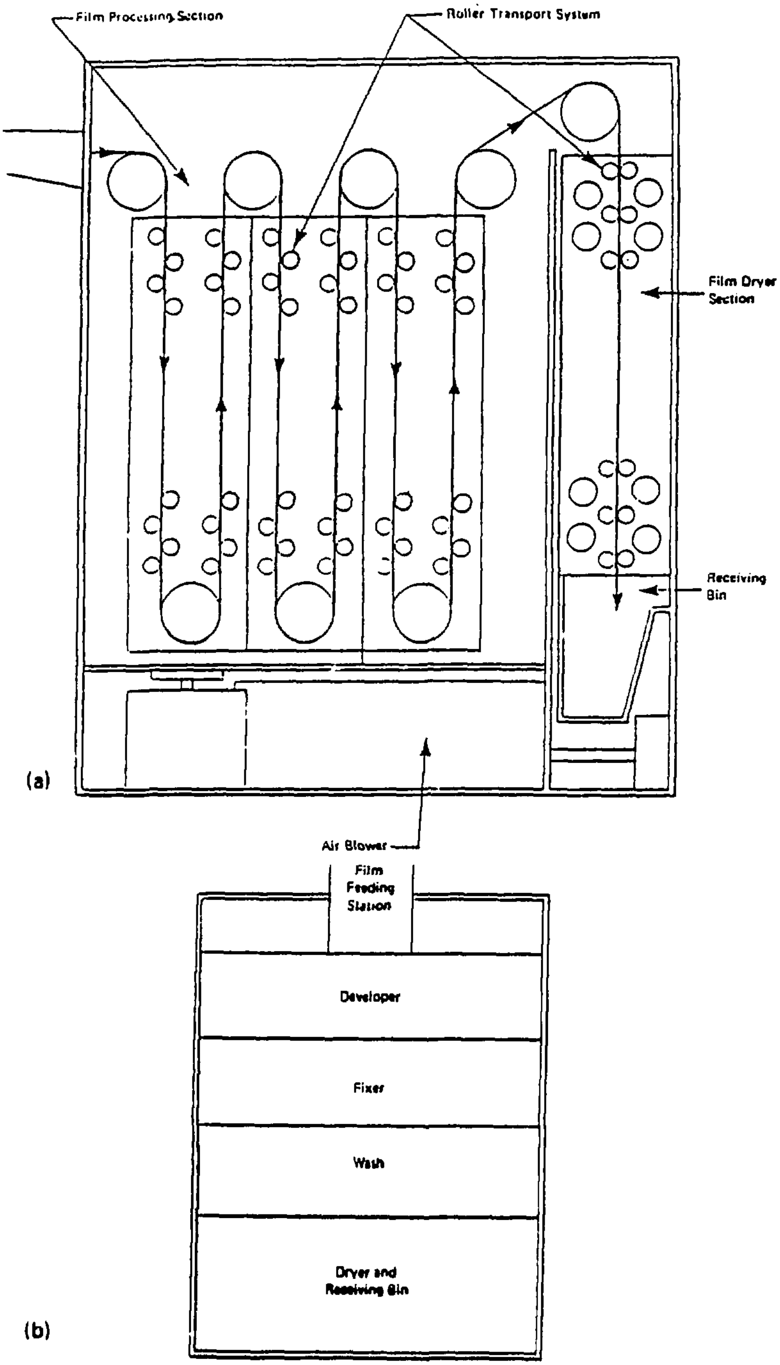


Figure 5.5 Sketch of an automatic processor (a) elevation , (b) plan.

not degraded. These three factors working together permit each film to be processed and dried in less than 2 min:

(a) the nature of the chemical system prepares the film properly.
(b) wash water is roller squeezed from the film as it leaves the wash tank, eliminating carry-over of surface water.
(c) as the film is moved along in the drier section, warmed air is directed at high speed through precision slits to both film surfaces.

5.6.3. Instant processing unit

It is meant for processing radiographs which are exposed on instant X-ray paper. The modern instant processing units promise 10 seconds as the total processing time. Instant X-ray paper and instant processing units are used when information is needed as quickly and cheaply as possible. Radiographic sensitivity is adequate for many situations where maximum sensitivity is not required.

5.7. DARKROOM

Good planning and layout of the darkroom is essential for *successful radiography*. It should be designed to meet individual requirements based upon the amount and nature of the work being done. The size should be related to the type of work, whether it will consist of a routine processing of radiographs, whether it includes enlarging, reducing, printing and copying, and whether it will be used to produce photographs. It is preferable to restrict the

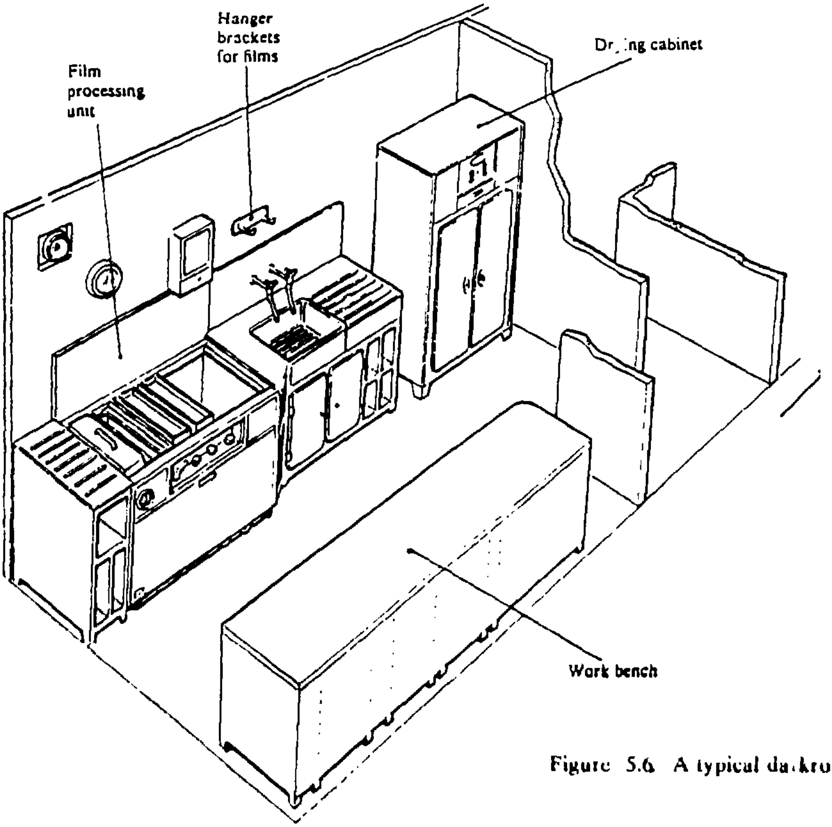


Figure 5.6. A typical darkroom layout.

darkroom to the processing of radiographic films. The darkroom should be kept clean. A light, glossy interior is practical. It should:

(i) be completely light proof and remote from sources of X-ray and gamma radiation.
(ii) be ventilated and heated for comfortable working conditions.
(iii) have running hot and cold water and good drainage.
(iv) be dry, easy to clean and located away from sunlight, have easy access to the radiographic work area, but be away from contaminating gasses from chemicals or coke ovens,and
v) be laid out so that the work can be carried out in a logical sequence, with wet and dry areas clearly established.

Figure 5.6. shows a typical darkroom layout.

5.8. HANDLING OF X-RAY FILMS

Films should always be handled carefully to avoid physical strains such as pressure, creasing, buckling and friction. Marks resulting from contact with fingers that are moist or contaminated with processing chemicals, as well as crimp marks, will be avoided if the films are always grasped by the edges and allowed to hang free. Avoid drawing film rapidly from cartons and exposure holders (any movement that causes friction) so that electric discharges do not occur and mark the film with circular or tree-like markings.

5.9. CHECK LIST OF PROCESSING DIFFICULTIES AND FILM BLEMISHES

Blemish or Difficulty	Causes
Black crescents	Kinking of film before processing
White crescents	Sharp bending or folding of the processed film
Over-all fog	Over-development Over-age film Prolonged exposure to safelight Safelight too filter Unsuitable safelight filters Insufficient protection in storage from radiation sources. Film stored where temperature and/or humidity are too high. Viewing developed film before it is properly fixed
Black streaks or blotches	Light leaks due to faulty film holders or cassette
Streaks	White and black streaks at points where film was attached to hanger caused by processing solution remaining on clips from prior use. Inadequate agitation during development. Removing film to view during development period causing developer to run across film unevenly. Contamination by chemically-active deposits. Interaction of developer and fixer

Blemish or Difficulty	Causes
Drying spots and streaks	Drops of water on semi-dried film or drops of water running down semi-dried surface.
Black spots	Developer splashes before placing entire film in developer.
Brown stains	Inadequate fixing or exhausted fixing solution. Prolonged development in old developer. Inadequate rinsing.
Dark deposits	Oxidised products from developer or reacting silver salts.
White crystalline deposits Milky appearance	Inadequate washing after processing Incomplete fixing. Exhausted fixing bath.
Sharply outlined light and dark areas	Uneven development. Films not agitated during development. Films hung too close together in developer.
Blisters	Formation of gas bubbles in film emulsion.
Air bubbles (light spots or patches)	Air trapped on film surface during development.
Reticulation (leather-like appearance)	Solution to warm Extreme temperature differences in successive processing baths.
Frilling (loosening of emulsion)	Fixing in warm or exhausted bath. Prolonged washing at high temperature.
Static marks (black bird track effects)	From static electric discharges caused by friction between film and some other object.
Scratches (black, crack-like lines)	Improper handling
Dark fingerprints	Film touched with dirty fingers before development.
Light fingerprints	Film touched with greasy fingers before development.
White spots and areas	Pitted or worn screens Dirt on film screens
Brittle radiographs	Excessive hardening in fixer Excessive drying time Too high drying temperature.

6. RADIOGRAPHIC QUALITY AND EXPOSURE

6.1. GEOMETRIC ASPECTS OF SHADOW FORMATION

A radiograph is a shadow picture of an object recorded on a photographic film using X-rays or gamma rays. To obtain a radiograph, therefore, we place the specimen between a source of X or gamma radiation and a photographic film for a predetermined time, Figure 6.1. The appearance of the shadow of a defect is influenced by the following factors.

(i) Shape of the defect.
(ii) Orientation of the defect with respect to the direction of radiation and the plane of the film.
(iii) Size of source and its distances from the defect and the film.
(iv) Position or location of the defect in the specimen.

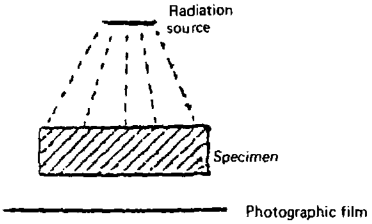


Figure 6.1 Source, specimen and film arrangement to obtain a radiograph.

As regards the geometric aspects of shadow formation only the rectilinear propagation property of the X or gamma rays is important and, therefore, we shall discuss the shadow formation in terms of ordinary light.

6.1.1. Shape of the defect

Defects of different shapes will give rise to different types of shadows e.g. a gas hole will be shown up as a circular patch, a crack if detected will form a line, etc.

6.1.2. Orientation of the defect with respect to the direction of radiation and the plane of the film

If the beam direction is not perpendicular or if the plane of the defect is not parallel to the plane of the film the shadow will be distorted as shown in Figure 6.2.

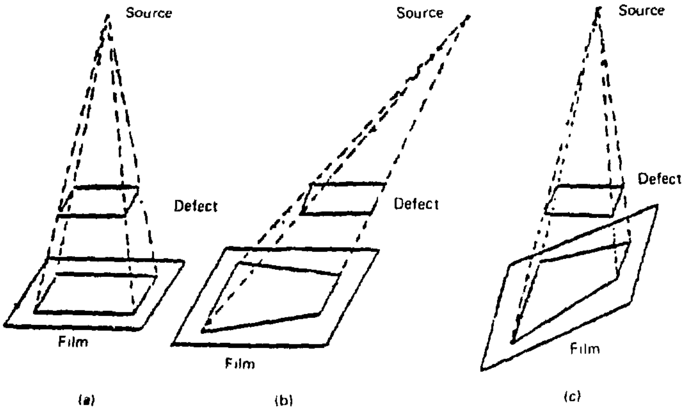


Figure 6.2 Effect of (a) normal beam, (b) oblique beam and (c) inclined film on the shadow.

Because of this distortion sometimes a particular defect can produce a shadow which may be interpreted as some other type of defect. A fine crack may be diffused altogether hardly leaving any image behind. Although before taking a radiograph one may not have any idea about the orientation of the defects present, efforts are usually made to place the film as parallel to the specimen and as normal to the direction of radiation as possible.

6.1.3. Size of the source and its distance from the defect and the film

Figure 6.3. elaborates the formation of shadow of a defect due to a source of finite dimension AB.

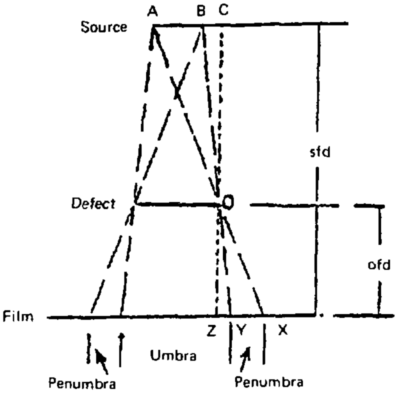


Figure 6.3 Formation of shadow of a defect.

Each and every point of the source AB emits radiation. The shadow cast by the defect on the film will be the resultant of overlapping shadows cast by these points which are slightly displaced from one another. The net effect is that the shadow is diffused around the boundaries. The shadow may be divided into two portions :-

Umbra Where no direct rays are incident on the film.

Penumbra The area which is partially exposed. This gives rise to the unsharpness of the image and is undesirable in radiography.

Considering the simple geometry of Figure 6.3. it can be shown that:

$$\frac{XY}{AB} = \frac{Z0}{C0} = \frac{Z0}{CZ-Z0} \qquad ....(6.1)$$

Where,

XY = Size of the Penumbra = P.
AB = Size of the source (or focal spot) = F
Z0 = Distance of the defect from the film = ofd
CZ = Source (or focal spot) to film distance = sfd (or ffd)

Equation 6.1 can be written in terms of the above symbols i.e.

$$\frac{P}{F} = \frac{ofd}{sfd-ofd} \quad \text{or} \quad P = \frac{F.\,ofd}{sfd-ofd} = \frac{F}{\dfrac{sfd}{ofd} - 1} \qquad ....(6.2)$$

Since penumbra, P, is the cause of unsharpness of the shadow, attempts should be to reduce P as far as possible. From equation (6.2) it is obvious that P decreases when

(i) F decreases
(ii) sfd increases and
(iii) ofd decreases

Hence to reduce P or to increase the sharpness of the shadow :

(i) Size of the source (or focal spot) should be as small as possible.
(ii) Source to film distance should be as large as practicable and
(iii) Film should be as close to the specimen as possible.

It has been found that the image of a defect recorded on a film is reasonably sharp when the penumbra is 0.25mm. This is the limiting value for critical examination because the human eye can not detect any difference in sharpness below this limit. For rough work penumbra up to 0.5mm is usually acceptable.

In a particular X-ray machine or gamma ray source, the source dimensions are fixed. Hence we have little control on this variable. While calculating penumbral size, distance of the defect from the film is taken to be the distance between the top surface of the specimen (i.e. the surface towards the radiation source) and the film. This ensures that the penumbral size of any defect even if it is very near to the top surface remains within acceptable limits. It is usually possible to place the film just below the specimen and ofd in this case will be the thickness of the specimen itself.

We can calculate the minimum source to film distance that will give rise to penumbra within the limiting values for any defect present in a specimen of thickness d placed on the film.

Equation (6.2) can be written as

$$\text{Sfd} = \text{ofd}\ (F/P + 1) \text{...........} (6.3)$$

Hence

$$\text{sfd}_{\text{min}} = d\ (F/0.25 + 1) \text{ .... for critical examination.}$$

$$\text{and sfd}_{\text{min}} = d\ (F/0.5 + 1) \text{ ..... for rough work.}$$

(All dimensions in mm).

6.2. IMAGE QUALITY IN RADIOGRAPHY

6.2.1. Sensitivity of flaw detection

Quantitatively the sensitivity of flaw detection, S_f, can be defined as,

$$S_f = \frac{\text{Size of the smallest detectable flaw} \times 100}{\text{Specimen thickness}}$$

This is an ideal but impractical formula, because sensitivity of flaw detection is a complex function of the size, shape, position and absorption coefficient of flaw, grade of the film used and density of the image obtained. It is, therefore, not possible to calculate or find the sensitivity of flaw detection. However, it is desirable to have some idea about it. Fortunately radiographic sensitivity is indicative of sensitivity of flaw detection and there are means available to measure it.

6.2.2. Radiographic sensitivity

The sensitivity of a radiograph is an indirect indication of its ability to reveal flaws or thickness changes in the specimen being examined, and it is, therefore, a measure of radiographic quality. The sensitivity is expressed numerically in terms of smallest detectable variation in specimen thickness as a percentage of total thickness.

Though definition of sensitivity in the above form, applies to specimens which are examined to detect internal flaws, it is not of particular value in the radiography of assemblies. Since in this type of specimen, radiographic inspection is usually concerned with correctness of assembly rather than the quality of material used in its construction. In this application of radiography, the individual details of assembly themselves will usually provide a reliable means of assessing radiographic quality.

6.2.3. Image quality indicators

Radiographic sensitivity is usually measured in terms of some artificial element which does not necessarily bear much resemblance to a flaw in the specimen. Thus, the two most widely used methods are :

(i) To specify sensitivity in terms of the ability to detect a wire of the same material as the specimen examined, when the wire is laid on the surface of the specimen remote from the film. The diameter of the thinnest detectable wire is used as a criterion of sensitivity.
(ii) To use series of drilled holes in a plate of the same material as the specimen, which is laid on the specimen, and to specify sensitivity in terms of the smallest hole which can be detected on the radiograph.

These devices - sets of wires of different diameters, or step wedges with drilled holes - are called Image Quality Indicators (IQI).

6.2.4. Characteristics of an I.Q.I.

The desirable characteristics of an I.Q.I. are as follows :

(i) It should be sensitive in its readings to changes in radiographic techniques.

(ii) The method of reading the image of the IQI should be as simple and as unambiguous as possible; different inspectors should obtain the same value from the radiograph.

(iii) It should be versatile - i.e. applicable to a range of specimen-thickness.

(iv) It should be small - the image of IQI has to appear on a radiograph and therefore it should not mask or be mistaken for flaws in the specimen.

(v) It should be easy to use.

(vi)It should incorporate some means of identification of its size.

6.2.5. Types of Image Quality Indicators

The perfect design has not yet been found, but after extensive experiments on two patterns of I.Q.I., one originating in France and the other in Germany and Scandinavia, the International Institute of Welding (I.I.W.) recommends these patterns as international standards.

These have been accepted by International Standards Organisation (I.S.O.) and published as ISO Recommendation R1027 (1969) "Radiographic Image Quality Indicators, Principles and Identifications".

These two patterns are :

6.2.5.1. Wire-type I.Q.I.

These consist of series of straight wires (at least 25mm long) of the same basic material as the specimen, with wire diameters selected from the values shown in Table 6.1. The tolerance on the wire diameter is ± 5%.

The wires are placed parallel and 5mm apart, between two sheets of low x-ray absorbent material such as polyethylene sheet. For the thinnest wires it may be preferable to stretch them across a metal wire frame and have no absorbent sheet, although this results in a relatively fragile construction. The IQI should have identifying symbols showing the material of the wires and the wire numbers used.

TABLE 6.1. WIRE DIAMETERS FOR I.Q.I.

Wire Number	Diameter (mm)	Wire Number	Diameter (mm)
1	0.032	12	0.400
2	0.040	13	0.500
3	0.050	14	0.630
4	0.063	15	0.80
5	0.080	16	1.00
6	0.100	17	1.25
7	0.125	18	1.60
8	0.160	19	2.00
9	0.200	20	2.50
10	0.250	21	3.20
11	0.320		

6.2.5.2. Step and hole type I.Q.I.

These consist of a part or an assembly having a series of steps of the same material as the specimen. Each step has one or more drilled holes through the full thickness of the step at right angles to the surface.

The diameter of the hole is equal to the thickness of the step and is taken from the values shown in Table 6.2. Steps with thickness greater or equal to 0.8mm have only one single hole. Steps with a thickness of less than 0.8mm may have two or more holes arranged differently from step to step. The distance from the centre of the hole to the edge of the step, or between the edges of two holes, should in no case be less than the hole diameter plus 1mm.

TABLE 6.2. RECOMMENDED HOLE DIAMETERS AND STEP THICKNESSES

Step Number	Hole diameter and step thickness(mm)*	Step Number	Hole diameter and step thickness(mm
1	0.125	10	1.00
2	0.160	11	1.25
3	0.200	12	1.60
4	0.250	13	2.00
5	0.320	14	2.50
6	0.400	15	3.20
7	0.500	16	4.00
8	0.630	17	5.00
9	0.800	18	6.30

* The tolerance on these dimensions is ± 5% .

Image Quality Indicators, based on the above two patterns, commonly used in radiography are now discussed.

6.2.5.3. British Standard (S.S) image quality indicators

The British Standard (BS 3971, 1980) describes IQI's suitable for assessing the quality of radiographs on materials having a thickness range of 3mm to 150mm inclusive.

(a) Britisb Wire Type

British wire type IQI consists of straight wire having a length of 30mm, and spaced parallel at intervals of 5mm and having diameters selected from Table 6.1. These image quality indicators are standardised in a series of models A to E.

Model A contains wires 4-10 inclusive.
Model B contains wires 9-15 inclusive.
Model C contains wires 15-21 inclusive.
Model D contains wires 1-21 inclusive.
Model E contains wires 1-7 inclusive.

Model D, containing all 21 wires, has been included for general purposes, and model E, containing the very small diameter wires, is intended to be used for radiography of thin materials.

(b) British Step/Hole Type IQI

British step/hole type IQI consists of a series of uniform thickness metal each containing a hole drilled through the full thickness and at right angles to the upper surface.

The step thicknesses and diameters of holes shall be selected form Table 6.3.

TABLE 6.3. DIAMETERS AND DIMENSIONS OF STEPS AND HOLES RESPECTIVE OF BS STEP/HOLE IQI

Step No.	Diameter and step thickness mm	Step No.	Diameter and step thickness mm
1	0.125	10	1.00
2	0.160	11	1.25
3	0.200	12	1.60
4	0.250	13	2.00
5	0.320	14	2.50
6	0.400	15	3.20
7	0.500	16	4.00
8	0.630	17	5.00
9	0.800	18	6.30

For steps 1 to 8 two holes shall be drilled, each hole being located approximately 3mm from each other and from the edge of the step. For steps 9 to 18 a single hole, located in the centre of the step, shall be drilled.

For convenience, the plaque may be machined as a series of steps on a single plate or, for flexibility, separate plates may be mounted on low radiation absorbing material. The individual steps shall be rectangular or triangular, with a side having a length of approximately 12.5mm.

These image quality indicators are standardised in a series of models, A to C as shown in Table 6.4.

TABLE 6.4. STANDARD MODELS OF BS STEP/HOLE TYPE IQI'S

Model	Step/hole type
A	1 to 6 inclusive
B	7 to 12 inclusive
C	13 to 18 inclusive

(c) BS IQI Identification

Marking of BS image quality indicators is as shown in Figure 6.4. Here the number of the thinnest and thickness wires or smallest and largest hole sizes and the material are indicated by lead symbols of sufficient thickness to show clearly on the radiograph.

6.2.5.4. German Standard (DIN)/ISO Image Quality Indicators

The German Standard IQI (DIN 54109) consists of 16 wires of diameters given in Table 6.5.

TABLE 6.5. WIRE DIAMETERS FOR DIN TYPE IMAGE QUALITY INDICATORS

Wire diameter - mm		Wire number
0	Tolerance	
3.20	± 0.03	1
2.50		2
2.00		3
1.60	± 0.02	4
1.25		5
1.00		6
0.80		7
0.63		8
0.50	± 0.01	9
0.40		10
0.32		11
0.25		12
0.20		13
0.16		14
0.125		15
0.100	± 0.005	16

The DIN IQI is standardised in three sizes. Each size is composed of 7 wires, placed parallel at 5mm distance from each other. They are 50 or 25mm long (see Table 6.6). The IQI is marked according to Figure 6.5. The top is marked with DIN 62 (62 means the year of introduction of the standard) and the designation of material (e.g. Fe) and at the bottom is marked with the number of thickest wire, ISO, and number of the thinnest wire. The marking ISO means that these image quality indicators are also adopted by the International Standards Organisation (ISO).

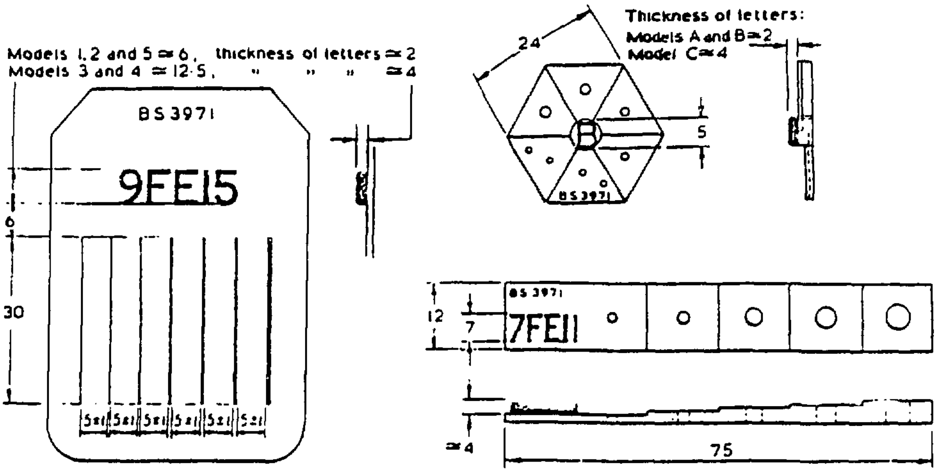


Figure 6.4. Sketches of BS image quality indicators (a) Wire type, (b) Steps with holes type.

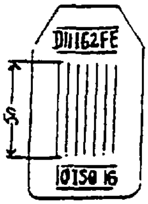


Figure 6.5. Design of DIN type image quality indicators.

TABLE 6.6. MARKING,CONSTRUCTION AND MATERIAL OF THE DIN TYPE IMAGE QUALITY INDICATORS

Marking	Number of wires according to TABLE 6.5	wire length mm	wire material	To be used for testing of
DIN FE 1/7	1 2 3 4 5 6 7	50	steel	iron and steel products
DIN FE 6/12	6 7 8 9 10 11 12	50 or 25	(non alloy)	
DIN FE 10/16	10 11 12 13 14 15 16	50 or 25		
DIN CU 1/7	1 2 3 4 5 6 7	50		copper, zinc and their alloys
DIN CU 6/12	6 7 8 9 10 11 12	50	copper	
DIN CU 10/16	10 11 12 13 14 15 16	50 or 25		
DIN AL 1/7	1 2 3 4 5 6 7	50		aluminium and its alloys
DIN AL 6/12	6 7 8 9 10 11 12	50	aluminium	
DIN AL 10/16	10 11 12 13 14 15 16	50 or 25		

6.2.5.5. **French Standard IQI**

The French Standard IQI (NF A04-304) consists of metal step wedges in which each step has one or two holes with diameter equal to thickness.

The step thickness and hole diameter shall be chosen from the following standard series; 0.32, 0.4, 0.5,0.8,1,1.25,1.6,2, 2.25, 3.2, 4,5, 6.3, 8,10, 12.5, 16mm

Steps thicker than 0.8mm have only one hole whereas thinner than 0.8mm have two holes. The distance of the holes from each other and from the edge of the step cannot be less than d + 1, where d is the thickness of the step in *mm*.

There are various models of step wedge; the step wedges with rectangular steps have square steps measuring 15 x 15mm in dimension; and step wedges with triangular steps have side of the triangle step measuring 14mm in length. Figure 6.6 gives various designs of the French Standard *image quality* indicators.

6.2.5.6 **JIS Image Quality Indicators**

The Japanese wire type IQI consists of 7 wires of the diameters shown in TABLE 6.7

TABLE 6.7. JIS IMAGE QUALITY INDICATORS

Unit:mm

Marking	Range of weld thickness used		Series of wire diameter	Distance between centres of wire (D)	Length of wire (L)
	Ordinary class	Special class			
F 02	Up to 20	Up to 30	0.10 0.125 0.16 0.20 0.25 0.32 0.40	3	40
F 04	10 ~ 40	15 ~ 60	0.20 0.25 0.32 0.40 0.50 0.64 0.80	4	40
F 08	20 ~ 80	30 ~130	0.40 0.50 0.64 0.80 1.00 1.25 1.60	6	60
F 16	40 ~160	60 ~300	0.80 1.00 1.25 1.60 2.00 2.50 3.20	10	60
F 32	80 ~320	130 ~ 500	1.60 2.00 2.50 3.20 4.00 5.00 6.40	15	60
Permissible variations in dimensions			The smaller of the values specified in JIS G 3522 or ± 5 %	±15 %	±1

The marking of the JIS IQI is as shown in Figure 6.7. Here the diameter of the middle wire and the material are indicated by lead symbols of sufficient thickness to show clearly on the radiograph.

6.2.5.7. **ASTM/ASME Image Quality Indicators**

In general, a different *pattern* of *image quality indicators* is used in the U.S.A. and these are usually called penetrameters. There are several minor variations of the same basic type. The best known is the ASTM (American Society for Testing Materials) design which consists of a uniform thickness plate containing three drilled holes and identification letters. If the plate thickness is T, the hole diameters are T, 2T and 4T with an over-riding limit that the minimum hole diameters are 0.010" (0.254mm) and 0.040"(1.016mm) respectively. The plate must be of the same material as the specimen.

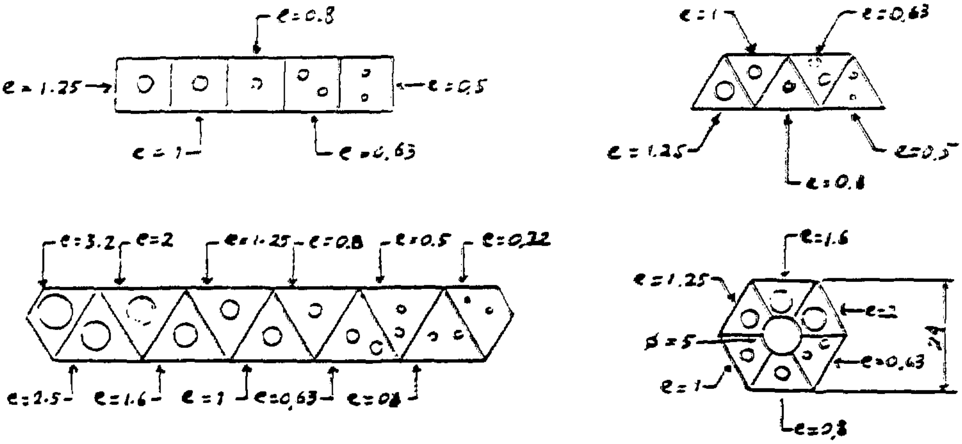


Figure 6.6 Design of French Standard image quality indicators

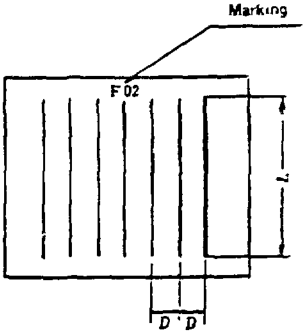


Figure 6.7 JIS IQI marking

The dimensions of three ASTM penetrameters are shown in Figure 6.8. The same penetrameters are accepted also by ASME (American Society For Mechanical Engineers) Boiler and Pressure Vessel Code).

6.2.5.8. Identification of ASTM/ASME Penetrameters

The rectangular penetrameter is identified with a number made of lead which is attached to the penetrameter. The number indicates the thickness of the penetrameter in thousand of an inch. The penetrameter thickness is selected from Table 6.8 to indicate the proper quality level. Lead numbers are placed adjacent to the circular penetrameter to provide identification.

6.2.5.9. Other types of image quality indicators

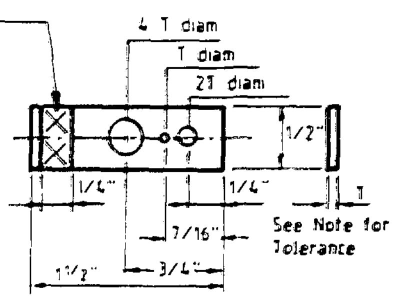
Two other types of image quality indicators both originating in U.K., are the British Welding Research Association (B.W.R.A.) image quality indicator and the Central Electricity Research Laboratories (CERL) Duplex wire type image quality indicator.

(a) BWRA Image Quality Indicator

It consists of a step wedge of 1/12" square steps which contains small drilled holes forming a symbol or number. B.W.R.A. recommends two sizes of image quality indicator. Size 1 is used for specimen thickness up to 5cm and size 2 for specimen thickness ranging from 5cm to 10cm. Figure 6.9. shows the design of B.W.R.A. image quality indicators.

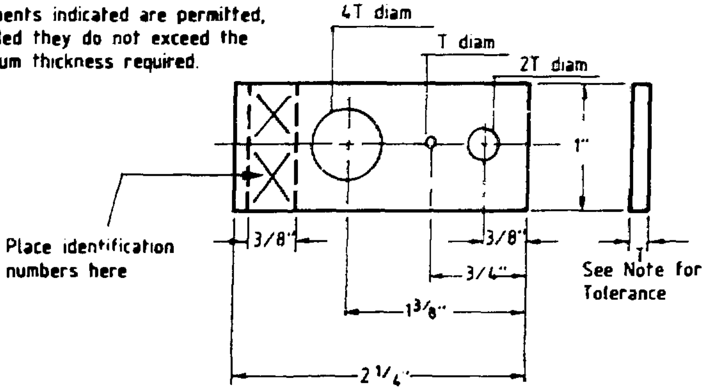
Minimum Penetrometer Thickness ______ 0.005"
Minimum Diameter for 1T Hole ______ 0.010"
Minimum Diameter for 2T Hole ______ 0.020"
Minimum Diameter for 4T Hole ______ 0.040"

Holes shall be True and Normal to the Surface of the Penetrameter
Do Not Chamfer

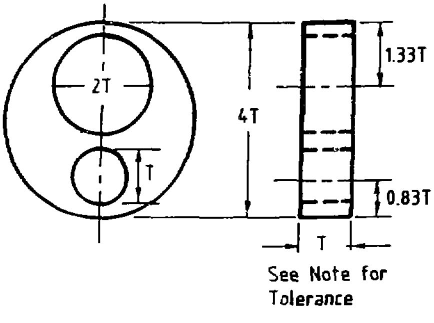


Design for Penetrameter Thickness 0.005 in. and including 0.050 in.
From 0.005 in. through 0.012 in. See Table 1
From 0.012 in. through 0.020 in. Made in 0,0025 in. increments
From 0.020 in. through 0.050 in Made in 0.005 in. increments

Penetrameter thickness between the increments indicated are permitted, provided they do not exceed the maximum thickness required.



Design for Penetrameter Thickness from 0.060 in. to and Including 0.160 in. Made in 0.010 in. Increments.



Design for Penetrameter Thickness of 0.180 in. and Over Made in 0.020 in. Increments.

NOTE 1. Tolerances on Penetrameter thickness and hole diameter shall be ±10 percent or one half of the thickness increment between penetrameter sizes, whichever is smaller.

2. 1 in. - 15.2 mm.

Figure 6.8 Design of ASTM/ASME penetrameters (image quality indicators).

TABLE 6.8. DIAMETER OF WIRE IQI CORRESPONDING TO HOLE TYPE (1T, 2T, 4T)

Hole IQI No.	Diameter of Wire With EPS of Hole, in.		
	1T	2T	4T
5	...	...	0.006
6	...	0.004	...
8	0.0032	0.005	0.008
10	0.004	0.006	0.010
12	0.005	0.008	0.013
15	0.006	0.010	0.016
17	0.008	0.013	0.020
20	0.010	0.016	0.025
25	0.013	0.020	0.032
30	0.016	0.025	0.040
35	0.020	0.032	0.050
40	0.025	0.040	0.063
50	0.032	0.050	0.080
60	0.040	0.063	0.100
70	0.050	0.080	0.126
80	0.063	0.100	0.160
100	0.080	0.126	0.200
120	0.100	0.160	0.250
140	0.126	0.200	0.320
160	0.160	0.250	...
200	0.200	0.320	...
240	0.250	...	...
280	0.320	...	...

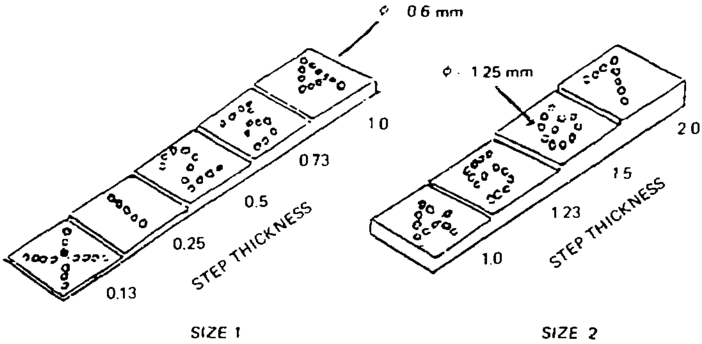


Figure 6.9 Design of BWRA image quality indicators.

(b) CERL Duplex Wire Type Quality Indicator

The CERL Duplex wire type image quality indicator is a completely different pattern of image quality indicator. It is now included in the British Standard BS 3971:1980 on "IQI and Their Uses". The normal percentage value for radiograph sensitivity is replaced by independent measurements of image contrast (mm 'thickness sensitivity') and image definition (mm 'unsharpness'). This is achieved with the use of two different types of element, a plain rectangular element, 5 x 7.5 mm in area with thickness ranging from 0.13 to 5 mm (part A of the IQI) to measure image contrast, and a closely spaced pair of parallel wires or thin strips (parts B and C) to measure unsharpness.

The duplex wire IQIs parts B and C are in two sizes in BS:3971:1980 as Type IIIA (Figure 6.10) and Type IIIB. Type IIIA consists of pairs of straight wires, 15 mm long, of circular cross-section and is used for materials of thickness less than 90 mm steel. Type IIIB consists of 15 mm long strips of rectangular cross-section and is used for materials thicker than 90 mm steel or its equivalent. The wires are made of high density metal (either platinum or tungsten) and each pair in Type IIIA is spaced one diameter apart. The spacing between the strips or elements in Type IIIB is equal to the width of the elements in the pair. Both models are mounted in a rigid plastic moulding and each image quality indicator has identification symbols in lead.

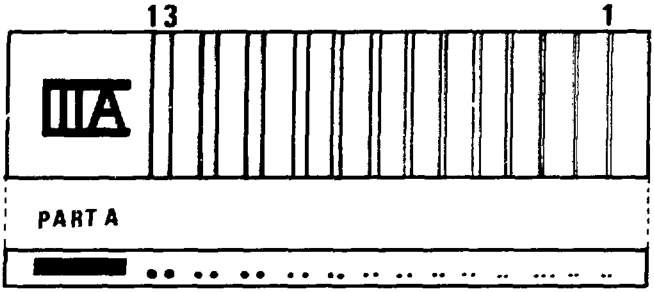


Figure 6.10 CERL duplex type image quality indicators.

When placed on the source side of a specimen, the discernibility of the wire pairs is judged by eye and the image of the first merged pair, that is the first pair which can not be seen as two separate wires, is taken as the criterion of the total unsharpness of the radiographic image. TABLE 6.9 gives the unsharpness values for different pairs of elements.

TABLE 6.9. VALUES OF THICKNESS SENSITIVITY (A) AND UNSHARPNESS (B/C)

Element No.	A(mm)	B/C(mm)	Element No.	A(mm)	B/C(mm)
1	5.00	1.60	10	0.63	0.20
2	4.00	1.26	11	0.50	0.16
3	3.20	1.00	12	0.40	0.13*
4	2.50	0.80	13	0.32	0.10*
5	2.00	0.63	14	0.25	
6	1.60	0.50	15	0.20	
7	1.25	0.40	16	0.16	
8	1.00	0.32	17	0.13	
9	0.80	0.25			*B only

6.2.6. Calculation and assessment of radiographic sensitivity

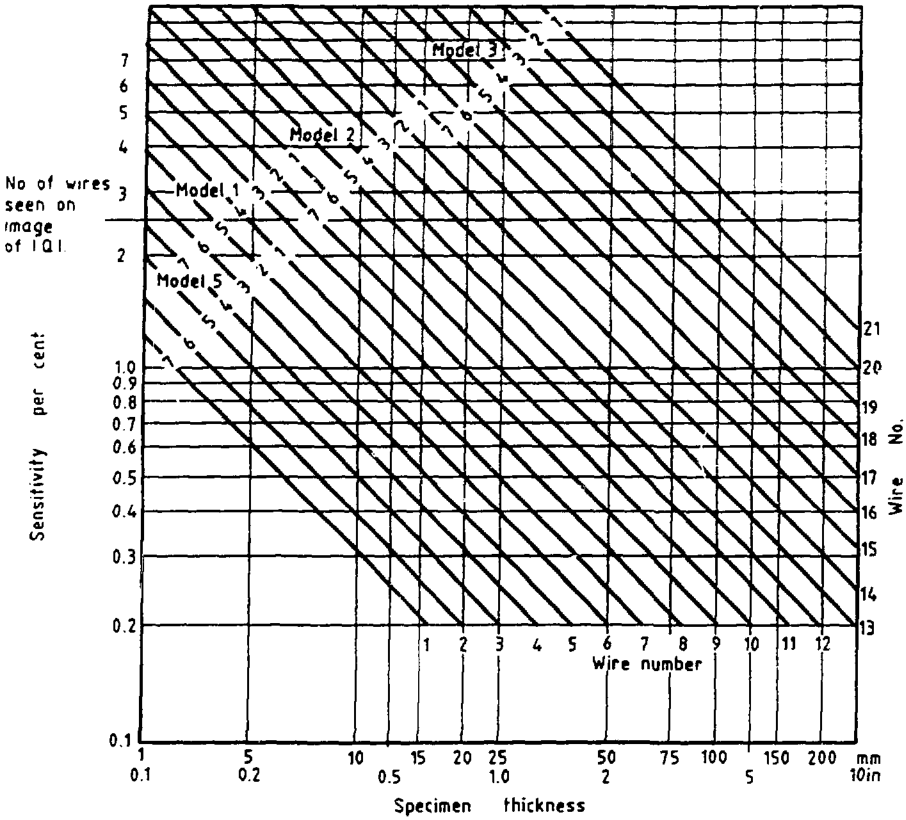
Radiographic sensitivity is usually assessed by the following formula :

$$\text{IOI sensitivity}(\%) = \frac{\text{Thickness of the thinnest wire ,hole,step visible}}{\text{Specimen thickness}} \times 100 \quad (6.4)$$

While using equation (6.4) to assess radiographic sensitivity, it is necessary to quote the type of image quality indicator. Most of the standards also give their own criteria for the assessment of sensitivity. These are discussed below.

6.2.6.1. British Standard

British Standards use equation 6.4 for the assessment of sensitivity. Figure 6.11 and 6.12, based on equation 6.4, can be used for calculating numerous values of sensitivity for each image quality indicator.



Method of use. Read off the number of wires visible on the appropriate model of I.Q.I. against the specimen thickness.

Figure 6.11 Graph for calculating wire I.Q.I. sensitivity.

6.2.6.2. German Standard

The criterion used in this standard is to quote radiographic sensitivity in terms of the number of the thinnest wire still visible. This number is called "image quality number" and is indicated by the letters Bz (a German abbreviation).

Two categories are specified, which are given in Table 6.10. Category 1 is for high sensitivity techniques while category 2 is for normal sensitivity techniques.

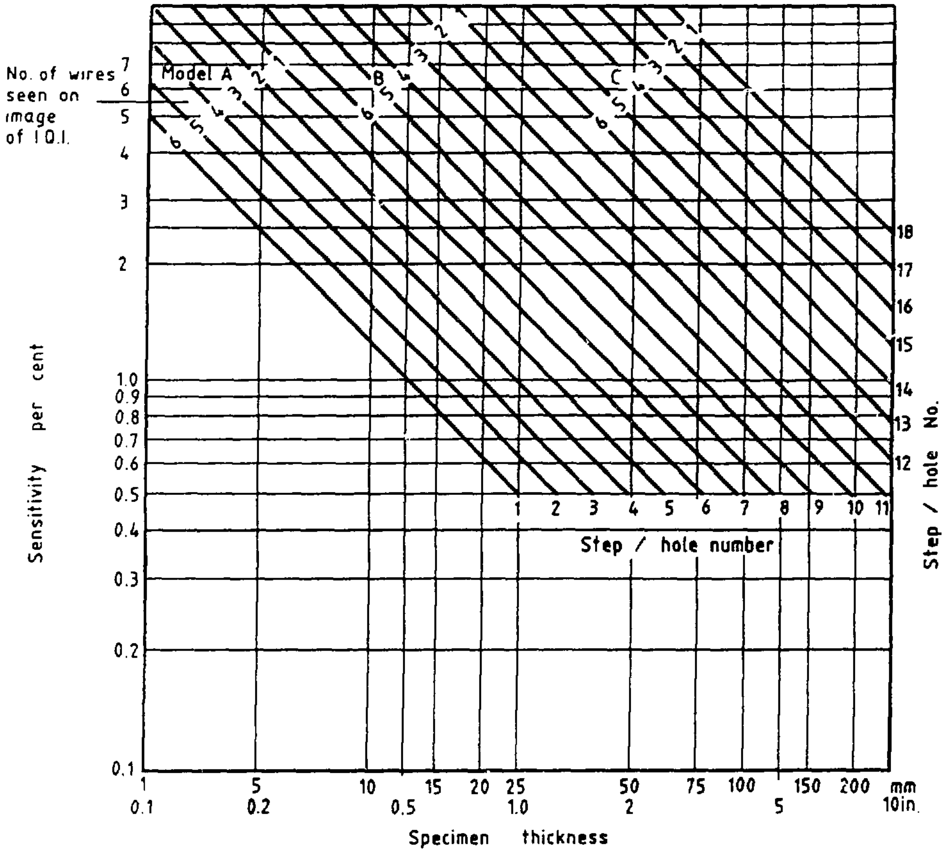
6.2.6.3. French Standards

For the assessment of sensitivity, note is taken of the number of holes (a) visible on the radiograph and the number (b) of holes which would be visible if the limit of visibility were given by the hole whose diameter is equal to or immediately above 5% of the thickness of the material in question.

The index of visibility, N, is then given by the formula

$$N = a - b \qquad \text{................ (6.5)}$$

N can be (in decreasing order of quality) positive, zero, or negative.



Method of use. Read off the number of steps on the image of the I.Q.I. in which holes are visible on the appropriate model, against the specimen thickness.

Figure 6.12. Graph for calculating step/hole I.Q.I.sensitivity.

As an example, to calculate the sensitivity given by an IQI of the following thicknesses and hole diameters : 0.5, 0.63, 0.8, 1, 1.25mm.

The examined object is 17mm thick. On the radiograph four holes are visible (a=4). The diameter corresponding to 5% is

$$\frac{17 \times 5}{100} = 0.85\text{mm}.$$

The next higher diameter is 1mm and is taken in to the calculation of b=2.

The sensitivity index is N = 4 - 2 = 2.

The sensitivity index can give an idea of the relative radiographic sensitivity, which can be read from TABLE 6.11.

TABLE 6.10. IMAGE QUALITY NUMBERS (BZ) FOR TWO CLASSES OF IRON AND STEEL PRODUCTS (DIN 54109)

Image quality class I

Thickness of Fe		BZ
Over	To	
0	6	16
6	8	15
8	10	14
10	16	13
16	25	12
25	32	11
32	40	10
40	50	9
50	80	8
80	150	7
150	200	6

Image quality class II

Thickness of Fe		BZ
Over	To	
0	6	14
6	8	13
8	10	12
10	16	11
16	25	10
25	32	9
32	40	8
40	50	7
50	80	6
80	150	5
150	170	4
170	180	3
180	190	2
190	200	1

TABLE 6.11. SENSITIVITY INDEX N ACCORDING TO FRENCH STANDARD (NF A 04-304)

N = a - b	Positive						0	Negative					
	6	5	4	3	2	1		1	2	3	4	5	6
Relative radiographic sensitivity in% of the examined thickness	1.25	1.6	2	2.5	3.2	4	5	6.3	8	10	12.2	16	20

6.2.6.4. American Standard (ASTM/ASME)

Radiographic sensitivity is specified in terms of quality levels. Three quality levels of inspection 2-1T, 2-2T and 2-4T are available through the design and application of the penetrameter as shown in TABLE 6.12.

The first number of the quality designation refers to penetrameter thickness expressed as a percentage of specimen thickness. The second number refers to the diameter of the penetrameter hole, expressed as a multiple of the penetrameter thickness, which must be clearly visible.

TABLE 6.12. QUALITY LEVELS OF INSPECTION ACCORDING TO ASTM E142/ASME-SE142

Level of Inspection	Penetrameter Thickness	Minimum Perceptible Hole Diameter	Equivalent Penetrameter Sensitity Percent.
2-1T	(2 percent) of specimen thickness	1 T	1.4
2-2T		2T	2.0
2-4T		4T	2.8

(a) Normal quality levels of inspection.

Level of Inspection	Penetrameter Thickness	Minimum Perceptible Hole Diameter	Equivalent Penetrameter Sensitivity percent.
1.1T	1/100 (1 percent) of specimen thickness	1T	0.7
1.2T		2T	1
4.2T	1/25(4 percent) of specimen thickness	2T	4

(b) Special quality levels of inspection.

6.2.6.5. BWRA Image Quality Indicators

For BWRA image quality indicators the IQI sensitivity is calculated by using equation 6.4.

6.2.7. Placement of IQI

For the placement of IQI's, the following points should be kept in mind:
(i) The IQI should be placed on the source side of the specimen. If, because of specimen design, it is impossible to place the IQI on the source side of the specimen, it is probably best not to use an IQI, but if necessary, the technique to be used should be checked on a mock-up specimen of the same thickness and geometry.

(ii) The IQI must preferably be placed near the boundary of the area of interest, with the thinner step (step/hole IQI) or thinnest wire (wire type IQI) farthest from the beam axis.

(iii) In weld radiography,the step-with-hole type IQI's should be placed on a shim and then placed near and parallel to the weld and the wire type should be placed in such a way that the wires lie across the weld length.

(iv) In the case of radiography of multi-thickness castings, more than one IQI should be used corresponding to the different thicknesses in the casting.

(v) For a too small or too complicated specimen, which does not allow the IQI to be placed on itself, the IQI should be put on a uniform block of the same material as the specimen and be radiographed along with the specimen.

(vi) One IQI should represent an area of the radiograph within which the radiographic densities do not vary by more than - 15 to + 30 percent. Otherwise two image quality indicators should be used, one showing the sensitivity level at the more dense portion of the radiograph, and the second the sensitivity level of the least dense portion.

(vii) For a panoramic exposure a minimum of one image quality indicator should be used for each quadrant.

6.2.8. Factors affecting radiographic sensitivity

Radiographic sensitivity or radiographic quality depends upon radiographic contrast and radiographic definition.

6.2.8.1. Radiographic contrast

Radiographic contrast is defined as the difference in densities of two selected portions of a radiograph. The greater the difference, the greater is said to be the radiographic contrast, Figure 6.13.

Radiographic contrast is composed of two factors; subject contrast and film contrast. Subject contrast is the variation in intensity of radiation impinging on the film (Figure 6.14). These variations are caused by the variation in the amount of radiation absorbed by the specimen.

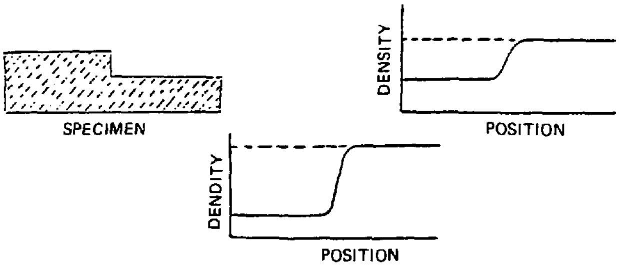


Figure 6.13 Illustration of radiographic contrast.

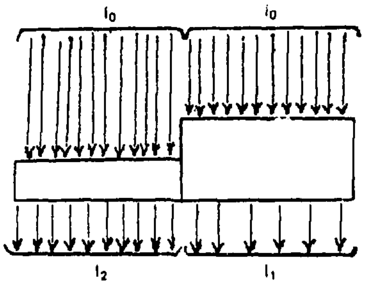


Figure 6.14 Illustration of subject contrast.

Film contrast is a measure of the response of the emulsion of the film to the intensity of impinging radiation and is a characteristic of a given film.

6.2.8.2. Radiographic definition

Radiographic definition is a term used to indicate the different densities and clearness of the fine details in an image or in other words it represents the degree of sharpness of the image, Figure 6.15.

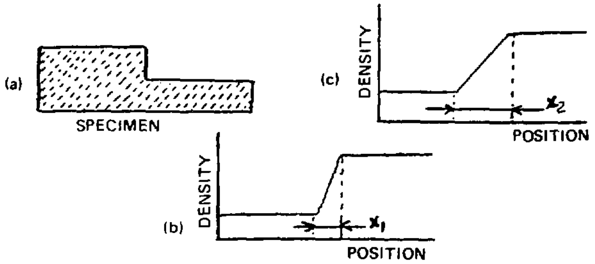


Figure 6.15. Illustration of radiographic definition.

Radiographic definition is determined by:

(i) Geometric unsharpness.
(ii) Inherent unsharpness.
(iii) Graininess.

Factors that influence radiographic contrast and radiographic definition are listed in Table 6.13 and are described subsequently.

TABLE 6.13 . FACTORS INFLUENCING RADIOGRAPHIC SENSITIVITY

Radiographic Sensitivity/Radiographic Quality				
Radiographic Contrast		Radiographic Definition		
Subject Contrast	Film Contrast	Geometric Unsharpness	Inherent Unsharpness	Graininess
i)Radiation energy	i.Film type ii.Density iii.Development iv.Fog level	i.Source to film/distance (sfd) ii. Object to film distance (ofd)	i.Radiation Energy	i.Film Type ii.Radiation Energy iii.Development
ii.Scattered radiation		iii. Focal spot size		iv.Screens
iii. Specimen		iv. Vibration		
iv. Lead screens				
v. Masking				
vi. Filter				
vii. X-ray set				

(a) Radiation Energy

For a given specimen, subject contrast would decrease with increasing radiation energy because the absorption co-efficient of the material decreases with increasing radiation energy.

Increase in radiation energy also increases inherent unsharpness by increasing the energy of the secondary electrons.

Graininess also increases with increasing radiation energy. All of above factors diminish radiographic sensitivity.

(b) Film Type

Different types of films exhibit different contrast and graininess characteristics. In general, coarse grain films will have low contrast and high graininess and therefore low radiographic sensitivity.

(c) Development

Increasing developing times in a particular developer of a given strength and temperature will increase graininess, contrast and fog level of the radiograph, thus deteriorating its quality.

(d) Density

For all direct-type films, increase in radiographic density, increases the contrast of the radiograph. This is because the inherent contrast of the film increases with increasing density.

(e) Specimen

The energy of radiation required to radiograph a particular specimen depends upon the thickness, material density and atomic number of the specimen. Specimens with high density, high atomic number or large thickness would required a high energy to be used. Both contrast and definition in such cases would be inferior.

Furthermore the amount of scattered radiation also depends upon the specimen. Specimens which result in high scattered radiation would produce a low sensitivity radiograph.

(f) Scattered Radiation

An increase in scattered radiation causes an increase in the fog density of a radiograph thus decreasing its contrast and hence its sensitivity.

(g) Screens

Lead screens reduce scattering and, therefore, help in improving the sensitivity, while the use of salt screens increases graininess thereby reducing the quality of the radiograph.

(h) Filters

The effect of filters interposed between the source of radiation and the film is to reduce the proportion of soft radiation in the beam. Thus they harden the beam and hence decrease contrast, thereby reducing radiographic sensitivity.

In some circumstances, a filter may reduce scattered radiation to cause an improvement in the quality of a radiograph. This effect is mostly used in the radiography of complicated specimens.

(i) Fog Density

Increase in the fog density of a film, decreases the radiographic sensitivity by decreasing the contrast of the radiograph.

(j) sfd

Increase or decrease in sfd, decreases or increases geometric unsharpness and hence improves or deteriorates radiographic sensitivity.

(k) ofd

ofd increases or decreases the geometric unsharpness thus spoiling or improving the radiographic sensitivity.

(l) Focal Spot (Source) Size

Increase in the size of the focal spot or source increases geometric unsharpness thereby reducing radiographic sensitivity.

(m) Vibration of Source, Specimen or Film

If the specimen, source of radiation and film vibrate relative to each other , overlapping images will be formed which will spoil radiographic definition and hence radiographic sensitivity.

(n) X-ray Set

For the same exposure conditions, two X-ray sets of similar ratings may not be identical in their radiation outputs, thereby rendering different quality radiographs.

(o) Masking

Masking improves radiographic quality by reducing scattered radiation.

6.3 EFFECT OF SCATTERED RADIATION ON RADIOGRAPHIC QUALITY

6.3.1 Origin and effect of scattered radiation

Whenever a beam of radiation strikes some material object, it gives rise to scattered radiation. The scattering is in all directions. An ideal radiograph should give point to point representation of the specimen. Now in a typical scheme for taking a radiograph it can be seen that scattered radiation can arise from the specimen itself, the film cassette, the floor, the walls and any other object on which the beam of radiation falls.. This increases the fog level which causes loss of contrast thereby spoiling the radiographic image.

Scattering under certain circumstances can be several times more intense than the primary beam reaching the film. For example, in the X-ray radiography of 5cm of aluminium, scattered X-ray intensity may be 2.5 times the primary radiation reaching the film.

The scattering seldom offers any problem when low kV (e.g. 40 - 100 kV) and specimens of low density material are involved. However in the mid kV range (e.g. 100 - 200 kV) and heavy metal specimens , scattering becomes troublesome. With still more penetrating X-rays and gamma rays (except very low energy gammas) the effect of scatter on the radiograph becomes less noticeable. This is due to the fact that scattered radiation is mostly in the forward direction at high energies and it, therefore, tends to assist the image formation rather than to spoil it. Besides, the amount of scattering also depends upon the shape of the specimen.

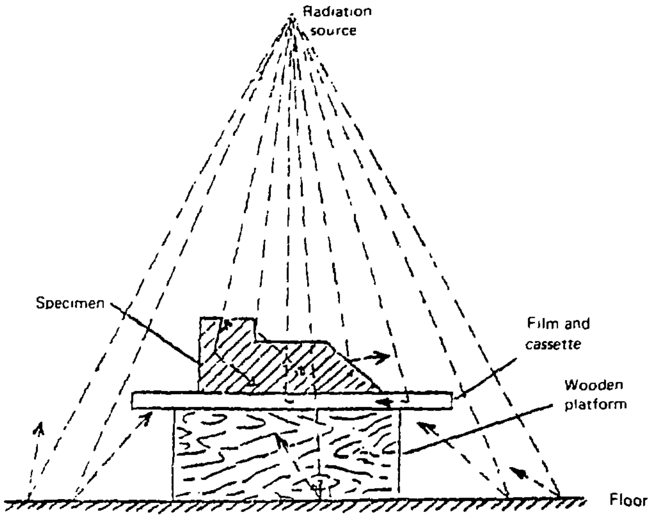


Figure 6.16 Sketch showing sources of scattered radiation while taking radiograph of an object.

6.3.2 Remedial measures

From the above discussion, it becomes necessary that some effective remedial measures should be taken to minimise the ill effects of scattered radiation. Given below are certain routine precautions which are helpful to achieve the above objective.

(i) To cut down the back scatter from the floor, a lead topped table should be used for placing film and specimen.

(ii) The beam should be restricted with the help of diaphragms or collimators just on to the specimen or its portion of interest. With this arrangement the area irradiated by the beam is reduced thereby reducing the scattered radiation, Figure 6.17.

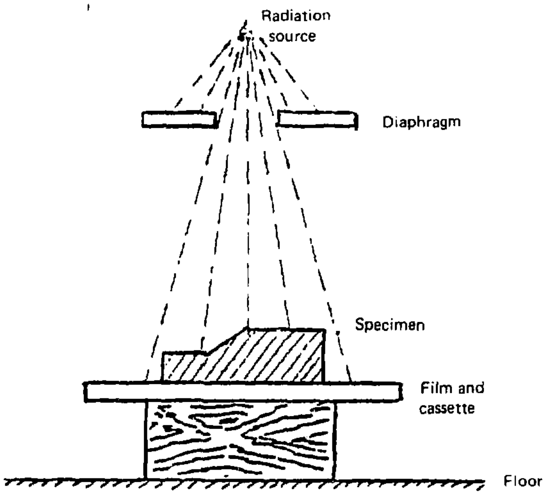


Figure 6.17 Sketch elaborating the use of a diaphragm.

(iii) The specimen and the unused portion of the film should be properly masked leaving only the areas of interest. Masking can be achieved as follows :-

(a) For specimens of regular shape, masking can be achieved using lead sheets.

(b) Masking can be achieved by packing a dense paste or clay around the specimen. To make a typical paste add 100gm of liquid paraffin and 170 gm of light machine oil and warm and then add 120 gm of Japan wax and 200 gm of Kaolin and knead the mixture with 1 kg of barium sulphate. The paste opacity to X-rays is approximately equal to that of steel.

To make a clay, mix 1 kg of lead powder with 250 gm of Plasticine and add 30 gm of Lanolin to this mixture to prevent drying. The amount of lead powder can be varied to produce masking clays of different opacities.

(c) Masking may also be done by lead, copper or steel shots with a diameter of about 0.25mm. These shots are specially useful for radiography of irregular castings.

(d) Liquids, e.g. solutions of lead salts, organic halogen derivatives, carbon tetrachloride, etc., may be used as masking media in certain cases.

(iv) Lead intensifying screens may be used in contact with the film specially when working in mid KV range to reduce the effect of scatter. The front screen cuts the scattered radiation arising from the specimen and the back screen guards against the back scatter.

(v) The use of copper or lead filters in the path of the X-ray beam helps to reduce scatter by filtering away the comparatively softer radiation from the X-ray spectrum. This, however, reduces contrast due to hardening of the beam.

In the radiography of *aluminium*, a copper filter 0.04 of the greatest thickness of the specimen should prove thick enough. In the case of steel, a copper filter might be 0.2 and a lead filter 0.03 of the greatest specimen thickness for useful filtration.

6.4. RADIOGRAPHIC EXPOSURE

The radiographic exposure is defined as the product of source strength and time for which the film is exposed to the radiation. In the case of X-rays.

Exposure = Tube current (mA) x time (sec),
(miliampere-second),

(Tube current is a measure of the X-ray output i.e. the quantity of radiation emitted by the target).

And for gamma rays

Exposure = Strength (ci) x time (hour),
(Curie-hour)

(Strength in curies is a measure of the quantity of radiation emitted by the radioactive source)

6.5. METHODS OF EXPOSURE DETERMINATION

The determination of the correct radiographic exposure for a given specimen is very necessary to produce the best results. It saves labour, time and radiographic materials. The following methods may be used to determine the correct exposure.

6.5.1. Reference to previous data

Sometimes a record of previous exposures is very helpful in determining the exposure for a specimen. If a similar specimen was radiographed in the past, its exposure may be used under similar conditions. It is, therefore, recommended that a log-book should be maintained by the radiographer.

6.5.2. Use of characteristic curve

The characteristic curve of the film can be used to determine the correct exposures especially for samples made from mixed materials for which an exposure chart is normally not available. A trial exposure (estimated from the density and thickness of the specimen material) is taken and the density thus obtained is measured. This test exposure is then corrected with the help of the characteristic curve of the film used to give the standard density of 2.0. The method can be understood as follows:

Let the trial exposure 'E_t' give a density 'D_t' and the standard density required to be achieved be D_r. The relative exposures corresponding to these densities can be read from the characteristic curve of the film (Figure 6.18). Let 'E_{ct}' be the exposure corresponding to density D_t and 'E_{cr}' corresponding to density D_r as read from the characteristic curve. Then the correct exposure E, to obtain the required density, is given by :

$$\frac{E}{E_t} = \frac{E_{cr}}{E_{ct}}$$

or

$$E = \frac{E_{cr} \times E_t}{E_{ct}}$$

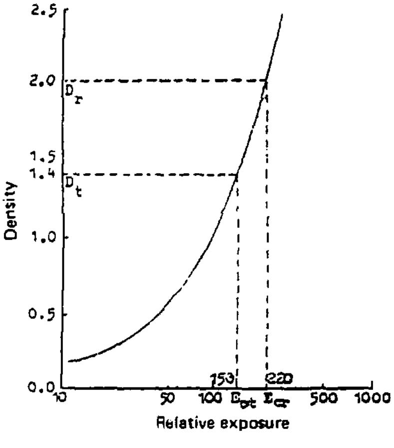


Figure 6.18 Characteristic curve for a typical direct type film.

Example

Suppose that the film used has the characteristic curve shown in Figure 6.18. The trial exposure (E_t) given is 15mA-min which gives a density of 1.4. It is required to calculate the correct exposure to give a density of 2.0. From the curve we see that:

Relative exposure corresponding to trial density

$$1.4 = E_{ct} = 150$$

Relative exposure corresponding to density

$$2.0 = E_{cr} = 220$$

The exposure required to give a density of 2 is

$$E = \frac{220}{150} \times 15 \text{ mA-min} = 22\text{mA-min}$$

6.5.2.1. <u>Construction of characteristic curve</u>

A characteristic curve can be made by exposing a strip of the film to X-rays so that different areas of the film receive different known exposures. The strip is normally exposed in steps so that each step is given twice the exposure received by the previous step. The exposed strip is then developed according to standard procedure and dried. A density step wedge is thus obtained. The density of each step is measured on a densitometer and the values are plotted against corresponding exposures and the required characteristic curve is obtained.

6.5.3. Exposure chart method

An exposure chart is a graph relating the exposure to the material thickness. Correct exposures for specimens made of simple materials (e.g. mild steel, copper, aluminium etc.) can be obtained from charts prepared for each material. A good radiograph of a uniformly thick object can be produced in a single exposure. Also with the help of exposure charts radiography of more complicated castings can be done quickly and effectively.

An exposure chart is normally prepared for a particular X-ray set or a particular gamma-ray source. The methods of preparation of charts for X-rays and gamma rays are dealt with separately.

6.5.3.1. <u>Construction of exposure chart for X-rays</u>

To prepare an exposure chart for X-rays the following parameters should be kept fixed:-

(i) X-ray set
(ii) Film type
(iii) Film density
(iv) Development (Type of developer, development time and temperature of the developer).
(v) Specimen material
(vi) Intensifying screens
(vii) Source to film distance
(viii) Filter (Material and thickness of the filter)

These parameters must be mentioned on the exposure chart.

It is also helpful to decide what kilovoltages are required to correspond to which lines on the exposure chart.

Two different methods of making exposure charts are discussed below.

(a) <u>First method</u>

The characteristic curve of the film to be used is required in this method and is made before hand at the mid KV range of the set according to the method already described. A step wedge of the material for which the chart is to be made is also needed for this method. The wedge should have a range of thicknesses to suit the X-ray unit. For a 150KV unit, for example, a wedge of steel with 2.0mm steps and a maximum thickness of about 4.0 cm would be suitable. An aluminium step wedge with 5.0mm steps and a maximum thickness of 8.0 cm would also be suitable for this set. Radiographs of the metal step wedge are made at various KV's for which lines on the exposure chart are required. The exposures should be reasonably chosen at each KV to give a full spectrum of densities on the radiograph. The processing of the films should be strictly in accordance with the standard procedure.

The densities of the various steps are measured on a densitometer and tabulated against the thickness of the corresponding steps. Each KV would thus result in one such table.

The correct exposure for the required density (2.0) is then calculated for every thickness using the characteristic curve in the manner already explained. The corrected exposures are then plotted against thickness on a semilog graph paper for each KV to obtain the required exposure chart. Figure 6.19 shows one such chart.

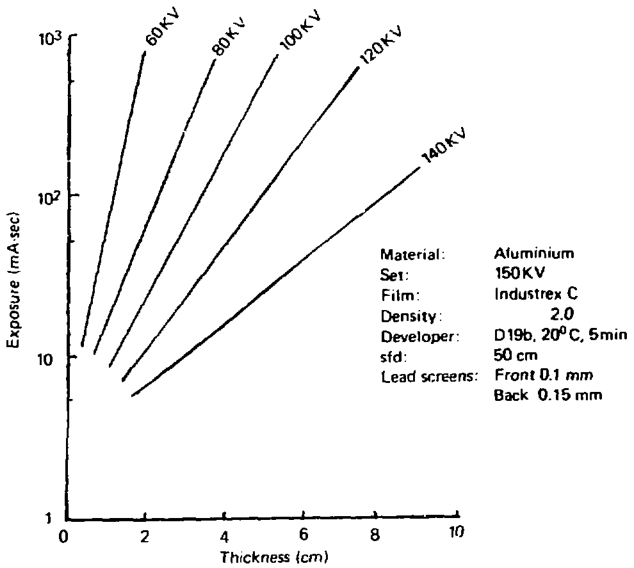


Figure 6.19 A typical exposure chart.

(b) Second method

This method is lengthy but is more reliable and exact. A slot about 1.0cm wide 20cm long (a little less than the length of the step-wedge) is cut in a lead sheet.

A radiograph of the step-wedge is taken by placing it on the slot and covering the rest of the film with extra lead. An exposure (say 1 mA-min) is given at a KV (say 60KV) sufficient to produce densities close to the required density (e.g. 2.0) for thin steps.

The slit is then moved to the next unexposed position of the film and an exposure almost double the previous exposure (2mA-min) is given at the same KV (i.e. 60 KV).

In this way five or six exposures should be taken, every time doubling the previous exposure, so that the whole thickness range of the step wedge is covered. Thinner steps may be masked at higher exposures to avoid excessive fogging of the film by scattered radiation.

The film is developed under the standard procedure. Densities are read from the densitometer and the results are tabulated for each exposure. By plotting these results on a linear-linear graph paper, curves similar to those of Figure 6.20 are obtained. Thickness values for which various exposures will produce the required density 2.0 are directly read from these curves. These values are plotted against exposure on a semilog graph paper and a line for a KV (60KV) is obtained.

This procedure is repeated for other KV's and corresponding lines on the exposure chart are obtained.

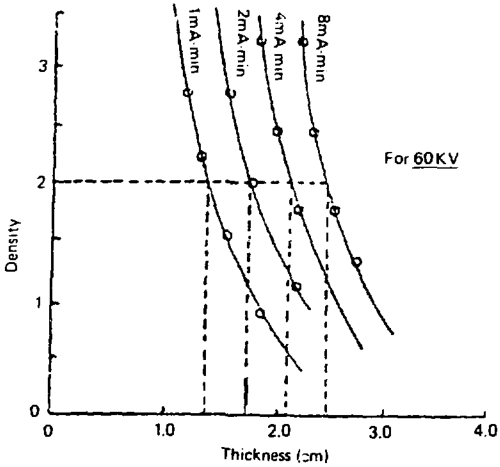


Figure 6.20 Thickness-density curves for various exposures.

6.5.3.2. Construction of exposure chart for gamma sources

Exposure charts for a gamma ray source can be prepared in a similar way as for X-rays. Any of the methods can be used. It must, however, be emphasised that due to the great penetrating power of gamma rays, lead masking may not be sufficient. Therefore, while preparing the characteristic curve or exposing the step wedge, a separate strip of X-ray film should be used for every exposure. The step-wedge should be chosen so as to have a suitable minimum and maximum thicknesses depending on the source. These thickness ranges have already been given in chapter 3. The source emits gamma rays of fixed energy, therefore a change of KV, as for X-rays, is not necessary.

Also it is usual practice to make the exposure chart for gamma rays for more than one density. One such chart is shown in Figure 6.21.

Charts for a number of gamma ray sources using Agfa Gevaert and Kodak films are available.

6.5.3.3. Exposure range

The interval of correct exposure corresponds to density limits which may not be exceeded on the radiograph. This limit is determined on the one hand by whatever gradient is considered as minimum (see point 'a' on characteristic curve of Figure 6.22) and on the other hand by the greatest density which can be read on the film viewer (see point 'b' on curve of Figure 6.22).

Exposure range is determined as the difference of logarithms of relative exposures, corresponding to those density limits. An exposure lower than the lowest limit is called an underexposure, and higher than the highest limit, an overexposure. In the example given on Figure 6.22 the exposure range is 0.8. This corresponds to 6.3 on the linear scale. This means that the highest exposure can be 6.3 times greater than the lowest exposure.

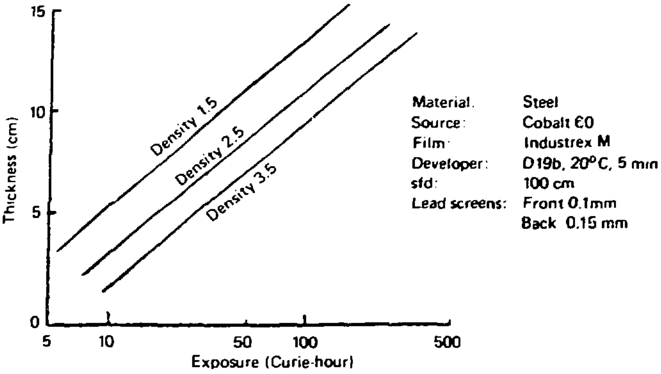


Figure 6.21 A typical gamma ray exposure chart.

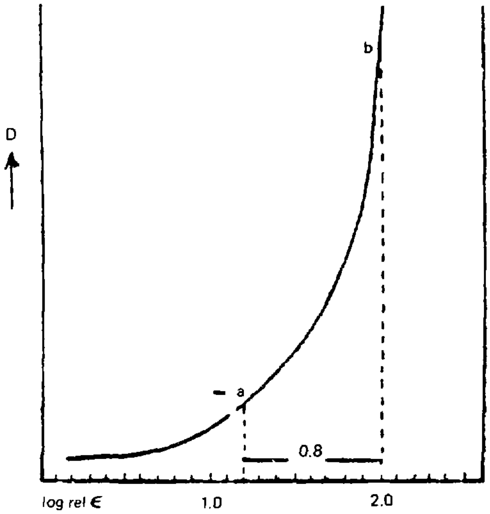


Figure 6.22 Exposure range calculation.

From Figure 6.23 one can see that the correct exposure range depends not only on the lowest admissible gradient and the highest density but also on the shape of the characteristic curve itself.

6.5.3.4. How to use the exposure chart

Proper use of the exposure chart can save a lot of time and labour. Some interesting and valuable uses are given.

(i) Specimen of uniform thickness

The exposure is read from the chart against the specimen thickness. The chart should be for the same material as that of the specimen. The lowest KV should be used which gives a reasonable exposure - not too short and not unmanageably long (e.g. the minimum exposure is 20-30mA-min when fine grain high contrast films are used). This exposure will give the density for which the chart is made (say 2.0) if the conditions mentioned on the chart are kept the same. If, however, one has to change one or more of these conditions, the following procedure should be adopted. To change the film, the relative speeds of the films (Table 6.14) should be taken into account. For example, to use Industrex-D instead of Industrex M, the exposure read from the chart should be divided by 8.

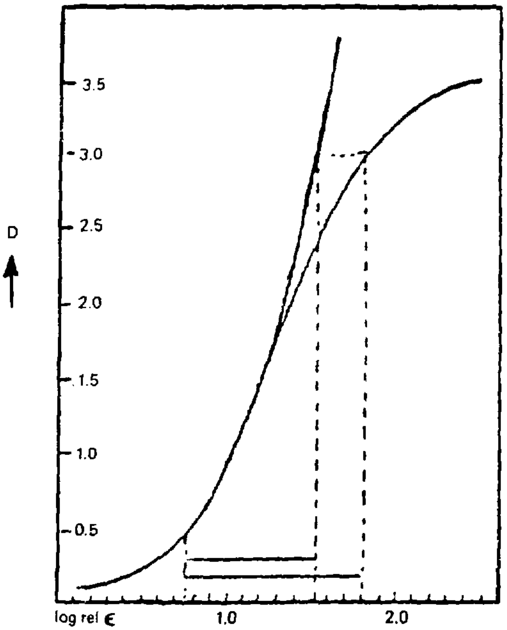


Figure 6.23. Exposure range for two different X-ray films.

TABLE 6.14. RELATIVE SPEEDS OF VARIOUS FILMS

Kodak Film	Relative Speed	Agfa Gevaert Film
-	0.5	Structurix D2 (single coat)
-	1	Structurix D2
Industrex M	4	Structurix D4
-	8	Structurix D5
Industrex A	16	Structurix D5
Industrex C		
Industrex D	32	-
Kodirex	64	Structurix D10

TABLE 6.15. APPROXIMATE RADIOGRAPHIC EQUIVALENCE FACTORS.

Material	X-rays					Gamma rays		
	50 KV	100 KV	140 KV	220 KV	400 KV	Ra-226	Co-60	Ir-192
Magnesium	0.05	0.05	0.05	0.08	-	-	-	-
Aluminium-1100	0.08	0.08	0.12	0.18	-	0.40	0.35	0.35
Aluminium-2024	0.12	0.12	0.13	0.14	-	-	0.35	0.35
C steel,ss,etc	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper	-	1.5	1.5	1.4	1.4	1.1	1.1	1.2
Brass(normal)	-	-	1.4	1.3	1.3	1.1	1.1	1.1
Zinc	-	-	1.4	1.3	1.3	1.0	1.0	1.1
Monel	-	1.7	1.5	1.2	-	-	-	-
Lead	-	-	14.0	11.0	-	2.3	2.3	4.0
Zirconium	-	2.4	2.0	1.9	1.5	-	-	-
Uranium	-	-	-	18.0	12.0	-	-	-

To change the source to film distance apply the inverse square law, e.g. to change sfd from 100 cm to 50 cm, the exposure read from the chart (sfd 100 cm) should be multiplied by (50)/(100) to obtain the required exposure, or in general $E_1 / E_2 = r^2_1 / r^2_2$

To change the radiographic density use the characteristic curve, as explained under section 6.4.2. to modify the exposure read from the chart.

A change of material can also be accommodated to some extent by the use of radiographic equivalence factors (TABLE 6.15). For example, to use the exposure chart of steel for the radiography of aluminium (1100) at 100 KV, the thickness of the aluminium specimen should be multiplied by 0.08 to get the equivalent thickness in steel.

(ii) Specimen of varying thickness

Specimens having more than one thickness are often required to be radiographed. For critical examination of such samples, exposures should be determined from the chart for each thickness. But critical examination, being uneconomical and time-consuming, is normally not required. It is usual practice to radiograph such a sample in a single shot which covers the complete thickness range. Exposure can be determined from the chart as follows.

Measure the minimum and maximum thickness of the sample. Decide the maximum and minimum densities required to appear in the radiograph. A good film density range is 1.0 - 3.0 and may be changed (say to 1.7 - 3.5) depending on the illuminator brightness available for film viewing. Read the relative exposures from the characteristic curve at the minimum and maximum densities. Find the ratio of these exposures. On the exposure chart mark two exposures which have the same ratio as those from the characteristic curve. Make a rectangle on the exposure chart with the help of the minimum and the maximum thicknesses and the two exposures. Draw the diagonal of this rectangle and select that KV line which is parallel or almost parallel to this diagonal. On this KV line, now read the corresponding exposures for the maximum and minimum thicknesses of the specimen.

With these exposures the density for which the chart is made (e.g. 2.0) would be obtained for the respective thickness. Therefore, modify these exposures with the help of the characteristic curve to obtain the minimum density for the maximum thickness and the maximum density for the minimum thickness. If the KV line chosen is exactly parallel to the diagonal then both these exposures would be the same. If, however, it is not parallel then the two exposures would be slightly different. Take the mean of the two and take the shot with this mean exposure. The required radiograph will be obtained.

Example

Let maximum specimen thickness = 4cm and minimum specimen thickness = 1 cm

We require a density of 1.0 for 4 cm and a density 3.0 for 1 cm. From the characteristic curve the relative exposure for these two densities has a ratio say, 10:1. On the exposure chart of Figure 6.24 we choose the exposures 100-mA-sec and 1000mA-sec which have the same ratio of 10:1 (one may choose 10 and 100 or 10,000, etc.). Make a rectangle on the exposure chart as shown and draw the diagonal. It can be seen that the 180 KV line is parallel to the diagonal.

We therefore select this KV line. On this line the exposure for 4 cm is 630mA-sec. This exposure will give a density of 2.0 for 4 cm but we require a density of 1.0. Therefore, a correction is made with the help of the characteristic curve and it comes out to be, say 350 mA-sec. Also 63mA-sec exposure will give a density of 2 for 1 cm thick section while a density of 3.0 is required. Corrected exposure for this section will also come out as 350mA-sec because the 180 KV line is exactly parallel to the diagonal. Hence if 180 KV is used and a 350 mA-sec exposure is given, we will get the required radiograph of the specimen and the film density range would be 1.0 - 3.0.

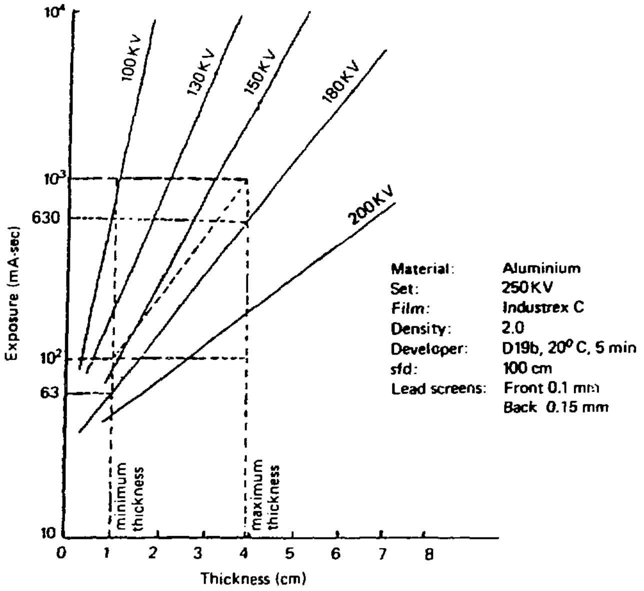


Figure 6.24 Diagonal method for determination of exposure.

6.5.4. Use of slide rules

Gamma ray exposures can also be calculated with the help of special slide rules which have scales for film speed, source strength, source-to-film distance, type of source, density required, and specimen thickness. By setting different variables on these scales exposure time can be read directly. Usually a booklet for guidance is provided with such slide rules.

6.5.5. Automatic devices

Automatic devices are now available for use in closed-loop controlled modern X-ray tubes. These devices automatically adjust the exposure. Knowledge of specimen thickness and material is not necessary. All one has to do is to select the film density.

6.6 RELATIVE ANGLE BETWEEN DIRECTION OF RADIATION AND FLAW DIRECTION

JIS Z 3104 (Methods of Radiographic Test and Classification of Radiographs for Steel Welds) specifies the radiographic arrangement as follows so that the degree of detection of planar defects such as cracks does not show a great difference between the centre and corners of a radiograph of a butt weld of flat plates. " The distance between the source and the penetrameter L_1 shall,as a rule, be not less than n times the effective length of the tested part L_3. The coefficient n shall be 2 for the common class and 3 for the special class." If a crack which is at right angles to the weld line and is present in the thickness direction is supposed to be formed, the radiation angle relative to the transverse crack is given by the following equation , as shown in Figure 6.25.

For the common class($L_1 \geq 2L_3$)

$$= \tan^{-1}\frac{(L_3/2)}{L_1} = \tan^{-1}(1/4)$$

$$= 14(\text{degrees})$$

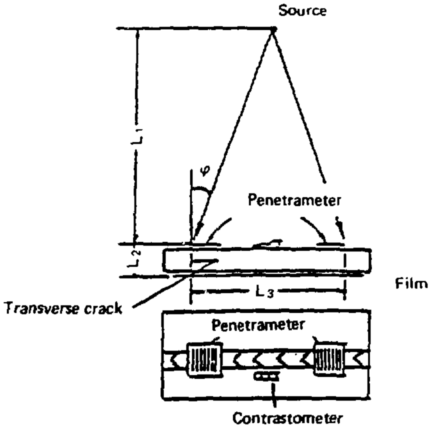


Figure 6.25 Radiographic arrangement for determining angle of radiation relative to transverse crack

For the special case ($L_1 \geq 3L_3$)

$$= \tan^{-1}\left(\frac{L_3/2}{L_1}\right) = \tan^{-1}(1/6)$$

$$= 9 \text{ (degrees)}$$

That is to say, this standard limits the effective length of the tested part so that the radiation angle relative to the transverse crack (hereinafter called the radiation angle) is approximately 14 degrees or less for the common class and approximately 9 degrees or less for the special class.

7. QUANTITATIVE EVALUATION METHODS FOR RADIOGRAPHIC IMAGE QUALITY

7.1. DETECTION AND DETAIL VISIBILITY OF FLAWS

Whether a defect can be identified on a radiograph or not is determined by the relationship between the density difference shown by the defect image, the radiographic contrast ΔD corresponding to the defect and the minimum density difference that allows the defect to be identified, namely, the minimum perceptible density difference ΔD_{min}.

$$|\Delta D| \geq |\Delta D_{min}| \quad (7.1)$$

$$|\Delta D| < |\Delta D_{min}| \quad (7.2)$$

The density difference is perceptible in the case of Equation (7.1), and not perceptible in the case of Equation (7.2)

Radiographic contrast , ΔD, is related to the material of the object to be radiographed, absolute value of its thickness and the difference in thickness, quality of the penetrating radiation,dose of scattered radiation which depends on the geometrical arrangement of irradiation, source size and intensity distribution, quality of X-ray film (including intensifying screen), and dose characteristics. Minimum perceptible density difference ΔD_{min} is related to the image size and density distribution, graininess of X-ray film(intensifying screen quality of radiation), density of the radiograph, viewing conditions for the radiograph (brightness of the film illuminator,brightness of the observation room,user non-use of the mask, and observation distance), and human factors.

Radiographic contrast ΔD when the density of a radiograph has changed is proportional only to film contrast

As shown in Figure 4.9, with no-screen X-ray film (low sensitivity,ultra-fine grain film), increases almost linearly with increase in density.

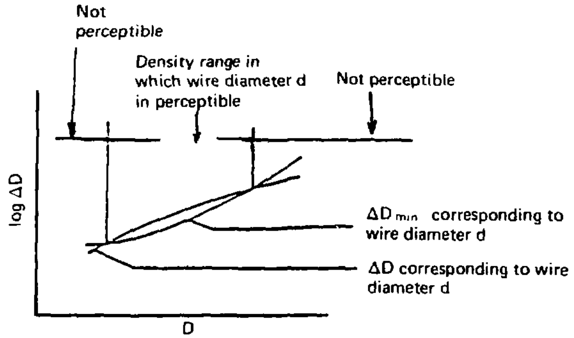


Figure 7.1 Relationship between density, ΔD and ΔD_{min}

The relationship between the density and minimum perceptible contrast ΔD_{min} of the wire image is shown in Figure 7.1. Here as long as ΔD corresponding to wire diameter d is above ΔD_{min} , a wire with a diameter of d is perceptible. In the low density range where γ is small, radiographic contrast ΔD is smaller than ΔD_{min}. Thus the wire is not perceptible. On the other hand, in the high density range where increase in ΔD_{min} due to density is greater than increase in ΔD, the wire is perceptible.

To discuss the perceptibility of a defect quantitatively, therefore, it is necessary to obtain the values of ΔD and ΔD_{miu} quantitatively.

7.2. RADIOGRAPHIC CONTRAST

Radiographic contrast D corresponding to a wire of diameter d of a penetrameter placed on a plate whose thickness is T can be obtained from the following formula.

$$D = -0.434.\gamma.\mu_p.\sigma.d/(1+n) \qquad 7.3$$

where γ = Gradient of the tangential line at density D of X-ray film characteristic curve
μ_p = X-ray quality when the sensitivity coefficient of the X-ray film is considered
σ = Correction coefficients by focal spot size and geometrical conditions of irradiation
n = Quotient obtained by dividing the dose rate of the scattered radiation that reaches the X-ray film uniformly multiplied by its sensitivity coefficient, by the dose rate of the penetrated radiation multiplied by its sensitivity coefficient.

Therefore once basic data on each factor is obtained, D corresponding to the radiographic conditions can be obtained by calculation.

7.2.1 **Film contrast**

Film contrast is defined in paragraph 4.7. Figure 7.2 shows examples of film contrast for several combinations of X-ray film and intensifying screens.

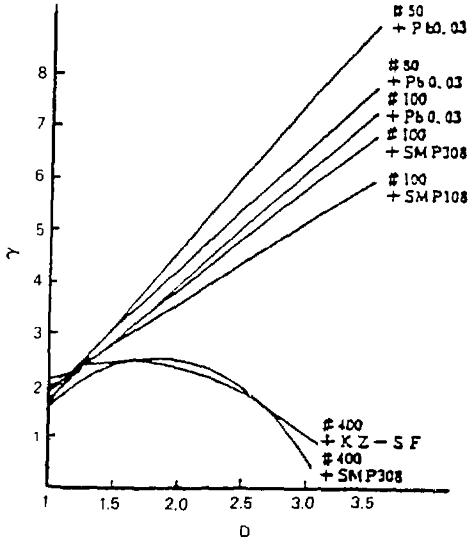


Figure 7.2 Relationship between density and film contrast for different combinations of X-ray films and intensifying screens.

7.2.2. **Correction coefficient of geometrical conditions**

When radiography is made with the arrangement shown in Figure 7.3, the apparent focal spot size d' at the position of a wire of a penetrameter can be obtained from the following formula.

$$d' = f.l/L \qquad 7.4$$

where l = Penetrameter - film distance
L = Focus - film distance

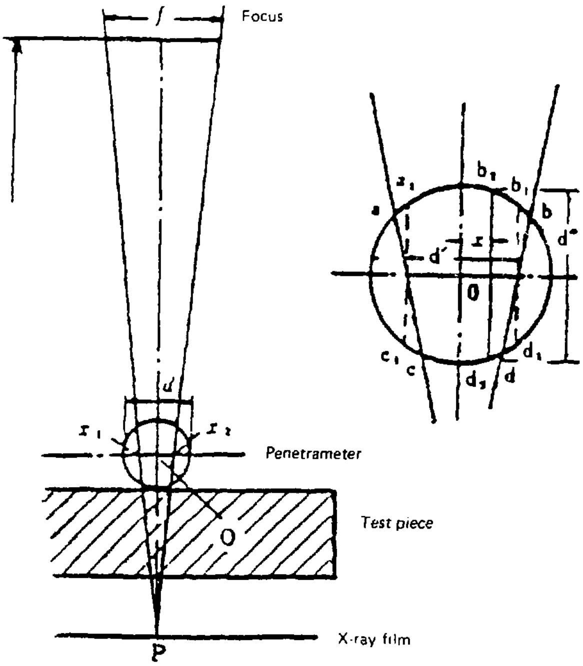


Figure 7.3 Absorption of X-rays by wire of penetrameter

where,

f = Focal spot size
L = Focus - film distance
d = Wire diameter
l = Penetrameter - film distance

Figure 7.4 shows the relationship between d'/d and σ.

The maximum value of σ is 1.0.

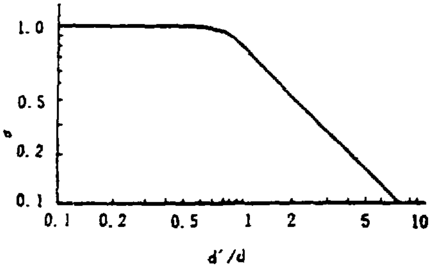


Figure 7.4 Relationship between d'/d and σ (wire)

7.2.3. Measurement of scattered radiation intensity ratio with X-ray Film

(1) Measurement by characteristic curves

Figure 7.5 shows the ordinary radiographic arrangement used in conducting a radiographic test(exposure of a large radiation field). The density of a radiograph taken with the radiographic arrangements shown by Figure 7.6 is denoted by D_1 and that of a radiograph

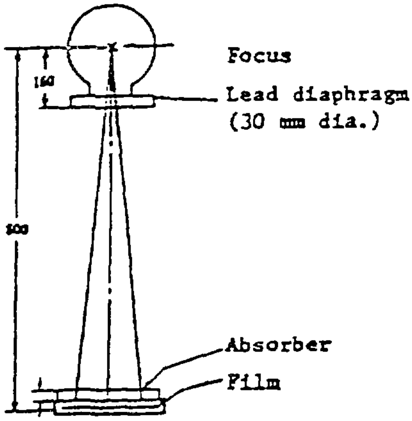


Figure 7.5 Radiographic arrangement

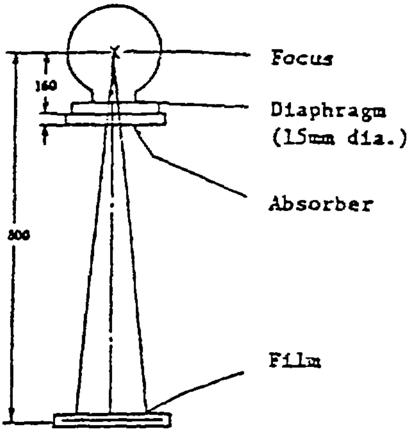


Figure 7.6 Radiographic arrangement

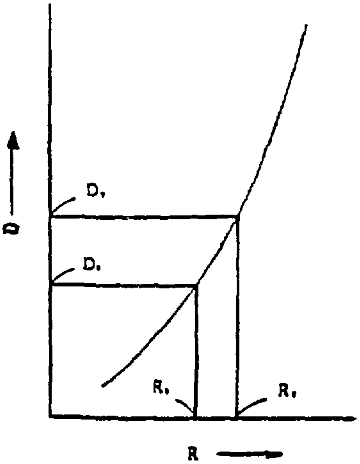


Figure 7.7 X-ray film dose characteristic curve

taken with the radiographic arrangement shown by Figure 7.5 is denoted by D_2, both under the same conditions. Then R_1 and R_2 against respective densities can be obtained from the X-ray dose characteristic curve shown by Figure 7.7. (R_1 and R_2 can be relative exposures.) he scattered direct radiation intensity ratio n is obtained from R_1 and R_2 by using the following equation.

$$n = R_2/R_1 - 1 \qquad 7.5$$

Figure 7.8 shows a scattered direct radiation intensity ratio curve.

(2) Measurement by exposure chart

Radiographs are taken with the radiographic arrangements shown by Figure 7.5 and Figure 7.6 and then an exposure chart such as shown by Figure 7.9 is prepared. If the exposure for a narrow radiation field where the amount of scattered X-rays is negligibly small is denoted by e'_1 and that for a wide radiation field by e_1, the scattered direct radiation intensity ratio n can be obtained from the following equation:

$$n = e'_1/e_1 - 1 \qquad 7.6$$

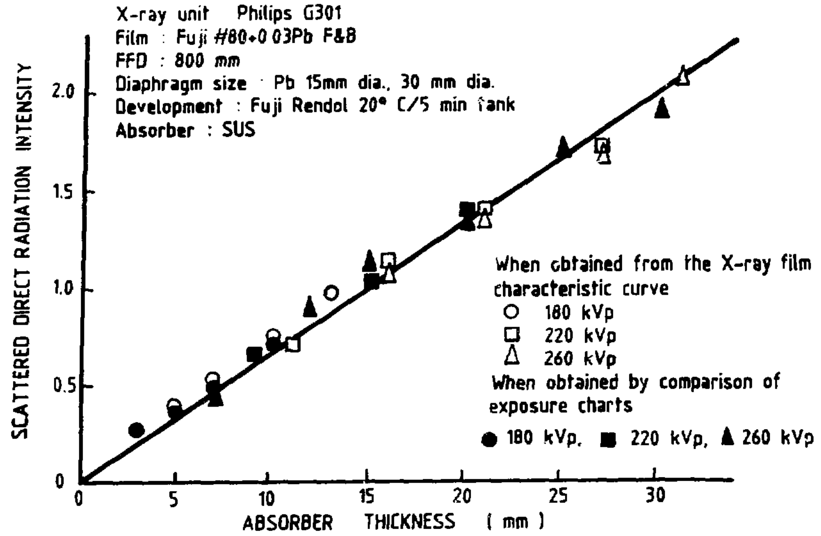


Figure 7.8 Relation between scattered direct radiation intensity and absorber thickness.

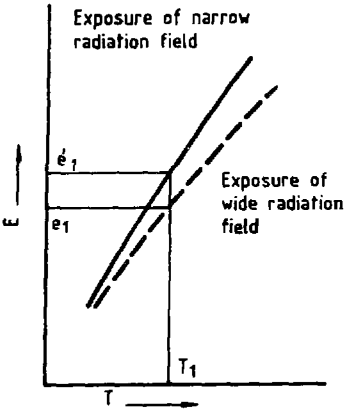


Figure 7.9 Exposure chart

7.3. MINIMUM PERCEPTIBLE CONTRAST

Minimum perceptible contrast ΔD_{min} is related to various factors such as those mentioned above. Figure 7.10 shows the relationship between the density of a radiograph observed in a dark room using a KS-3 type film illuminator and minimum perceptible contrast ΔD_{min}.

As shown in Figure 7.10 ΔD_{min} of the wire image increases with increase in density, and the smaller the width of the wire image ,the more remarkable the rate of increase. Figure 7.11 shows the relationship between the width of the wire image and ΔD_{min} as obtained from Figure 7.1.

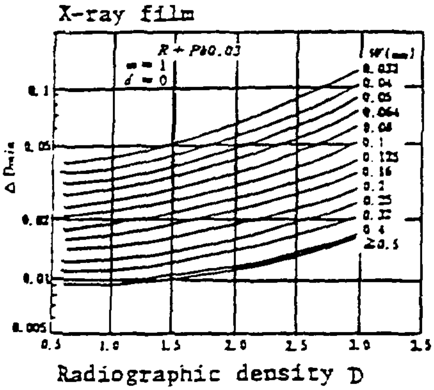


Figure 7.10

Relationship between radiographic density and minimum perceptible contrast (viewing conditions dark room, KS-3 type film illuminator)

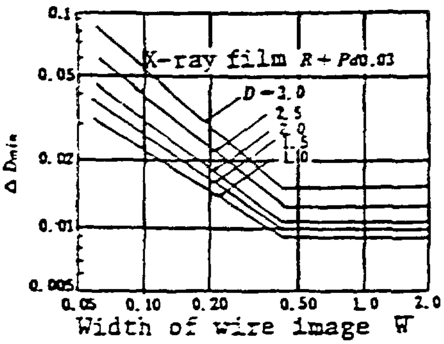


Figure 7.11

Relationship between the width of wire image and minimum perceptible contrast (obtained from Fig.7.1)

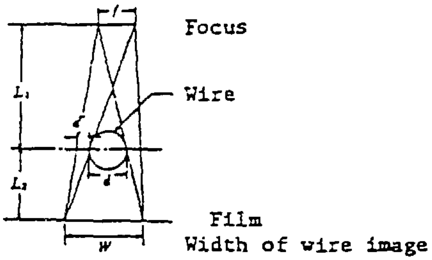


Figure 7.12 Width of wire image

Here the image width W of a wire of diameter d as shown by Figure 7.12 is given by the following formula.

$$W = m\,(d + d') \qquad 7.7$$

where,

m = magnifying factor
d' = apparent focal spot size at the position of a penetrameter wire

The value m is given by the following formula.

$$m = \frac{(L_1 + L_2)}{L_1} \qquad 7.8$$

where,

L_1 = focus - penetrameter distance
L_2 = *penetrameter - film distance*

So long as the width of the wire image is large, ΔD_{min} is constant, but it increases with decrease in width. The rate of this increase varies with the density and the higher the density the higher the rate of increase.

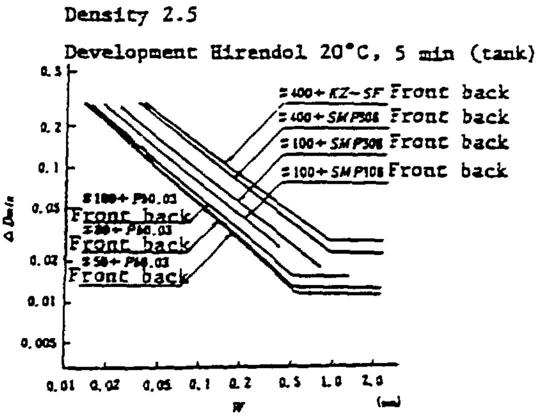


Figure 7.13 Relationship between wire image width of X-ray films and intensifying screens and ΔD_{min} for different combinations.

Figure 7.13 shows the relationship between the width of the wire image and minimum perceptible contrast ΔD_{min} for different combinations of X-ray films and intensifying screens. ΔD_{min} at the same width is maximum when the screen type X-ray film (#400 + KZ-SF) is combined with a fluorescent intensifying screen, and decreases with improvement in the graininess of the no-screen type X-ray films combined with a lead intensifying screen.

Table 7.1 shows a comparison of the number of cracks that can be detected when the combination of the X-ray film and intensifying screen is changed. To make the exposure time equal, it is necessary to increase the tube voltage with ultra-fine grain X-ray films (#50), and the difference in the number of cracks that can be detected is obvious.

TABLE 7.1. NUMBER OF PERCEPTIBLE CRACKS DEPENDING ON THE COMBINATION OF X-RAY FILM AND INTENSIFYING SCREEN

Film	Intensifying screen	Tube voltage	Photographic density		Radio-graphic contrast ΔD − A − B	Penetrameter sensitivity			Detectability of cracks			
			Base metal (maximum) A	Contrast meter 1 mm B		No. of cracks	ϕ mm	%	Clear	Normal	Not clear	Impossible
Fuji # 50	Lead foil Front back both 0.03 mm	200 kVp	2.04	1.90	0.14	4	0.20	1.1	14	7	5	0
Fuji # 80		212 "	2.08	1.92	0.16	4	0.20	1.1	12	6	5	3
Fuji #100		182 "	2.03	1.86	0.17	4	0.20	1.1	9	8	6	3
Fuji #100	SMP 108	158 "	1.96	1.70	0.26	4	0.20	1.1	7	10	4	5
Fuji #100	SMP 308	150 "	1.96	1.72	0.24	3	0.25	1.4	6	10	3	7
Fuji #150	Lead foil Front back both 0.03 mm	160 "	2.04	1.86	0.18	3	0.25	1.4	7	7	5	7
Fuji #200		138 "	1.95	1.81	0.14	3	0.25	1.4	4	3	8	11
Fuji #400	SMP 308	112 "	1.48	1.28	0.20	3	0.25	1.4	4	8	6	8
Fuji #400	KZ-SF	107 "	1.76	1.51	0.25	3	0.25	1.4	4	3	7	12

particularly in contrast to the combination of #400 film and KZ-SF. The better the graininess the higher the perceptibility. It is also to be noted that there is a great difference in the number of cracks that can be detected though there is not much difference in the penetrameter sensitivity. Therefore, in selecting a radiographic screen it is necessary to select an X-ray film and intensifying screen suited to the purpose.

7.4. APPARENT RADIOGRAPHIC CONTRAST

If the viewing room is well lighted, the light coming into the eyes includes the penetrating light of intensity L from the radiograph and the light of L_{s1}. Also ,if a fixed mask adjusted to the film size is not used , the light of L_{s2} around the edge of the radiograph is further added. Given $(L_{s1}+L_{s2})/L = n'$, the apparent radiographic contrast ΔD_a can be obtained from the formula

$$\Delta D_a = \frac{\Delta D}{1 + n'} \qquad 7.9$$

Addition of L_{s1} and L_{s2} reduces the apparent radiographic contrast , ΔD_a, to $1/1+n'$ of ΔD. The symbol n' in Equation (7.9) is the ratio of the intensity L_s (the sum of L_{s1} and L_{s2}) other than the penetrating light to the intensity L of the penetrating light. Therefore if L_s is constant, n' becomes larger as the density increases. Namely, the viewing of a high density radiograph is not influenced by the brightness of the room and the fixed mask of the illumination. Thus in order to prevent the apparent contrast ΔD_a of the radiograph from decreasing it is necessary to minimise light intensity L_s other than the penetrating light.

7.4.1. **Effect of brightness of film illuminator**

The relationship between ΔD and ΔD_{min} corresponding to wire diameter d when a film illuminator of a fixed brightness L'_0 is used is shown by the solid lines in Figure 7.14. Next suppose we observe a radiograph using a film illuminator of brightness L''_0 $(L''_0 > L'_0)$ When a radiograph of density D_1 is observed with a film illuminator of brightness L''_0 the following relationship holds between radiographic densities D_1 and D_2 which make equal the intensities of the beams of the penetrating light.

$$D_2 - D_1 = \log(L''_0/L'_0) \qquad 7.10$$

If both beams of the penetrating light have the same intensity when the minimum perceptible contrast ΔD_{min} is the same , ΔD_{min} with the illuminator of brightness L'' as calculated from equation 7.10 will be as shown by the broken line in Figure 7.14 which can

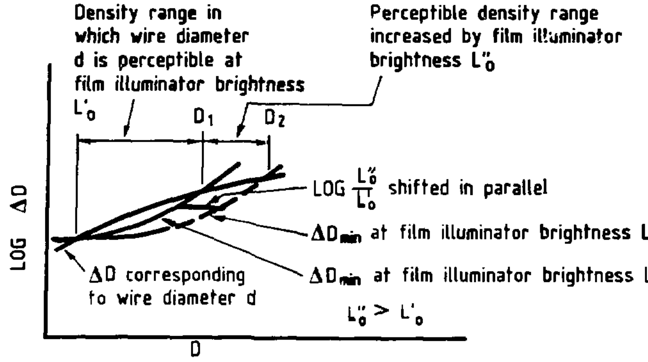


Figure 7.14 Relationship between density and penetrameter sensitivity (influence of film illuminator brightness)

be obtained by shifting the solid curve for ΔD_{min} by log (L'_o/L_o) in parallel sideways. If L'_o is four times as bright as L_o, ΔD_{min} corresponding to L'_o is obtained by shifting the curve in parallel to the right by log 4 $= 0.6$ in density.

7.4.2. **Effect of room brightness**

The relationship between ΔD and ΔD_{min} corresponding to wire diameter d in dark room observation is shown by a solid line in Figure 7.15.

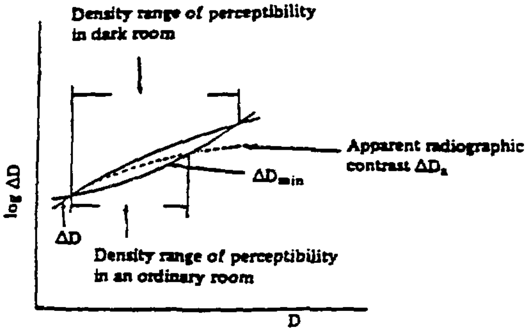


Figure 7.15 Relationship between density , ΔD and ΔD_{min}(influence of room brightness)

Now suppose that besides the penetrating light, light of a constant intensity L_{s1} comes into the eyes during observation in a room. At low density, n' is small because of the high intensity of the penetrating light and as is clear from equation (7.9) ΔD does not decrease appreciably. At high density however n' is large because of the low intensity of the penetrating light and apparently ΔD increases considerably. The above relationship is shown by the broken line in Figure 7.15.

Therefore when observation is made in an ordinary room the density range in which wire diameter d is perceptible is narrow as compared with that in a dark room as shown by Figure 7.15. This indicates that when viewing a radiograph it is necessary to exercise care that no light other than the penetrating light comes into the observer's eyes.

7.5. SELECTION OF SOURCE, FILM AND SCREEN

Radiographic contrast ΔD for a small defect whose thickness is ΔT is as shown in formula (7.3). To detect very small defects whose thickness is ΔT it is necessary to increase ΔD ,μ and σ and decrease n, as shown in formula (7.3). Of these factors, μ and n change greatly depending on the type of the source used for radiographic inspection that is the radiographic quality.

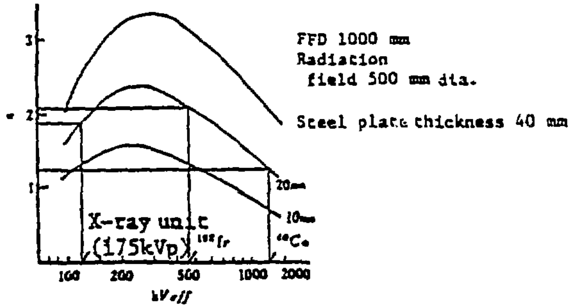


Figure 7.16 Relationship between effective energy and scattered direct radiation intensity ratio

TABLE 7.2 RELATIONSHIP BETWEEN TYPE OF SOURCE AND $\mu/(1+n)$ (TEST PIECE 20mm THICK STEEL PLATE)

Source	μ(Fe) (cm^{-1})	kV*eff*	*n*	$\frac{\mu}{1+n}$ (cm^{-1})
X-ray unit (175 kVp)	2.2	120	1.9	0.76
^{192}Ir	0.67	450	2.1	0.22
^{60}Co	0.42	1,250	1.2	0.19

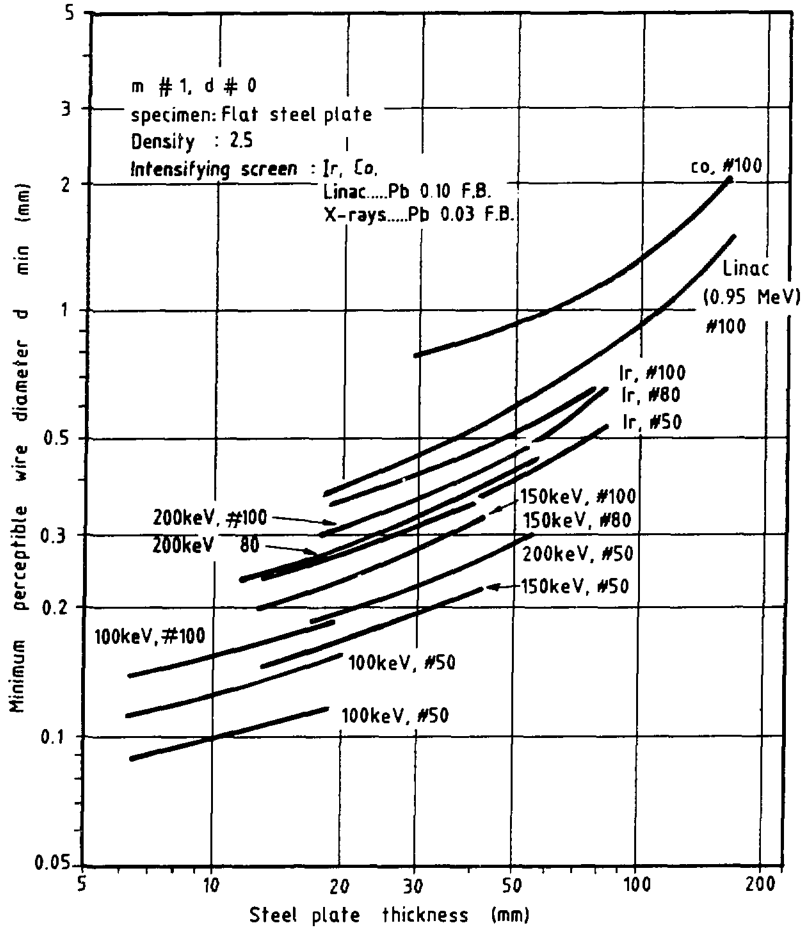


Figure 7.17 Relationship between the types of radiation source, film and screen and the minimum perceptible wire diameter

Regarding X-rays it is obvious that the absorption coefficient of X-rays is greater than those of Co^{60}, Cs^{137} and Ir^{192} sources when absorption coefficient μ (Fe) is considered as the radiation quality corresponding to the tube voltage. Figure 7.16 shows the relationship between the scattered direct radiation intensity ratio with respect to a steel plate of constant thickness. If there is no change in the type of the X-ray film ,density of the radiograph and photographic arrangement ,the radiographic contrast of a very small defect whose thickness is ΔT is proportional to $\mu/(1+n)$ calculated for an X-ray unit and gamma ray units (Ir^{192} and Co^{60}). Table 7.2 shows that $\mu/(1+n)$,that is radiographic contrast ΔD, is greater with the X-ray unit(tube voltage 175 KVp) and decreases in order of Ir^{192} and Co^{60} sources.

The image quality of a radiograph varies greatly depending on the combination of radiation source, film and screen. Figure 7.17 shows the relationship between the steel plate thickness and the minimum perceptible wire diameter obtained by calculations. In the calculations the effects of image enlargement and geometrical unsharpness are not taken into consideration. In Figure 7.17 when #100 X-ray films are used the minimum perceptible wire diameter decreases from 0.79mm diam., to 0.47mm diam., to 0.42mm and to 0.37mm diam. in the order of the radiation source : Co^{60}, Linac (output:0.95 MeV), Ir^{192} and X-rays (effective energy : 200 keV) respectively at a steel plate thickness of 30mm for example. When the type of X-ray film is varied with the radiation source, the minimum perceptible wire diameter for the X-ray films #100,#80, and #50 is decreased to 0.37mm, 0.34mm and 0.23mm respectively on the assumption that the steel plate is 30mm thick and that the radiation source is X-rays (effective energy : 22 keV). These results are helpful in selecting the radiation source , film and screen when steel castings are radiographed.

8. RADIOGRAPHIC TECHNIQUES

8.1. BASIC PRINCIPLES

The ability to develop correct radiographic procedures or techniques for parts of any size or material is gained primarily through experience. There are, however, certain fundamentals that are important and useful as guides in this process, and these are as follows:

(a) The correct film, screens and radiation energy must be used;
(b) Scattered radiation must be understood and controlled;
(c) Those factors that affect contrast and definition must be understood and procedures employed to produce the optimum sensitivity. For example, the film should generally be as close to the part as possible and proper d/t ratios should be used.

Before the proper radiographic procedure or technique can be determined each of the following factors must be considered;

(i) any specification requirement that must be followed;
(ii) available information on the end use of the part, such as service requirements, areas of stress, amount and location of machining or finishing, safety standards, etc.
(iii) Selection of the correct orientation of the beam of radiation, the area or areas of the specimen being examined and the location of the film;
(iv) the minimum number of exposures needed to provide for a thorough and proper assessment of the specimen according to its requirements;
(v) the determination of exposure conditions to be used for each exposure, considering also the proper film, screens, filters etc.

The proper technique to be used is a function of the size, shape and composition of the specimen. As a casting becomes larger and more complex so the radiographic technique becomes more complex. Technique can also be affected if a specific type of defect is suspected. For example, a different approach may be necessary to locate a dispersed type of defect such as porosity than that needed to locate a crack or hot tear. The geometry and composition of a specimen are also responsible for the amount of scattered radiation that may reach the film. The technique must be adjusted to minimise the effects of scatter.

8.1.1. Selection of film, screens and radiation energy

Selection Guides for the selection of industrial radiographic films of four major manufacturers are given in TABLE 8.1. to 8.4. These guides also give some idea (i) about the radiation energy to be used, and (ii) the use of the film with or without lead screens or with fluorescent screens.

8.1.2. Problems of scatter

Scattered radiation can be a major problem in the radiography of large or complex parts, especially those of the heavier metals such as steel, bronze and cast iron. In general, parts can be divided into three groups in relation to the scatter problem.

8.1.2.1. Group 1

A part of fairly uniform thickness where good contact between the film and the part can be maintained and where the part itself absorbs most of the scattered radiation before it reaches the film. In this case scatter is no real problem and special precautions are not necessary.

8.1.2.2. Group 2

A part that produces scatter at the edges but has sufficient area that some loss of sensitivity at the edges is acceptable.

TABLE 8.1. SELECTION GUIDE FOR AGFA GEVAERT INDUSTRIAL RADIOGRAPHIC FILMS

Suggestions for using STRUCTURIX films with X-rays

Thickness of material (inches)		Energy range and suggested film types				
		50-80 kV	80-120 kV	120-150 kV	150-250 kV	250-400 kV
Magnesium	0 - 1/4	D2-D4	D2	D2	D2	
	1/4 - 1/2	D4-D2	D2-D4	D2-D4	D2	
	1/2 - 1	D4-D5-D7	D4-D5	D4	D2	
	1 - 2	D7	D4-D5	D4	D4	D2 D4
	2 - 4		D7	D4 D5-D7	D4	
	4 - 8			D7	D4	
Aluminium	0 - 1/4	D2-D4	D2-D4	D4	D2	
	1/4 - 1/2	D7-D5	D4	D2-D4	D2	
	1/2 - 1	D7	D4-D5	D4-D5	D2	
	1 - 2	D7	D7-D5	D7-D5-D4	D4	D5
	2 - 4		D7	D7	D4-D5	
	4 - 8				D7	D7
Steel	0 - 1/4		D7	D7-D5-D4	D2-D4	
	1/4 - 1/2			D7-D5-D4	D7-D5-D4-D2	D4-D2
	1/2 - 1			D7	D7-D5-D4	D7-D5-D4
	1 - 2				D7-D4	D7-D5-D4
	2 - 4					D7

Suggestions for using STRUCTURIX films with gamma rays

Thickness of material (inches)		Source (1 curie) and suggested film types		
		IRIDIUM-192	CAESIUM-137	COBALT-60
Magnesium	1/2 - 1	D2-D4		
	1 - 2	D4		
	2 - 4	D4-D5-D7		
	over 4	D7		
Aluminium	1/2 - 1	D2-D4		
	1 - 2	D4-D5		
	2 - 4	D7		
	over 4	D7		
Steel	0 - 1/4	D2-D4		
	1/4 - 1/2	D4-D5-D7-D2	D4-D2	
	1/2 - 1	D7-D5-D4	D4-D5-D7	D4
	1 - 2	D7-D5-D4	D7	D4-D5-D7
	2 - 4	D7	D7	D7-D5
	over 4			D7

TABLE 8.2. SELECTION GUIDE FOR KODAK(UK) INDUSTRIAL RADIOGRAPHIC FILMS

Material thickness In	50 to 80 KV	80 to 120 KV	120 to 150 KV	150 to 250 KV	Iridium 192	250 to 400 KV	1 mev	Cobalt 60	2 mev	Radium	6 to 31 mev
					Steel						
0 to ¼	KNF	KNF	AX,CX								
¼ to ½		KNF	AX,CS	AX,CX		MX					
½ to 1			KNF	AX,CS	AX,CX	AX,CX	MX		MX	AX,CS	
1 to 2				KNF	AX,CX	AX,CX	MX	AX,CX	MX	AX,CX	MX
2 to 4					KNF		AX,CX	AX,CX	AX,CX	KNF	MX
4 to 8							KNF	KNF	AX,CX	KNF	AX,CX
Over 8									KNF		AX,CX
					Aluminium						
0 to ¼	MX	MX									
¼ to ½	AX,CX	MX	MX	MX							
½ to 1	AX,CX	MX	MX	MX		MX					
1 to 2	KNF	AX,CX	AX,CX	MX	MX	MX					
2 to 4		KNF	AX,CX	AX,CX	MX	AX,CX					
4 to 8			KNF	KNF	AX,CX	KNF					
					Bronze						
0 to ¼		KNF	AX,CX	MX	MX	MX	MX				
¼ to ½		KNF	AX,CX	AX,CX	AX,CX	MX	MX		MX		
½ to 1				KNF	AX,CX	AX,CX	MX	AX,CX	MX	AX,CX	
1 to 2					KNF	KNF	MX	AX,CX	MX	AX,CX	MX
2 to 4					KNF		AX,CX	KNF	AX,CX	KNF	MX
4 to 8							KNF	KNF	AX,CX		AX,CX
Over 8									KNF		AX,CX
					Magnisium						
0 to ¼	MX	MX									
¼ to ½	MX	MX	MX								
½ to 1	AX,CX	MX	MX		MX						
1 to 2	AX,CX	MX	MX	MX	MX						
2 to 4	KNF	AX,CX	AX,CX	MX	AX,CX						
4 to 8		KNF	AX,CX	AX,CX	KNF						

MX = Industrex MX, AX = Industrex AX, CX= Industrex CX KNF = Kodak No Screen F

Note: All of the above films shall be used with or without lead screens.

TABLE 8.3. SELECTION GUIDE FOR KODAK(USA) INDUSTRIAL RADIOGRAPHIC FILMS

Material thickness In.	50 to 80 KV	80 to 120 KV	120 to 150 KV	150 to 250 KV	Ir-192	250 to 400 KV	1 mev	Co-60	2 mev	Radium	6 to 31 mev
Steel											
0 to ¼	KNF	KNF	AX,AA	R,M,TMX T							
¼ to ½	KBBF	KNF	AX,AA	AX,AA		R,M, TMX,T					
½ to 1		KBBF	KNF*	AX,AA	AX,AA	AX,AA	R,M, TMX,T		R,M, TMX,T	AX,AA	
1 to 2				KNF	AX,AA	AX,AA	R,M, TMX,T	AX,AA	R,M, TMX,T	AX,AA	R,M,TMX,T
2 to 4				KBBF	KNF	KBBF	AX,AA	AX,AA	AX,AA	KNF	R,M,TMX,T
4 to 8						KBBF	KNF	KNF	AX,AA	KNF	AX,AA
Over 8									KNF		AX,AA
Aluminium											
0 to ¼	R,M, TMX,T	R,M, TMX,T									
¼ to ½	AX,AA	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T							
½ to 1	AX,AA	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T		R,M, TMX,T					
1 to 2	KNF	AX,AA	AX,AA	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T					
2 to 4	KBBF	KNF	AX,AA	AX,AA	R,M, TMX,T	AX,AA					
4 to 8		KBBF	KNF	KNF	AX,AA	KNF					
Over 8					KBBF						
Bronze											
0 to ¼	KBBF	KNF	AX,AA	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T				
¼ to ½		KNF	AX,AA	AX,AA	AX,AA	R,M, TMX,T	R,M, TMX,T		R,M, TMX,T		
½ to 1		KBBF	KBBF	KNF	AX,AA	AX,AA	R,M, TMX,T	AX,AA	R,M, TMX,T	AX,AA	
1 to 2			KBBF	KBBF	KNF	KNF	R,M, TMX,T	AX,AA	R,M, TMX,T	AX,AA	R,M,TMX,T
2 to 4					KNF	KBBF	AX,AA	KNF	AX,AA	KNF	R,M,TMX,T
4 to 8							KNF	KNF	AX,AA		AX,AA
Over 8									KNF		AX,AA
Magnesium											
0 to ¼	R,M, TMX,T	R,M, TMX,T									
¼ to ½	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T								
½ to 1	AX,AA	R,M, TMX,T	R,M, TMX,T		R,M, TMX,T						
1 to 2	AX,AA	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T	R,M, TMX,T						
2 to 4	KNF	AX,AA	AX,AA	R,M, TMX,T	AX,AA						
4 to 8		KNF	AX,AA	AX,AA	KNF						
Over 8				KBBF							

KNF = Kodak No, screen film   AX = Industrex AX   KBBF = Kodak Blue Brand Film

AA = Industrex AA   R = Industrex R   M = Industrex M   TMX = Industrex TMX

T = Industrex T

Note: All the above films except KBBF shall be used with or without lead screen KBBF shall be used with salt screens.

TABLE 8.4. SELECTION GUIDE FOR FUJI INDUSTRIAL RADIOGRAPHIC FILMS

Material and Thicknesses (mm)		X-ray Tube Voltage (kVp)							Cobalt-60
		below 50	50~80	80~120	120~150	150~250	250~400	1000	
Light Metals	0 ~ 6	50 · 80	50	50					
	6 ~ 13	50 · 80	50 · 80	50 · 80	50				
	13 ~ 25	80 · 100	50 · 80	50 · 80	50 · 80	50			
	25 ~ 50	100 · 150	80 · 100	50 · 80	50 · 80	50			
	50 ~ 100	150	100 · 150	80 · 100	80 · 100	80 · 100			
	over 100		400*	150	100	80 · 100			
Iron and Steel	0 ~ 6	150	150	80 · 100	80 · 100	50 · 80	50	50	50
	6 ~ 13		400* · 150	150	80 · 100	80 · 100	50 · 80	50	50
	13 ~ 25			400* · 150	150	100	80 · 100	50 · 80	50 · 80
	25 ~ 50			400*	400* · 150	150	100	50 · 80	50·80·100
	50 ~ 100				400*	400* · 150	100 · 150	80 · 100	80·100·150
	over 100					400*	400* · 150	100 · 150	100· 150
Bronze	0 ~ 6		400* · 150	100 · 150	80 · 100	50 · 80	50	50	50
	6 ~ 13			400* · 150	100 · 150	80 · 100	50 · 80	50	50 · 80
	13 ~ 25			400*	400*	150	80 · 100	50 · 80	50 · 80
	25 ~ 50				400*	400*	100 · 150	80 · 100	80 · 100
	50 ~ 100						400*	80·100·150	100 · 150
	over 100							150	150

* Indicates combined use of fluorescent screens.

These may be X-rayed in a manner similar to that used for well-blocked parts, although the use of standard lead screens or a filter may be required.

8.1.2.3. Group 3

Parts in which scatter from one section undercuts the image of another section and reduces the film sensitivity. For example, parts that have some sections an appreciable distance from the film or where reduced sensitivity at the edges cannot be allowed. These parts may require the use of masking or blocking techniques, filters, high-energy radiation or a combination of these in order to reduce scatter. Remedial measures for protection against scattered radiation are given in section 6.3.2.

8.2. Radiography of welds

In the radiography of welds, the arrangement of the film, weld and source of radiation is very important. Keeping this consideration in view, welds are discussed under three main headings:-

Seam welds
Circumferential welds
Nozzle welds

8.2.1. Seam welds

The usual technique is where the film lies parallel to and adjacent to one surface of the weld and the source of radiation is on the other side of the weld at some distance from it.

Careful location is necessary as it is often not possible to see both sides of the welds at a time.
A few source-film arrangements suitable for radiography of seam welds in specimens of different shapes are shown in Figure 8.1.

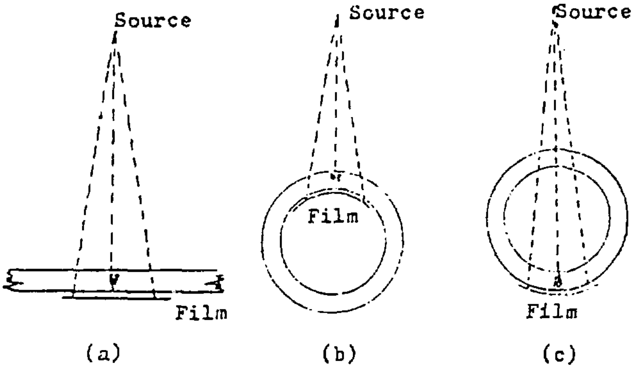


Figure 8.1 Radiography of seam welds.

In the case of welded plain sheets, the arrangement is very simple as shown in Figure 8.1.a.

In the case of seam welds in pipes, the film, if possible, is placed inside the pipe and the source of radiation outside or vice versa (Figure 8.1.b).

In the case where the inside of the pipe is inaccessible both the film and the source of radiation are placed outside the pipe but on opposite sides (Figure 8.1.c).

8.2.2. Circumferential welds in pipes

8.2.2.1 Location of source and film

Circumferential welds occur in pipes as well as in spherical specimens. The following techniques are used to take radiographs of circumferential welds in pipe:-

(a) Film inside, source outside

This technique (Figure 8.2) can only be used when the pipe is large enough to make access to the weld possible.

(b) Film outside, source inside

This technique with the source at the centre, Figure 8.3.a. allows the complete weld to be examined in a single shot thereby saving a considerable amount of time. However, the size of the source to be used is determined by the radius of the pipe and the thickness of the weld.

Sometimes the smallest available source placed at the centre may not satisfy the penumbral conditions. Off centring it , Figure 8.3.b., may allow this technique to be used, but a number of shots would be required for complete examination of the weld.

(c) Film outside, source outside

This technique may be applied in two ways. One is the double wall single image method (Figure 8.4.a) where the source to film distance is kept short so as to diffuse the image of the upper part of the weld and give a radiograph of the part closest to the film.

The second is the double wall double image method (Figure 8.4b) where the sfd is kept long giving an elliptical image of the weld.

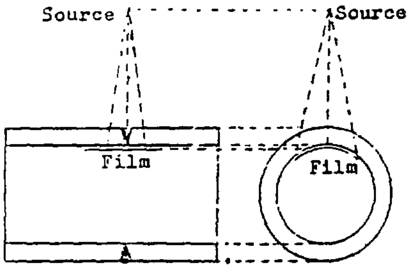


Figure 8.2. Film inside, source outside arrangement.

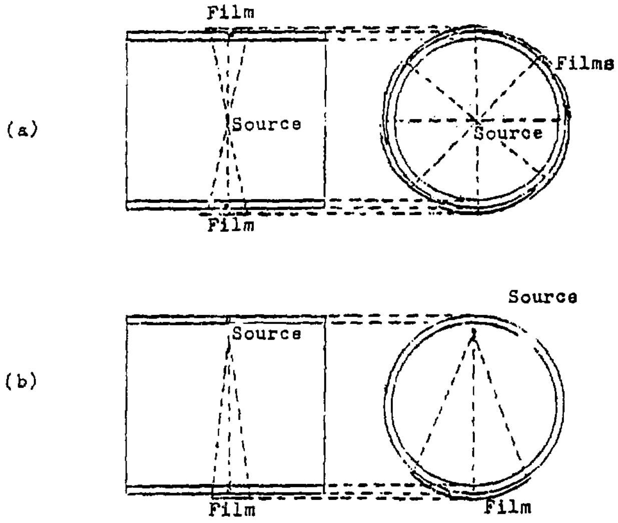


Figure 8.3. Film outside, source inside arrangement.

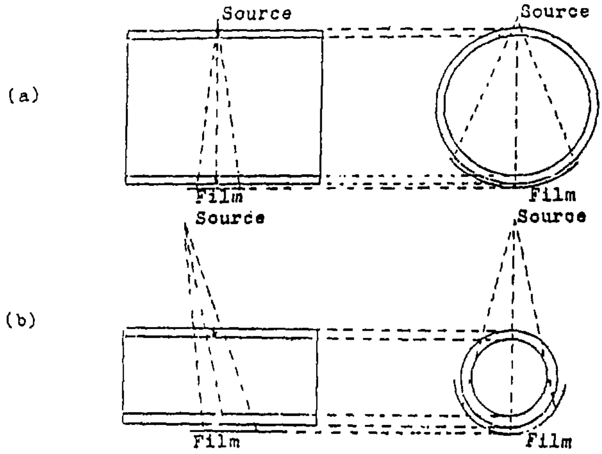


Figure 8.4 Film outside, source outside method.

8.2.2.2. Number of radiographs in a weld seam

(a) Double wall single image technique

In a double wall single image technique for circumferential welds of pipe, the outside diameter of the pipe is denoted by G, as shown in Figure 8.5,the wall thickness by t, the focus-film distance by L, and the film-specimen surface distance by L_f, the specimen surface being on the film side. If the maximum specified value of the angle of radiation with the transverse crack is denoted by ϕ (degree) , the range of the test portion that meets the specified angle (hereinafter called the effective range of the test portion) is the hatched portion in Figure 8.5 and the centre angle ,2α (degrees) is given by the following equation:

$$2\alpha = 2\,(\eta + \phi)$$

$$= \frac{2\{\sin^{-1}(1-2t/G)\sin\phi + \phi\}}{2(G/L-L_f)^{-1}-1} \qquad 8.1$$

Equation (8.1) is written as Equation (8.2) when considering a case where the effective range of the test portion is maximum, that is , a case where the outside diameter of the pipe ,G, is equal to L - L_f and the wall thickness is sufficiently small as compared to the outside diameter.

$$(2\alpha)_{max} = 4 \qquad 8.2$$

Equation 8.1 is written as Equation 8.3 regardless of the wall thickness when the effective area of the test portion is maximum, that is , when the focus to film distance is infinite.

$$(2\alpha)_{min} = 2\phi \qquad 8.3$$

The number of radiographs is given by the following equation when the film is wound round the pipe in the double wall single image technique:

$$N = 360°/2\alpha \qquad 8.4$$

Therefore when the results of Equations 8.2 and 8.3 are expressed in other words, the maximum number of radiographs, N_{max}, in the double wall single image technique is given by the following equation regardless of the shape of the pipe:

$$N_{max} = 360°/2\phi = 180°/\phi \qquad 8.5$$

The minimum number of radiographs, N_{min}, is given by the following equation. N_{min} cannot be smaller than 1/2 of N_{max}.

$$N_{min} = 360°/4\phi = 90°/\phi \qquad 8.6$$

(b) Internal-film technique

As shown in Figure 8.6 , if the hatched portion is the effective range of the test portion in one radiograph in the internal film technique for circumferential welds of pipe, the angle, 2α, with the effective range of the test portion is given by the following equation:

$$2\alpha = 2\{\phi - \eta\}$$

$$= \frac{2\{\phi - \sin^{-1}(1+2t/g)\sin\phi\}}{2(g/L-L_f)^{-1}+1} \qquad 8.7$$

where g is the inside diameter of the pipe . Equation 8.7 is rewritten as Equation 8.8

regardless of the wall thickness when the effective range of the test portion is maximum, that is , when the focus-film distance is infinite.

$$(2\alpha)_{min} = 2\phi \tag{8.8}$$

The number of radiographs is given by the following equation in the internal-film technique:

$$N = 360^{\circ}/2\alpha \tag{8.9}$$

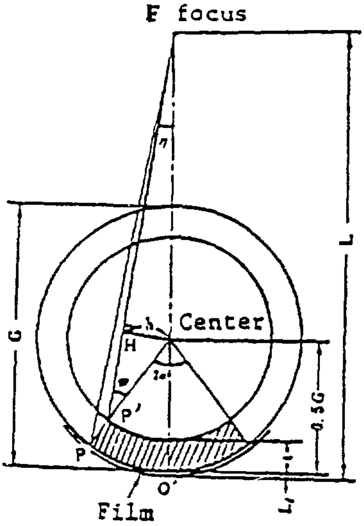


Figure 8.5 Double wall single image technique

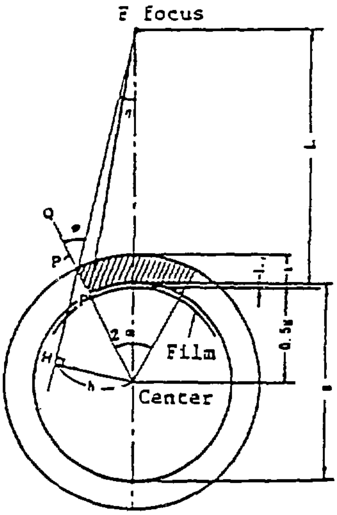


Figure 8.6 Internal film technique

(The hatched portions indicate the effective range of the test portion)

Therefore when the results of Equation 8.8 are expressed in words the minimum number of radiographs, N_{min} in the internal film technique is given by the following equation. However ,since the focus-film distance is finite, the number of radiographs must be larger than that obtained by this equation.

$$N_{min} = 360^{\circ}/2\phi = 180^{\circ}/\phi \tag{8.10}$$

8.2.2.3. **Number of radiographs when the radiographic technique and the angle of radiation with cracks is considered**

When the angle of radiation with a crack exceeds 15 degrees, the crack cannot often be detected with increase in the angle of radiation and the degree of crack detection decreases remarkably.

If the specified maximum angle of radiation with a transverse crack in a circumferential weld in a pipe is 15 degrees (corresponding to the common class specified in JIS Z 3104), the number of radiographs by each technique is as follows:

(a) Double wall single image technique and double wall double image technique

The number of radiographs in the double wall single image technique and double wall double image technique varies a little depending on the outside diameter and wall thickness of the pipe and radiographic arrangement. As is apparent from Equation (8.6), at least six or more radiographs must be taken. However, it is unnecessary to take radiographs exceeding 12 in number if there is no change in the arrangement of the source,film and specimen during radiography.

(b) Internal source technique

In the internal source technique, it is general practice to take a radiograph by setting the focus at the centre of the pipe. In this case, the effective range of the test portion relative to a transverse crack in the thickness direction is the full circumference of the pipe.

(c) Internal film technique

As is apparent from Equation (8.10) at least 12 or more radiographs must be taken in the internal film technique.

8.2.3. Nozzle weld

The arrangement of the film and source of radiographic examination of a nozzle weld is shown in Figure 8.7.

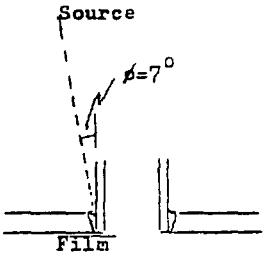


Figure 8.7 Radiography of nozzle welds.

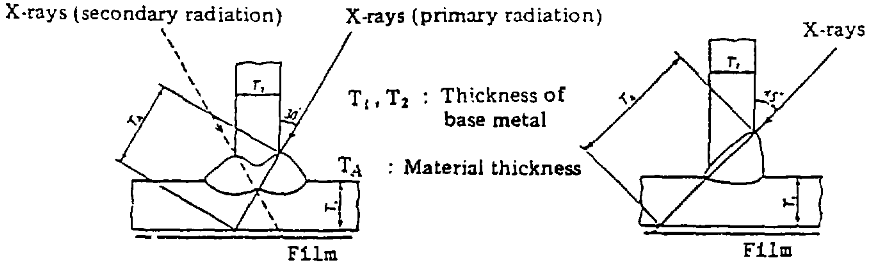
The source of radiation is placed such that the beam axis makes an angle of about 7° with the vertical wall of the nozzle.

8.2.4 Radiographic examination of Tee welds

The direction of radiation of X-rays has a considerable effect on the results of the radiographic examination of Tee welds. Therefore, it is necessary to specify the standard direction of radiation.

In Figure 8.8(a) the penetrated thickness of the weld is somewhat small and therefore X-rays as a rule are radiated from the 30° direction.

In Figure 8.8(b) X-rays as a rule are radiated from the 45° direction.



$T_A = 1.1 \times (T_1 + T_2)$

(a) Angle of radiation of 30°

$T_A = 1.4 \times (T_1 + T_2)$

(b) Angle of radiation of 45°

Figure 8.8 Direction of radiation of X-rays and material thickness for T - welds.

In a Tee weld the largest penetrated thickness in the test portion is about two times the smallest penetrated thickness. Therefore, if radiography is carried out in this state, it is very difficult to keep the whole test portion within a high density range of a radiograph. As shown in Figure 8.9 if a thickness compensating wedge is used to reduce this thickness difference radiography is easy and it is also very easy to observe the radiograph making it possible to check the weld thoroughly.

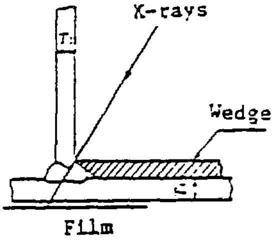


Figure 8.9 Thickness compensating wedge

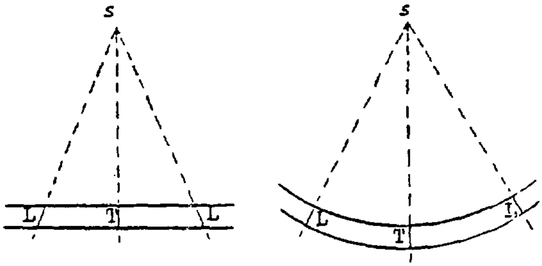


Figure 8.10 Maximum permissible diagnostic length.

8.2.5. **Diagnostic length of weld**

The following are two rules which are used to find the maximum permissible diagnostic length i.e. the length of the weld that can be covered in a single exposure.

(a) For critical examination.

$$L = 1.06T$$

Where L and T are the oblique and the normal thickness respectively as seen by the radiation, Figure 8.10.

(b) For general purpose examination

$$L = 1.1T.$$

8.3. RADIOGRAPHY OF CASTINGS

From the point of view of radiography, castings may be studied under the following two headings.

Single thickness castings
Multithickness castings

8.3.1. **Single thickness casting**

This is the simplest of all the castings encountered in radiography. The required exposure can be determined as discussed under section 6.4.

8.3.2. Multithickness casting

The various techniques employed in radiography of multithickness castings are as under;

(a) Addition of defectless material

In the case of a casting which has a finite number of thicknesses which are regular in geometry, the difference in thickness is compensated by adding defectless material. The exposure will correspond to the maximum thickness. The technique is based on the optimum density consideration for every thickness involved.

(b) Diagonal method

This is based on an acceptable density range consideration (e.g. 1.7 to 3.5). If the maximum thickness involved in a multithickness casting falls within the scope of the exposure chart to be used, the diagonal, hence the KV, etc., can be found corresponding to the maximum and the minimum thickness (discussed in detail under section 6.5.3.4).

In case the thickness range is too large to give a diagonal exactly or nearly parallel to a KV line in the exposure chart, the thickness range can be divided into a number of subranges.

(c) Multiple Film Technique

A combination of films of different speeds may be used to radiograph a multithickness casting. This is discussed in detail under section 8.5.1. The technique is also known as the sandwich technique.

The methods discussed above are usually used for general purpose radiography. For critical examinations every thickness should be exposed separately for optimum density (e.g. density of 2.0).

8.4. LOCATION OF DEFECTS

A radiograph is a two-dimensional shadow picture of an object having three dimensions. An image formed at point C, Figure 8.11, in a radiography may be due to a defect located anywhere on the line AB parallel to the beam direction. One radiograph cannot, therefore, reveal the position of the defect in the third dimension. But a knowledge of the position of a defect in three dimensions is necessary;

(i) to help in interpretation.
(ii) to assess the severity of the defect.
(iii) to help in the necessary repairs.

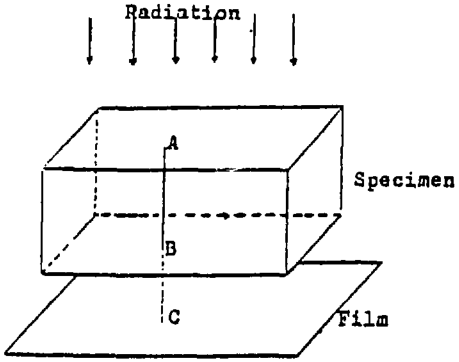


Figure 8.11 Two dimensional shadow formation of a defect.

The following methods can be used to locate a defect in three dimensions.

8.4.1. Right angle method

If the dimensions of the specimen permit, two radiographs are made from two positions at right angles to each other as shown in Figure 8.12.

Either of the two radiographs will give the position of the defect in two dimensions while the other radiograph will provide the third dimension.

This method is the simplest yet is very accurate. The limitation is that at least two dimensions of the specimen should be such as to make the radiography possible with the available radiation.

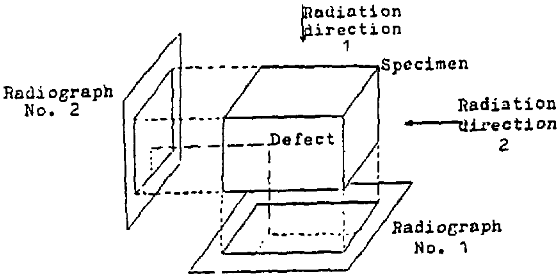


Figure 8.12 Right angle method.

8.4.2. Tube shift method

This method is specially suitable for plate like objects and in situations where the right angle method is not possible.

The method is as follows:

(i) A normal radiograph is made and the two dimensional position of the defect is marked on the top of the specimen.

(ii) Two exposures are made on the same film, each of approximately half the total exposure at a known sfd. Between these exposures the tube is shifted through a measured distance in a plane parallel to the film and across the larger dimension of the defect Figure 8.13.

(iii) After processing, the shift of the image of the defect is measured.

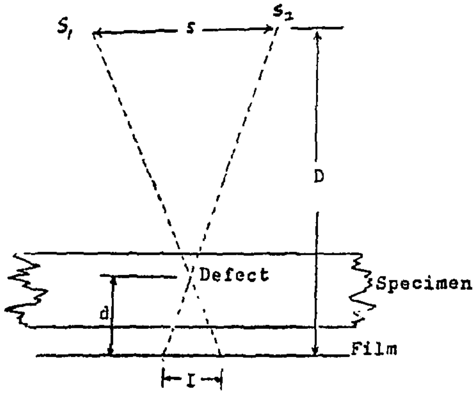


Figure 8.13 Tube shift method.

Let,

S = total tube shift.
D = sfd (measured along the normal).
I = Image shift.
D = height of the defect above the film.

For similar triangles we have

$$S/I = (D-d)/d = D/d - 1$$

or

$$d = \frac{D/(S + I)}{I} = \frac{DI}{S + I}$$

To find out the height of the defect above the bottom of the specimen one can subtract the thickness of cassette and the screen, if used, from d.

The tube shift should not be too large or too small as this may distort the images or may result in insufficient separation of the images making the measurement of the image shift more difficult. A suitable value may by 1/3rd of sfd.

8.4.3. Lead marker method

This is one of the most common methods of defect location. The procedure is somewhat similar to the tube shift method but in this case the tube shift and the sfd need not be measured. The method is as follows.

(i) Make a normal radiograph and mark the two dimensional position of the defect on the top of the specimen.

(ii) Two lead markers (fine wires of lead or of any other heavy metal) are placed one on the source side of the specimen and the other on the film side near to and along the length and on either side of the defect. Care must be taken that the images of the defect and markers do not coincide or get mixed (Figure 8.14).

(iii) Two exposures are made on a single film, each of half the total exposure. Between these exposures the tube is shifted through a distance in a plane parallel to that of the film and across the length of the defect (Figure 8.14).

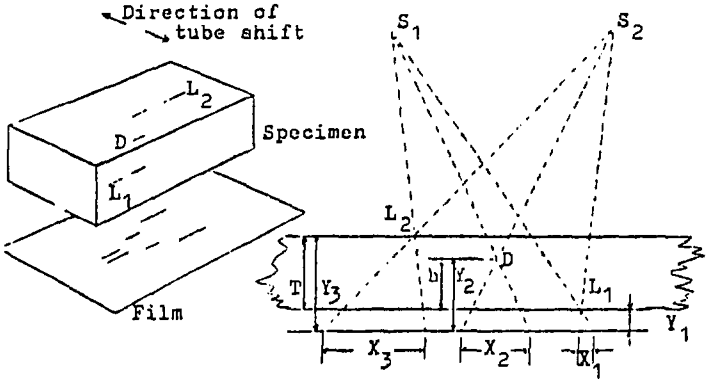


Figure 8.14 Lead marker method.

(iv) After processing, the shifts of the images of the defect and the markers are measured.

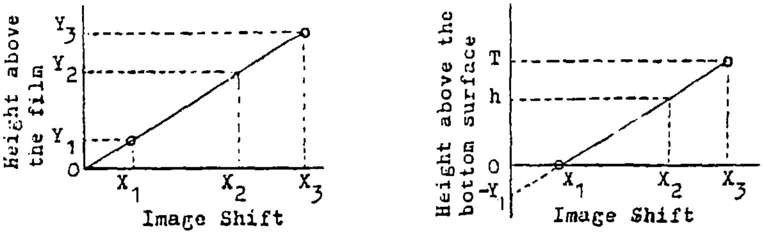
It can be shown that, provided the markers are placed fairly close to the defect, the image shifts of the defect and markers are proportional to their distances from the film. The thickness of the markers is considered to be negligible.

Let h = height of the defect above the bottom of the specimen.
and X_1, X_2 and X_3 be image shifts of lower marker, defect and upper marker respectively.

Y_1. Y_2 and Y_3 be heights above the film of the lower marker, defect and upper marker respectively.

A straight line is be obtained (Figure 8.15.a) when the height above the film (Y) is plotted against the image shift (X) for the two markers. From this graph height of the defect above the film can be read against the image shift of the defect.

A better and more practical way is to plot the height above the bottom surface of the specimen against the image shift (Figure 8.15.b). This eliminates the measurement of the thickness of cassette and screens. In this case the height of the lower marker is zero and that of the upper one is T (thickness of the specimen).



(a) (b)

Figure 8.15. Height vs image shift.

From Figure 8.15. one can find out the height h of the defect from the bottom of the specimen, if its image shift (X) is known. 'h' can also be calculated by the formula,

$$h = \frac{T.(X_2 - X_1)}{(X_3 - X_1)}$$

8.4.4. Stereo-radiography

Two radiographs of the specimen are taken from two slightly different directions. The angle between these directions is the same as the angle subtended by the human eyes while viewing these radiographs. In the stereo viewer the left eye sees one radiograph and the right eye the other. In this way a realistic three dimensional effect is obtained giving the visual assessment of the position of the defect. The principle of the stereo-radiography is illustrated in Figure 8.16.

8.5 MISCELLANEOUS TECHNIQUES

By using different types of radiation and recording systems or by arranging these in a special manner, different techniques have been evolved for special purposes. Some of those more commonly used are discussed below.

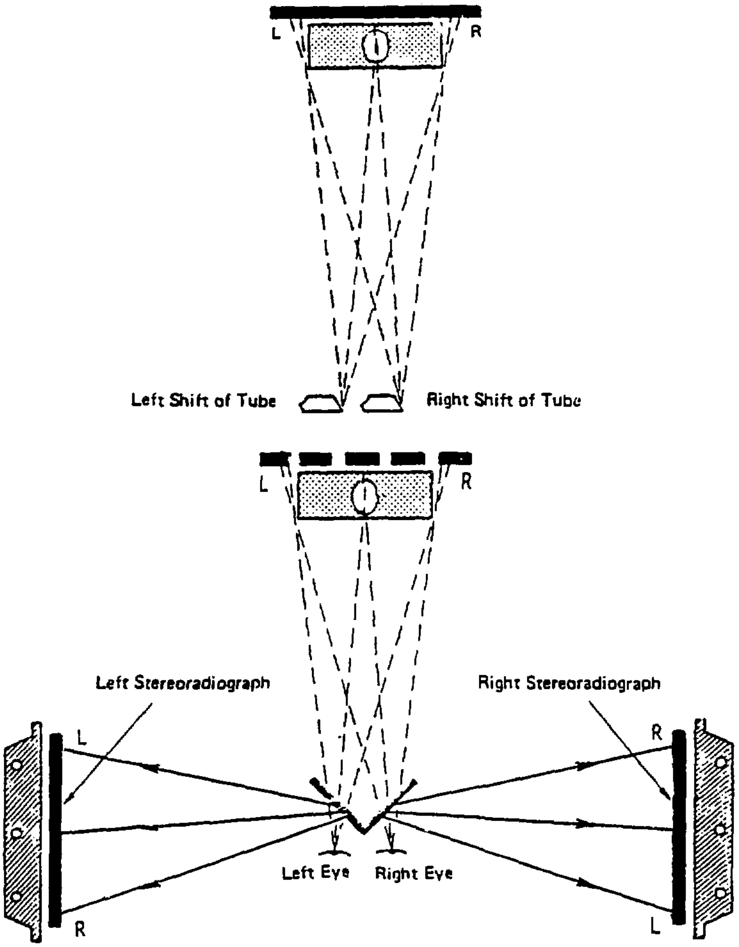


Figure 8.16 Schematic diagrams showing the methods of making and viewing stereo-radiographs.

8.5.1. Radiography of multithickness objects

In the case of multithickness objects it is often difficult to get acceptable densities under thick and thin sections in a single radiograph. This difficulty can be overcome in three ways.

Firstly, by reducing the contrast of the radiograph by using :

(i) higher KV X-rays or higher energy gamma rays.
(ii) filters between the X-ray tube and the specimen,
(iii) low contrast film.

The second method is to compensate for the difference of thicknesses by using some material which is known to be defect-free. This method would be applicable for samples of regular shape.

The third method is to use films of different speeds. The kilovoltage, the exposure and the combination of films are selected in such a way that in a single exposure, correct density is obtained under the thick sections on the faster films, whereas the slower films record correct images of the thin sections.

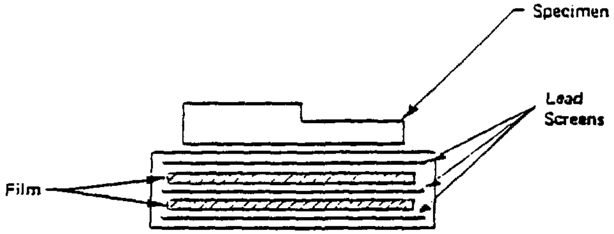


Figure 8.17 Double film technique

The lead intensifying screens, if used, will cause an increase or decrease in the exposure ratios of the films depending upon their relative positions. For example, if a slower film with lead screens is placed in front of a faster film, the exposure ratio decreases because the faster film has effectively become less fast due to the absorption of radiation in the lead screens of the slower film. Vice versa is also true. In this way it is possible to vary differentially the relative exposures of the films. Hence the use of intensifying screens may be, sometimes, advantageous.

8.5.2. Measurement of pipe wall thickness

It is sometimes required to measure the wall thickness of a pipe radiographically. Different arrangements for this purpose and formulae are given below.

(a) Large diameter pipes

The shadow of the wall is recorded on a film using the arrangement shown in Figure 8.18 and the width of this shadow, BM, is measured.

If O = 30° then the wall thickness W is given by

$$W = R - \frac{h(3.73R - d)}{1.73h - d} - R.\frac{1.73h - d}{(1.73h-d)^2 + h^2} \qquad 8.1$$

If 0 = 45° then

$$W = R - \frac{h(2.414R - d)}{h - d} - R.\frac{h - d}{(h-d)^2 + h^2} \qquad 8.2$$

If 0 = 60° then

$$W = R - \frac{h(1.73R - d)}{.577h - d} - R.\frac{.577h - d}{(.577h-d)^2 + h^2} \qquad 8.3$$

If 0 = 90° then

$$W = R - \frac{h\ (R - d)}{d} + R.\frac{d}{h^2 + d^2} \qquad 8.4$$

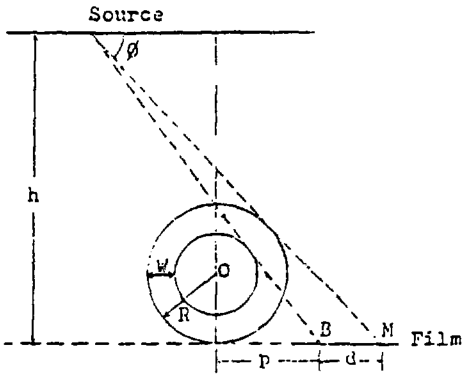


Figure 8.18 Wall thickness measurement of large diameter pipe.

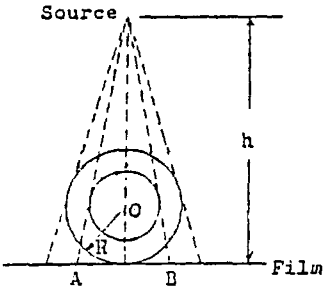


Figure 8.19 Wall thickness measurement of small diameter pipe.

(b) Small diameter pipes

The full image of the pipe is recorded using the arrangement shown in Figure 8.19 and the distance AB measured. The wall thickness, W, is then given by :

$$W = R - \frac{(h - R)p}{p^2 + h^2} \quad , \text{ where } p = \frac{AB}{2}$$

8.5.3. Micro-radiography

Specially prepared thin samples are radiographed at extremely low energies (e.g. 5KV) on an ultrafine grain film. The radiograph when enlarged gives the structural details of the specimen. Micro-radiography is mainly applied in metallurgical studies.

8.5.4. Enlargement radiography

In some situations an enlarged image of an object is desired. To get the enlargement of the image the object to film distance is increased. To overcome the penumbral effects a source of an extremely small size in used.

8.5.5. High speed or flash radiography

For the radiography of moving objects, the exposure time should be very small and, at the same time, the intensity of the X-rays should be extremely high. This is achieved by discharging huge condensers through special X-ray tubes which give current of the order of thousands of amperes for a short time (of the order of a millionth of a second).

This technique is normally applied in ballistics.

8.5.6. Auto-radiography

In this case the specimen itself contains the material in radioactive form. When a film is placed in contact with the specimen, an autoradiograph is obtained showing the distribution of the radioactive material within the specimen. The technique is mainly used in the field of botany and metallurgy.

8.5.7. Electron transmission radiography

A beam of high energy X-rays is used to produce photoelectrons from a lead screen. These electron after passing through the specimen (of very low absorption like paper etc.) expose the film and an electron radiograph is obtained. The arrangement is shown in the Figure 8.20. The clear film on the back is used to absorb any electrons emitted by the cassette.

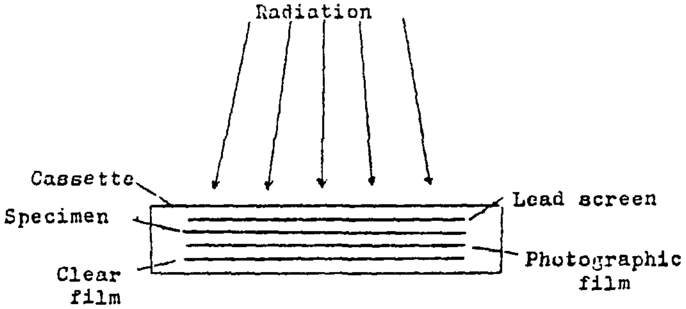


Figure 8.20 Arrangement for electron transmission radiograph.

8.5.8. Electron emission radiography

In this case a beam of X-rays is used to produce photoelectrons from the specimen itself. These electrons expose the film which is placed in contact with the specimen. Since emission of electrons depends upon the atomic number of an element, the electron emission will give the distribution of elements of different atomic numbers.

8.5.9. Neutron radiography

In this case a neutron beam is used to radiograph the specimen. The recording system in this case will not be photosensitive film since these are insensitive to neutrons. The following methods are used to record the image :-

(i) A gold foil is used which records the image in terms of the activity produced. This image can be transferred on to a film by taking an autoradiograph of the foil. Some other suitable material can replace gold.

(ii) Neutrons transmitted through the specimen are made to strike a thin neutron scintillator plate. The scintillations thus produced expose the film which is in contact with the scintillator.

In certain cases neutron-radiography is advantageous as compared to X or gamma radiography *for example* :-

1. if the specimen is radioactive.
2. if the specimen contains thermal neutron absorbers or light elements.
3. if two elements whose atomic numbers are not very different have to be distinguished.

8.5.10. Proton radiography

For special type of studies a proton beam can also be used. The number of protons transmitted through a specimen whose thickness is close to the proton range is very sensitive to exact thickness. This helps in detecting very small local variations in density and thickness.

9. RADIOGRAPHIC VIEWING AND INTERPRETATION

9.1. VIEWING OF RADIOGRAPHS

The most important stage in radiography is film viewing. It is of little use taking care to obtain maximum detail on the radiograph, if the viewing conditions are such that this detail is not perceived. To achieve satisfactory viewing of radiographs, film density, illuminator brightness, background lighting and human eye visibility must fulfil certain requirements. These factors are individually discussed here.

Density. In deciding on an optimum film density and suitable film viewing conditions for maximum sensitivity, it is important to emphasise that film density and viewing screen brightness are inter-related parameters. Minimum observable contrast, i.e. the minimum discernible density difference on a film placed on an illuminated screen, depends on the brightness of the light reaching the eye of the observer through the film and on the degree of dark-adaptation of the observer. It is reasonable to assume that the discernibility of fine detail such as low contrast lines (crack images, etc.) also depends in the same manner on the brightness of the image, as presented to the eye of the observer. It follows therefore that it is possible to have information on a radiograph which, when it is placed on an illuminated screen of suitable brightness, is not visible. By changing the screen brightness (usually increasing), more detail may be made visible. Therefore "correct film density" is only meaningful on the assumption that illuminations of suitable brightness are used, and conversely suitable film-viewing conditions have to relate to the film density being used. Most codes of good practice for radiographic inspection specify an acceptable film density which is based on the density contrast characteristics of good commercial X-ray films. This acceptable film density is usually approximately 2.0 for films for use with metal intensifying screens, but densities as high as 3.0 are sometimes recommended.

Illuminator Brightness : Recommendations for illuminator brightness are detailed for three film densities, 1.0, 2.0, and 3.0. Values of screen brightness for intermediate densities can be interpolated. Densities greater than 4 are not generally used. In addition to screen brightness, it is necessary to consider the importance of glare. Fine-grain film increases in contrast up to a very high density (of at least 6) and it may be argued that to get maximum sensitivity such high densities should be used. If suitable high-intensity illuminators for these very high densities are built, however, there are such serious problems with glare when films are changed or badly masked, that the inherent advantage of the high density tends to be lost. The colour of the illuminator light should normally be white, but colours between orange and pale green are acceptable.

The luminance (of brightness) of the illuminated radiograph should be not less than 30 cd/m , and wherever possible approximately 100cd/m or greater.

This minimum value requires the following illuminator brightnesses :

for film density 1.0 : 300 cd/m ,
for film density 2.0 : 3000 cd/m ,
for film density 3.0 : 30000 cd/m ,

The brightness of a viewing screen can be checked with most ordinary photographic exposure meters, if a suitable light meter is not available. The exposure meter should be held with its sensitive element close to the screen and should be set for a film speed of 100 ASA. Then a reading on the meter of an exposure of 0.01 at f: 10 corresponds to a screen brightness of 1000 cd/m .

Background Lighting : The light should be diffused, but it need not be fully diffused; for example, one sheet of thin opal glass will usually be found to be adequate (greater thicknesses absorb more light and so reduce the screen brightness). The illuminated area should be masked to the minimum required for viewing the radiographic image. The edge of the radiograph should always be masked, and if the radiograph contains regions of density which are considerably less dense than the area under examination, these also should be masked off. The radiograph should be examined in a darkened room or enclosure, with care being taken that as little light as possible is reflected off the film surface directly toward the observer. In practice there is usually sufficient light transmitted through a radiograph on an illuminated screen to provide ambient light for writing, etc. but, if desired, the ambient lighting can be increased, provided that the source of this light does not produce any specular reflections off the surface of the radiograph. The luminance of a white opaque card put in place of the radiograph, due to the ambient light, should not exceed 10% of the luminance of the illuminated film in the area under inspection. (This can be checked with a photographic exposure meter).

Eyesight of observer: All film readers should be checked annually for their ability to see small details at their normal film viewing distance. Wearing of reading spectacles or use of a magnifying lens may be necessary. All film readers should be able to read the letters and numbers in the eye testing charts such that:

(a) Distant vision should equal to 20/30 or better in at least one eye, either uncorrected or corrected.
(b) Near vision should permit reading a minimum of Jaeger number 2 or equivalent type and size letters not less than 30cm on a standard Jaeger test chart for near vision, in at least one eye, corrected.
(c) Colour vision should be sufficient that the observer can distinguish and differentiate contrast between the colours used in the NDT method concerned.

As adaptation depends markedly on the lighting conditions to which the observer is subjected before viewing, firm rules are not possible. As guidance, an observer coming from full sunlight should allow at least 10 min in subdued lighting before commencing viewing; from ordinary artificial room lighting about 30s adaptation is necessary. The adaptation time should be one continuous period of time. If the eyes are subject to the full brightness of the illuminator during the changing of radiographs, at least 30s re-adaptation is necessary.

The film viewing distance should be that at which the observer passes the eyesight test but the maximum distance should be of the order of 40cm. The use of a low power magnifying lens (x3 to x4) of reasonable area is strongly recommended and such a lens should always be available.

Viewing of radiographs requires, beside the factors mentioned above, full concentration and peace of mind. If possible it should be carried out in a separate, calm and quiet room situated in a less noisy environment.

It would be preferable to have an illuminator of variable brightness to give both low and high intensities at the discretion of the viewer.

9.2. EVALUATION OF RADIOGRAPHIC QUALITY

Radiographic quality may be defined in terms of contrast, definition and graininess present in a radiograph. These qualities in turn are influenced by a large number of factors important among which are radiation energy, filtration, specimen thickness, density and atomic number, size of the radiation source, geometric conditions of source-to-film (SFD) and object-to-film (OFD) distances, scattered radiations, film-screen combinations and film type and processing. Details of how these factors individually or collectively affect various parameters of radiographic image quality have been discussed in Chapter 6. In general an improvement in the radiographic quality can be brought about by the following :

(i) Energy of Radiation

The lowering of the energy in the case of X-ray, or the use of X-rays instead of relatively simpler-to-use gamma radiation, produces for thin wall thicknesses a clear improvement in contrast and thus image quality.

(ii) Use of Finer-grained Film

The use of finer-grained film also requires the extension of exposure periods. The gain in image quality does, however, allow finer imaging and so recognition of defects at the time of the test and not only when the defect has grown to such an extent as to become subject to a reclamation or even the cause of some damage.

(iii)Film-to-Screen Contact

The effect of a good or bad contact between film and screen on the radiograph, and thus on image quality, has only been systematically examined during the past two years. Two variables have made themselves apparent during this, namely that:

- the film density is appreciably lower when the screen has too large a separation from the film, because the intensifying effect of the screens is lost, and that:

- the loss of image quality, as evidenced by the image quality number, is measurable even when the distance between screen and film is only a few tenths of a millimetre.

These two points indicate the necessity to use evacuable cassettes or film-screen combinations vacuum-packed and sealed by the manufacturer.

(iv) Scattered Radiation

Although it is standard practice to use shuttering to limit the primary radiation at the tube window, or from the source, in order to reduce undesirable irradiation of the areas of the test object not being investigated, the practice of fixing a scatter radiation shield behind the film is more difficult to promote. As is known, such a shielding cannot be simply held in place with magnets and the use of sticky tapes is also similarly unsatisfactory. Despite these difficulties one should still regard such shielding as being of value if scattering bodies are in the near vicinity (distance < 1.5 m) which could be hit by primary radiation, generate scattered radiation themselves and expose the film, reducing contrast. Control radiographs, which can be relatively quickly produced, prove in an unequivocal manner the necessity of this measure.

In practice it is very complicated and expensive to assess radiographic quality by making on each radiograph measurements of contrast, definition and graininess. What is done instead is to use Image Quality Indicators (IQIs), of which there are different types, to get an idea of the flaw detection capability. This is measured in terms of IQI sensitivity.

The values of IQI sensitivity desirable in good radiographic work range from 1 to 2%. While assessing the radiographic sensitivity with the help of IQIs it should be seen that the appropriate IQIs suited to the test specimen (according to type and thickness of the test specimen) have been used. The method of their placement on the test specimen is the next important thing to be noted. The sensitivity should then be calculated from the wire or the step which is visible in the radiograph using the formula given in Section 6.2.

The procedure for processing the film should be investigated and the density of the radiographic image measured. Knowing that the radiographic quality of especially contrast is better at higher densities, only radiographs having proper density should be accepted for interpretation and evaluation. 1.5 to 3.0 is usually accepted as an acceptable range. The procedure of film processing itself can produce some spurious indications on the radiograph which can be confusing and there is a chance that these be mistaken for real defects. Such spurious indications should therefore be carefully identified before undertaking interpretation of radiographs for defects. These spurious indications which are also sometimes termed as misleading images or artefacts have been explained in Section 5.9. The films used should be as fresh as possible and should have a fog level which is admissible. A fog density of up to 0.3 is treated as tolerable in many situations. The sources of fog density, if suspected, should be known. If it is due to aging of the film the stock must be replaced while if it is due to scattering or overdevelopment corrective measures should be taken.

Each radiograph should have an identification number to enable correlation of defects from the radiographs with the size and location of these defects in the actual test specimen. This is important both from the point of view of repairing the defective specimen as well as for accepting or rejecting the specimen.

In addition all the other factors which have an influence on the radiographic quality should be thoroughly understood and verified for proper assessment and ultimate control and improvement of radiographic quality.

9.3. NATURE OF DISCONTINUITIES IN RADIOGRAPHY

A radiograph is a shadow picture of an object recorded on to a photographic film using X-rays or gamma rays. To obtain a radiograph, therefore, we place the specimen between a source of X or gamma radiation and a photographic film for a predetermined time. The appearance of the shadow of a defect is influenced by the shape of the defect, orientation of the defect with respect to the direction of radiation and the plane of the film and the size of the source and its distances from the defect and the film. As regards the geometric aspects of shadow formation only the rectilinear propagation property of the X or gamma rays is important and, therefore, we shall discuss the shadow formation in terms of ordinary light.

Defects of different shapes will give rise to different types of shadows. It is to be remembered that a radiograph gives a two-dimensional picture of a three-dimensional defect. For example a gas hole which is actually spherical in nature will show up as a circular patch. A crack which actually has a length, width and depth, if detected, will form a line. Pipes and other cylindrical defects will have different shapes in the radiograph depending upon their orientation with respect to the beam direction.

If the beam direction is not perpendicular or if the plane of the defect is not parallel to the plane of the film the shadow will be distorted as shown in Figure 9.1. Because of this distortion sometimes a particular defect can produce a shadow which may be interpreted as some other type of defect. A fine crack may be diffused altogether hardly leaving any image behind. Although before taking a radiograph one may not have any idea abut the orientation of the defects present, efforts are usually made to place the film as parallel to the specimen and as normal to the direction of radiation as possible.

The image sharpness or definition will depend on the source dimensions, the object-to-film distance and the source to film distance. Better definition may be obtained by making the focal spot size of the source as small as possible, by keeping the source-to-film distance as

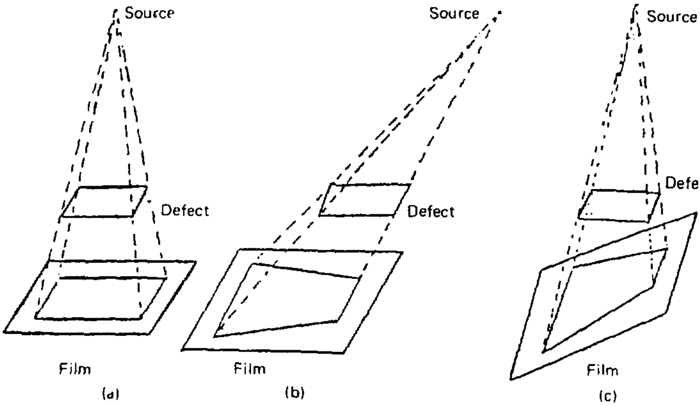


Figure 9.1 Effect of (a) normal beam, (b) oblique beam and (c) inclined film on the shadow.

large as possible and by placing the film in contact with the specimen. The values of unsharpness permitted for critical examination are of the order of 0.025mm while those for general work are 0.05mm. Based on these the minimum source-to-film distance recommended for critical examination is given by

$$\frac{d(F + 1)}{0.025}$$

where d is the specimen thickness
and F is the diagonal cross-section of the focal spot.

For general work the minimum value of source-to-film is

$$\frac{d(F + 1)}{0.05}$$

The defects closer to the film i.e. in the lower portions of a thick specimen will therefore be better defined as compared to the defects located away from the film i.e. in the upper portions of the specimen.

9.3.1. Typical defects of interest in radiographic inspection

Radiography is basically involved in the detection of all sorts of material discontinuities which can influence the attenuation of radiation. In weldments these discontinuities are cracks, porosity, blow holes, metallic and non-metallic inclusions, lack of fusion, lack of penetration, undercut, root and other cavities, excessive penetration, overlap, burn through and misalignment etc. The typical defects associated with various casting processes and which need to be detected by radiography are porosity, blowholes, piping, inclusions, sponginess, shrinkage, hot tears, cold shuts, unfused chaplet, misplaced core, segregation etc. The forging and rolling defects of interest are laminations, seams, forging laps, centre bursts, clinks (thermal cracks) and flakes (hairline cracks), hot tears, stringers, overheating and pipes.

The ability of radiography to detect planar type defects, such as cracks, lack of side wall fusion and inter-run fusion in welds,and seams, laps and laminations in forgings,is limited. It is not always possible to predict the location and orientation of a crack and if the defect lies in a plane that differs substantially from that of the beam of radiation it will not be revealed. The visibility of the radiographic image of a crack in such circumstances is also influenced by the width and depth of the crack and by the irregularity of its path through the section in which it lies.

9.4. INTERPRETATION OF RADIOGRAPHIC IMAGES

The objective of radiographic examination of a specimen is to detect and identify the internal defects. Correct interpretation of radiographs, therefore, is of great importance. Images in a radiograph may be due to one of the following reasons :-

(i) surface marks on the specimen
(ii) internal defects
(iii) artefacts

The outstanding requirement is that the causes of all the images in a radiograph must be identified and images due to internal defects be sorted. It is also essential that all the internal defects be identified in terms of their nature, size or extent and position. It must, however, be made clear that it is not strictly the responsibility of the interpreter of a radiograph to do any more than just report faithfully on the nature, size, location, etc., of the defects revealed by radiography, and the problem of acceptance or rejection of the specimen is not normally within his scope. However in situations where the interpreter is also expected to give his views on the acceptance and rejection of the test specimen then the interpretation must be done after correct understanding of the standards of inspection.

For effective interpretation of a radiograph a knowledge of the following is necessary.

(a) Radiographic technique employed and the sensitivity achieved (b) Characteristic radiographic appearances of various defects, and the modification of these appearances by various factors (c) Details about the specimen, its manufacturing process and the probable defects associated with this process. (d) Details of radiographic procedures. These are discussed briefly hereafter.

(a) Radiographic Technique

Factors such as the quality of radiation, geometry, films, intensifying screens and density all affect the sensitivity of fault detection. Therefore, without a knowledge of the technique employed, it is extremely difficult to interpret a radiograph. Sometimes it is necessary to reconstruct geometrically the condition of radiography, to assist in the identification of images in angled shots. The radiographic technique or procedure will specify at least information such as

i. Type of material to be radiographed
ii. Material thickness range to be radiographed
iii. Type of radiation source, effective focal spot or source size, X-ray equipment voltage rating, and manufacturer.
iv. Film brand or type, and number of films in cassette.
v. Type and thickness of intensifying screens and filters.
vi. Blocking or masking techniques, if used.
vii. Minimum source-to-film distance.
viii. Exposure conditions for procedure qualification: voltage, milliampere minutes, distance of film to object, geometric arrangements for the radiographs (sketch), orientation of location markers, description of the manner in which interval markers locate areas of interest.
ix. Description of or reference to the welding procedure, when applicable.

(b) Characteristic radiographic appearances of defects

Reference radiographs and different standards provide considerable aid in interpretation. These assist in recognising the nature of a defect and giving it standard nomenclature. These standards, however, give radiographic appearances of defects in simple and usually uniformly thick specimens. For the interpretation of more complex specimens, therefore, there can be no substitute for experience.

(c) Specimen

Interpretation of a radiograph will be better and more effective when backed with a good knowledge of the specimen and the method of its manufacture. With welds, for example, it is helpful to know the welding technique employed, the plate preparation and the nature of the expected defects. With casting it is advisable to have the history of the specimen, nature of casting, orientation when cast, type of mould etc. The drawings of the specimen may help considerably and the interpreter should, therefore, be conversant with engineering drawing. Availability of specimen at the time of interpretation will avoid any confusion between images due to surface defects and other images. If this is not possible the specimen should be thoroughly visually examined and the findings adequately noted.

9.4.1. Interpretation of radiographs of welds

A variety of surface and internal defects occur in welds. These have been classified and are discussed below.

9.4.1.1. Internal defects

(a) Gas inclusions

Gas may develop during welding due to many factors like the quality of the parent metal, the electrodes used, poor regulation of the arc current, etc. The gas may get entrapped and take various forms.

Gas pore. It is a small bubble of gas entrapped within the molten metal. It has a diameter usually less than 1.6mm(1/16 inch). A group of gas pores is termed porosity. In a radiograph a gas pore appears as a sharply defined dark shadow of circular contour. Porosity appears as a bunch of dark spots situated close to each other.

Blowhole. It is similar to a gas pore except that it is a little larger in dimensions. Its radiographic image is also a dark shadow of rounded contour.

Pipe or Wormhole. Some gas inclusions have an elongated form known as wormholes or pipes. They are usually almost perpendicular to the weld surface.

They can result from the use of wet powdered flux or from inadequate regulation of the welding current. Another typical form of pipe has the appearance of a branch of a tree. These can be caused by use of wet welding electrodes.

(b) Slag inclusions

Some slag may be trapped in the deposited metal during its solidification, particularly if the metal fails to remain molten for a sufficient period to permit the slag to rise to its surface. In multipass welding, insufficient cleaning between weld pass can leave portion of the slag coating in place to be covered by subsequent passes. A particular characteristic of slag inclusions is the 'slag line', intermittent or continuous. Such slag lines are often accompanied by a pronounced lack of fusion to the base metal.

These give dark indications on the radiograph. The shape of these dark images is generally irregular. Often the image density is variable even approaching that of the sound metal. The contrast of the slag images is lower than that of a gas cavity of the same size. Large isolated inclusions appear as dark shadow of irregular contour. Cluster of small inclusions appear as a group of dark ill-defined spots. Line inclusions appear as a dark shadow with wavy edges along the weld. It is sometimes found along both edges of a run of welding in roughly parallel lines.

Another discontinuity of different origin but of similar radiographic appearance, results from irregular deposits on successive passes which leave voids between passes. Such lack of fill can occur, for instance, in welds made in the overhead position.

(c) Tungsten inclusions

Tungsten inclusions are characteristic of the inert atmosphere welding methods. If the tungsten electrode which supports the electric arc comes into contact with the weld metal, some tungsten particles are trapped in the deposited metal.

These may be in the form of small splinters or even as the pieces of the tungsten wire. The tungsten inclusions appear as very light marks in the radiograph.

(d) Lack of root penetration

In butt welding a root opening is usually left at the bottom of the groove (in one-side welding) or at the centre of the weld (in two-side welding). If the opening between the two plates is narrow, it is difficult to achieve complete penetration and fusion at the root of the weld. A void remains in the root of the weld. Such discontinuities can arise from poor bevelling or preparation of the weld groove. It appears in the radiograph as a continuous or intermittent dark line at the centre of the weld seam. It may have both edges straight or one edge straight and the other wavy.

(e) Lack of fusion

This is due to the lack of union in a weld between the weld metal and parent metal or between parent metal and parent metal or between weld metal and weld metal. Lack of fusion can be of the following types.

(i) Lack of side fusion

This is caused by a lack of fusion between the weld metal and the parent metal at the side of a weld outside the root. In the radiograph it appears as a dark straight line, of low intensity, with sharply defined edges.

(ii) Lack of root fusion

This is caused due to the lack of union between the adjacent faces of the parent metal at the root. In the radiograph it is revealed as a dark straight line of low intensity with sharply defined edges.

(iii)Lack of Inter-run fusion

This is caused by a lack of union between adjacent runs of weld metal in a multi-run weld. In the radiograph it appears as a faint line with sharply defined edges.

(f) Cracks

Cracks can be defined as a discontinuity produced either by tearing of the metal while in a plastic condition (hot crack) or by fracture when cold (cold crack). In the radiograph the former is revealed as a fine dark line wandering in direction and tapered at the ends, often discontinuous, when the segments are roughly parallel but slightly displaced and possibly overlapping. A cold crack generally appears as a very fine line, straighter, continuous and free from bifurcations.

9.4.1.2. Surface defects

These defects are present on the surface and can be seen visually. As they also appear in the radiograph and may lead to wrong interpretation, some of these are discussed below.

(a) Undercut

During the final or cover pass the exposed upper edges of the bevelled weld preparation tend to melt and to run down into the deposited metal in the weld groove. The result is a groove which may be either intermittent or continuous, with more or less sharp edges along the weld reinforcement. The radiographic image of undercut is a dark line of varying width and extent with usually diffused edges occurring at the sides of the weld. The image density indicates the depth of the undercut.

(b) Concavity at the root of the weld

A concave surface at the root of the weld can occur specially in pipe welding (without a cover pass on the root side). In overhead welding this condition is a consequence of gravity which causes the molten metal to sag away from the inaccessible upper surface of the weld. It can also occur in the downhand welding with a backing strip at the root of the weld groove if slag is trapped between the molten metal and the backing strip. This is shown by a broad dark line at the centre of the weld image and having unsharp edges unlike the edges of lack of penetration.

(c) Change of electrode

At points where the electrodes are changed while making the cover pass, an unskilled welder may choose the wrong position for starting the new electrode. Sometimes slag inclusions occur at the point at which electrodes were changed. The radiograph shows a crescent shaped image corresponding to the point of change of electrode.

(d) Excessive penetration

In welds, sometimes, molten metal runs through the root of the weld groove producing an excessive reinforcement at the back side of the weld. In general this is not continuous but has an irregular shape with characteristic hanging drops of the excess metal. Excessive penetration will be shown as a line of lowered image density in the centre of the weld.

(e) Electrode spatter

If improper electrodes or long arcs are used, droplets of molten metal are spattered about the weld region.These drops stick to the metal surface near the weld seam. Since they correspond to local areas of increased thickness, a series of light round spots appear on the radiograph.

(f) Grinding marks

When weld reinforcements are not ground out smoothly, the resultant thickness varies above and below that of the base metal. In the radiograph it may appear as extended light or dark areas with diffused edges extended over the welded area or the parent metal.

9.4.2. Interpretation of radiographs of castings

A variety of defects may occur in castings. These may be classified in five groups namely voids, crack, cold shut, segregation, inclusions. The terminology used is in accordance with British Standard 2737. When supplemented with the general principles of interpretation the following definitions and illustrations should be helpful in interpreting the radiographs of castings. It must, however, be kept in mind that for the following reasons the identification of defects can be more difficult than the illustration might suggest :-

(i) Defects of more than one kind often occur together.
(ii) Quality of radiographic image depends upon the density and thickness of the metal as well as the radiographic technique used.
(iii) Illustrations are made from simple specimens. Complex specimen or different orientation may change the appearance of a defect in the radiograph.

9.4.2.1. Void

Void is defined as a cavity produced by

(a) entrapped gas evolved from the metal
(b) entrapped air
(c) entrapped gas evolved from the mould
(d) shrinkage of metal. Voids have been classified depending on their shape and size. The classes are described below.

Microporosity. A fine form of the defect due to shrinkage, or gas or both in which a number of cavities occur either around the grain boundaries (intercrystalline) or between the dendrite arms (inter-dendritic). In a radiograph this usually produces a general mottled or cloudy effect (plate 1). In nonferrous alloys the fine cavities may occur in layers (layer porosity) and produce dark streaks in the radiograph (plate 2).

Sponginess. A system of inter-crystalline or interdendritic cavities of a coarse and usually localised form which appear in a radiograph as a group of dark interconnected images which may be irregular in outline and of varying size and blackness (plate 3).

Pinhole porosity. Small cavities of less than about 1.6mm (1/16 inch) dia. occurring throughout the casting or localised within a particular area, which appear as an assemblage of small, rounded, widely distributed, dark images (plate 4). This defect occasionally arises from the injection of air during pressure die casting.

Gashole. A discrete cavity greater than about 1.6mm (1/16 inch) dia. due to gas evolved from the metal, mould or core. In the radiograph the image appears as a dark area of smooth outline which may be circular or elongated, (plate 5). A particular form of wormhole occurs as a tube like cavity usually normal to and almost reaching to the surface of the casting (plate 6).

Airlock. A cavity formed by air which has been trapped in the mould by the metal during pouring. The defect appears in a radiograph as a dark area with a generally smooth outline but may have discontinuities (plate 7).

Shrinkage cavity. A discrete cavity caused by contraction during solidification. The radiographic appearance is similar to that of a gashole but usually shows a less regular outline (plate 8) and may tend to taper.

Filamentary shrinkage. A coarse form of shrinkage defect in which the cavities are branching, interconnected and extensive. In the radiograph the images appear as continuous, irregular, dark, usually branched or occasionally in the form of a network (plate 9).

9.4.2.2. Crack

A crack is a discontinuity due to the fracture of the metal during or after solidification. Depending upon the cause, cracks have been classified as follows:

Hot tear. This type of crack develops near solidification temperature when the metal is weak. The defect occurs mainly, at, or near to, a change of section and may not be continuous. Radiographically a hot tear is revealed as a wavy, ragged, dark line. It is often discontinuous with parallel, slightly displaced and possibly overlapping parts (plate 10). Generally the ends taper and become very fine.

Stress crack. A well defined and approximately straight crack, formed, due to large stresses after the metal has become completely solid. In the radiograph it appears as a clearly defined smooth dark line (plate 11).

9.4.2.3. Cold shut

It is a discontinuity caused by the failure of a stream of molten metal to unite with a confluent stream or with solid metal, such as a chaplet, internal chill or pouring splash. This may often be caused if the pouring is interrupted. Usually it appears as a dark line (plate 12 and plate 13). A cold shut arising from a splash in the mould may appear as a dark crescent or circle.

9.4.2.4. Segregation

Segregation is a condition resulting from the local concentration of any of the constituents of an alloy.

General segregation. It extends over a considerable part of a casting. Radiographically it appears as an assemblage of small light or dark areas (plate 14).

Local segregation occurs when the shrinkage voids or hot tears are wholly or partially filled with a constituent of low melting point. It appears in a radiograph as light or dark areas coinciding with the original defect (plate 15).

Banded segregation. This is mainly associated with centrifugal castings but can occasionally occur in static casting also. Radiographically it appears as alternate light or dark bands.

9.4.2.5. **Inclusion**

An inclusion is foreign matter entrapped in the casting. This may be of different types i.e. sand, slag, flux or dross. It may appear radiographically either as a light or dark area depending upon the density of the inclusion, e.g. slag inclusion in steel will appear as rounded dark images (plate 16) and it is difficult to distinguish from a void.


CRACK


POROSITY

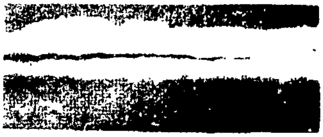

LACK OF PENETRATION

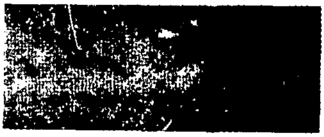

LACK OF FUSION


BLOWHOLE


SPATTER


TUNGST INCLUSION


CRACK

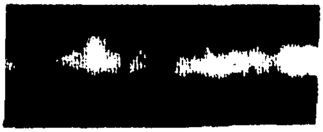

PIPE


SLAG INCLUSION


LINE INCLUSION

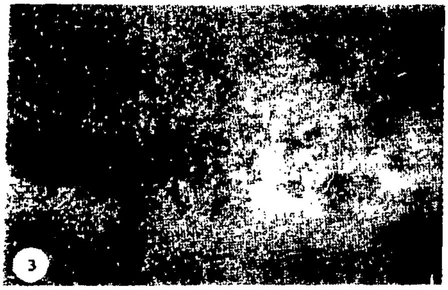

PIPE


UNDERCUT


RESTART OF ELECTRODE


1


2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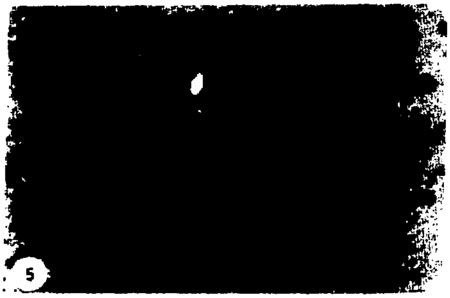
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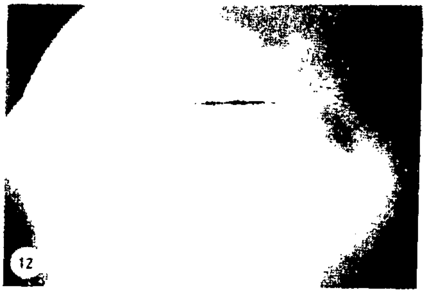

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10. CODES AND STANDARDS

10.1. QUALITY AND STANDARDISATION

10.1.1. Terminology

(i) Quality

Quality of an industrial product is defined as the "fitness of the product" to do the job required of it by its user.

(ii) Quality Control

Quality control can be defined as the controls applied at each manufacturing stage to consistently produce a quality product.

(iii) Standardisation

Standardisation of a process can be defined as the setting up of process parameters so that it constantly produces a product of uniform characteristics.

(iv) Standards

Standards are documents that govern and guide the various activities occurring during the production of an industrial product. Standards describe the technical requirements for a material, process, product, system or service. They also indicate, as appropriate, the procedures, methods, equipment or tests to determine that the requirements have been met.

(v) Codes and Specifications

Codes and specifications are similar types of standards that use the verbs "shall" or "will" to indicate the mandatory use of certain materials or actions or both. Codes differ from specifications in that their use is mandated with the force of law by governmental jurisdiction. The use of specifications becomes mandatory only when they are referenced by codes or contractual documents. A prime example of codes is the ASME Boiler and Pressure Vessel Code which is a set of standards that assure the safe design, construction and testing of boilers and pressur vessels.

(vi) Guides and Recommended Practices

Guides and recommended practices are standards that are offered primarily as aids to the user. They use verbs such as "should" and "may" because their use in usually optional. However, if these documents are referenced by codes or contractual agreements, their use may become mandatory. If the codes or agreements contain non mandatory sections or appendices, the use of referenced guides and recommended practices by them, are at the user's discretion.

(vii) Procedure

In non destructive testing, a procedure is an orderly sequence of rules which describe in detailed terms where,how and in which sequence an NDT method should be applied to a production.

(viii) Technique

A technique is a specific way of utilising a particular non destructive testing method. Each technique is identified by at least one particular important variable from another technique within the method (Example:RT method - X-Rays/Gamma Ray Technique

(ix) Examination and Testing

Examination and testing are those quality control functions which are carried out during the fabrication of an industrial product by a qualified person who is an employee of the manufacturer.

(x) Inspection

Inspections are the quality control functions which are carried out during the fabrication of an industrial product by an "authorised inspector".

(xi) Authorised Inspector

An authorised inspector is a person who is not an employee of the fabricator of an industrial product but who is properly qualified and has the authority to verify to his satisfaction that all examinations specified in the construction code of the product have been made to the requirements of the referencing section of the construction code.

(xii) Report

A report of a non destructive examination or of testing is a document which includes all the necessary information required to be able to:

(i) take decisions on the acceptance of the defects revealed by the examination,
(ii) facilitate repairs of unacceptable defects, and
(iii) permit the examination or testing to be repeated.

(xiii) Records

Records are documents which will give, at any time in the future, the following information about a non destructive testing examination, (i) the procedure used to carry out the examination, (ii) the data recording and data analysing techniques used, and (iii) the results of the examination.

10.1.2. Some important international and national standardising bodies

10.1.2.1. International Standardisation Organisation (ISO)

Table 10.1 gives the list of standards relating to radiographic testing developed by various ISO Committees. Any one wishing to consult or purchase any of the above mentioned standards should contact the national standard institution in his or her own country.

TABLE 10.1. LIST OF ISO STANDARDS RELATING TO RADIOGRAPHIC TESTING

Sr. No.	Standard Number	Title	Year of Publication
1.	ISO/DIS 5576	Industrial radiology-Nondestructive testing-Vocabulary (ISO/TC 135)	1982
2.	ISO/R 46	Surface roughness (ISO/TC 57)	1966
3.	ISO/R 41	Rules for construction of stationary boilers (ISO/RC 11)	1968
4.	ISO/R 947	Recommended practice for radiographic inspection of circumferential fusion-welded butt joints in steel pipes up to 50mm (2 in) wall thickness (ISO/RC 44)	1969

TABLE 10.1. (cont.)

Sr. No.	Standard Number	Title	Year of Publication
5.	ISO/R 1027	Radiographic image quality indicators-Principles and identification (ISO/TC 44)	1969
6.	ISO/R 1106	Recommended practice for radiographic inspection of fusion-welded butt joints for steel plates up to 50mm (2in) thick (ISO/RC 44)	1969
7.	ISO 1677	Sealed radioactive sources-General (ISO/TC 85)	1977
8.	ISO 1757	Personal photographic (ISO/RC 85)	1980
9.	ISO 1758	Direct-reading electroscope-type pocket exposure meters (ISO/RC 85)	1976
10.	ISO 2405	Recommended practice for radiographic inspection of fusion-welded butt joints for steel plates 50-200mm thick (ISO/TC 44)	1972
11.	ISO 2437	Recommended practice for the X-ray inspection of fusion-welded butt joints for aluminium and its alloys and magnesium and its alloys 5-50mm thick (ISO/RC 44)	1972
12.	ISO 2504	Radiography of welds and viewing conditions for film utilisation of recommended patterns of image quality indicator (IQI) (ISO/RC 44)	1973
13.	ISO 2604	(6 parts) Steel products for pressure purposes-Quality requirements (ISO/RC 17)	1975-1978
14.	ISO 2919	Sealed radioactive sources-Classification (ISO/TC 85)	1980
15.	ISO 3777	Recommended practice for the radiographic inspection of resistance spot welds for aluminium and its alloys (ISO/RC 44)	1976

TABLE 10.1. (cont.)

Sr. No.	Standard Number	Title	Year of Publication
16.	ISO 3897	Storage conditions for silver image photographic plates for record purposes (ISO/TC 42)	1976
17.	ISO 3925	Identification and certification of unsealed radioactive source (ISO/TC 85)	1978
18.	ISO 3999	Specification of apparatus for gamma radiography (ISO/TC 85)	1977
19.	ISO 5655	Sizes, quantity, packaging and labeling of films for industrial radiography	1982
20.	ISO/DIS 1027	Radiographic image quality indicators-Principles and identification (ISO/TC 44)	1982
21.	ISO/DIS 31/10	Quantities, units, and symbols Part 10: nuclear reactions and ionising radiations (ISO/RC 12)	

10.1.2.2. International Institute of Welding (IIW)

The list of standards and documents published by IIW which relate to radiographic testing is given in TABLE 10.2. In addition the IIW have also prepared the following collections of reference radiographs :

(i) Collection of reference radiographs of welds in steel (1962) (86 radiographs)
(ii) Collection of reference radiographs of welds in aluminium and aluminium alloys (1965) (51 radiographs)
(iii) Collection of reference radiographs and cross sections of welds in steel (34 radiographs and 34 drawings/cross sections)

TABLE 10.2. LIST OF IIW STANDARDS RELATED TO RADIOGRAPHY

Sr. No.	Standard/Document Number	Title	Year of Publication
1	IIS/IIW-183-65	Recommendations for the determination of the focal spot size of X-ray tubes	1965
2.	IIS/IIW-184-65	Recommendation concerning sensitometric test on radiographic films without screens or with lead screens	1965

TABLE 10.2 (cont.)

Sr. No.	Standard/Document Number	Title	Year of Publication
3.	IIS/IIW-185-65	Rules for the reading of the IQI recommended by Commission V	1965
4.	IIS/IIW208-66	Report on the investigation into the influence of plate thickness on the visibility of weld defects and on image quality in radiography of welds	1966
5.	IIS/IIW-275-67	Draft recommended practice for the examination with X-rays of resistance spot welds on aluminium and it alloys	1967
6.	IIS/IIW-412-72	The use and limitations of radiographic image quality indicators	1972
7.	IIS/IIW-423-73	Recommended practice for the radiographic examination of fusion-welded butt joints in steel plates from 0.5 to 50mm thick	1973
8.	IIS/IIW-424-73	Image quality indicators for use in the radiography of aluminium and its alloys in thicknesses up to 50mm	1973
9.	IIS/IIW-492-75	Recommended practice for radiographic inspection of fusion-welded circumferential joints in steel pipes from 1mm up to 50mm thickness (Revision of IIS/IIW-36-59)	1975
10.	IIS/IIW-572-78	Final report of the image quality indicator developed by the CERL (Central Electricity Generating Board) (UK)	1978
11.	IIS/IIW-585-79	Recommendations relating to the training of non-destructive testing personnel	1979
12.	IIS/IIW-636-80	Inspection of welds when fitness-for-purpose criteria are applied-preliminary recommendations	1980

TABLE 10.2 (cont.)

Sr. No.	Standard/Document Number	Title	Year of Publication
13.	V-658-79	The probabilistic forecasting of the real defect detectability based on the results of the detecting standard defects in welded joints by radiography	1978

10.1.2.3. International Commission on Radiological Protection (ICRP)

This commission is regarded as the foremost body providing fundamental principles upon which radiation protection measures can be based. The following publications are of interest to NDT personnel involved in radiographic testing , TABLE 10.3.

TABLE 10.3 LIST OF ICRP STANDARDS RELATING TO RADIOLOGICAL PROTECTION

ICRP Publication 7	Principles of environmental monitoring related to the handling of radioactive materials.
ICRP Publication 10	Evaluation of radiation doses to body tissues from internal contamination due to occupational exposure.
ICRP Publication 10A	The assessment of internal contamination resulting from recurrent or prolonged uptakes.
ICRP Publication 12	General principles of monitoring for radiation protection of workers.
ICRP Publication 14	Radiosensitivity and spatial distribution of dose
ICRP Publication 22	Implications of commission recommendations that doses be kept as low as readily achievable.
ICRP Publication 26	Recommendations of the international commission on radiological protection.
ICRP Publication 27	Problems involved in developing an index of harm
ICRP Publication 28	The principles and general procedures for handling emergency and accidental exposures of workers.
ICRP Publication 30	Limits for intakes of radionuclides by workers.

10.1.2.4. American Society of Mechanical Engineers (ASME)

The American Society of Mechanical Engineers set up a committee in 1911 to formulate standard rules for the construction of steam boilers and other pressure vessels. This committee is now called the Boiler and Pressure Vessel Committee.

The committee's function is to establish rules of safety governing the design, fabrication, and inspection during construction of boilers and unfired pressure vessels; and to interpret these rules when questions arise regarding their intent. The committee has published the ASME Boiler and Pressure Vessel Code (BPV Code) as an American National Standard. The first code was published in 1914 and revised and updated editions have been issued at regular intervals since.

The ASME Boiler and Pressure Vessels Code contains the following sections :

(a) Section I : Power Boilers

This section includes rules and general requirements for all methods of construction for power, electric, and miniature boilers and high temperature water boilers used in stationary service. This section also includes power boilers used in locomotive, portable, and traction service.

(b) Section II : Materials Specifications

Part A - Ferrous materials
Part B - Nonferrous materials
Part C - Welding rods, electrodes, and filler metals

This section is a service section to the other Code Sections providing material specifications adequate for safety in the field of pressure equipment.

(c) Section III : Rules for Construction of Nuclear Power Plant Components

This section provides requirements for the materials design, fabrication, examination, testing, inspection, installation, certification, stamping, and overpressure protection of nuclear power plant items such as vessels, concrete reactor vessels, and concrete containments, storage tanks, piping systems, pumps, valves, core support structures, and component supports for use in, or containment of, portions of the nuclear power system of any power plant. This section contains the following two divisions :

Division 1

Subsection NB - Class 1 components
Subsection NC - Class 2 components
Subsection ND - Class 3 components
Subsection NE - Class MC components
Subsection NG - Core support structure
Appendices

Division 2 - Code for concrete reactor vessels and containments

(d) Section IV : Heating Boilers

This section covers minimum safety requirements for designing, fabrication, installation and inspection of steam generating boilers, and hot water boilers intended for low pressure service that are directly fired by oil, gas, electricity, or coal.

(e) Section V : Nondestructive Examination

This section contains requirements and methods for nondestructive examination which are referenced and required by other Code sections. This section also includes manufacturer's examination responsibilities, duties of authorised inspectors and requirements for qualification of personnel, inspection, and examination. Examination methods included in this section, are intended to detect surface and internal discontinuities in material, welds and fabricated parts, and components.

(f) Section VI : Recommended rules for care and operation of heating boilers

This section covers the latest specifications, terminology, and basic fundamentals applicable to steel and cast iron boilers limited to the operating ranges of Section IV heating boilers. This section also includes guidelines for associated controls and automatic fuel burning equipment.

(g) Section VII : Recommended rules for care of power boilers

In order to promote safety in the use of stationary, portable, and traction type heating boilers, this section provides rules to assist operators of power boilers in maintaining their plants as safe as possible.

(h) Section VIII : Pressure Vessels

This section is divided into two divisions. Division 1 covers the minimum safety requirements applicable to the construction, design, and fabrication of pressure vessels under either internal or external pressure for operation at pressure exceeding 15 psig and to vessels having inside diameters exceeding six inches. Pressure vessels made according to the rules of Division 2 require closer inspection of the required fabrication details, material inspection, welding procedures and welding and more nondestructive examination,as the safety factor used for these vessels is less than the safety factor used for vessels fabricated according to the rules of Division 1.

(i) Section IX : Welding and Brazing Qualifications

This section covers rules relating to the qualification of welders, brazers, and welding and brazing operators in order that they may perform welding or brazing as required by other Code sections in the manufacture of components.

(j) Section X : Fibreglass-Reinforced Plastic (FRP) Pressure Vessels

This section covers minimum safety requirements for construction of an FRP pressure vessel in conformance with a manufacturer's design report. The production, processing, quality control, and inspection methods are prescribed to assure the quality of the vessel.

(k) Section XI : Rules for In-service Inspection of Nuclear Power Plant Components - Division 1

This section provides rules and requirements for in-service inspection of Class 1, 2 and 3 pressure retaining components and their supports, and in-service testing of pumps, valves, and components in light-water cooled nuclear power plants. This Division categorises the areas subject to inspection and defines responsibilities, provisions for accessibility, examination method and procedures, personnel qualifications, frequency of inspection, record keeping and reporting requirements, procedures for evaluation of inspection results and subsequent disposition of results of evaluation, and repair requirements. This Division provides for the design, fabrication, installation, and inspection of replacements.

10.1.2.5. **British Standards (BS)**

A list of the British Standards which relate to radiographic testing is given in TABLE 10.4

TABLE 10.4 BRITISH STANDARDS RELATING TO RADIOGRAPHY

Sr. No.	Standard Number	Title	Year of Publication
1.	BS 2597	Glossary of terms used in radiology	1955

TABLE 10.4 (cont.)

Sr. No.	Standard Number	Title	Year of Publication
2.	BS 2600	Methods for radiographic examination of fusion welded butt joint in steel	1973
	Part 1	5mm up to and including 50mm thick Amendment AMD 1566 (October 1974) (Revised specification in draft August 1982)	
	Part 2	Over 50mm up to and including 200mm thick Amendment AMD 2285 (June 1977)	1973
3.	BS 2737	Terminology of internal defects in castings as revealed by radiography	1956
4.	BS 2910	Methods for radiographic examination of fusion-welded circumferential butt joints in steel pipes	1973
5.	BS 3385	Direct-reading pocket-type electroscope exposure meters	1973
6.	BS 3490	Sizes of film for industrial radiography and X-ray crystallography	1972
7.	BS 3510	A basic symbol to denote the actual or potential presence of ionising radiation	1968
8.	BS 3664	Film badges for personnel radiation monitoring	1963
9.	BS 3683	Glossary of terms used in nondestructive testing	1963
	Part 1	Penetrant flaw detection	1963
	Part 2	Magnetic-particle flaw detection Amendment PD 6369 (March 1968)	1963
	Part 3	Radiological flaw detection Amendment PD 6370 (March 1968)	1964
	Part 4	Ultrasonic flaw detection Amendment PD 6371 (March 1968)	1965
	Part 5	Eddy current flaw detection	1965
10.	BS 3890	General recommendations for the testing, calibration, and processing of radiation monitoring films	1965

TABLE 10.4 (cont.)

Sr. No.	Standard Number	Title	Year of Publication
11.	BS 3971	Specifications for image quality indicators for radiography (including guidance on their use)	1980
12.	BS 4031	X-ray protective lead glasses	1966
13.	BS 4094	Recommendations for data on shielding from ionising radiation	
	Part 1	Shielding from gamma-radiation	1966
	Part 2	Shielding from X-radiation	1971
14.	BS 4304	X-ray film cassettes (flat, rigid type)	1968
15.	BS 5230	Method for the measurement of speed and contrast of direct type films for industrial radiography. Amendment AMD 3503 (September 1981)	1975
16.	BS 5288	Sealed radioactive sources	1976
17.	BS 5566	Recommendations for installed exposure rate meters, warning assemblies, and monitors for X or radiations of energy between 80keV and 3 MeV	1978
18.	BS 5650	Specifications for apparatus for gamma radiography	1978
19.	BS 5868	Guide to ionising radiation thickness meters for materials in the form of sheets, coating, or laminates.	1980
20.	BS 6090	Specification for personal photographic dosimeters	1981
21.	BS 6251	Method for determining the luminance distribution of electro-optical X-ray intensifiers	1982
22.	BS 6252	Method for measuring the conversion factor of electro-optical X-ray intensifiers	1982
23.	PD 3542	Operation of a company standards department	1979

TABLE 10.4 (cont.)

Sr. No.	Standard Number	Title	Year of Publication
24.	PD 6493	Guidance on some methods for the derivation of acceptance levels for defects in fusion welded joints	1980
25.	M 34	Method of preparation and use of radiographic techniques in aerospace.	1970

10.1.2.6 **Japanese Industrial Standards**

The Japanese Industrial Standards Committee is the recognised body in the Ministry of International Trade and Industry for the preparation and promulgation of national standards.

A list of the Japanese Industrial Standards relating to radiographic testing is given in TABLE 10.5.

TABLE 10.5 JAPANESE INDUSTRIAL STANDARDS COVERING RADIOGRAPHIC TESTING

Standard No.	Title	Year
JIS Z 3104	Methods of radiographic test and classification of radiographs for steel welds	1968
JIS Z 3105	Methods of radiographic test and classification of radiographs for aluminium welds	1984
JIS Z 3106	Methods of radiographic test and classification of radiographs for stainless steel welds	1971
JIS Z 3107	Methods of radiographic test and classification of radiographs for titanium welds	1973
JIS Z 3108	Methods of radiographic test for circumferential butt welds of aluminium pipes and tubes	1986
JIS Z 3109	Methods of radiographic test for aluminium tee welds	1980
JIS G 0581	Methods of radiographic test and classification of radiographs for castings	1984
JIS Z 3861	Standards qualification procedure for radiographic testing technique of welds	1979
JIS H 0522	Radiographic inspection soundness requirements for aluminium and magnesium castings	

10.1.3. Survey of NDT Standards

The following useful summaries and surveys of NDT standards have been published :

1. Specifications and standards for nondestructive inspection of steels. Journal of NDT of the Japanese Society for Nondestructive Inspection, 19(9), 467 (September 1970).

2. Commonly used specifications and standards for nondestructive testing, Materials Evaluation. 27(7), 13A, (July 1969): 29(5), 17A (May 1971).

3. Bates, CC and Campkin, C. Nondestructive testing and standardisation in Great Britain, Proceedings of the International NDT Conference, Montreal, 274 (1967).

4. Bates, C C, Progress report on the activities of ISO TC 135 (including list of national standards), Proceedings of the 7th International NDT Conference Warsaw, Paper A03.

5. Hosokawa, T. List of MIL Specs for NDT, Japanese Journal of NDT, 24(10), 596(October 1975).

6. Campbell, H F, Standards of acceptance by NDI for raw materials and components, in AGARD-AG-20/,1, 57 (October 1975)

7. Marguglio, B W, Quality systems in the nuclear industry (and in other high technology industries), ATM Spec Tech Pub 616 (1977)

8. LaDonna Thompson, Beckman, K and Ricci, P, Standards Cross Reference List, MTS Systems Corp, Minneapolis (April 1977)

9. NDT specifications and codes of practice, Australian Nondestructive Testing Journal (July, August, September issues 1979)

10. Specifications and standards issued in NDT, Materials Evaluation, 25 (May 1980)

11. American British Canadian Australian Armies Standardisation program Quadripartite standardisation agreement 274 (certification of radiographic testing personnel)

12. NTIAC Handbook 79-1, edited by R E Engelhardt, NTIAC Southwest Research Institute, San Antonio, Texas, USA.

10.2. INTRODUCTION TO NDT CODES AND STANDARDS

Nondestructive examination is very significant means to ensure reliability of equipment and structural components. Quite often a product being designed and manufactured or fabricated follows a certain reference standard, code, or specification. In relation to NDT inspection, the purpose of standards and codes is to prescribe a test method or procedure which would give correct and uniform assessment of the quality of the product.

Competent NDT personnel are required to assess the quality of the product. This can only be achieved through proper training and education in NDT practices. This is why the qualification and certification of NDT personnel is being standardised throughout the world by drafting of an ISO standard.

The use and the performance of nondestructive testing in industry depends very much on standards. Standards are used to compare results, to calibrate equipment, to ensure uniform and reproducible results, and to help one to determine what is acceptable and what is not. Generally standards and codes, are classified in the following manner:

(i) Standards or codes on the product. This standard will normally specify or recommend, acceptable methods of manufacture and fabrication, requirements for test and inspection and also the acceptance criteria for the test and inspection.

Examples of such standards or codes are :

(a) ASME Boiler and Pressure Vessels Code Sections I, II and III
(b) BS 5500 Specification For Unfired Fusion Welded Pressure Vessels.
(c) AWS D 1.1. Structural Welding Code - Steel. etc.

(ii) Standards or codes on the method or procedure of test or inspection. Some of these types of standards specify general testing methods or procedures while others specify testing methods for specific products, shapes or materials such as pipe welds, etc. Some will also specify types, materials and shapes of the image quality indicators and sometimes contrast meters as in the Japanese Standards. Generally this type of standard will specify the radiographic arrangement, criteria for film selection, intensifying screen, selection of radiation energy, quality or sensitivity level etc. Some examples of such standards or codes are as follows:

(a) ASME Boiler and Pressure Vessels Code Section V.
(b) BS 2600
(c) BS 2910

(iii) Standards for collection of reference radiographs. Depending on the purpose, there are various collections of reference radiographs, such as those showing the correspondence between designation and shape of defects, those classifying defects by their shape, size, distribution, etc. and some even classify or grade the degree of severity of the comparison of radiographs of cast products whose judgment of the results cannot be easily determined quantitatively.

Examples of such standards include:

(a) IIW Collection of reference radiographs for welds
(b) ASTM E 186 reference radiographs for heavy welded steel castings.
(c) ASTM E 390 reference radiographs for steel fusion welds, etc.

The standards mentioned above, though basically similar, differ in their approach. The difference is noticed in the design concept of the IQI and thus the sensitivity, and also on the source to film distance. Thus to radiographically evaluate the quality of the products, generally it is required to make use of or refer to all or part of those three types of standards.

10.3. COMPARISON OF SOME IMPORTANT RADIOGRAPHIC TESTING STANDARDS

In this section comparison of some important technique parameters is made by considering the following recommended practices for radiographic testing.

(a) ISO/DIS 5579 (1983)
(b) BS 2600 (1973)
(c) ASME Code (Article 2 of Section V and SE 94 (1974), of Article 22 section V)
(d) JIS Z 3104

10.3.1. Classification of techniques

10.3.1.1. ISO/DIS 5579

Radiographic techniques are divided into the following two classes:

- Class A : a general technique
- Class B : a more sensitive technique intended for use where the usual method may give unsatisfactory results or is unlikely to reveal the anomalies sought.

Many applications are covered by the correct use of the rules given for class A.
Class B is intended for cases which require a greater degree of sensitivity. It generally requires longer exposure times.

In addition to having an adequate IQI, some applications of radiography require the radiographs to cover a range of specimen thickness. Several modifications of either class A or B will produce an increase in thickness latitude.

The decision on which class is required for a particular application must be agreed in advance between the customer and the supplier, taking into account the IQI required, the thickness latitude necessary, the equipment available, cost, accessibility etc.

10.3.1.2. **BS 2600**

In this standard a different classification of techniques is adopted. This classification is given in TABLE 10.6.

TABLE 10.6 : TECHNIQUE CLASSIFICATION ACCORDING TO BS 2600.

Radiation	Technique number	Type of film* *	Type of intensifying screen	Film density of weld area area under examination*
X-rays	1	Ultra-fine-grain high-contrast direct-type	Lead	2.0-3.0
	2	Fine-grain direct-type	Lead	2.0-3.0
	3	Medium-speed direct-type	Lead	1.7-3.0
	4	High-speed high-contrast direct-type	Lead	1.7-3.0
	5	Screen-type (high-definition	Salt	1.3-2.3
Gamma rays	6	Ultra-fine-grain high-contrast direct-type	Lead	2.0-3.0
	7	Fine-grain high-contrast direct-type	Lead	2.0-3.0
	8	Medium-speed direct-type	Lead	2.0-3.0

* A density of 3.0 can be exceeded for direct-type film provided that a high intensity illuminator is used.
* These techniques are not recommended for welds for Class 1 duties.
* The term 'non-screen' film is synonymous with 'direct- type' film.

10.3.1.3. **ASME Code**

No formal classification of techniques is given in this standard.

10.3.1.4. **JIS Z 3104**

In this standard two classes of technique are adopted. This classification is given in TABLE 10.7.

TABLE 10.7 CLASSIFICATION OF TECHNIQUE ACCORDING TO JIS Z 3104

Class	Ug	In radiation angle to transverse crack	IQI sensitivity	Density
Special	<0.2mm	< 9°	$0 < T < 100$ <1.5% $100 < T$ <1.3%	$0 < T < 50$ 1.0-3.5
Ordinary	<0.4mm	< 14°	<2.0%	$50 < T < 100$ 1.5-3.5 $100 < T$ 2.0-3.5

where T = material thickness

10.3.2. Films and screens

10.3.2.1. ISO/DIS 5579

The classification of radiographic films according to this standard is given in TABLE 10.8. Radiographic films which are used in combination with special techniques, e.g., fluorescent screens are not included in this table. For class A techniques GIII or finer films can be used while for class B techniques GII or finer films can be used.

TABLE 10.8. CLASSIFICATION OF FILMS ACCORDING TO ISO STANDARD

Film classes	Grain	Speed
G I	Very fine-grained film	Very slow
G II	Fine-grained film	Slow
G III	Film with medium grain size	Medium speed
G IV	Film with larger grain size	High speed

The intensifying screens can be selected according to TABLE 10.9. For a double film technique the use of an intermediate screen is recommended.

TABLE 10.9. CHOICE OF INTENSIFYING SCREENS ACCORDING TO ISO STANDARD

X-ray kilovoltage or gamma-source	Class A	Class B
< 400 kV (1)	0.02 to 0.25mm front and back screens of lead[1]	
Ir 192	0.05 to 0.25mm front and back screens of lead	
Co 60	0,1 to 0.5mm front and back screens of lead, steel[2] or copper	0.4 to 0.7mm front and back screens of steel steel[2] or copper
1 to 2 MV	0.1 to 1.0mm lead front and back screens	
2 to 6 MV	1.0 to 15mm front and back screens of copper or steel[2]	
6 to 12 MV	1.0 to 1.5mm front screen< 1.5mm back screen	of copper, steel[2] or tantalum
More than 12 MV	1.0 to 1.5mm front screen of tantalum or tungsten No back screen	

1. For X-ray kilovoltages below 100KV no front screen is necessary although a thin lead screen is sometimes useful to reduce scattered radiation.
2. Alloyed or unalloyed.

10.3.2.2. B.S. 2600

In this code radiographic films are classified according to the column "Type of film" of TABLE 10.4.

The thickness of the lead intensifying screens to be used should be as follows:

Radiation	Thickness of front screen	Minimum thickness of back screen
Below 120 KV	0.02 to 0.05mm	0.13mm
120 to 250KV	0.02 to 0.13mm	0.13mm
250 to 6000KV	0.10 to 0.15mm	0.13mm
Gamma rays	0.10 to 0.25mm	0.13mm

10.3.2.3. ASME Code

The classification of films adopted by ASME(SE-94) is given in TABLE 10.10. TABLE 10.11 gives a guide for selection of a proper film, taken from SE-94. ASME recommends the use of front lead intensifying screens of thickness up to 0.13mm with voltage up to 125KV wherever they improve radiographic quality. For voltages above 125KV the minimum thickness of front screen and the minimum thickness of back screen for any voltage value should be 0.13mm.

TABLE 10.10 . CLASSIFICATION OF FILMS ACCORDING TO ASME CODE

Film Type	Description			Characteristics
	Speed	Contrast	Graininess	
1	low	very high	very low	Extra fine grain and high contrast. Used to obtain the highest quality from high-voltage X-ray equipment or for light metals like Al or Mg. Recommended when the most critical radiography is required. For use direct or with lead intensifying screens.
2	medium	high	low	Fine grain and high contrast designed for the radiography of light metals at lower voltages and for megavolt radiography of heavier steel parts. Its grain is not quite so fine as that of type 1 but its higher speed makes it more widely useable. For use direct or with lead intensifying screens.
3	high	medium	high	Highest speed available when gamma rays or high voltage X-ray are used direct or with lead intensifying screens.
4	very	very high	dependent	Highest available speed and high upon high contrast when used with fluorescent fluorescent screens. Useful screen used for examination of steel brass etc. with radiation sources of limited kilovoltage. Medium speed contrast and graininess when used direct or with lead intensifying screens. Records large range of thickness in relatively small density range.

TABLE 10.11. GUIDE FOR THE SELECTION OF FILMS ACCORDING TO ASME

Material thickness in.	50 to 80kv	80to 120kv	120to 130kv	150to 250kv	Iridium 192	250to 400kv	1mev	Cobalt 60	2mev	Radium	6to31 mev
STEEL											
0 to 1/4	3	3	2	1							
1/4 to 1/2	4	3	2	2		1					
1/2 to 1		4	3	2	2	2	1		1	2	
1 to 2				3	2	2	1	2	1	2	1
2 to 4				4	3	4	2	2	2	3	1
4 to 8						4	3	3	2	3	2
Over 8									3		2
ALUMINIUM											
0 to 1/2	1	1									
1/4 to 1/2	2	1	1	1							
1/2 to 1	2	1	1	1		1					
1 to 2	3	2	2	1	1	1					
2 to 4	4	3	2	2	1	2					
4 to 8		4	3	3	2	3					
Over 8					4						
BRONZE											
0 to 1/4	4	3	2	1	1	1	1				
1/4 to 1/2		3	2	2	2	1	1		1		
1/2 to 1		4	4	3	2	2	1	2	1	2	
1 to 2			4	4	3	3	1	2	1	1	1
2 to 4					3	4	2	3	2	3	1
4 to 8							3	3	2		2
Over 8									3		2
MAGNESIUM											
0 to 1/4	1	1									
1/4 to 1/2	1	1	1								
1/2 to 1	2	1	1		1						
1 to 2	2	1	1	1	1						
2 to 4	3	2	2	1	2						
4 to 8		3	2	2	3						
Over 8				4							

It is worth mentioning here that various commercially available films can be identified according to the above classification.

10.3.2.4. JIS Z 3104

No formal classification of film and screen is given in this standard.

10.3.3. Focus-Film Distance

10.3.3.1. ISO/DIS 5579

The minimum distance between the radiation source and the nearest surface of the specimen is given in Figure 10.1. in terms of the specimen thickness t, and the effective optical focus size d. If the optical focal spot is similar to one of the forms in Figure 10.2 (idealised), in the calculation of the minimum source-to-object distance f the

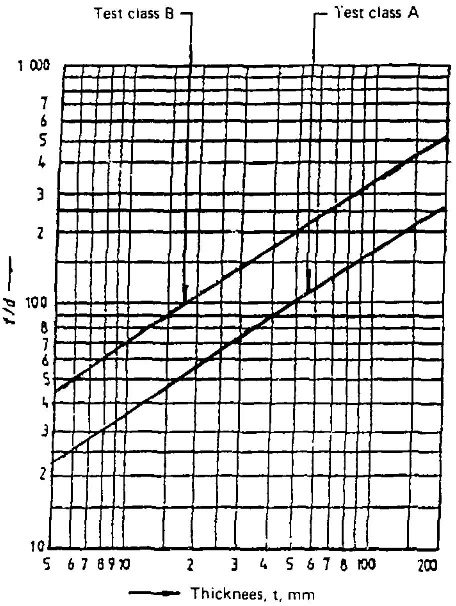


Figure 10.1 Required minimum values of ratio f/d in terms of thickness t

effective optical focus size of d is by convention :

d = a , for a square focus

$d = \frac{a + b}{2}$ for a rectangular focus

d for a circular focus

$d = \frac{a + b}{2}$ *for an elliptical focus*

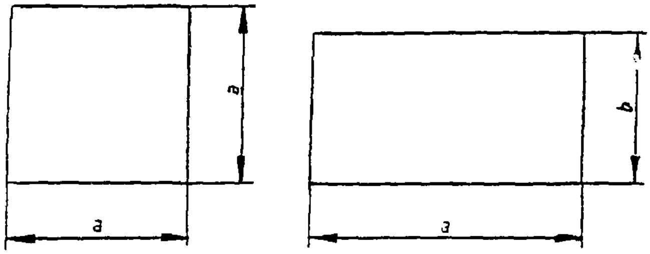
The nomogram of Figure 10.3. is then used to determine the minimum source to-object distance f in terms of material thickness t and effective optical focus size d in accordance with Figure 10.1. for classes A and B (for example, d = 3mm and t = 37mm then f = 300mm in test class B. The corresponding geometric unsharpness U can be calculated from the following formula and it should not be greater than 0.4 for *Class A techniques and 0.2 for* class B techniques for specimen thicknesses up to 40mm

Where $U_g = d.t/f$

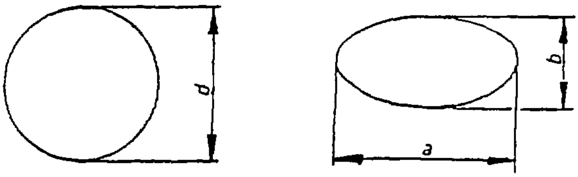
d is the effective optical focus size in accordance with annex A in millimetres:
f is the source-to-object distance in millimetres:
t is the material thickness in millimetres.

For specimen thicknesses in the range of 40 to 100mm, the source-to-object distance is usually a compromise between the technically desirable distance and an acceptable short exposure time.

In this thickness range an increase in f will generally produce an improvement in flaw sensitivity.



Square Rectangular



Circular Elliptical

Fig. 10.2 Focal spots (idealised)

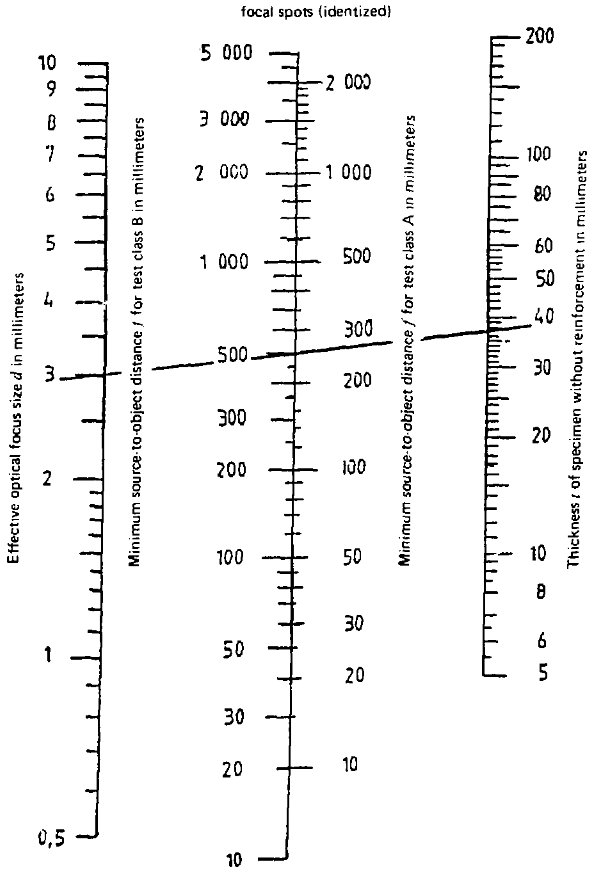
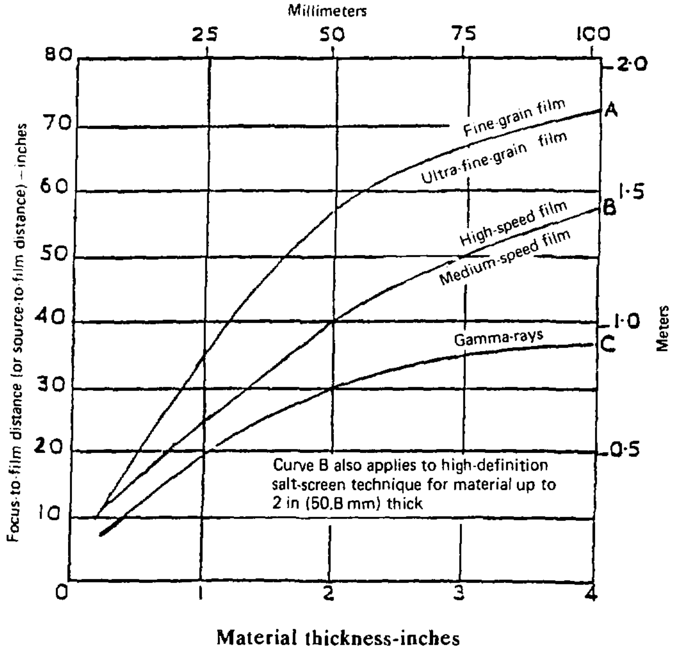


Figure 10.3 Nomogram for calculation of f

The cassette should be in close contact with the surface of the test object whenever possible. When this is not possible and when the distance b between the film and the test specimen is large compared to the thickness t, t should be replaced by (b+t) on the abscissa of Figure 10.1.

10.3.3.2. B.S. 2600

The British Standard B.S. 2600 gives several curves to calculate the minimum values of FFD, Figure 10.4.



Curve B also applies to high-definition salt-screen technique for material up to 2 in (50.8 mm) thick

Minimum values of focus-to-film distance (or source-to-film distance) Calculated for 7mm focal spot (Curves A and B) 4mm source (Curve C)

NOTE 1. For a focal spot of maximum effective dimensions s mm (other than 7mm) the focus-to-film distance Fz should be equal to or greater than the value calculated from the following formula :

$$Fz = sF_1/7$$

Where F_1 is the focus-to-film distance for a 7mm effective focal spot.

NOTE 2. For a source of diameter d mm (other than 4mm) the source-to-film distance Fz should be equal to or greater than the value calculated from the following formula :

$$Fz = dF_2/4$$

where F_2 = source-to-film distance for a 4mm diameter source.

Figure 10.4. Curves for the determination of sfd values according to B.S. 2600

10.3.3.3. ASME Code

The focus- film distance necessary to reduce geometric unsharpness to a negligible amount depends upon the film or film-screen combinations, focal-spot size and object-film distance. Geometric unsharpness is given, Figure 10.5.(a), by the equation :

$$U_g = Ft/d.$$

where,

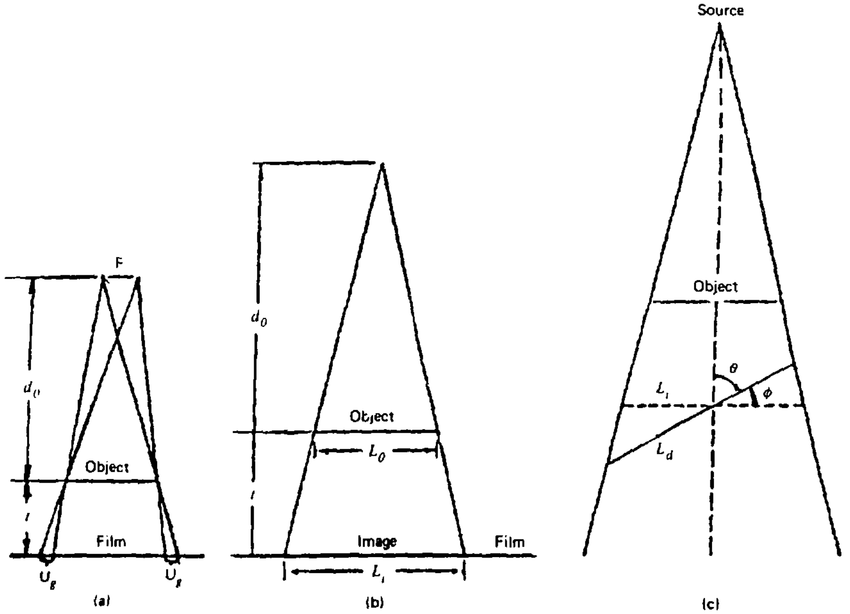
U_g = geometric unsharpness,
F = size of the radiation source,
t = specimen thickness, and
d = source-object distance.

A nomogram for the determination of U_g is given in Figure 10.6.
For example:

Given :

Source-film distance (d) = 40in.,
Source size (F) = 5.0mm, and
Source side of specimen to film distance(t) = 1.5in.

Draw a straight line (dashed in Figure 10.6) between 5.0mm on the F scale and 1.5in. on the t scale. Note the point of intersection (P) of this line with the pivot line. Draw



(a) Geometric Unsharpness, U_g (b) Radiographic Enlargement (c) Radiographic Distortion

Legend for (a) and (b)

d_0 = source to object distance
t = object to film distance
L_0 = dimension of object
L_i = dimension of image
% enlargement = $\Delta/L_0 \times 100$
$L_0 = L_i/(1 + t/d_0)$

Legend for (c)

L_i = dimension of undistorted image
L_d = dimension of distorted image
$L_d - L_i = \Delta L$
% distortion = $\Delta L/L_i \times 100$

Figure 10.5 Effects of object-film geometry

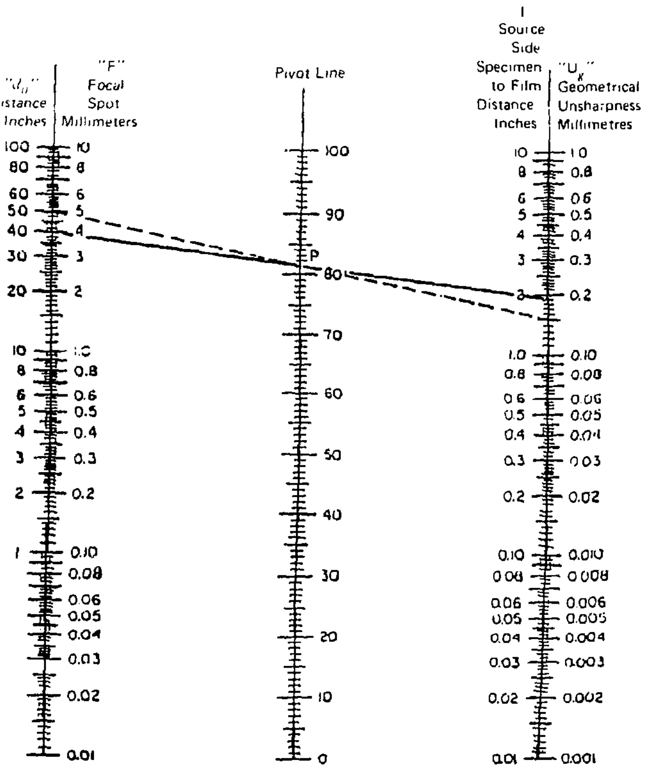


Figure 10.6 Nomogram for determining geometric unsharpness.

a straight line (solid in Figure 10.6) from 40in. on the d scale through point P and extend to the U_g scale. Intersection of this line with the U_g scale gives geometric unsharpness in millimetres which in the example is 0.19mm.

In as much as the source size, F, is usually fixed for a given radiation source, the value of U_g is essentially controlled by the simple d/t ratio.

Because X and gamma radiation is divergent, the radiographic image of an object, or of a structure within an object, will be larger than the object of the structure itself. The degree of enlargement will increase with decreasing source-object (structure) distance and with increasing object (structure)-film distance (Figure 10.5.(b).

If the film is not parallel to the object, the radiographic image will be distorted because different parts of the radiographic image will be enlarged by different amounts. A measure of the degree of distortion is given by the ratio of the change in image size caused by distortion to the size of the undistorted image (Figure 10.5. (c)).

Final acceptance of radiographs should be based on the ability to see the prescribed penetrameter image and the specified hole. The unsharpness formula is included for information and guidance, and will operate within practical limits, but is of less consequence as d/t ratios increase.

10.3.3.4. **JIS Z 3104**

i) Figure 10.7 shows a radiographic examination set up in JIS Z 3104. The image quality is divided into the ordinary class and the special class. The ratio of the source-penetrameter distance L_1 to the IQI film distance L_2 is denoted by m. The value m shall meet the following equations for each class.

Ordinary class $m \geq 2.5f$
Special class $m \geq 5f$

where, $m = L_1/L_2$
f = focus size (mm)

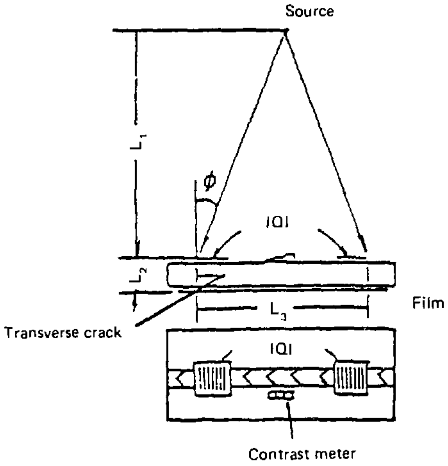


Figure 10.7 Radiographic arrangement for determining the angle of radiation relative to transverse crack

ii) JIS Z 3104 specifies the radiographic arrangement as follows so that the degree of detection of planar defects such as cracks does not show a great difference between the centre and corners of a radiograph of a butt weld of flat plates. The distance between the source and the penetrameter L_1 shall as a rule be less than n times the effective length of the tested part L_3. The coefficient n shall be 2 for the common class and 3 for the special class. If a crack which is at right angles to the weld line and is present in the thickness direction, is supposed to be formed , the radiation angle relative to the transverse crack is given by the following equation as shown in Figure 10.7.

For the ordinary class ($L_1 \geq 2\ L_3$)

$$= \tan^{-1}(2/L_1) = \tan^{-1}(1/4) = 14^\circ$$

For the special class ($L_1 \geq 3\ L_3$)

$$= \tan^{-1}\frac{(L_3/2)}{L_1} = \tan^{-1}(1/6) = 9^\circ$$

That is to say, this standard limits the effective length of the tested part so that the radiation angle to the transverse crack (hereinafter called the radiation angle) is approximately 14 degrees or less for the ordinary class and approximately 9 degrees or less for the special class.

10.3.4. Radiation energy

10.3.4.1. <u>ISO/DIS 5579</u>

According to this standard the maximum kilovoltage (KV) that can be used for a particular thickness is determined from Figure 10.8. Test ranges for high energy X-ray equipments and gamma ray sources are given in TABLE 10.12.

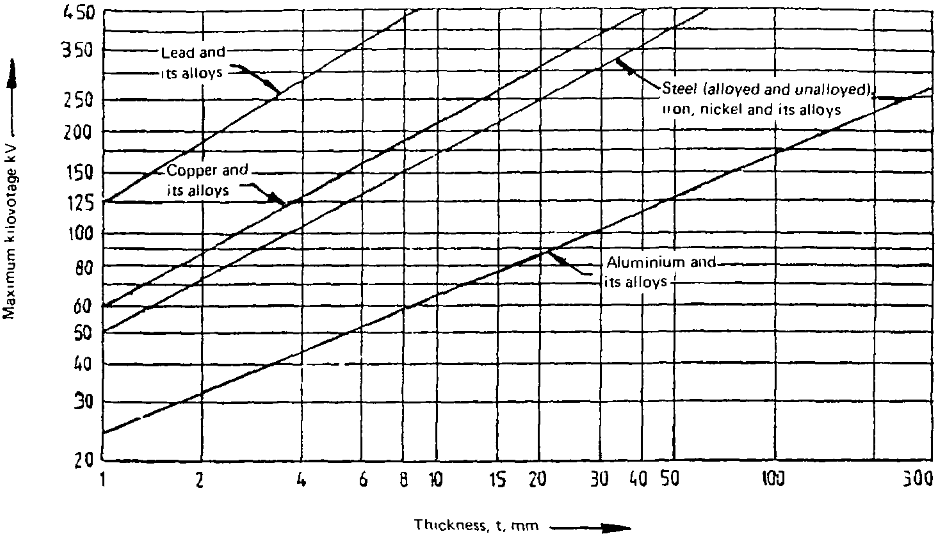


Figure 10.8 Maximum kilovoltage for X-rays up to 450KV for different materials for classes A and B in terms of material thickness.

TABLE 10.12 THE RANGE OF MATERIAL THICKNESSES (MILLIMETRES) FOR WHICH DIFFERENT RADIATION SOURCES ARE SUITABLE

Class A			
Radiation source	Steel, Iron, Nickel and its alloys	Copper and its alloys	Lead and its alloys
Ir 192	20 to 100 (10 to 100)	15 to 90	5 to 40
Co 60	40 to 200	20 to 170	15 to 125
X rays 1 to 2 MV	50 to 200	–	–
X ray more than 2 MV	50 and up	–	–
Class B			
Radiation source	Steel, Iron, Nickel and its alloys	Copper and its alloys	Lead and its alloys
Ir 192	40 to 90 (10 to 90)	35 to 80	15 to 35
Co 60	60 to 150	50 to 135	40 to 100
X rays 1 to 2 MV	60 to 150	–	–
X rays more than 2 MV	60 and up	–	–

10.3.4.2. B.S. 2600

Maximum X-ray tube voltages allowed by the B.S. 2600 are given in Figure 10.9.

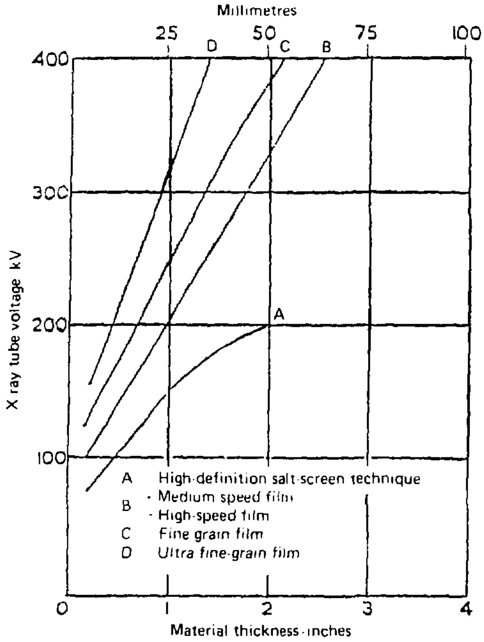


Figure 10.9 Maximum X-ray tube voltage according to B.S.2600

The curves for voltage are not extended beyond 400 KV as there is no commercial X-ray equipment in use in this country operating between about 400 and 1000 KV. For thicknesses of material greater than 3in (75mm) experience has shown that satisfactory radiographs can be obtained with any X-ray energy from 1 to 31 MeV provided that due attention is paid to the clauses on focus-to-film distance and density of radiograph.

The curves given on Figure 10.9. are used in the following way depending on the exposure techniques. The minimum exposure in mAmin is as follows:

Radiographic technique	Voltage curve	Minimum mAmin
1	D	30
2	C	20
3	B	15
4	B	8
5	A	8

Recommended thicknesses for gamma-ray sources are the following :

Cobalt 60 - from 50 to 200mm
Calcium 137 - from 25 to 100mm
Iridium 192 - from 6 to 90mm
Thulium 170 - up to 13mm

10.3.4.3. **ASME Code**

The maximum voltage used in the examination shall not exceed the value shown in Figure 10.10 (a), (b) or (c) as applicable. The recommended minimum thickness for which radioactive isotopes may be used is as follows :

	Minimum thickness	
Material	Iridium 192	Cobalt 60
Steel	0.75 in.	1.50 in.
Copper or High Nickel	0.65 in.	1.30 in.
Aluminium	2.50 in.	......

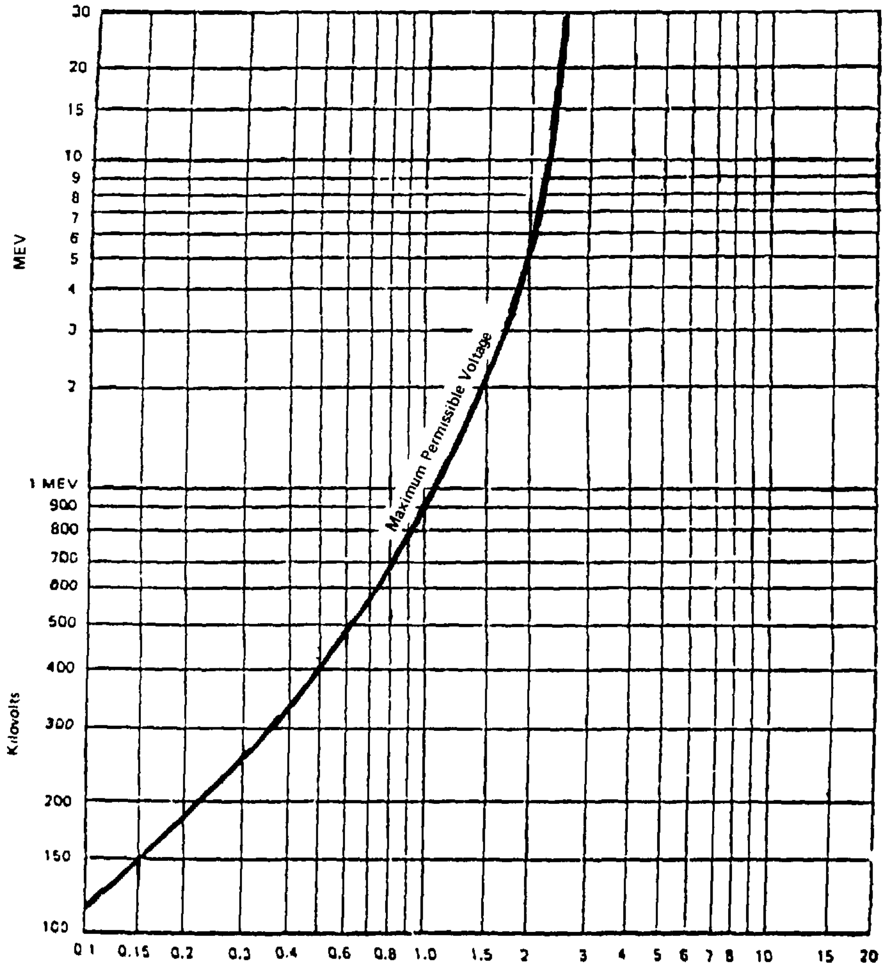


Figure 10.10(a) Maximum voltage for steel.

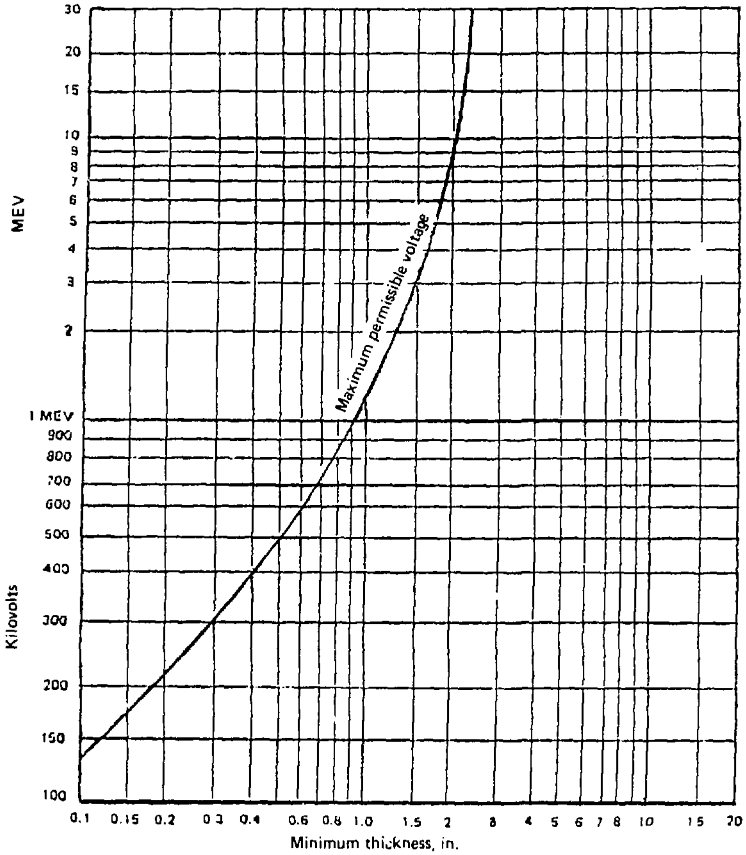


Figure 10.10(b) Max.voltage for alloys of copper and/or high nickel.

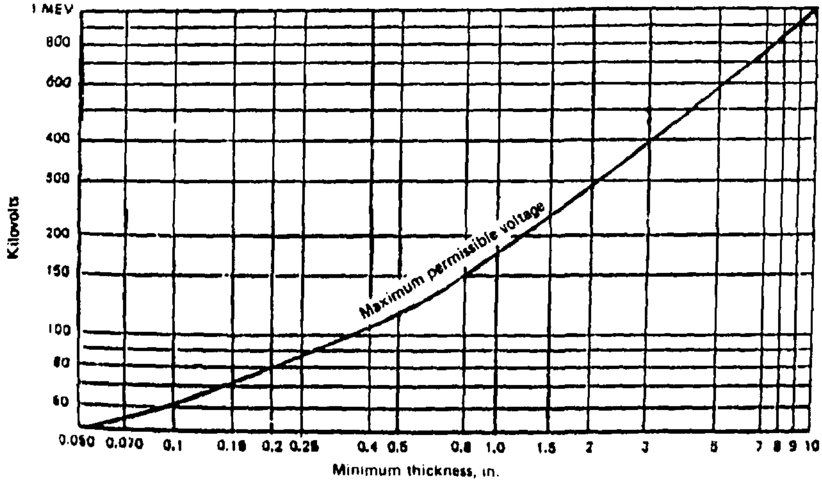


Figure 10.10(c) Max.voltage permitted for Al and Al alloys.

10.3.4.4. JIS Z 3104

No formal classification of radiation energy is given in this standard.

10.3.5. Radiographic density

10.3.5.1. ISO/DIS 5579

The recommended values of radiographic densities for various films are given in TABLE 10.13.

TABLE 10.13. RECOMMENDED RADIOGRAPHIC DENSITIES ACCORDING TO ISO STANDARD

Test class	Film density including fog	Permissible fog density	
		GI, GII, GIII	GIV
A	1.5 or more	0.3 or less	0.4 or less
B	2.0 or more	"	"

10.3.5.2. B.S.2600

TABLE 10.14 gives the recommended radiographic densities for various radiographic technique.

TABLE 10.14. RECOMMENDED RADIOGRAPHIC DENSITIES ACCORDING TO B.S.2600

Radiographic technique	Density of radiograph		Fog density
	min	max.	max.
1	2.0	3.0	0.2
2	2.0	3.0	0.2
3	1.7	3.0	0.3
4	1.7	3.0	0.3
5	1.3	2.3	0.3
6	2.0	3.0	0.2
7	2.0	3.0	0.2
8	2.0	3.0	0.3

10.3.5.3. ASME Code

The transmitted film density through the radiographic image of the body of the appropriate penetrameter and the area of interest shall be 1.8 minimum for single film viewing for radiographs made with an X-ray source and 2.0 minimum for radiographs made with a gamma ray source. For composite set shall have a minimum density of 1.3. The maximum density shall be 4.0. for either single or composite viewing. A tolerance of 0.05 in density is allowed for variations between densitometer readings.

If the density of the radiograph anywhere through the area of interest varies by more than minus 15% or plus 30% from the density through the body of the penetrameter, within the minimum/maximum allowable density ranges specified in T-282.1, then an additional penetrameter shall be used for each exceptional area or areas and the radiograph retaken. When calculating the allowable variation in density, the calculation may be rounded to the nearest 0.1 within the range specified above.

When shims are used the plus 30% density restriction above may be exceeded, provided the required penetrameter sensitivity is displayed and the density limitations set above are not exceeded.

10.3.5.4. JIS Z 3104

TABLE 10.15 gives the required radiographic densities for various material thicknesses.

TABLE 10.15 REQUIRED RADIOGRAPHIC DENSITIES ACCORDING TO JIS Z 3104

Material thickness (mm)	Density range
Up to 50	1.0 - 3.5
over 50 up to 100	1.5 - 3.5
over 100	2.0 - 3.5

10.3.6. Image quality indicators

10.3.6.1. ISO/DIS 5579

According to this standard the design of the IQI shall be as given in Chapter 6 of these notes. The sensitivity values required for the I.Q.I. shall be agreed between the contracting parties. These values merely provide a guide to the quality of the technique used and do not necessarily bear any direct relation to sensitivity as regards the detection of flaws.

10.3.6.2. B.S. 2600

The design of the IQI shall be according to that given in Chapter 6 of these notes. This standard does not give a value of IQI sensitivity which can be regarded as universally acceptable or desirable. It is stated that an acceptable value of IQI sensitivity should be determined by mutual agreement between the contracting parties. For guidance, however, the standard does give examples of I.Q.I. sensitivity which can be excepted to be obtained (TABLES 10.16 a and b). TABLE 10.16a is for more critical techniques such as technique 1 and 2 and TABLE 10.16b is for techniques such as 6,7 and 8.

TABLE 10.16. GUIDE TO THE SELECTION OF IQI SENSITIVITY ACCORDING TO B.S.2600

Specimen Thickness		I.Q.I. Sensitivity per cent		Specimen Thickness		I.Q.I. Sensitivity per cent	
mm	in	Wire type	Step/hole type	mm	in	Wire type	Step/hole type
3	1/8	2.4	5.1	3	1/8	-	-
6	1/4	1.6	3.6	6	1/4	-	-
12.5	1/2	1.4	3.0	12.5	1/2	2.4	4.6
25	1	1.2	2.5	25	1	1.7	3.0
40	1 1/2	1.1	2.1	40	1 1/2	1.5	2.5
50	2	1.0	1.8	50	2	1.3	2.2
75	3	0.9	1.6	75	3	1.1	2.0
100	4	0.8	1.4	100	4	1.0	1.8
150	6	0.7	1.3	150	6	0.9	1.8
	(a)				(b)		

10.3.6.3. ASME Code

The design of the I.Q.I. (penetrameter) is given in Chapter 6. The essential hole size and designated penetrameters are as specified in TABLE 10.17. A smaller hole or a thinner penetrameter than listed for each range may be used, provided all other requirements for radiography are met.

TABLE 10.17. SELECTION OF IQI ACCORDING TO ASME CODE

Nominal Single-Wall Material thickness Range, in.	Source Side		Film Side	
	Designation	Essential Hole	Designation	Essential Hole
Up to 0.25, inclusive	10	4T	7	4T
Over 0.25 through 0.375	12	4T	10	4T
Over 0.625 through 0.75	17	4T	15	4T
Over 0.75 through 0.875	20	4T	17	4T
Over 0.875 through 1.00	20	4T	17	4T
Over 1.00 through 1.25	25	4T	20	4T
Over 1.25 through 1.50	30	2T	25	2T
Over 1.50 through 2.00	35	2T	30	2T
Over 2.00 through 2.50	40	2T	35	2T
Over 2.50 through 3.00	45	2T	40	2T
Over 3.00 through 4.00	50	2T	45	2T
Over 4.00 through 6.00	60	2T	50	2T
Over 6.00 through 8.00	80	2T	60	2T
Over 8.00 through 10.00	100	2T	80	2T
Over 10.00 through 12.00	120	2T	100	2T
Over 12.00 through 16.00	160	2T	120	2T
Over 16.00 through 20.00	200	2T	160	2T

10.3.6.4. JIS Z 3104

The design of IQI is given in Chapter 6 of these notes. This standard gives two values of IQI sensitivity for two classes of radiographic techniques as shown in TABLE 10.18.

TABLE 10.18 IQI SENSITIVITY ACCORDING TO JIS Z 3104

Class	Material thickness (mm)	IQI Sensitivity (%)
Special	Up to 100	1.5
	Over 100	1.3
Ordinary	----------	2.0

10.4. GENERAL RULES FOR RADIOGRAPHIC TESTING

Besides the technical parameters discussed in the preceding section, the following rules are given as a guide for carrying out a good quality radiographic inspection. Most of these rules are taken from ISO/DIS 5579 but some of these rules are modified by considering B.S. 2600, B.S. 2910 and ASME Code.

10.4.1. Protection

Exposure of any part of the human body to X-rays or gamma-rays can be highly injurious to health. It is therefore essential that, whenever X-ray equipment or radioactive sources are in use, adequate precautions should be taken to protect the radiographer and any other person in the vicinity. Safety precautions to be taken against X-rays and gamma-rays are those in force in each country.

10.4.2. Surface preparation

In order to obtain the best flaw sensitivity, it is always advisable to remove surface imperfections before taking radiographs. In general, surface preparation may not be necessary for radiography, but where surface irregularities might cause difficulty in detecting internal discontinuities, the surface should be ground smooth.

10.4.3. Identification and marking

Letters or symbols should be affixed to each section of a test object being radiographed. The image of these markers should appear in the radiograph to ensure unequivocal identification of the section. The use of a film imprinter or other means prior to development is also permitted.

In general, permanent markers on the test object will provide reference points for the accurate re-location of the position of each radiograph. Where the nature of the material and its service conditions render stamping impossible, other suitable means for re-locating the radiographs should be sought. This may be done by paint marks or by accurate sketches.

If the position of the area to be examined cannot be recognised from the shape of the work piece, markers should be placed so that the position of the area can be identified on the radiograph.

10.4.4. Overlap of films

In radiographing a continuous length of weld, the separate radiographs should overlap sufficiently to ensure that no portion of this length remains unexamined.

10.4.5. Use of gamma sources instead of X-ray equipment

If the use of X-ray equipment with respect to accessibility is technically impossible or if there exists larger probability of flaw detection due to a more advantageous direction of radiation beam, it is recommended that radioactive sources are used instead of X-ray tubes in the thickness ranges given in TABLE 10.11, although image quality of radiographs taken with X-ray equipment in these thickness ranges may be better than that with gamma rays.

10.4.6. Thickness latitude

For some applications, where the thickness or the absorption of the specimen changes rapidly over a small area, it is desirable to use a modified or a special radiographic technique to ensure that the range of "thickness" required to be examined falls within the useful film density region.

Precise rules cannot be formulated for a general case, but any of the five techniques listed below may be used:

(a) Use a higher X-ray kilovoltage than shown in Figure 10.8. together with a filter at the X-ray tube window. Suitable filter thicknesses are:

- for 200 KV X-rays : 0.25 to 0.5mm lead;
- for 400 KV X-rays : 0.8 to 1mm lead;

(b) expose two films of the same speed in one cassette, each to have a density at the minimum value specified in TABLE 10.13 under the thinnest part of the specimen. Superimpose the two films to examine the thicker region;

(c) expose two film of different speeds in one cassette, using an exposure suitable for producing acceptable film densities on the image of the thickest part of the specimen on the faster film and on the thinnest part of the specimen on the slower film;

(d) use a special single emulsion film, for example line copying film;

(e) reduce the minimum permissible density to 1.0 for class A and to 1.5 for class B.

The techniques mentioned in (d) and (e) lead to a poorer flaw sensitivity than would be obtained with a normal technique.

10.4.7. Precautions against scattered radiation

Scattered radiation reaching the film is an important cause of reduced image quality, particularly with X-rays between 150 and 400 KV. Scattered radiation can originate from both inside and outside the specimen. In order to minimise the effect of scattered radiation, the area of the field of radiation should be masked, so that it covers only the area of interest. This is normally done by collimating the primary cone of the radiation beam, either with a physical cone or with a diaphragm on the tube head. The film must also be shielded from radiation scattered from other parts of the specimen or from objects behind or to the side of the specimen. This can be done by using a back intensifying screen of extra thickness or by using a sheet of lead behind the film screen combination; this extra sheet may be inside the cassette or placed immediately behind the cassette.

Depending on the set-up, typical lead thicknesses are in the range of 1 to 4mm.

If the edge of the specimen is within the radiation field, a method of reducing undercutting scatter is generally necessary. Figure 10.11 shows two typical methods.

With X-rays of 6MV energy or more used without back intensifying screens, shielding against scattered radiation is not necessary, unless there is scattering material close behind the film.

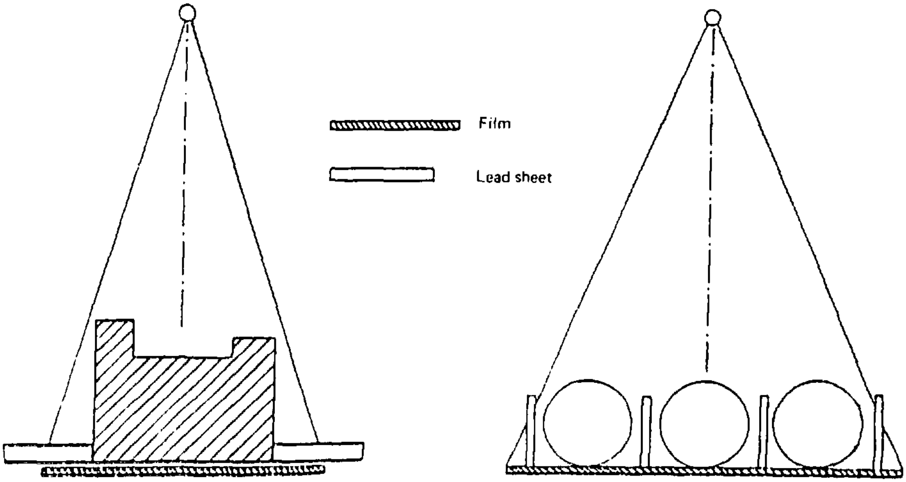


Figure 10.11 Methods of reducing the effect of scattered radiation

In general, with X-rays between 150 and 400 KV and with gamma rays, if a beam restrictor cannot be used, such as when panoramic exposures are being made, the exposure should be made in as large a room as possible, so that extraneous scatter is attenuated by distance; the specimens, when ever possible, should be well above floor level and the floor near the specimen should be covered with lead.

10.4.8. Cassettes

Films and screens (if used) should be contained in cassettes. Rigid cassettes are recommended, but flexible cassettes may be used. In either case, adequate precautions should be taken to ensure a good film-to-screen contact.

10.4.9. Processing

Film should be processed in accordance with the recommendations of the film manufacturer. Particular attention should be paid to temperature and developing time. The radiographs should be free from artefacts, due to processing or other causes, which would interfere with interpretation.

10.4.10. Viewing

The radiographs should be examined in a darkened room on an illuminated diffusing screen and the illuminated area should be masked to the minimum required for viewing the radiographic image. The brightness of the viewing screen should preferably be adjusted so as to allow satisfactory reading of the radiographs.

10.4.11. Test arrangement

The test arrangement consists of the radiation source, test object and the film or film-screen combination in a cassette. It depends on the size and shape of the object and the accessibility of the area to be tested. Generally one of the arrangements illustrated in Figure 10.12 to 10.14 should be used. The sketches in these Figures are suggested techniques. Other exposure arrangements may be used provided they comply with the requirements of the applicable standard. The beam of radiation should be directed at the middle of the section under examination and should be normal to the surface at that point except when it is known that certain flaws are better revealed by a different alignment of the beam.

When radiographs are taken in a direction other than normal to the surface, this should be indicated in the test report.

Double-wall techniques should only be used if single-wall techniques are technically not practical.

10.4.12. Size of area examined per exposure

The area to be taken into consideration at each exposure should be such that the thickness of material at the extremities of the exposed area, measured in the direction of the beam incident at that point, does not exceed the actual thickness at that point by more than 6% for high sensitivity techniques (ISO class B and Techniques 1 and 2 of B.S.-2600) and 10% for general purpose techniques (ISO class A and Techniques 3 to 8 of B.S.-2600).

A more practical way, especially for pipe radiography, is to determine the size of this area by the interpretable area from the first radiograph taken.

10.4.13. Back-scatter radiation check

As a check on back-scattered radiation, a lead symbol "B" with minimum dimensions of 12mm in height and 1.5mm in thickness, should be attached to the back of each film holder.

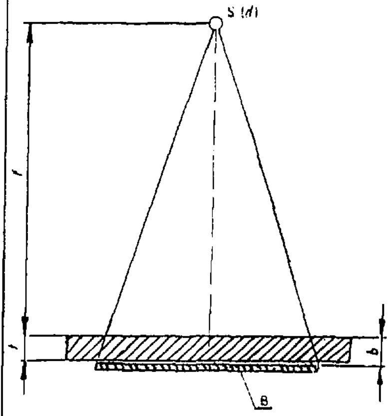
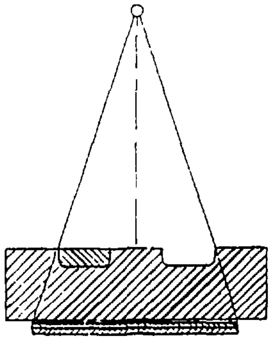
Arrangement No.	Exposure Technique	Radiograph Viewing	Test Arrangement	I.Q.I Selection & Placement	Size of Area covered per exposures
1	Single wall penetration, objects with plane walls	Single wall	 S Radiation source with an effective optical focus size d (See section 10.6.1.3p and fig.10.2) B film f Source-to-object distance t material thickness b distance between film and the surface of the object nearest the source.	SEE SECTION 10.3.6.3	SEE SECTION 10.4.12
2	Single wall penetration; objects with plane or curved walls of different thicknesses or materials; two films of the same or different speeds.	Single wall			

Figure 10.12a Single wall radiographic test arrangements

10.4.14. Source size

The equipment manufacturer's or supplier's publications, such as technical manuals, decay curves, or written statements documenting the actual or maximum source size or focal spot, should be acceptable as source size verification. For X-ray machines 320 KV and less, the focal spot size may be determined by the pinhole method.

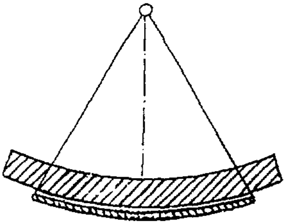
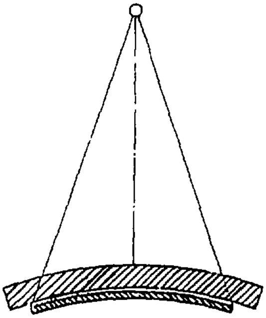
Arrangement No.	Exposure Technique	Radiograph Viewing	Test Arrangement	I.Q.I Selection & Placement	Size of Area covered per exposures
3	Single wall penetration objects, with curved walls, source on concave side film on convex side	Single wall	 Note:-This arrangement is preferred to arrangement 4:-	SEE SECTION 10.3.6.3	SEE SECTION 10.4.12
4	Single Wall penetration, objects with curved walls, source on convex side, film on concave side				

Figure 10.12b Single wall radiographic test arrangements

10.4.15. Step wedge film and densitometer

The density of step wedge comparison films and densitometer calibration should be verified by comparison with a calibrated step wedge film traceable to a national standard.

10.5. RADIOGRAPHIC TESTING PROCEDURES

A radiographic testing procedure is an orderly sequence of rules which describe in detailed terms, where, how and when a radiographic technique should be applied to a product. Radiographic procedures are normally formulated to meet inspection specifications. Inspection specifications are defined as :

(a) Customer Specifications

Inspection specification issued by the customer to the manufacturer when ordering.

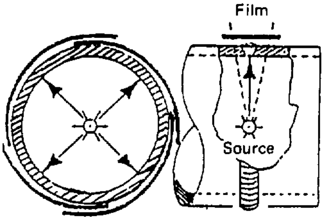
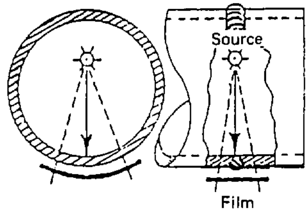
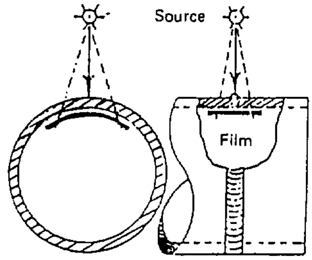
Arrangement No.	Pipe No.	Exposure Technique	Radiograph Viewing	Test Arrangement	I.Q.I Selection & Placement	Size of Area covered per exposures
1	Any	Single wall	Single wall		SEE SECTION 10.3.6.3	SEE SECTION 10.4.12
2	Any	Single wall	Single wall			
3	Any	Single wall	Single wall			

Figure 10.13 Single wall test arrangements for pipes.

(b) Approved Specifications

Inspection specifications submitted by the manufacturer to the customer.As an example, the following section gives inspection specifications for the radiographic testing of welds in a pressure retaining iron tube.

10.5.1. Inspection specifications for radiographic testing of butt welds in a pressure retaining iron tube

10.5.1.1. General

In addition to radiographic testing, non destructive examination of the welded joints shall be carried out using ultrasonic testing to inspect for internal cracks and magnetic particle testing to inspect for surface cracks.

10.5.1.2. Radiographic testing

This requirement applies to the butt-welded joints of a pressure retaining iron tube. The inspection shall conform to ISO/DIS 5579 (1983) "Non destructive testing Radiographic examination of metallic materials by X-and gamma rays-Basic rules" and be carried out under the following conditions.

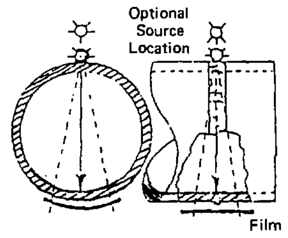
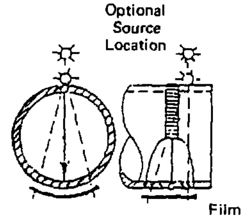
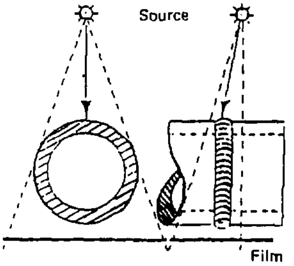
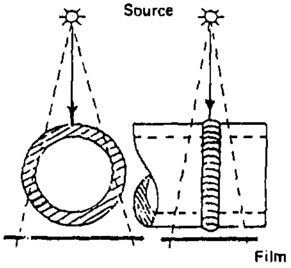
Arrangement No.	Pipe No.	Exposure Technique	Radiograph Viewing	Test Arrangement End view Side view	I.Q.I Selection & Placement	Size of Area covered per exposures
1	Any	Double-wall: penetration atleast 3 exposures 120 deg. to Each other for complete coverage	Single wall		SEE SECTION 10.3.6.3	SEE SECTION 10.4.12
2	Any	Double wall: penetration Atleast 3 exposures 120 deg. to Each other for complete coverage	Single wall			
3	90 mm or Less	Double Wall : penetration atleast 2 exposures at 90 deg. to Each other for complete coverage	Double wall (Ellipse) and offset source side & Film side images			
4	90 mm or Less	Double wall: penetration at least 3 exposures at 60 deg or 120 deg. to each other for complete coverage	Double wall Read super imposed source side and film side images			

Figure 10.14 Double wall test arrangement for pipes

10.5.1.2.1. Scope and conditions of radiography

(1) Longitudinal joints and circumferential joints of tube cylinder.

Material/joint	Longitudinal joint	Circular joint
SM 58Q	20% or more	15% or more
HT 80	100%	100%

Notes : (a) For HT 80, the scope of radiography is subject to change through agreement between the customer and the manufacturer according to the progress of work.

(b) When sampling inspection is carried out, the above mentioned values shall be satisfied.

(c) Test arrangements shall be specified by the customer's inspector.

(2) Time of examination

The radiographic test shall be conducted within 24 hours of completion of welding.

(3) Criteria for acceptance or rejection

Judgment shall be made by the customer on the acceptance or rejection of radiographs and weld lines, based on the following criteria:

(a) Criteria for acceptance or rejection of radiographs: Radiographs shall be compared with IIW reference radiographs and defects of level 'Green' and above shall be rejected.

(b) Criteria for acceptance or rejection of weld lines: If films used in radiographing the same weld line contain no rejected film, this weld line shall be accepted.

10.5.2. *Preparation of procedures*

As with the approved specifications, procedures shall, as a rule, be approved by the customer. However, this approval can be omitted by agreement between the customer and the manufacturer. The approval by the customer is necessary when the procedure is used in place of the approved specifications.

The procedure will be developed on the basis of the following outline :-

1.0. SCOPE. Identifies the type of test, inspection and examination, its application i.e., welds, formed materials, etc, and a statement that the procedure is in accordance with the specification for which it was written.

2.0. REFERENCES. This section will list the specifications and codes that the procedure complies with and will consist of 2.1 and 2.2 as described below:

2.1. The following documents, of the issue in effect, as referenced on the purchase order or contract are made a part of this procedure to the extent specified herein.

2.2. As required, a listing of reference material used in preparation of the procedure, ie., manufacturer's operating manual, tests, contract requirements, safety manuals, personnel certification procedure, equipment calibration or certification procedures, etc.

3.0. PERSONNEL QUALIFICATIONS. This section will invoke the applicable personnel certification procedure, and state the required level of certification for individuals performing the process of parts for which the procedure is written.

4.0. EQUIPMENT. This section will describe the equipment used in the method; if possible it will be a detailed description, however, it may be general. This section will also state calibration or certification procedure, if needed.

5.0. PROCESS. This section will delineate the process, preferably in a step by step manner. This section will cover surface requirements, process requirements, i.e. sensitivity, amperage, dwell times, coverage, etc., and interpretation environment. Whenever possible, the format of this section will be standardised for each method, i.e., penetrameter requirements will be specified by the same paragraph number in all radiographic testing procedures, etc.

6.0. REPORTS. This section will list the information required on reports and technique sheets, and may include examples of typical report forms.

7.0. ACCEPTANCE STANDARDS. This section shall contain general interpretation criteria and state the acceptance criteria of each applicable specification listed in Section 2.0.

The following section gives an example of radiographic testing procedure for welds in pressure retaining iron tubes.

10.5.3. Radiographic testing procedure for a pressure retaining iron tube

10.5.3.1. Scope

10.5.3.1.1. Applicable standards

These requirements apply to the radiographic test of welded portions of a water pressure retaining iron tube in accordance with the following standards:

(1) Ordinance for Establishing Technical Standards Pertaining to Hydraulic Equipment for Power Generation.
(Ordinance No. 59 of the Ministry of International Trade and Industry, 1965).

(2) Technical Standards for Water Gate Iron Tubes (Water Gate Iron Tube Association, November 1981)

(3) Supplement to Commentary of Water Pressure Iron Tube in Technical Standards for Water Gate Iron Tubes (Water Gate Iron Tube Association, June 1974).

(4) Regulations for the Prevention of Ionising Radiation Hazards : (Ordinance No. 41 of the Ministry of Labor, September 30, 1972).

10.5.3.1.2. Purpose of examinations

Radiographic test shall be conducted to detect internal defects of welded portions.

10.5.3.1.3. Time of examinations

The radiographic test of HT 80 welded portions shall be carried out more than 24 hours after the completion of welding.

10.5.3.1.4. Personnel qualifications

Engineers engaged in radiographic testing shall have the qualifications given in TABLE 10.19.

10.5.3.1.5. Object to be tested

Figure 10.15 and TABLE 10.20 show the object to be radiographed. The scope of test can be reduced through mutual agreement.

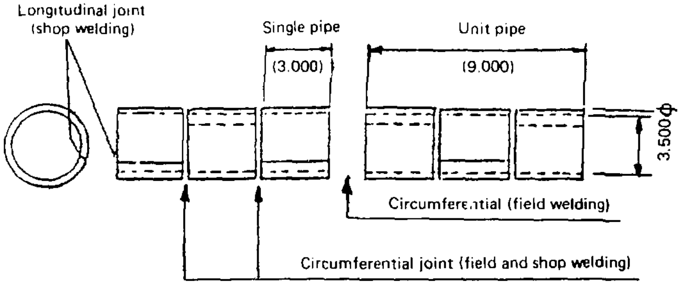


Figure 10.15 Object to be tested.

TABLE 10.19 CONTENTS OF WORK AND PERSONNEL QUALIFICATION FOR PERFORMING RADIOGRAPHIC INSPECTION

Contents of work	Required qualification (Note 1)
(1) Planning and implementation of test according to ISO standard (2) Preparation of specifications and procedures. (3) Interpretation of related standards. (4) Drafting of work standards. (5) Guidance of test engineers. (6) Calibration of equipment necessary for its use. (7) Evaluation of test results and grade classification. (8) Preparation or approval of records. (9) Preparation of reports. (10) Decision of criteria. (11) Comprehensive judgment. (12) Preparation or approval of reports.	Level-3 personnel
(1) Execution of test work according to ISO standard. (2) Evaluation of test results (3) Preparation of records (4) Instructions to Level 1 personnel	Level 2 personnel
(1) Execution of test work according to ISO standard. (2) Recording of test results	Level 1 personnel

10.5.3.2. Equipment and materials used

(1) Portable X-ray unit.

The following portable X-ray unit shall be used

Type: Andrex-300 (made by Andrex, Denmark).
Rated tube voltage: 300 kVp.
Rated tube current: 5mA.
Focal spot size: 2.3 x 2.3mm

(2) X-ray film:

Type: Structurix D7 (made by Agfa Geavert Ltd.).
Size: 10 x 40cm

TABLE 10.20 DATA ABOUT THE WELDS TO BE TESTED

Place	Type of joint	Material	Plate thickness mm		Inside diameter mm		Number of joints
Shop	Longitudinal	SM 58Q	26	43	4000	3500 and 2100	196
		HT 80	30	49	3500	2100	124
Field Shop	Circumferential	SM 58Q	26	43	4000		64
					3830		1
					3670		1
					3500		14
			45	46	2100		4
		HT 80	30	49	3500		80
					2800		1
					2100		0

(3) Intensifying screen:

Type:	Lead foil intensifying screen
Thickness:	For X-rays 0.03mm
	For gamma rays 0.10mm
Size:	10 x 40cm

(4) I.Q.I.

IQI Type 10/16 and type 7/12 as specified in ISO 2504.

(5) Film viewer.

Type: KS-3 (made by Seikosha)

(6) Densitometer

Type: PDA-81 (made by Konishiroku Photo Industry Co., Ltd.).

10.5.3.3. **Method of radiography**

10.5.3.3.1. Effective range of test zone

The effective range of a test zone per radiograph shall be as shown in TABLE 10.21.

TABLE 10.21. EFFECTIVE RANGE OF TEST ZONE

Type of joint	Inside diameter (mm)	Number of divisions of one joint	Effective length of test zone (mm)	Effective width of test zone
Longitudinal		9	334	
Circumferential	4,000	36	350	
	3,830	34	354	
	3,670	32	361	
	3,500	32	344	
	2,800	24	367	
	2,100	18	367	

(1) Longitudinal joint

The test arrangement for longitudinal joints is shown in Figure 10.16.

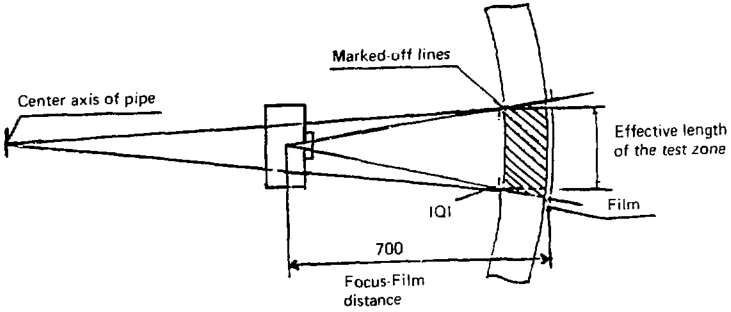


Figure 10.16 Test arrangement for longitudinal joints.

(2) Circumferential joint

The test arrangement for circumferential joints is shown in Figure 10.17.

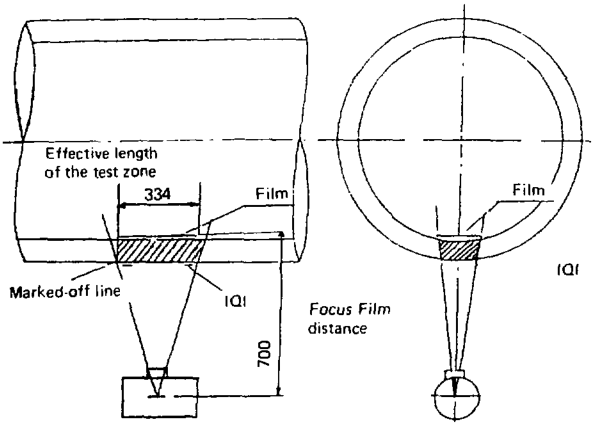


Figure 10.17 Test arrangement for circumferential joints.

10.5.3.3.2. Radiographic conditions

Radiographs shall be taken under the conditions mentioned below in 10.5.3.4.

10.5.3.4. Requirements of radiographs

10.5.3.4.1. Minimum wire diameter of IQI perceptible in test zone

In a radiograph, wire diameters as small as the values given in TABLE 10.22 shall be clearly perceptible in the effective range of a test zone.

TABLE 10.22 MINIMUM WIRE DIAMETER OF IQI

Plate thickness (mm)	Minimum wire diameter ofIQI(mm)
24 or more and less than 28	0.40
28 or more and less than 36	0.50
36 or more and less than 46	0.64
46 or more and not more than 49	0.80

When the plate thickness differs in a butt-welded joint, the smaller thickness shall be adopted as the plate thickness.

10.5.3.4.2. Density range of radiographs

The radiographic density of parts of the test zone except defects shall be 2.0 or more but not more than 3.5. When the plate thicknesses differ in a butt-welded joint, the larger thickness shall be adopted as the plate thickness.

10.5.3.4.3. Others

In the effective range of a radiograph, there shall be no irregularity of development, stain or scar that may be mistaken for a defect.

10.5.3.5. Judgment of acceptance or rejection of radiographic testing results

Radiographs shall be compared with IIW reference radiographs for welds. Welds having radiographic results of level'Green', 'Blue' or 'Red' shall be rejected.

10.5.3.6. Judgment of acceptance or rejection of welded joints

When all welded portions tested in the same welded joint are accepted by the judgment on acceptance or rejection in 10.5.3.5. above, this welded joint shall be accepted. When a welded portion is rejected by the judgment of acceptance or rejection, the following measure shall be taken.

10.5.3.6.1. Correction

The rejected portion shall be corrected. After ascertaining that this welded portion is accepted by a retest, it shall be accepted.

10.5.3.7. Frequency and method of repairs

Repairs shall be made in accordance with the procedure for repairs.

10.5.3.8. Recording

Results of the classification of radiographs and of the judgment of acceptance or rejection of welded joints shall be recorded in a list of records of radiographic testing.

10.5.3.9. Report

Non-destructive testing reports shall be prepared and submitted together with radiographs for approval.

10.6. FORMULATION OF INSTRUCTIONS FOR RADIOGRAPHIC TESTING

The use of written instructions in radiographic testing is to ensure that all jobs are performed according to and conform to radiographic testing procedures and specifications. A written radiographic testing instruction can be classified into a few parts. The general classification can be done as follows :

1. Instructions for warming up the X-ray machine, if used.
2. Date about the test specimen.
3. Test arrangement.
4. Equipment and devices.
5. Identification plan for test specimen.
6. Exposure conditions.

7. Requirement for radiograph.
8. Radiographic processing.

To write radiographic testing instructions one should fully understand the technical requirements for executing a specific radiographic job. This requires detailed information on radiographic testing procedures and practical experience.

The general content of radiographic testing instructions can be derived if the method of executing the job is understood. This includes all necessary steps to be carried out by the operators. The format of NDT procedures may vary from one job to another depending on the application and requirements needed for a particular job.

10.7. PERFORMANCE OF TEST IN ACCORDANCE WITH WRITTEN INSTRUCTIONS

10.7.1. Records of operating conditions

The operation conditions of a radiographic test is to be recorded on a "Data Record Form". The data record form may be of any desirable format but should as a minimum include the following information.

1. Instruction sheet number, title, date of issue, and revision number.
2. Data about the specimen.
3. Sketch of test arrangement.
4. Operating exposure conditions.
5. Area of interest.
6. Markers used to mark the area of interest.
7. Radiographic density and IQI sensitivity obtained.
8. Interpretable length of radiographs.
9. Total number of radiographs taken.
10. Other remarks if any.

10.7.2. Evaluation of task of Level 1 personnel

The task carried out by level 1 personnel can be evaluated by checking the following factors.

1. Quality of Radiographs

All radiographs should be free from mechanical, chemical, or other blemishes to the extent that they cannot mask or be confused with the image of any discontinuity in the area of interest of the object being radiographed. Such blemishes include, but are not limited to :

(a) fogging.
(b) processing defects such as streaks, water marks, or chemical stains.
(c) scratches, finger marks, crimps, dirtiness, static marks, smudges, or tears.
(d) loss of detail due to poor screen-to-film contact.
(e) false indications due to defective screens or internal faults.

2. Density of the radiograph

The density of the radiograph obtained should be within the range specified in the given instruction sheet.

3. IQI Sensitivity

The IQI sensitivity obtained should be within the range specified in the given instruction sheet.

4. Placement of IQI

The IQI should be placed in such a way that (i) its identification numbers are clearly visible on the radiograph and (ii) these marks are not masking any portion of the area of interest.

5. Identification marking

Identification marking should be according to the instruction sheet, and the markers used should be clearly visible on the radiograph and they should not mask any portion of the area of interest.

6. Marking of area of interest

The area of interest should be marked according to the instruction sheet and the markers should be clearly visible on the radiograph and should not mask any portion of the area of interest.

11. RECORDING OF TEST, INTERPRETATION AND EVALUATION OF RESULTS

11.1. DOCUMENTATION OF TEST RESULTS

The results obtained from non-destructive examination can be recorded automatically or manually. In the case where recording has to be done manually, a system of documentation or recording of test results has to be formatted. The documentations are normally divided into two following parts:

1. Mapping
2. Reporting

In the case of radiography, mapping of the defects is not required because these are permanently recorded on radiographic film. But mapping of film (location, position, etc.) can be done as part of identification requirements. An example of radiographic mapping is shown in Figure 11.1.

A radiographic report is normally documenting information about identification and interpretation. Identification reports can be done by level 1 personnel and in this case, the interpretation report (include material quality, defects type/location, etc.) is completed by Level 2 personnel. Usually, the radiographic report is recorded by using a standard form. A typical example of radiographic report form is shown in Figure 11.2.

11.2. INTERPRETATION AND EVALUATION OF TEST RESULTS

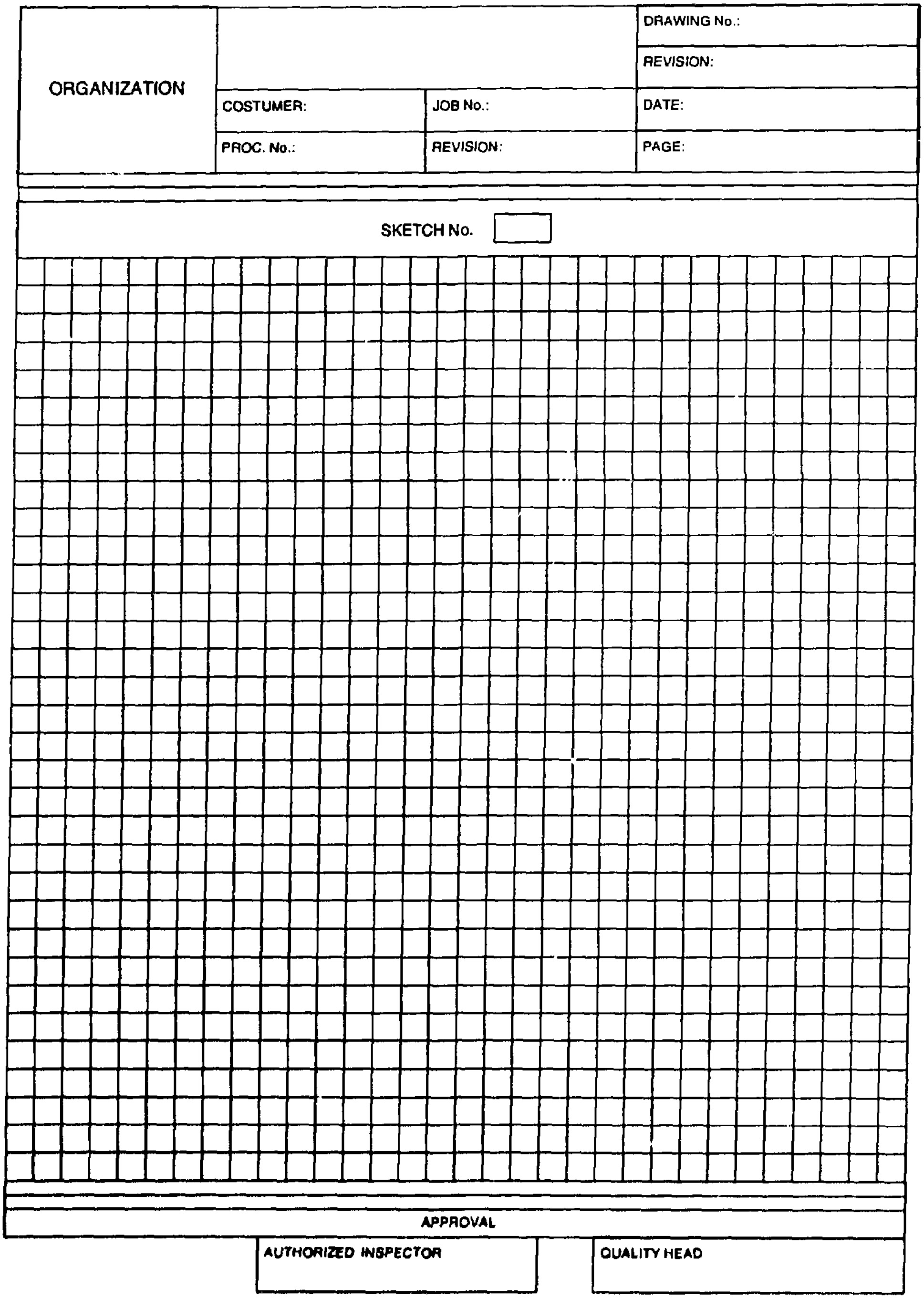
The final parts of radiographic process are evaluation and interpretation of a radiograph. A good quality radiograph will give significant and meaningful results only if the completed radiograph is interpreted intelligently.

To be an interpreter, one should have good eye-sight. For radiography and other NDT methods, human eye is the actual detector of radiographic process. Radiographic interpretation is the most important phase of radiography. It is during this phase that an error in judgment can produce disastrous consequences. The efforts of the whole radiographic process are centred in this phase whereby the material is either accepted or rejected. The conditions of unsoundness, or other product defects are overlooked, or misunderstood, in an improper interpretation.

The ever changing materials and processes which are subjected to radiographic testing, make it impossible to make radiographic interpretations as a standard reference. Radiographic inspections cannot easily or completely be learned by book study. Even guidance in interpretation available in literature by itself, is never sufficient to enable the 'uninitiated' to undertake interpretation with confidence and reliability.

Reliability and confidence in interpretation can be acquired through training, and continuous practical experience on the job. Among other things that can be of help in making good interpretations are understanding the procedure used to produce the radiograph and knowing the materials under investigation or examination.

Note that the presence of some defects or flaws does not mean the item cannot serve its intended purpose. Therefore, the person who interprets radiographs must exercise some judgment as to the degree of imperfection or discontinuity that exists and whether the discontinuity or imperfection will prevent the item from being used or fulfilling its purpose. However, it is very difficult for the interpreter to decide with confidence and reliability without any guide or specifications of quality level required. For this matter, scientific group (scientist, engineers, etc.) designing the product should establish an accept-reject criterion for such a product. In many cases, the manufacturer may use certain radiographic



ORGANIZATION			DRAWING No.:
			REVISION:
	COSTUMER:	JOB No.:	DATE:
	PROC. No.:	REVISION:	PAGE:

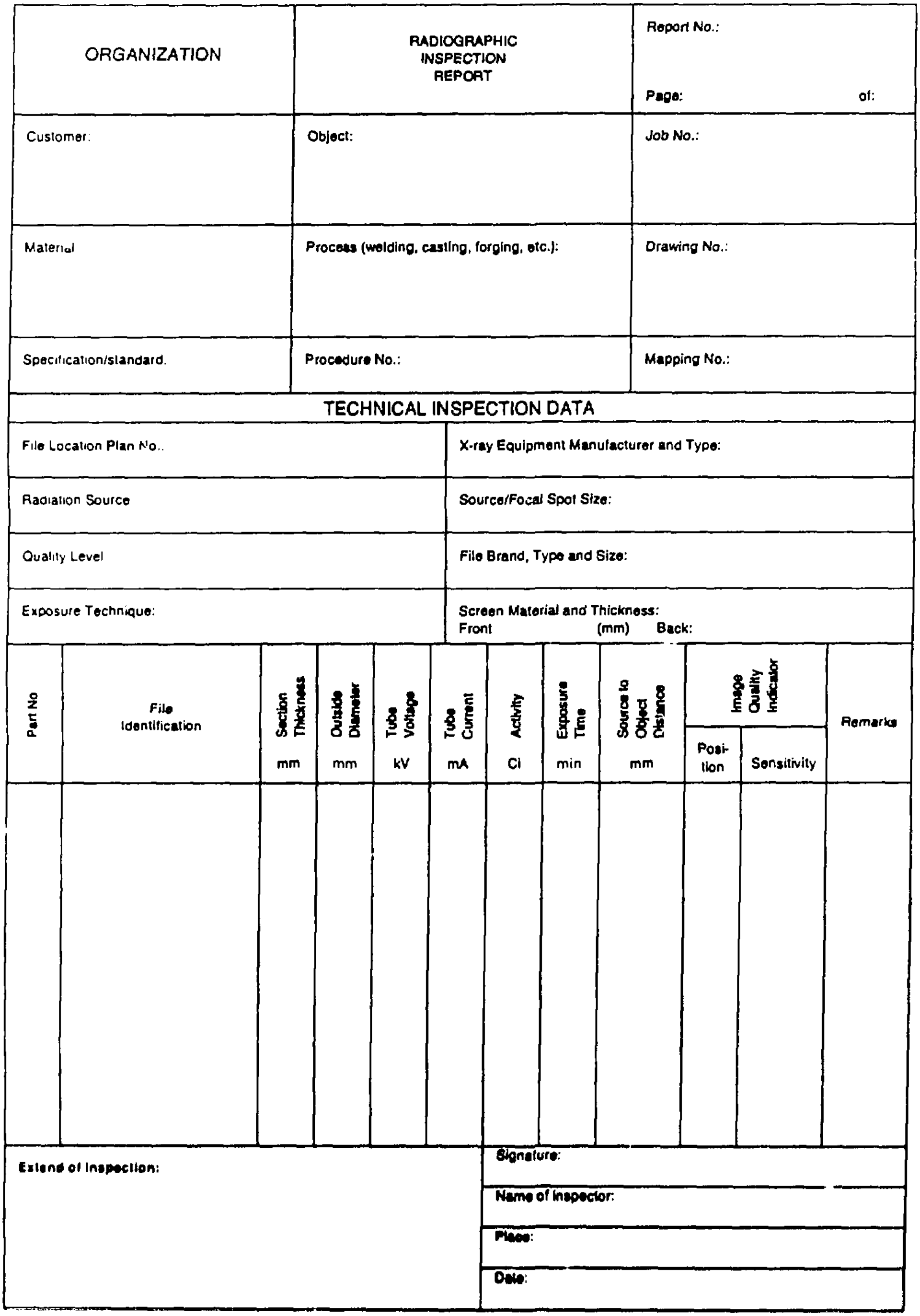
SKETCH No. ☐

APPROVAL

AUTHORIZED INSPECTOR

QUALITY HEAD

Figure 11.1 Form for mapping radiographic film location etc.



ORGANIZATION	RADIOGRAPHIC INSPECTION REPORT	Report No.: Page: of:
Customer:	Object:	Job No.:
Material	Process (welding, casting, forging, etc.):	Drawing No.:
Specification/standard.	Procedure No.:	Mapping No.:

TECHNICAL INSPECTION DATA

File Location Plan No..	X-ray Equipment Manufacturer and Type:
Radiation Source	Source/Focal Spot Size:
Quality Level	File Brand, Type and Size:
Exposure Technique:	Screen Material and Thickness: Front (mm) Back:

Part No	File Identification	Section Thickness mm	Outside Diameter mm	Tube Voltage kV	Tube Current mA	Activity Ci	Exposure Time min	Source to Object Distance mm	Image Quality Indicator		Remarks
									Position	Sensitivity	

Extend of Inspection:	**Signature:**
	Name of inspector:
	Place:
	Date:

Figure 11.2(a) A typical example of a radiographic testing report form.

ORGANIZATION	RADIOGRAPHIC REPORT		*Report No.:* Page:
COSTUMER:		CONTRACT No.:	
JOB No.:		PLACE:	
SOURCE TYPE/No./ACTIVITY:			TECHNIQUE:
FILM TYPES/SIZES:		QUALITY STD.:	MAPPING No.:
PROCEDURE No.:	RP PROC. No.:	EQUIPMENT No.:	DRAWING No.:

RESULTS

WELD No./ PART No.	RADIOGRAPH No. OR POSITION	DENSITY	RADIOGRAPHIC QUALITY A/R	MATERIAL QUALITY A/R	TYPE OF DEFECT	POSITION OF DEFECT

LEGEND:

: ACCEPT
: REJECT
: POROSITY
: SLAG INCLUSION
: LACK OF FUSION
: INCOMPLETE PENETRATION

C : CRACK
U : UNDERCUT
SC : SHRINKAGE CAVITY
AR : ARTIFACTS (SPECIFY)
II : INCORRECT IQI

APPROVAL

CLIENT: AUTHORIZED INSPECTOR

DATE:

CERTIFICATION:

REMARKS:

Figure 11.2(b) A typical example of a radiographic testing report form.

codes, standards and other reference in setting up the accept/reject criterion for his product. The interpreter must, therefore, familiarise himself with the standard being used in order to make proper judgments for the product evaluation. The code, specification or standard upon which the interpretation of radiographs is based may serve two functions as follows :

(1) As a guide for identifying types of discontinuities.
(2) To specify or indicate acceptable and unacceptable soundness conditions for products. Some of the important codes and standards for the accept-reject criteria for welds are given in the following section.

11.3. ACCEPTANCE STANDARDS

In general two methods are used to give the acceptable quality of defects in welds. The first refers to the reference radiographs, the other gives maximum dimensions of acceptable defects. Both methods have this in common that they are based on radiography.

11.3.1. Reference radiographs

The application of the ASME E-390 Standard Reference Radiographs for Steel Fusion Welds is as follows: To arrive at acceptance standards in the application of ASTM-390 Standard Reference Radiographs for Steel Fusion Welds to film interpretation, the following rules should be observed :

(i) The graded reference radiographs may be used in whole or in parts as applicable to particular requirements.

(ii) The length of the welding to which the selected standard applies shall be established. These designated lengths shall not contain any discontinuity whose severity exceeds that in the reference.

(iii) When the production radiograph is interpreted as showing equal or less severe discontinuities than the selected standard, the weld shall be judged radiographically acceptable. When the production radiograph is interpreted as showing greater severity than the selected standard, the weld shall be judged unacceptable and shall be repaired in accordance with contractual agreements.

(iv) If more than one type of discontinuity occurs in the same radiograph, the predominating type alone governs acceptability unless the severity represented by the combination of discontinuity types is such as to make the overall condition unacceptable for the intended application.

(v) When two or more discontinuity types are present in the same radiograph to an extent equal to the maximum acceptable for two of these types the weld shall be judged unacceptable, with repair welding to be done according to contractual agreement.

(vi) When repair welding is permitted, the repair need only be to that extent which will bring the weld quality to within the acceptable reference.

11.3.2. Acceptance standards for pressure vessels

In the ASME Boiler and Pressure Vessel Code, the following acceptance standards are given. Sections of weld that are shown by radiography to have any of the following types of imperfections shall be judged unacceptable and shall be repaired and the repair radiographed:

1. Any type of crack, or some of incomplete fusion or penetration.
2. Any elongated slag inclusion which has length greater than :

- 6.35mm for thickness t up to 19mm
- 1/3 t for 19 t = 57mm
- 19mm for t > 57mm

3. Any group of slag inclusions in line that has an aggregate length greater than t in a length of 12 t, except when the distance between the successive imperfections exceeds 6L where L is the length of the longest imperfection in the group.

11.3.2.1. Acceptance criterion for rounded indications

The following criterion is given in ASME Code Sections I, III and VIII (1983 Edition) for ferritic, austenitic and nonferrous material:

A. Terminology

A-1 Rounded Indications

Indications with a maximum length of three times the width or less on the radiograph are defined as rounded indications. These indications may be circular, elliptical, conical, or irregular in shape and may have tails.

When evaluating the size of an indication, the tail shall be included. The indication may be from any source in the weld, such as porosity, slag, or tungsten.

A-2 Aligned Indications

A sequence of four or more rounded indications shall be considered to be aligned when they touch a line parallel to the length of the weld drawn through the centre of the two outer rounded indications.

A-3 Thickness

t is the thickness of the weld of the pressure retaining material, or of the thinner of the sections being joined, whichever is least. If a full penetration weld included a fillet weld, the thickness of the fillet weld throat t shall be included in t.

B Acceptance Criteria

B-1 Image Density

Density within the image of the indication may vary and is not a criterion for acceptance or rejection.

B-2 Relevant Indications (See TABLE 11.3 for Examples).

Only those rounded indications which exceed the following dimensions shall be considered relevant:

1/10t for t less than 1/8 in;
1/64 in. for t equal to 1/8-1/4 in., inclusive.
1/32 in. for t greater than 1/4-2 in., inclusive.
1/16 in. for t greater than 2 in.

B-3 Maximum Size of Rounded Indication

The maximum permissible size of any indication shall be 1/4t or 5/32 in., whichever is less; except that an isolated indication separated from an adjacent indication by 1 in. or more may be 1/3t or 1/4 in., which ever is less. For t greater than 2 in., the maximum permissible size of an isolated indication shall be increased to 3/8 in.

B-4 Aligned Rounded Indications

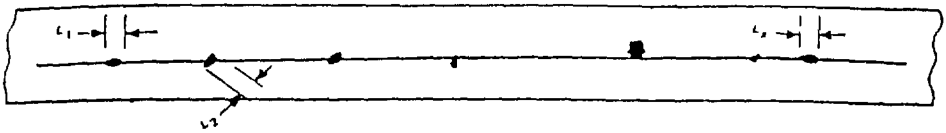
Aligned rounded indications are acceptable when the summation of the diameters of the indications is less than t in a length of 12t (see Fig.11.3a). The length of groups of aligned rounded indications and the spacing between the groups shall meet the requirements of Figure 11.3 b.

TABLE 11.1. MAXIMUM SIZE OF NON RELEVANT INDICATIONS AND ACCEPTABLE ROUNDED INDICATIONS (EXAMPLES ONLY)

Thickness t in.	Maximum size of acceptable rounded indication in.		Maximum size of non relevant indication in.
	Random	Isolated	
< 1/8	1/4 t	1/2 t	1/10 t
1/3	0.031	0.042	0.015
3/16	0.047	0.063	0.015
1/4	0.063	0.083	0.031
5/16	0.078	0.104	0.031
3/8	0.091	0.125	0.031
1/16	0.109	0.146	0.031
1/2	0.125	0.168	0.031
9/16	0.142	0.188	0.031
5/8	0.156	0.210	0.031
11/16	0.156	0.230	0.031
3/4-2 inclusive	0.156	0.250	0.031
> 2	0.156	0.375	0.063

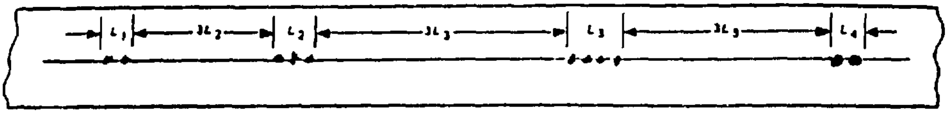
B-5 <u>Spacing</u>

The distance between adjacent rounded indications is not a factor in determining acceptance or rejection, except as required for isolated indications or groups of aligned indications.



Sum of L_1 to L_x shall be less than t in a length of 12t.

Figure 11.3 (a) Aligned rounded indications



The sum of the group lengths shall be less than t in a length of 12 t.

Maximum Group Length	Minimum Group Spacing
L = 1/4in. for t less than 3/4in.	3L where L is the length of the longest adjacent group being evaluated.
L = 1/3t for t equal to 3/4in. to 2 1/4in.	
L = 3/4in. for t greater than 2 1/4in.	

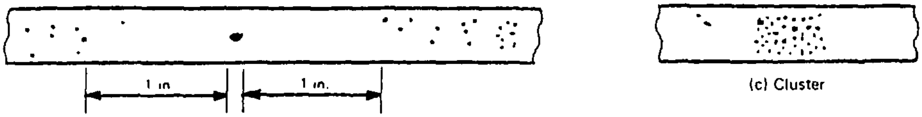
Figure 11.3 (b) Groups of aligned rounded indications.

B-6 Rounded Indication Charts

(a) The rounded indications as determined from the radiographic film shall not exceed that shown in the charts.

(b) The charts in Figures 11.4 a through 11.4 f illustrate various types of assorted, randomly dispersed, and clustered rounded indications for different weld thicknesses greater than 1/8in. These charts represent the maximum acceptable concentration limits for rounded indications.

(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in..length of weld)

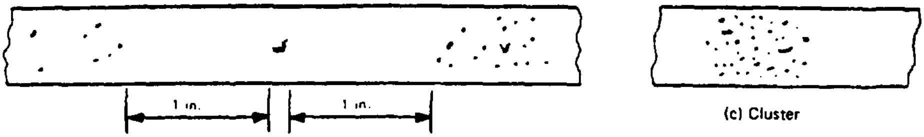


(c) Cluster

(b) Isolated Indication
(Maximum size per Table 11.1)

Figure 11.4(a) Charts for t equal to 1/8 - 1/4 in. inclusive.

(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in..length of weld)

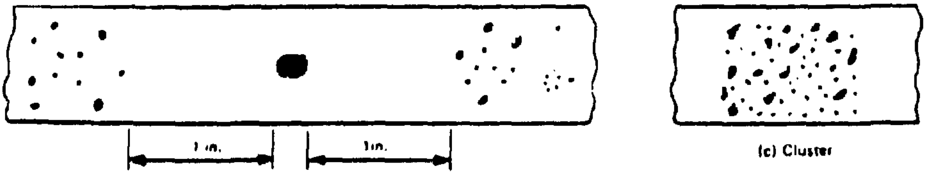


(c) Cluster

(b) Isolated Indication
(Maximum size per Table 11.1)

Figure 11.4(b) Charts for t over 1/4 - 3/8in. inclusive.

(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in. length of weld)

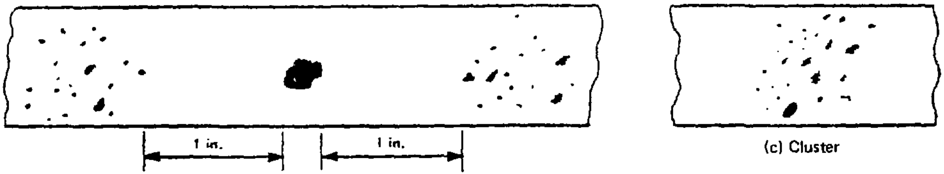


(c) Cluster

(b) Isolated Indication
(Maximum size per Table 11.1)

Figure 11.4(c) Charts for t over 3/8 - 3/4in. inclusive.

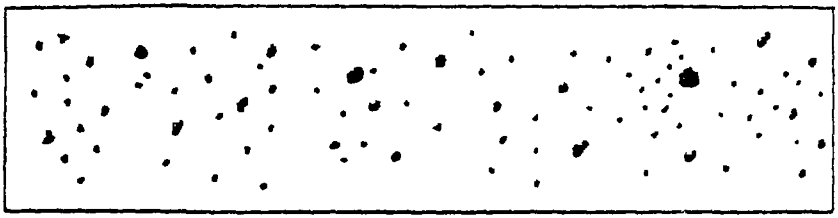
(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in., length of weld)



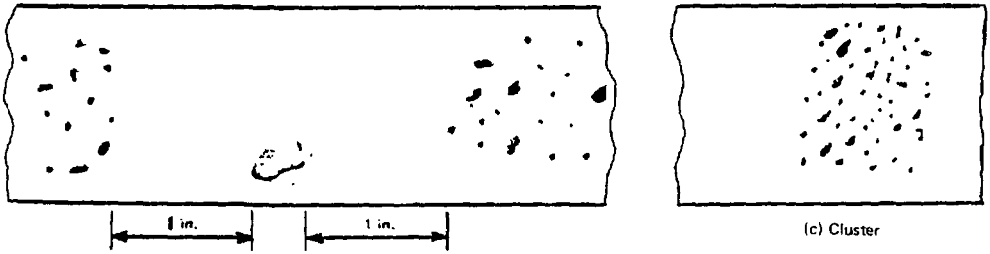
(b) Isolated Indication
(Maximum size per Table 11.1)

(c) Cluster

Figure 11.4(d) Charts for t over 3/4 - 2in. inclusive.



(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in., length of weld)



(b) Isolated Indication
(Maximum size per Table 11.1)

(c) Cluster

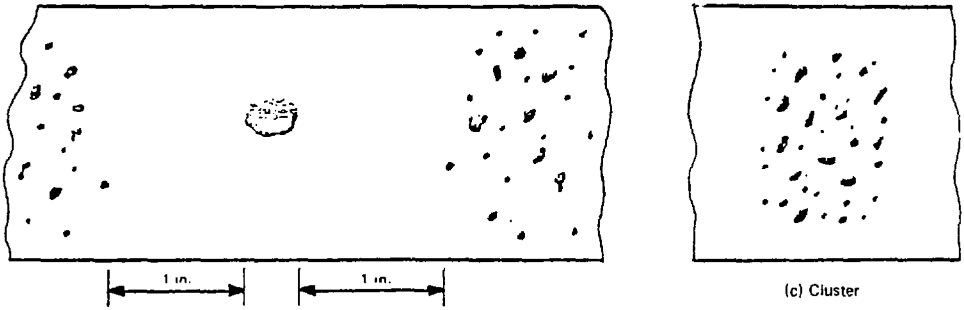
Figure 11.4(e) Charts for t over 2 - 4in. inclusive.

(c) The chart for each thickness range represents full-scale 6in. radiographs and shall not be enlarged or reduced. The distributions shown are not necessarily the patterns that may appear on the radiograph, but are typical of the concentration and size of indications permitted.

B-7 Weld Thickness t Less Than 1/8in.

For t less than 1/8 in. the maximum number of rounded indications shall not exceed 12in. a 6in. length of weld. A proportionally fewer number of indications shall be permitted in welds less than 6in. length.

(a) Random Rounded Indications
(Typical concentration and size permitted
in any 6 in..length of weld)



(b) Isolated Indication
(Maximum size per Table 11.1)

(c) Cluster

Figure 11.4(f) Charts for t over 4in.

B-8 Clustered Indications

The illustrations for clustered indications show up to four times as many indications in a local area, as that shown in the illustrations for random indications. The length of an acceptable cluster shall not exceed the length of 1in. or 2t. Where more than one cluster is present, the sum of the lengths of the clusters shall not exceed 1in. in a 6in. length of weld.

11.3.3. Acceptance/rejection criteria of BS 5500 (1982)

Acceptance/Rejection criteria given in BS 5500 "Specification for unfired fusion welded pressure vessels" is as follows.

11.3.3.1. General

Subject to the requirements of appendix C, the following subclauses apply to the main constructional welds of pressure vessels. Other joints such as tube/tube plate welds may be the subject of special requirements agreed between the contracting parties.

11.3.3.2. Quality Control level of acceptance

The defect acceptance levels given in TABLE 11.2 shall be imposed during fabrication as a means of quality control.

11.3.3.3. Assessment of defects

Defects may be assessed according to one or other of the following alternatives. Defects which are unacceptable shall be rejected or repaired.

TABLE 11.2 ACCEPTANCE LEVEL FOR DEFECTS

Defect Type	Permitted maximum
Crack and lamellar tears	Not permitted
Lack of root fusion Lack of side fusion Lack of inter-run fusion	Not permitted
Lack of root penetration	Not permitted
(a) isolated pores (or individual pores in a group)	Dia.$< e/4$ and Dia.3.0mm for e up to and including 50mm Dia.4.5mm for e over 50mm up to and including 75mm Dia. 6.0mm for e over 75mm
(b)uniformally distributed or localised porosity	2% by area *(as seen in a radiograph) for $e < 50$mm and pro rata for greater thickness
(c) linear porosity	Linear porosity parallel to the axis of the weld may indicate lack of fusion or lack of penetration and is therefore not permitted
(d) wormholes isolated	$l < 6$mm, $w < 1.5$ mm
(e) wormholes aligned	As linear porosity
(f) crater pipes	As wormholes isolated
(g) surface cavities	Not permitted
(a)individual and parallel to major weld axis NOTE: Inclusions to be separated on the major weld axis by a distance > the length of the longer and the sum of the lengths of the inclusions shall not exceed the total weld length	Main butt welds $l = e < 100$mm w or $h = e/10$ < 4mm Nozzle and branch attachment welds Inner: 1/2 of cross section w or $h = e/4 < 4$mm $l = e/4 <$ 100mm Outer: 1/4 of cross section w or $h = e/8 < 4$mm $l = e/8 <$ 100mm
(b) individual and randomly oriented (not parallel to weld axis)	As isolated pores
(c) Non-linear group	As localised porosity

TABLE 11.2 (contd)

* Area = length X width of an envelope enclosing the affected volume of weld metal measured on a plane substantially parallel to the weld face(i.e. as seen on a radiograph)

Tungsten inclusions	
(a) isolated	As isolated pores
(b) grouped	As uniformly distributed or localised porosity
Copper inclusions	Not permitted
Undercut	Slight intermittent undercut permitted, depth should not exceed approx. 0.5mm.
Shrinkage grooves and root concavity	As for undercut, depth should not exceed 1.5mm.
Excess penetration	h < 3mm . Occasional local slight excess is allowable
Reinforcement shape	The reinforcement shall blend smoothly with the parent metal and dressing is not normally required provided the shape does not interfere with the specified NDT technique
Overlap	Not permitted
Linear misalignment	See clause for assembly tolerances

Abbreviations used:
e is the parent metal thickness. In the case of dissimilar thicknesses e applies to the thinner component
w is the width of the defect
l is the length of the defect
h is the height of the defect
Dia. is the diameter of the defect
c is the mean nozzle circumference

NOTE 1 The simultaneous presence of more than one type of allowable defect within a given length of weld is permitted and each type should be individually assessed.
NOTE 2 The significant dimension of a defect in terms of its effect on service performance is the height or through thickness dimension. If ultrasonic flaw detection is employed , it is probable that defect indications of very minor cross section will be obtained. In interpreting the requirements of this table , such indications having a dimension h of 1.5mm or less, should be disregarded unless otherwise agreed between the manufacturer, the purchaser and the Inspecting Authority.
NOTE 3 Inner half of cross section refers to the middle region, the remainder being the outer quarters.

11.3.3.4. Category 1 and Category 2 constructions

If any defects present do not exceed the levels specified in Table 11.2, the weld may be accepted without further action. Details for vessels intended for operating in the creep range may require special consideration.

11.3.3.5. Category 1 Constructions

When acceptance levels different from those given in TABLE 11.2 have been established for a particular application and are suitably documented, they may be adopted by specific agreement.

Particular defects in excess of those permitted in TABLE 11.2 may be accepted by specific agreement between the purchaser, the manufacturer and the Inspection Authority after consideration of material, stress and environmental factors.

11.3.3.6. Category 2 construction (see Figure 11.3)

If any defects classified in TABLE 11.2 as 'not permitted' are present in the samples examined, the total length of welded seam represented by the original examination shall be examined by the same non-destructive testing method(s) and assessed in accordance with 11.3.3.5 (Note that the acceptance levels in 11.3.3.5 permit some relaxation of 'permissible' defect size for components in construction category 2)

Alternatively if there are no defects classified as 'not permitted' but other defects in excess of the maxima permitted by Table 11.2 are present in the original examination two further random checks representative of the weld length for the type of weld under consideration shall be made and assessed. If these checks indicate that the two additional areas are acceptable, then the original area inspected shall be assessed and if outside of these requirements repaired , re-examined by the same NDT method and re-assessed. If one or both of the additional areas are unacceptable , the total length of weld represented by the original examination shall be examined by the same NDT method(s) and assessed in accordance with 11.3.3.5.

Table 11.3 Acceptance levels (reassessment of Category 2 construction)

Defect type	Permitted maximum		
(a) Isolated pores (or individual pores in a group)	Dia. $< e/4 <$ 6mm		
(b) Uniformly distributed or localised porosity	**2% by area* (as seen in a radiograph)**		
(c) Slag inclusions, individual parallel to major weld axis **NOTE Inclusions to be separated on the major weld axis by a distance > the length of the longer inclusion and aggregate length not to exceed the total length**	**Main butt welds $l = 2e$** **w or h $= e/4 <$ 4mm**		
	Nozzle and attachment welds	**Inner 1/2 of cross section**	**Outer 1/4 of cross section**
		w or h $= e/2 <$ 4mm **$l < e/2 <$ 100mm**	**w or h $= e/4 <$ 4mm** **$l < e/4 <$ 100mm**
(d) Slag or tungsten non-linear group	**4% by area*(as seen on a radiograph)**		

*** Area is the product of length and width of an envelope enclosing the affected volume of weld metal measured on a plane substantially parallel to the weld face(i.e. as seen on a radiograph)**
NOTE : The symbols are as defined in TABLE 11.2.

11.3.3.7. Acceptance levels re-assessment of Category 2 Construction

The acceptance levels given in TABLE 11.2 except as modified by TABLE 11.3 shall be applied.

TABLE 11.3 PARTIAL NON DESTRUCTIVE TESTING (NDT) CATEGORY 2 CONSTRUCTIONS

```
                          10% NDT
                             :
                             :
                             :
                  Assess against TABLE 11.2
                             :
-----------------------------------------------------------------
Pass                Fail                       Fail
:             Non-planar defects     Planar and/or other
:                    :               non-permitted defects
:                    :                         :
:             Examine two                      :
:             additional areas                 :
:                    :                         :
:                    :                         :
:             Assess against                   :
:             TABLE 11.2 ------------          :
:                    :              :          :
:                    :              :          :
Accept               Pass           Fail       :
                     :              :          :
                     :              :          :
                     Assess         :          :
                     original       :          :
                     defects        :          :
                     against        :          :
                     11.3.3.6       :          :
                     :              :          :
                     :              :          :
              ------------------    :          :
              Pass           Fail   Examine 100%
              :              :      :
              Accept Repair all planar and/or other non-
                     permitted plus non-planar defects according to
                     11.3.3.8.
                             :
                           Accept
```

11.3.3.8. Repair of welds

No rectification, repair or modification shall be made without the approval of the purchaser.

Unacceptable defects shall be rejected or repaired . Repair welds shall be carried out to an approved procedure and subjected to the same acceptance criteria as original work.

12. PERSONAL SAFETY AND RADIATION PROTECTION

12.1. INTRODUCTION

The public and professional anxiety about the ill effects of radiation dates all the way back to 1895 when Roentgen discovered X-rays. The discovery not only presented man with a tool to diagnose and cure diseases, but it also resulted in providing evidence of the potential hazards of these rays. Just two years after its discovery, 69 cases of skin injuries due to over exposure to X-rays were published. The large number of cases are attributed to the fact that 20 years before man knew about X-rays, it had been used in research in the form of the Crookes High Vacuum Tube. In 1895 when Becquerel discovered radioactivity it gave man yet another source of ionising radiations. By 1900 the first skin injury from overexposure to radioactive material was observed. It was also known that ionising radiation in sufficient quantities could cause sterility, loss of hair, anaemia, reduction in the white cells count, produce illness and sometimes death. The first X-ray fatality in the US was reported in 1904. A dramatic demonstration of radiation hazards occurred in 1920s when luminous watch dials came into production. Workers who painted the numbers on the dials followed their customary practice of dipping brushes in the paint and then pointing the tips with their lips. The small amount of radium in the luminous paint got into their bodies and lodged in bones. Years after their work of dial painting ended, those personnel began to die mysteriously. An investigation showed that their death was due to the bone cancer which most of them had developed. The atomic bombing of Hiroshima & Nagasaki demonstrated the havoc that radiation can play to man. As time advanced, with the development of power reactors, high energy particle accelerators and the large scale application of radioisotopes in medicine, agriculture and industry, it became clear that radiation hazard is no more a matter of concern for doctors, radiologists and research workers only. It has damaged the life of many individuals in the general population. It therefore demands that to derive maximum benefits from the new tools employing radiation and radioisotopes, the hazards associated with their use are well understood. This is specially true in the case of industrial radiographers who are known to be among the most highly exposed group of persons who are occupationally exposed to ionising radiation.

The various sources from which human beings can receive radiation include cosmic rays, naturally occurring radioisotopes, radioactivity released by some industrial processes, atmospheric testing of atomic bombs, medical diagnosis and treatment using X-ray machines and radioisotopes, industrial uses of radioisotopes such as radiographing and radiotracing etc and the nuclear industry. In radiography the sources are radioisotopes, the variety of X-ray equipment and nuclear reactors (when doing neutron radiography).

Different definitions and units describing the characteristics and use of radiation such as radioactivity, roentgen, rad, rem, half life etc. have already been explained in a previous Section. Here it should suffice to summarise and say that roentgen is the unit of radiation exposure or intensity and it applies to X-rays and gamma rays and their interactions with air. Rad is the unit of radiation absorbed dose. Biological effects are usually related to radiation absorbed dose and therefore the rad is the unit most often used when describing the radiation quantity received by a living organism be it an experimental animal, a patient, a radiation worker or a radiographer. The use of rad allows a quantification of the amount of ionising radiation energy transferred by any type of radiation to any target material, not just air. Rem (rad equivalent man) is the unit used when analysing personnel monitoring devices such as film badges. The rem is the unit of dose equivalent or occupational exposure. Some types of radiation produce more damage than X-rays. The rem accounts for these differences in biologic effectiveness. The curie is a unit of radioactivity related to the three preceding units of radiation. It is a unit of the quantity of radioactive material and not the radiation emitted by that material. Electron volt (eV) is the unit in which the energy of X-rays and gamma rays is measured.

For most practical purposes when the problems of protection against X-rays and gamma rays are to be considered, it is sufficiently accurate to take the roentgen, rad and rem as numerically equal. With other types of radiations this generalisation is not true.

A table describing the older customary units and the SI units is given below as TABLE 12.1. Also TABLE 12.2. helps to convert the older and conventional units to modern SI units.

TABLE 12.1 CONVENTIONAL AND SI UNITS OF RADIATION

Quantity	Customary Unit		SI Unit	
	Name	Symbol	Name	Symbol
Exposure	roentgen	R	Coulomb per kilogram	C/kg
Absorbed dose	rad	rad	gray	Gy
Dose equivalent	rem	rem	sievert	Sv
Activity	curie	Ci	becquerel	Bq

TABLE 12.2. INTERCONVERSION OF VARIOUS RADIOLOGICAL UNITS

Divide number of C by B to obtain number of A
Multiply number of A by B to obtain number of C

A	B	C
R	2.58×10^{-4}	C/kg
rad	0.01	Gy
rem	0.01	Sv
Ci	3.7×10^{10}	Bq

12.1.1. **Effects of radiation**

Gamma rays and fast neutrons can penetrate deep into the body; beta rays can penetrate a few mm of the body tissue. Bremsstrahlung radiation sometimes produced by high energy beta particles constitutes a greater hazard than the primary electrons. Positrons are very short lived but their annihilation is accompanied by the emission of two gamma photons. Alpha particles have very weak penetrating power such that they can be stopped by a sheet of paper or by the outer layer of the skin. However, alpha particles have high specific ionisation and are most hazardous when their source is inside the human body.

Nuclear radiations are harmful to living tissues because of their direct or indirect ionising properties. The damage done by radiation is sinister as human senses are not capable of detecting even lethal doses of radiation. The human body has an instinctive defence against heat and to some extent, against ultraviolet rays, but unfortunately not against radiation. Severe damage may be produced by radiation in the body before the subject ^T what has happened. No detectable sign and symptom is revealed until the damage has been done.

For example if a man has been exposed to a radiation dose of 1000 rem which is fatal when the whole body is exposed, the heat produced in the body would be 0.0022 calories/gm of tissue. His body would develop a temperature rise of about 0.002 C. This is not perceivable by human senses.

The overall outcome of exposure to ionising radiation is initiated by damage to the cell which is the basic unit of any organism. The effects of radiation are of two types namely Somatic and Genetic and these will be considered here separately.

12.1.1.1. Somatic effects

The somatic effect cannot be fully understood without some notion of the factors beside the actual dose which combine to produce the final reactions. The first of these factors is the rate at which the dose is administered. The living tissues of the body usually begin the repair processes as soon as some degree of damage by whatever means has been received daily. When the body is able to keep up with the damage, no visible damage or change will be seen in the irradiated individual. However, the same amount of radiation given all at once would produce a violent reaction. It is thus the rate of exposure that is the first factor to be considered when assessing the effects of radiation. The second is the extent and part of the body irradiated. It is known that certain cells are more sensitive to radiation than others. Hence, the overall effect of radiation depends on the extent and part of the body irradiated. In general radiosensitive cells are those dividing actively and not differentiate. These include the white blood cells formed in the tissues of the spleen, lymph nodes, bone narrow etc.; the cells of gonads, skin and the digestive tract; the cells that absorb oxygen from the inhaled air and release CO_2 in the exhaled air. Lesser sensitive areas are the cells of the heart, kidneys and blood vessels and the cells providing important enzymes for digestion, while the muscle and nerve cells are quite resistant to radiation.

Although the radiosensitive tissues are damaged at intermediate doses (tens to few hundreds R of gamma), their very generative nature enables the surviving cells to divide and repopulate the organs and become fully functional within months. However, when muscle or nerve tissue which are exposed to radiation due to negligence, though the required dose is high (thousands of R) permanent disability will result as the cells are fully differentiated and no replacements are possible.

The part of body irradiated refers to whether the whole body or part of the body is irradiated. Partial body irradiation will usually result in mild effects on the whole body except in cases where the most vital organs are affected such as heart, lungs and brains which can lead to death. For local irradiation permanent scars may be observable. But the same dose or even lower if given uniformly to the whole body especially the upper abdomen will result in severe reaction and ensuing illness. This is attributable to the fact that most of the vital organs are situated in the upper abdomen.

The third important factor is the age of the affected individual. Persons growing physically are in an accelerated stage of cells reproduction and most of the cells in the body are dividing and hence sensitive to radiation. For this reason an exposure of a given amount should be considered more serious for a young person than for an adult. As a rough guide persons below the age of 18 are supposed to have a zero level of radiation dose.

The somatic effects can either be immediate or delayed. Given below is a summary of immediate effects when the whole body is irradiated with a range of X-ray exposures.

0-25R. No detectable injuries and no clinical effects. Probably no delayed effects.

25-50 R. Slight transient blood changes. No other clinically detectable effects. Delayed effects are possible, but serious effects on an average individual are very improbable.

50-100 R. Nausea and fatigue with possible vomiting. Marked changes in blood count picture i.e. reduction in lymphocytes and neutrophils with delayed recovery. Delayed effects may shorten life expectancy. No disability.

100-200 R. Nausea,fatigue, vomiting within 24 hours. Latent period about one week. Following the latent period, epilation, loss of appetite, general weakness, sore throat and diarrhoea. Other injuries and disabilities possible. Possible death in 2 to 6 weeks in a small fraction of the exposed individuals. Recovery is very likely in most cases unless complicated by previous poor health, injuries or infections.

200-600 R. Nausea, fatigue and vomiting within 2 hours. Latent period of one week where the victim seems relaxed and recovering. The critical period follows with epilation, loss of appetite and general weakness accompanied by fever, severe inflammation of the mouth and throat, diarrhoea, nose bleeding and rapid emaciation (loss of weight). Death due to infections could occur in 0-80% of the exposed individuals within 2 months.

600-1000 R. Nausea, fatigue and vomiting within 1 hour. Serious depletion of leucocytes. After a latent period diarrhoea, vomiting, inflammation of mouth and throat will appear. Purplish discolouration of skin due to haemorrhage (purpura) can also be seen along with fever, infection, rapid emaciation. Death occurs within 2 months in 80 - 100% of the exposed individuals due to haemorrhage and infections. Possible therapy is in the form of blood transfusion and bone marrow transplantation.

1000 R. Lethal range. Organs affected are gastrointestinal tract for exposure of 1000-1500 R and central nervous system for exposure 1500 R.

1000-1500 R. Severe nausea, fatigue and vomiting within 1 hour, followed by fever and diarrhoea and haemorrhage. Rate of survival is very poor and death occurs within 2 weeks in 90-100% of exposed individuals.

1500 R. Damage on the central nervous system, characterised by cramps, involuntary movements of the muscles (ataxia) followed by coma (lethargy). Death occurs within 2 days due to irreversible circulatory cerebral oedema and probably heart failure.

Exposure to ionising radiation may not produce immediate consequence but some delayed effects may appear a long time after the exposure. These types of effects are called delayed somatic effects and are outlined below ;

i. Local scars or chronic damage to the skin. May be ulcerous or cancerous.
ii. Cataract of the eye-lens.
iii. Bone cancer due to irradiation of bone tissue
iv. Lung cancer
v. Aplastic anaemia caused by radiation damage of bone marrow.
vi. Leukemia, tumours.
vii. Shortening of life span and premature aging.

12.1.1.2. Genetic effects

It is a fact that children inherit characteristics from their parents such as appearance, strength, resistance to disease, temperament, etc. The reason for the similarity of parents and their off spring is that in the production of a new member of the species, each parent supplies a set of plans for the new addition to the family. The result is a combination of these two supplied plans. The plans are not the plans that we are familiar with, such as the plan when a new house is being built, but a set of plans which control the development of the species. They are known as 'genes'. The genes are contained in the sperm and egg cells of the parents producing them. Radiation can damage or destroy these genes. This is an important long term effect of low level radiation exposure. When a change occurs in the genes of a new member of the species, this genetic change is permanent and is passed on to subsequent generations just as a blue eyed person can pass on the tendency for blue eyes to his children.

An important point to be always kept in mind is that genetic effects are significant only if gonads receive radiation exposure because the sperm and the egg cells are contained in it.

Therefore, one of the means of keeping the radiation induced genetic changes down in the population is to restrict radiation exposure of the gonads to as few people in the community as possible and if these few people are beyond the age of production, no genetic effects should arise.

12.1.2. Radiation exposure

(i) External and internal exposure

When the human body is subjected to radiation exposure from sources outside the body itself, the exposure is termed "External Exposure". Conversely when the human body is subjected to radiation exposure from sources inside the body itself, the exposure is termed "Internal Exposure". Since there is little chance of internal exposures in industrial radiography, only external exposures will be discussed.

(ii) Acute and chronic exposure

If a human body is exposed to high levels of radiation in a short period of time, the exposure is termed Acute Exposure. On the other hand if a human body is exposed to a low level radiation for a long period the exposure is termed "Chronic Exposure". One hundred rem received in one hour is an example of Acute Exposure and the same amount of radiation received during thirty years is an example of "Chronic Exposure". It must be remembered that Acute Exposure is more hazardous than the equivalent amount of "Chronic Exposure".

(iii) Natural background exposure

Man has always been exposed to radiation from natural sources. These natural sources comprise cosmic rays, the K-40, U-238 and Th-232 decay series, and C-14, H-3 and other radionuclides in low concentration. The total exposure of the human body due to these natural sources varies from region to region. On the average a person receives 100 mrem exposure per year due to these natural sources. In regions where radioactive deposits are present, exposure due to natural sources is as high as 800-900 mrem/year (Monazite region in India). Any significant departure from the environmental condition in which man has evolved may entail a risk of possible deleterious effect. Thus any exposure beyond the natural background cannot be considered safe in the absolute sense.

(iv) Medical exposure

Man of modern age is exposed to radiation during medical diagnostic tests.

Type of Exposure	Exposure
Chest X-ray best conditions	40 mrem
Average Chest X-ray	100-2000 mrem
Dental X-ray	1.5 - 15 rem
Fluoroscopic tests	5 - 50 rem
Pregnancy tests	20 - 65 rem
Treatment of malignant tumour	3000 - 7000 rem

12.2. MAXIMUM PERMISSIBLE DOSE

In accordance with the recommendations of the International Commission on Radiological Protection, (ICRP), the permissible dose is a dose of ionising radiation that, in the light of present knowledge and in the opinion of competent medical authority,is not expected to cause appreciable bodily injury to a person at any time during his lifetime and carries negligible probability of genetic malformations. Moreover the ensuing effects must be acceptable to the individual exposed and to the society of which he is a part. Maximum permissible dose levels in case of external exposures for occupational and non-occupational workers are discussed below.

(a) Occupational Workers

(i) The maximum permissible occupational dose of whole body exposure in the forty years of working lifetime of an individual is 200 rems which includes all occupational exposures but does not include medical and dental exposures. The maximum accumulated dose to a radiation worker of age N years is given by (N-18) x 5. This means that no person less than 18 years of age can be employed for radiation work.

Taking 40 hours a week and fifty weeks a year, the permissible levels can be easily derived to be 5 rems/year, 100 mrem/week and 2.5mrem/hour and this is the dose-rate to be applied to all areas surrounding radiographic installations which are accessible to only classified workers.

(ii) Doses up to 3 rems may be incurred in any quarter (13 weeks) of a year provided it happens only once a year and the condition of 5rems/year is maintained. The above recommendations i & ii apply to gonads, bone marrow, and whole body exposures. For other parts of the body the following table must be used.

S. No.	Organ	Rems/year	Rems/quarter
1.	Skin	30	15
2.	Bone	30	15
3.	Thyroid	30	15
4.	Hands & Feet	75	37.5
5.	Fore arms & ankles	75	37.5
6.	Other organs	15	7.5

(iii) Permissible neutron fluxes, which give a dose of 100 mrem over a 40 hour week, are given in a tabular form as follows.

Neutron Energy	Max. Permissible Neutron Flux
Thermal to 10 ev	666 neutrons/cm /sec
10 KeV	333 " "
0.1 MeV	66 " "
0.5 MeV	26 " "
1.0 MeV	20 " "
2.0 MeV	13 " "
3 to 10.0 MeV	10 " "

(b) Non-occupational workers

For all non-occupational workers and members of the public being exposed to external radiation, the above mentioned permissible doses and doses rates must be reduced by a factor of 10.

12.3. RADIATION MONITORING AND MEASUREMENT

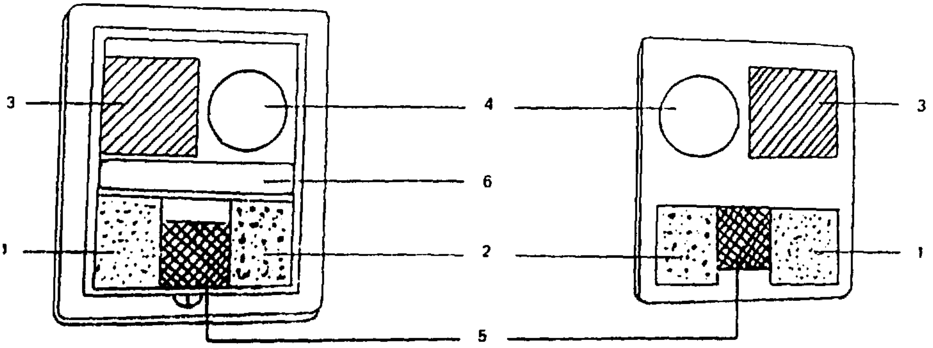
Radiation workers such as radiographers are subjected to ionising radiation while performing their work. The amount of radiation dose received depends on various parameters and conditions such as time, distance, shielding and working procedure. Thus, to ensure the safety of radiographers, it is important for higher level personnel to continuously observe and record the amount of radiation received by each radiographer working under him. Such an activity is called personnel monitoring.

In general, the main purposes of personnel monitoring are to ensure that the maximum permissible dose is not exceeded, to limit the exposure of the individual radiographer, to assist the medical authority in making analysis in the case of accidental over exposure and to provide information about work practices and personal dose history. The other type of monitoring is area monitoring in which the environment around the workers is monitored. This includes checking the radioisotopic equipment, the exposure making enclosures and the correctness of the exposure procedures. Personnel monitoring devices include film badges, pocket dosimeters and thermoluminescence dosimeters (TLD). These are briefly described below.

12.3.1. Film badge dosimeter

The discoverer of X-rays very quickly discovered that photographic films exposed to X-rays turned black when developed. Gamma rays also have a similar effect on photographic films. This property of X and gamma radiation to produce blackening of films is used in X and gamma dosimetry. The principle is very simple. The amount of blackening that appears on the film, depends on the radiation dose it has received. The higher the radiation dose, the blacker the film becomes. By measuring the amount of blackening on the film, the radiation dose it has received can be estimated. The badge dosimeter employing this principle is called the film badge dosimeter. A film badge measures the total dose received during the time it was worn. A particular advantage of the film badge is that it provides a permanent record which can be checked and verified at any later stage. The photographic film is wrapped in a paper-cover to protect it from ordinary light. The film is generally worn in a film holder on the person's body attached to the belt of the trouser or front pocket of the shirt. A film is normally used for a period of four weeks and then replaced by a new film. The used film is returned for processing and dose assessment. Usually a film badge contains much more than a film. Some of these materials are for additional dose measurements by foil activation and thermoluminescence but there are small strips of metal (Cu, lead) covering a part of the film. These metallic strips are known as filters. It has been found that a film exposed to 1 rem of X-rays is blackened more than a film exposed to 1 rem of harder gamma rays and the low energy X-rays produce more blackening than high energy X-rays. A combination of metal filters of varying thickness are used to correct for the above mentioned non-linear response of the film. Figure 12.1 shows a typical film badge dosimeter.

The X and gamma dose received by a person wearing a film badge is assessed from the blackening of the film under the filters. A part of the film is usually left without any



(a) Cassette: inside front cover

(b) Cassette: inside back cover

1. 0.3mm copper
2. 0.05mm copper
3. 1.2mm copper
4. open window
5. 0.8mm lead
6. aperture through which number of the film packet is visible.

Figure 12.1 A typical film badge.

covering filters. This open window helps to find whether the user of the film badge is being exposed to beta radiation, which would be completely absorbed by the filters. The blackening of the open part of the film along with the reading under the metal filters enables the beta dose of the film wearer to be estimated. The films worn by workers along with a set of standard films exposed to a series of known amounts of radiation, are developed under similar conditions and their density measured with the help of a transmission densitometer. With the help of standard films a dose-density calibration curve is drawn, which in turn is used to assess the dose received by an individual. The dose assessment is dependent on the processing conditions which must be strictly controlled and the set of films to be used should be from the same emulsion batch. The film badge has wide range from 20mrem to 20 rem.

12.3.2. Pocket dosimeters

The personnel monitoring devices using the ionisation produced by radiation as an indicator may be either a complete electroscope or simply an ion chamber, each of which is about the size of a fountain pen. One is directly readable and the other is read with the help of a reader charger unit. Both of these types of dosimeters are briefly described here. Pocket ionisation chamber dosimeters consist of an ionisation chamber which is charged and read on a separate charger reader unit containing an electrometer and a voltage source. This is considered to be a less convenient arrangement, since the chamber must be carried to the charger-reader unit before the exposure can be determined. The dose range covered is from 40 mrem to 200 mrem. These chambers especially with perforated walls, provide an extremely good response to low energy X, gamma and beta radiations.

The other type namely the pocket quartz fibre electroscope dosimeter is based on the working principle of the Gold Leaf Electroscope. When the electroscope is charged the two electrodes(gold leaves) are in the farthest position. As the discharge takes place the two electrodes come nearer to one another. In this dosimeter one electrode is fixed and the other is movable. A small compound microscope is a part of the dosimeter which helps in viewing the movable fibre electrode. A separate battery charger places an initial electrical charge on the system. In this position the fibre is at zero of the scale calibrated in mrem. Ions (produced by radiation) collected in the collecting volume decrease the total charge on the system, thus changing the position of the quartz fibre on the scale. Light for viewing the fibre through the microscope comes through a window on one end of the dosimeter. The dosimeter can be read with the help of an eye piece fixed within the instrument. The scale is visible when the dosimeter window is exposed to light and read through the eye piece. The dosimeter has a range of 0-200 mrem and it can be used over and over again after recharging. Other ranges cover 0-500 mrem, 0-5 rem, 0-50 rem. Pocket (Quartz fibre) dosimeters have the advantage that their reading can be checked directly at any time and place during the work. Figure 12.2 shows a pocket dosimeter.

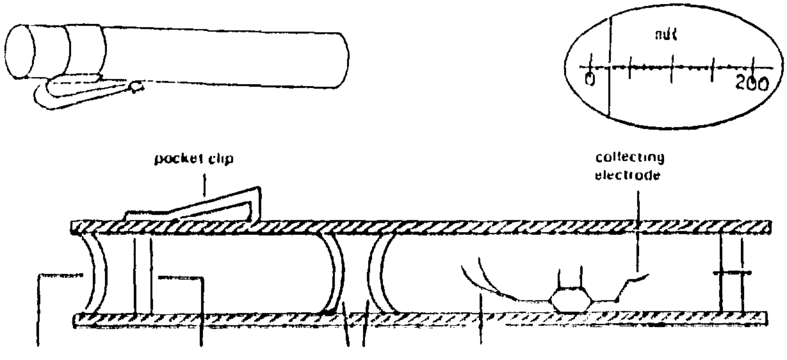


Figure 12.2 The cut away drawing of a pocket dosimeter

12.3.3. Thermoluminescent dosimeter

This is a relatively new method of measuring radiation dose. The principle of this device is embodied in its name, "thermo" meaning "heat" and "luminescent" meaning "light producing". Certain materials when exposed to radiation undergo slight structural changes. These changes are not obvious to and observable by the naked eye; but if the irradiated material is heated gently, it gives out a flash of light. The higher the dose it has received, the bigger the light flash it will emit when heated. The size of the light flash can be measured using photomultiplier light detector and thus the dose that the thermoluminescent material has received can be estimated. LiF and CaF are the two used among the many useful materials with LiF being the one usually used as a thermoluminescent dosimeter. This dosimeter can cover a wide range of radiation doses from a few mrem to many thousands of rem and is useful in measuring X, gamma and beta doses. It is being used as a personal dosimeter. It measures the total dose a person has received during the period he has been wearing it.

12.3.4. Area monitoring

Area monitoring is done with the help of survey meters which are either the ionisation chamber type or the Geiger-Muller type. These have already been explained in Section 2.5.

12.3.5. Factors affecting radiation dose

The factors affecting the dose from a radiation source at a place are distance, time and shielding and these are separately explained as follows:

12.3.5.1. Distance

The intensity of radiation (and therefore radiation dose rate) of an isotopic source, is inversely proportional to the square of the distance from the effective centre of the source. The above statement is called the inverse square law which has already been explained in Section 2.1.6. This means that the radiation hazard (dose rate) decreases rapidly as we move away from the radiation source. As an example, the dose rate due to a radiation source at a distance of 10 meter from the source would be only one hundredth of the dose rate due to the same source at 1 meter. This is the simplest practical way in which a person working with external radiation sources can keep his radiation dose down. Practically while handling radioisotopes, the distance can be increased by the use of long tongs and remote handling devices. For radiography the cables between the control consoles and the X-ray machine should be long enough. The distance between the operators and the radioisotope position in field gamma radiography should be adequate. We may recall that this adequate distance can be defined keeping in view the maximum permissible doses.

12.3.5.2. Time

It is rather obvious that if the time of exposure is reduced, the radiation dose would also be reduced by the same factor. For example if the dose rate at a work location is 500 mrem/hour, then reducing the work time from 1 hour to 30 minutes would half the radiation dose (i.e. from 500 mrem to 250 mrem). This reduction can be achieved by proper planning of experiments and distribution of work among workers. The best means of reducing man-hours on a particular job is to preplan the job carefully, making sure that all the tools which may be required are on hand and then carrying out the job quickly. In cases where radiation levels are high, it is useful if the work can be practised on a "mock up" (rehearsal basis) with no radiation field present.

12.3.5.3. Shielding

If distance and time factors can not reduce the radiation dose rate level to acceptable low values, it is still possible to reduce the radiation level by shielding the radiation source. Any material can be used as a shielding material but the effectiveness of the material used for shielding depends upon its physical properties and also on the characteristics of the radiation in question. Shielding presents protection to worker by maintaining effective barriers between the radiation source and the worker. The process of reduction of radiation intensity (dose) in a barrier is called attenuation. Attenuation is the result of complex interactions between the radiation and the shield materials. The concepts of absorption mechanism, the law of radiation attenuation, linear attenuation coefficient and the build up factor have been given in Sections 2.2 - 2.4. The detailed procedure for making shielding calculations will be described in Section 12.4.4. For the moment it should suffice to say that the most common materials used for radiation shielding are lead, concrete, loaded concrete and depleted uranium etc.

12.4. SPECIFIC SAFETY REQUIREMENTS FOR X AND GAMMA RADIOGRAPHY

12.4.1. Radiation monitoring and recording

In any radiographic set up where radiography is to be performed whether it is a fixed installation in a well designed laboratory or it is under field conditions a radiation survey must be undertaken before starting work. This survey can be undertaken using any of the radiation detectors explained in Section 2.5. The detectors or survey meters should be properly calibrated. The importance of properly using a survey meter cannot be overemphasised. It is desirable that the accuracy of any instrument used for this purpose should be reasonably independent of radiation energy, since it must be capable of detecting and measuring soft, scattered radiation intensities up to 200-300 millirads per hour. A single scale micro-ampere meter is employed for this purpose, the basic range of the selector switch. It is usually arranged that the basic scale range can be increased by a factor of 10 or 100 as necessary. It is most important, however, that the instrument should be able to measure accurately intensities up to only 3.0 millirads per hour in view of the maximum dose rates permitted by the regulations.

An initial survey of the radiographic exposure device should be made upon removing the exposure device from storage. This initial survey will verify that the source is in its proper storage position in the exposure device and that the survey instrument is working properly. It will also provide a baseline value of intensity for comparison with later radiation survey results. Next a survey should be made with the source operating at its maximum output and pointing in all directions. It is essential that the area to be surveyed should be systematically scanned for any leakage of radiation. The speed of scanning should be slow enough to allow the instrument to respond to any local variations in the general radiation level. Areas of particular importance are those that are continuously occupied by personnel. Leakage of radiation is most likely to occur at the base of walls and barriers, at the bottom and sides of door openings, and at open cable ducts and ventilators. Roof areas over exposure rooms should not be neglected, particularly if these are likely to be used by workmen engaged in maintenance and repairs. Warning notices should be placed in such regions where an excessive leakage of radiation is found if the frequency of occupancy does not warrant the erection of permanent shielding of roof areas. The monitoring of a control room serving more than one x-ray set should be carried out with all the sets working at full power. An annual survey should be made of all permanent radiographic departments and sites and this should be supplemented by additional tests after any alterations or repairs have been made to the protective arrangements, or when a significant change has occurred in the type of equipment in use, or in its location and manner of use.

Particular attention should be paid to screening cabinets, and all lead rubber curtains and observation windows must be checked at frequent intervals. It is equally important that all safety switches and relays should be tested at the commencement of each day's work.

If possible the indication of the radiation level which is expected to be present should be made on the radiation signs. If there are restrictions in the possible beam directions which are not physically controlled by mechanical or electrical limiting devices, permanent notices explaining these are necessary. The radiographer should also observe his survey meter while exposing the source during a radiographic operation. A survey of the high radiation area boundary should not be made as this would lead to unnecessary radiation exposure to the operator. While retracting the source, the operator should also observe his survey meter. The operator should then survey the exposure device on all sides and the entire length of the guide tube to the source stop or collimator to assure that the source is properly shielded. The proper use of a survey meter can avoid any accidental radiation exposure.

Some x-ray sets can continue to emit X-rays for a few seconds after the HT has been switched off. This should be kept in mind and the x-ray room should be surveyed if there is a need to enter it immediately after the machine is switched off. With very high energy x-ray equipment short life radioactivity can be induced in some materials by photonuclear reaction. Therefore after long exposures with such high energy sources it is desirable to monitor the level of any activity before handling the specimens.

While making a survey of the area surrounding the radiographic exposure rooms the sky-shine radiations from the source should also be kept in mind. High energy x-ray equipment produces radiations which have great penetrating power. These can also travel upwards and outwards and if the laboratory has a relatively thin roof it can spread outside the laboratory. It is usually not feasible to build a roof of the same thickness as the side walls of the building, so that account must be taken of the radiation extending into the air above the laboratory which is absorbed and scattered back to regions outside the laboratory at ground level. Sky shine is at a maximum at a distance from the building wall approximately equal to the wall height.

Monitoring and surveying should include all the rooms adjacent to the exposure room. Similarly the personnel working in and around the radiation area should be monitored for the amount of radiation received by them.

This is usually done through the use of film badges or radiation dosimeters which are worn on the body of the concerned individuals and provide the record of doses received.

All radiation dose as determined by various individual monitoring methods should be recorded. The accumulated dose of radiation received should be regularly compiled and updated. A health record including any results available from medical examination, in a form to be approved by the competent authority should be kept for every worker exposed to ionising radiation. It is always advisable for each radiographer to have a record of the amount of radiation dose received by him (monthly). With this record available, the radiographer will be kept aware of the dose received by him so that necessary action can be taken to reduce the exposure.

12.4.2. Radiographic exposure rooms

The following considerations must be taken into account when designing an x-ray exposure room :

(a) provision of adequate shielding against the primary beam
(b) control of leakage of scattered radiation;
(c) manner of use of the equipment, and
(d) convenience and accessibility of the room.

In the light of these considerations the specific requirements for X-ray and gamma ray exposure rooms will be described separately.

12.4.2.1. X-ray exposure room

In designing the exposure room for x-rays, the following points must be considered :

(i) It should have enough space to house the equipment. The equipment planned to be purchased in future and which are to be placed in this room may also be kept in view.

(ii) It should have water and electric connection within it.

(iii) If pipes, ducts, conduit or cables must pass through walls of an exposure room, then passages must be designed properly so that no significant radiation will escape through. Figure 12.3. illustrates the methods of designing this passage.

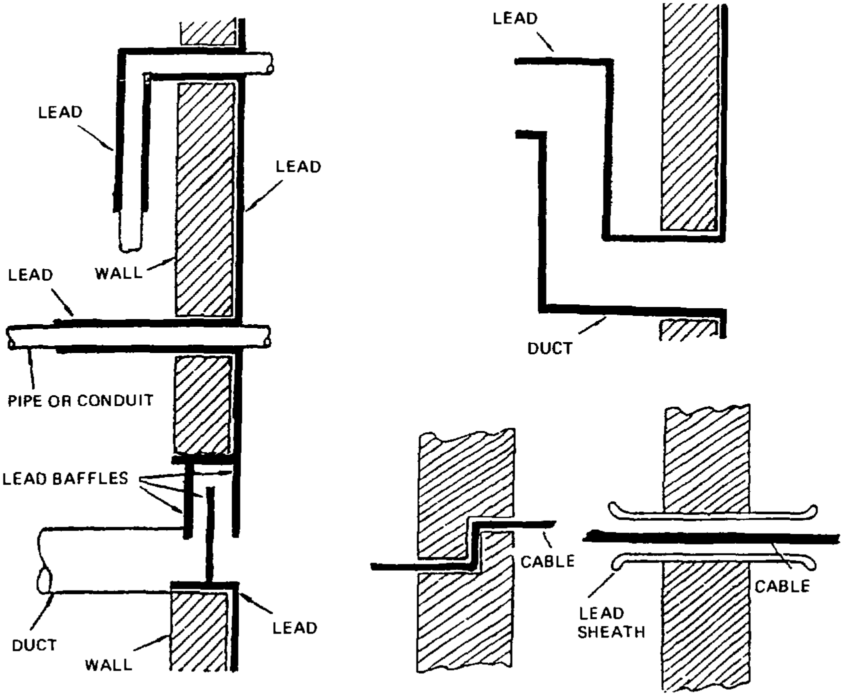


Figure 12.3 Methods of shielding when pipes, ducts, conduits or cables must pass through walls of exposure room.

(iv) There should be a separate place to house the control/console so that the operator is not exposed to the radiation. This should be outside the room in which the x-ray tube is placed. If due to any reason the control console is to be located within the exposure room it should be within a well shielding cabinet or enclosure.

(v) The thickness and the material of the walls should be sufficient to reduce the dose below the maximum permissible level when a direct beam hits the walls. Usually dense concrete walls of sufficient thickness are used for this purpose. Occurrence of voids during construction should be avoided. The use of concrete blocks can present some streaming problem and therefore should be kept in mind. Lead lining of the walls is common specially when the concrete walls are thin. The thickness of shielding is calculated keeping in view the direction of the primary beam and the occupancy factor of the adjoining area. If for example, the primary beam is permanently restricted to fire vertically downwards to irradiate the floor, the walls of the exposure room will require a considerably lesser thickness of shielding than would be required if the beam were capable of manipulation into any direction.

In the latter instance, it is necessary to assume that all the walls may, as a result of the ordinary use of the equipment, be irradiated by the primary beam from time to time, and they would then be required to be fully shielded. The wall shielding should be extended below the floor level or a narrow apron of lead added to on the surface of the floor close to the wall.

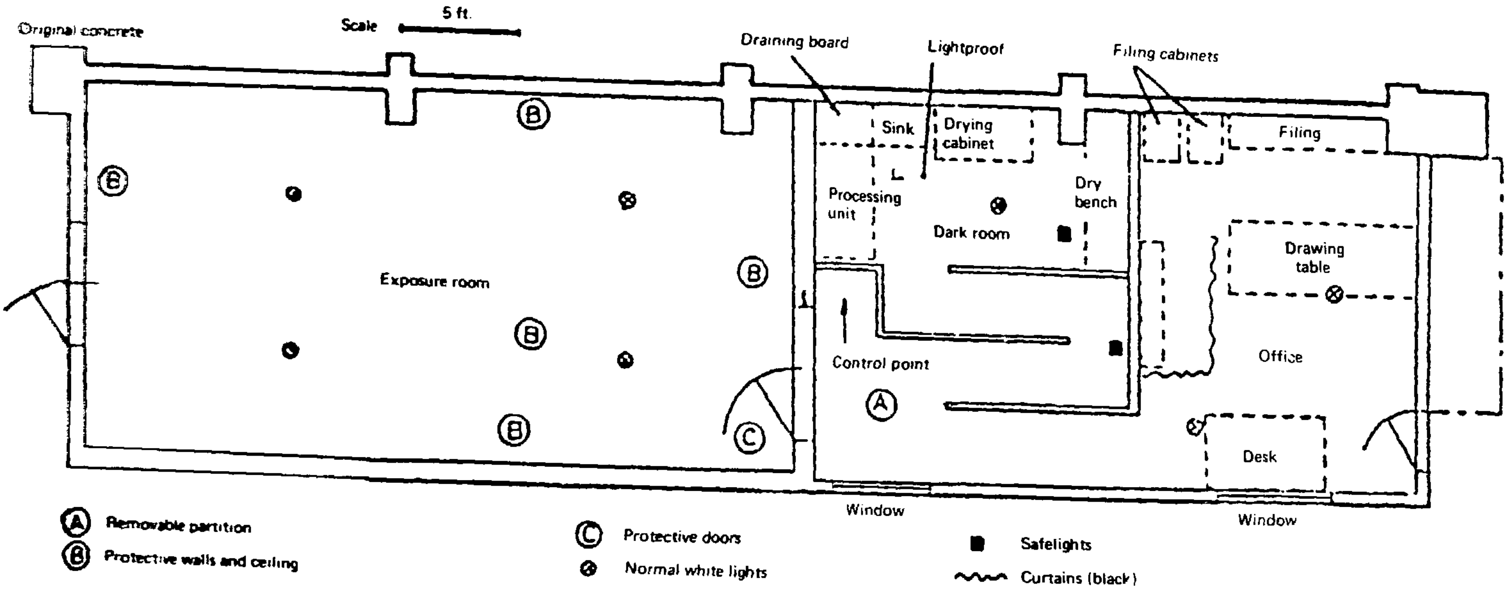


Figure 12.4 Floor plan of radiographic section

(vi) It should have a door that provides adequate shielding against radiation. A switch may be used so that the tube does not operate unless the door is properly closed. The shielding layer on the door and that on the wall should overlap by at least 5 cm. In the instance of sliding doors the two protective layers must be immediately adjacent to each other and not separated by the thickness of the door.

(vii) The door of the x-ray room should be such that it can easily be opened from inside.

(viii) It should be possible to switch off the X-ray generating unit from inside the room. This is helpful in case a person gets locked up inside accidentally. Similarly all means of exit should be so constructed that such a person can leave the enclosure without delay.

(xi) A blinking light or a sound alarm should be used to indicate the operation of the X-ray machine.

12.4.2.2. Gamma -ray exposure room

For a gamma ray exposure room , the following considerations must be taken into account:

(i) The shielding walls of the room should depend on the types of radioisotopes to be used. The dose rate outside the room should not exceed the permissible level.
(ii) There should be a shielded apartment within the room preferably underground where the radioisotopes along with their containers can be stored while not in use. The key to this enclosure should be kept with care and responsibility.
(iii) There should be a facility to load and unload the radioactive sources.
(iv) A survey meter which is required for checking the dose level before entering the room should be made available in the laboratory.
(v) The flooring and the ceiling of the room should be such as to give the minimum back scatter. (see Fig. 12.4). An ideal situation would be lead lining of the wall, floor and ceiling. The method of lead lining the floor is illustrated in Fig. 12.5.

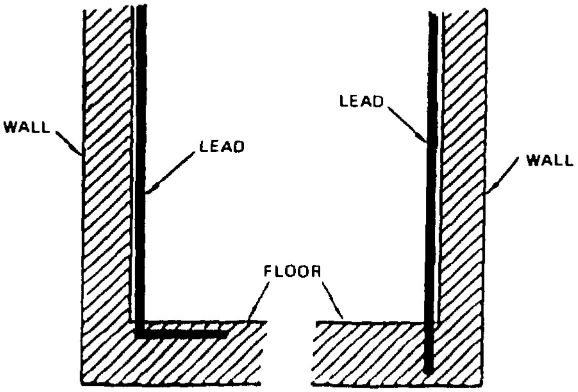


Figure 12.5 Method of lead lining the floor

(vi) The room should have a shielding door which can be easily manipulated from the inside and outside. The door should have a permanent lock and the key to it should always be with the authorised person.

12.4.3.Calculation of shielding thickness

To calculate the shielding thickness for a certain installation the information required is as follows:

(i) The maximum energy of the X-ray set, or the type and strength of the gamma ray source.

(ii) Dose rate in roentgens per unit time for the maximum tube current and kilovoltage at a known distance from the focal spot of the X-ray tube. With gamma ray sources the dose rate will be known from their RHM value if the information in (i) above is known.

(iii) Distance between the source of radiation and the area to be shielded.

(iv) The maximum permissible dose rate for the shielded area, i.e. 2.5 mr/h for classified workers or 0.25 mr/h for unclassified workers.

Some simple methods of making shielding calculations will be briefly described here:

12.4.3.1. Half-value layer (HVL) method

Half - value layer (HVL) is the thickness of the shield material which reduces to half the intensity of radiation at a point. Mathematically HVL= $0.693/\mu$. Similarly Tenth-value Layer (TVL) = $2.303/\mu$. By knowing the value of μ for the particular energy and the type of shield material proposed we can calculate the shield thickness required to reduce the intensity to half or to one tenth of its original intensity without a shield. Values of u are available from curves for different materials such as lead, concrete, iron, uranium and water etc.

Sometimes the values of μ_m , the mass absorption coefficient, are given which when multiplied by the value of density, ρ , of the shield material will result in the desired value of μ. TABLE 12.3 gives the values of HVL and TVL for various sources and materials of interest.

TABLE 12.3. APPROXIMATE TVL AND HVL VALUES FOR SHIELDING MATERIALS (VALUES SHOWN ARE IN MILLIMETRES)

Source	Lead		Steel		Concrete	
	TVL	HVL	TVL	HVL	TVL	HVL
100KV (Peak)	0.8	0.25	8	2.5	58	18
250KV (Peak)	2.5	0.8	30	10	91	28
400KV (Peak)	7.6	2.2	84	25	109	33
1000KV(Peak)	25	8	203	64	152	46
2000KV(Peak)	38	13	267	89	203	62
gamma - rays						
Co-60	41	12	74	22	229	68
Cs-137	21	6.3	57	17	180	53
Ir-192	16	4.8	-	-	157	48

The relationship between half value layer and intensity is $2^n = I_0/I$ where n is the number of half value layers, I_0 is the intensity at a point without a shield and I is the intensity at the same point after n number of half value layers of shielding material have been interposed between the source and the point.

Example

Calculate the dose from a 37 GBq Co-60 source at 1m with the beam passing through 50 mm of lead. Given that 37 GBq of Co-60 produces a radiation dose of 1.32 R/h at 1 m and the HVL = 12.5mm for lead.

No. of HVL used = $\frac{50}{12.5} = 4$

given that I_0 = 1.23 R/h $\qquad I = \frac{I_0}{2^4} = \frac{1.23}{2^4} = \frac{1.23}{16} = 0.0825$ R/h

Example

Find the thickness of concrete required to reduce the radiation level from 2000 mR/h to 2 mR/h given that the TVL for the radiation in question is 225 mm of concrete.

$$\frac{I_0}{I} = 10^n$$

$$\text{or } 10^n = \frac{2000}{2} = 1000. \text{ Therefore } n = 3$$

As 1 TVL = 225mm, therefore 3 TVL = 675mm of concrete

TABLE 12.4. CORRESPONDING THICKNESSES FOR THE SAME ABSORPTION (EQUIVALENT THICKNESSES IN MILLIMETRES)

	Lead	Steel	Brick (density = 1.6)	Concrete (density = 2.4g/cm^3)
100kV X-rays	1	17	120	75
200kV X-rays	1	14	110	65
300kV X-rays	1	8	60	25
400kV X-rays	1	7	45	28.5
1MV X-rays	1	4	-	6.2
5MV X-rays	1	1.5	-	5
20MV X-rays	1	1.5	-	4.7
Iridium-192	1	4	-	8.8
Cobalt-60	1	1.6	-	5.4

12.4.3.2. **Attenuation factor method**

The attenuation factor can be calculated knowing the dose from the source of radiation and the dose which is required through the use of shielding. The attenuation factor is the ratio of desired to actual dose. Curves are available relating the values of these attenuation factors to the thickness of various shielding materials for various energies of radiations.

Figures 12.6 - 12.9 show some of these curves.

Example

400 KV, 10mA X-ray set with an output 50R/min at 1m. To determine the thickness of concrete needed at 3m distance for the dose-rate to be reduced to 2.5mR/h. By the inverse square law, the dose-rate at 3m is

$$50 \times 60/9 = 33R/h.$$

Thus, the attenuation factor needed is :

$$\frac{2.5 \times 10^{3}}{333} = 0.0000075$$

From Figure 12.6 this attenuation is provided by 58cm of concrete. Alternatively, 6mm lead will provide an attenuation of 0.04 and the additional attenuation will be provided by 43cm of concrete.

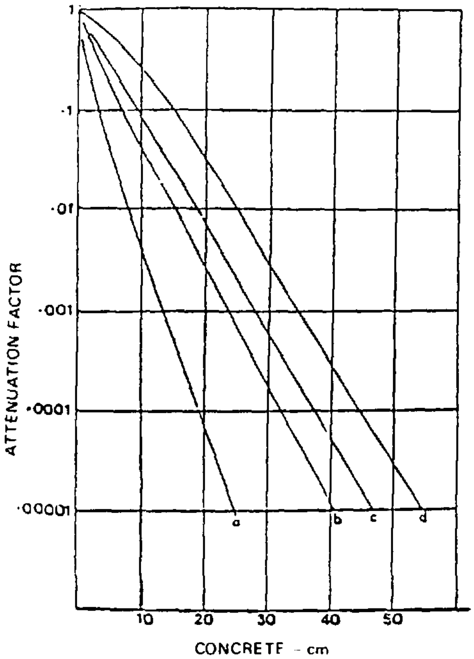


Figure 12.6

Attenuation of X-rays in concrete broad beam conditions.
a) 100KV X-rays, b) 200KV X-rays
c) 300KV X-rays, d) 400KV X-rays.

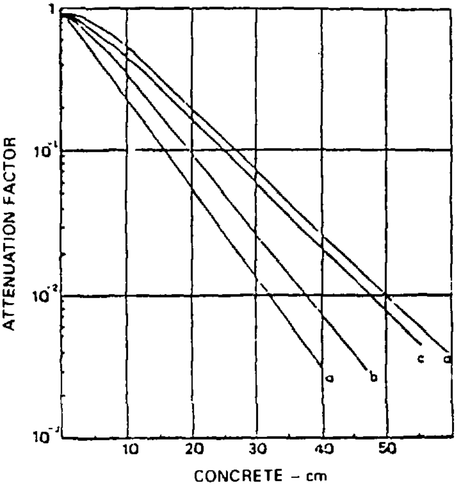


Figure 12.7

Absorption of gamma rays in concrete a) Ir- 192,b) Cs-137
c) Cs-134, d) Co-60

The attenuation factor when multiplied by 100 gives percent transmission. Curves are available which relate the percent transmission through various shield materials with different types of sources of radiation (Figure 12.10 - 12.14)

__Example__

Radiation energy :	150KV
Dose rate at 1m from focal spot :	350R/h
Distance between focal spot and area to be shielded :	5m
Maximum permissible dose rate :	2.5 mR/h

Using the inverse square law, dose rate (unshielded) at 5m:

$$\frac{350}{5 \times 5} = 14R/h$$

To reduce this to 2.5mr/h, the required attenuation factor is

$$\frac{2.5}{14 \times 1{,}000}$$

= 0.0000017 or 0.017 percent transmission

From the curve for 150 KV in Figure 12.10 it can be found that a thickness of 2.5mm lead corresponds to a transmission of 0.017 percent.

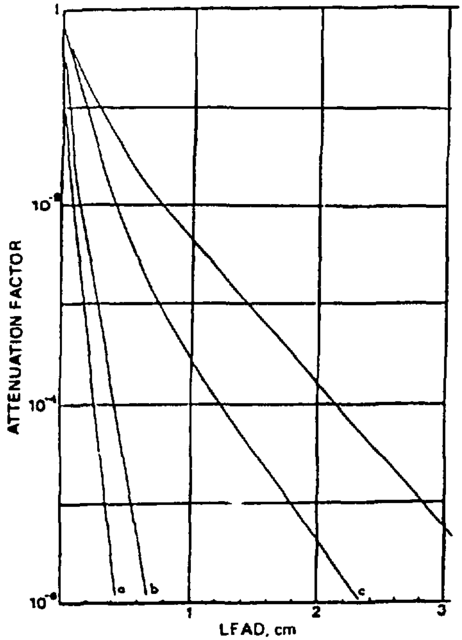


Figure 12.8 Attenuation of X-rays in lead: broad beam conditions.
a) 100KV X-rays, b) 200KV X-rays
c) 300KV X-rays, d) 400KV X-rays

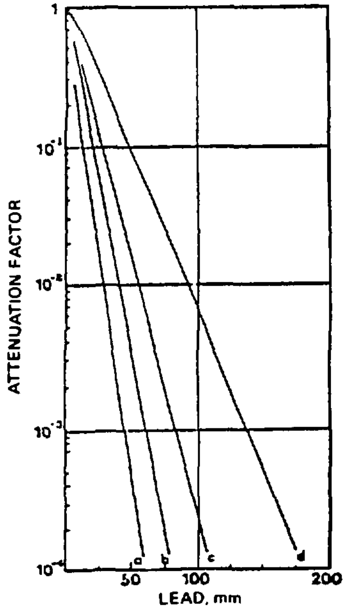


Figure 12.9 Absorption of gamma rays in lead : broad beam conditions a) Ir-192, b) Cs-137
c) Cs-134, d) Co-60

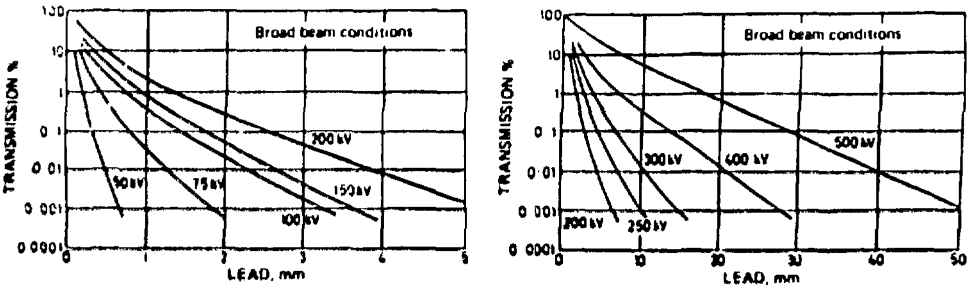


Figure 12.10a

Figure 12.10b

% Transmission for lead and different radiation sources

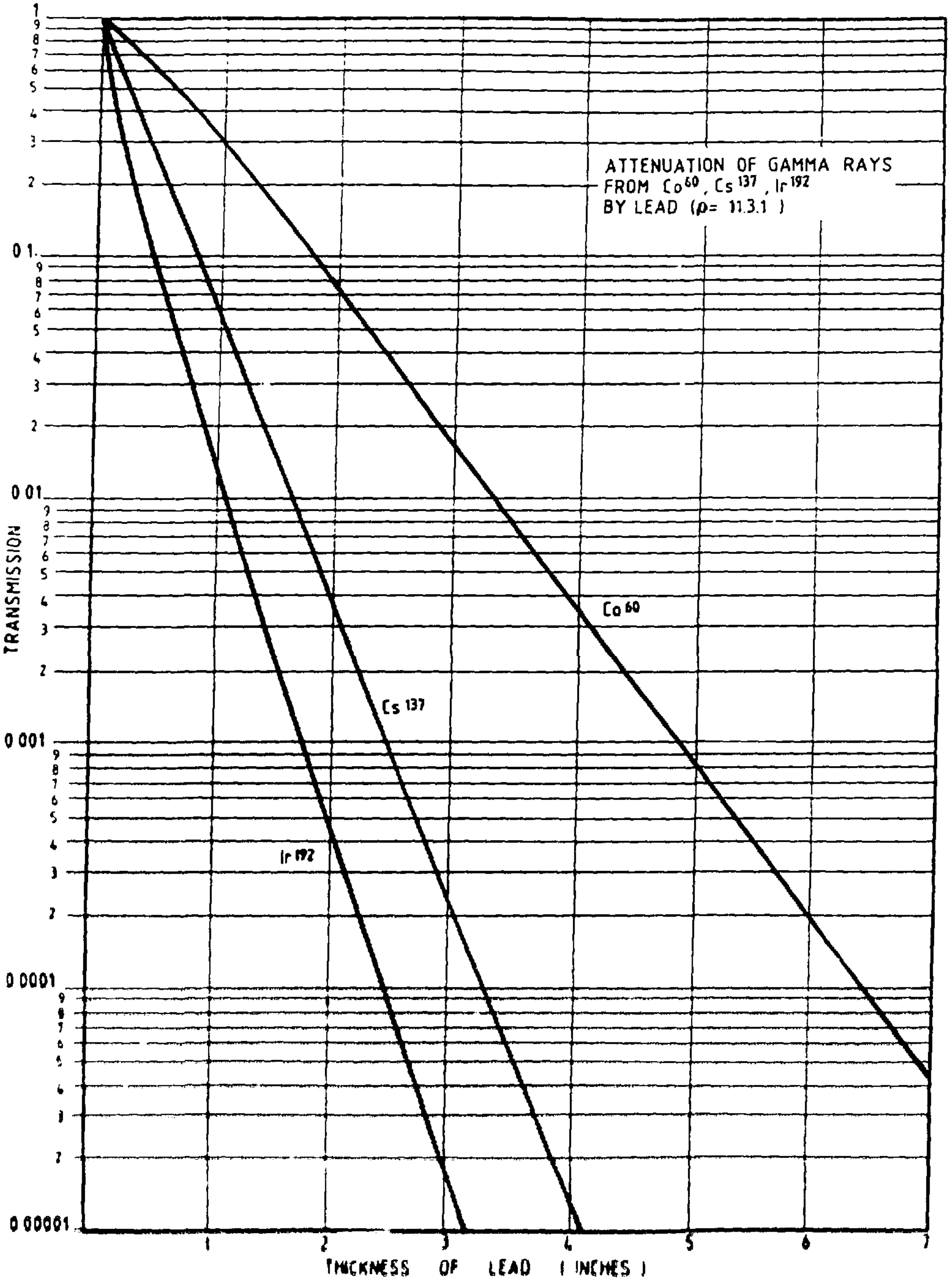

ATTENUATION OF GAMMA RAYS
FROM Co60, Cs 137, Ir192
BY LEAD (ρ= 11.3.1)
TRANSMISSION
1
9
8
7
6
5
4
3
2
0.1
0.01
0.001
0.0001
0.00001
Co60
Cs 137
Ir 192
1
2
3
4
5
6
7
THICKNESS OF LEAD (INCHES)

Figure 12.11

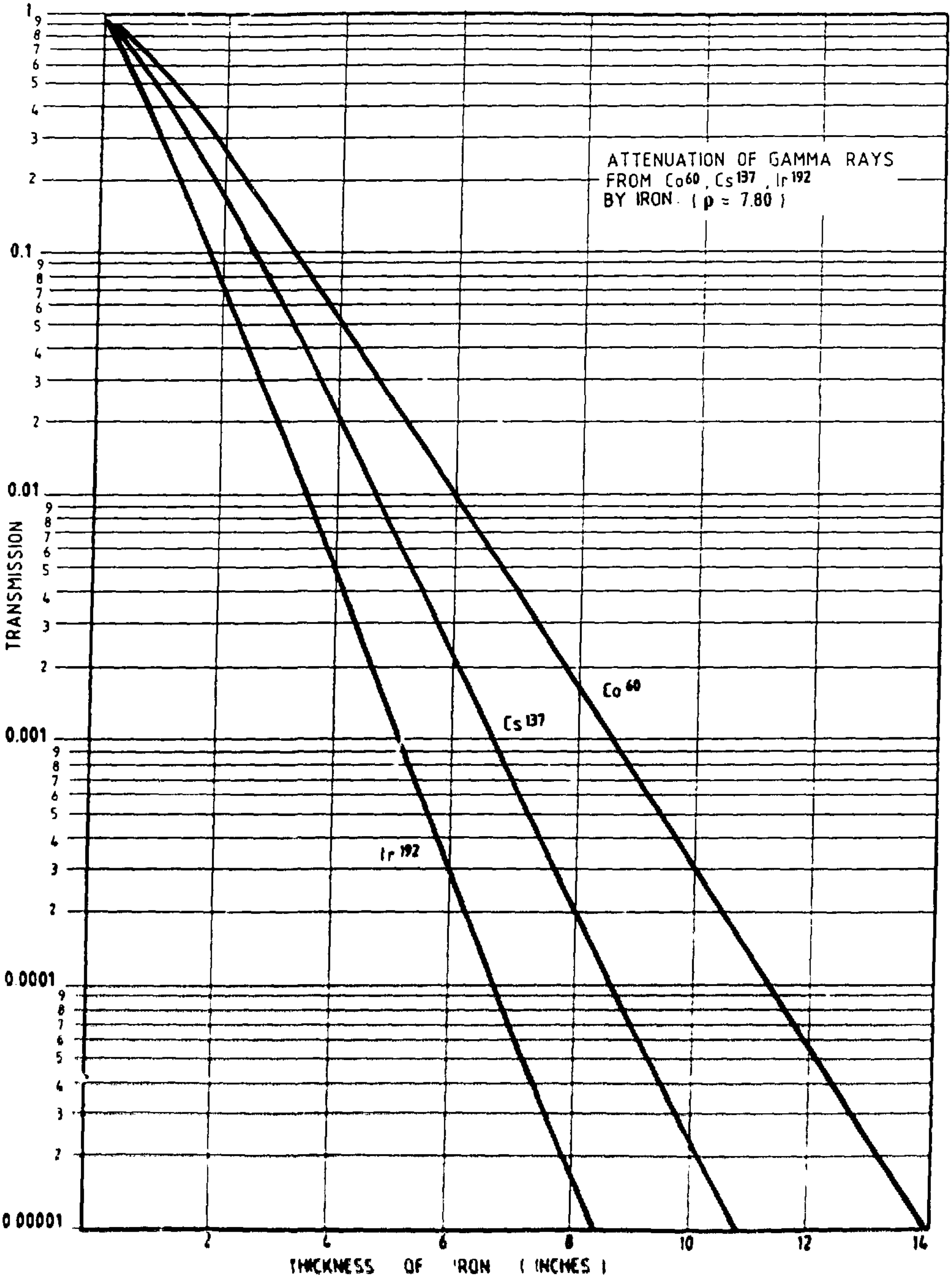

ATTENUATION OF GAMMA RAYS FROM Co60, Cs137, Ir192 BY IRON (ρ = 7.80)
TRANSMISSION
1
0.1
0.01
0.001
0.0001
0.00001
Co 60
Cs 137
Ir 192
2
4
6
8
10
12
14
THICKNESS OF IRON (INCHES)

Figure 12.12

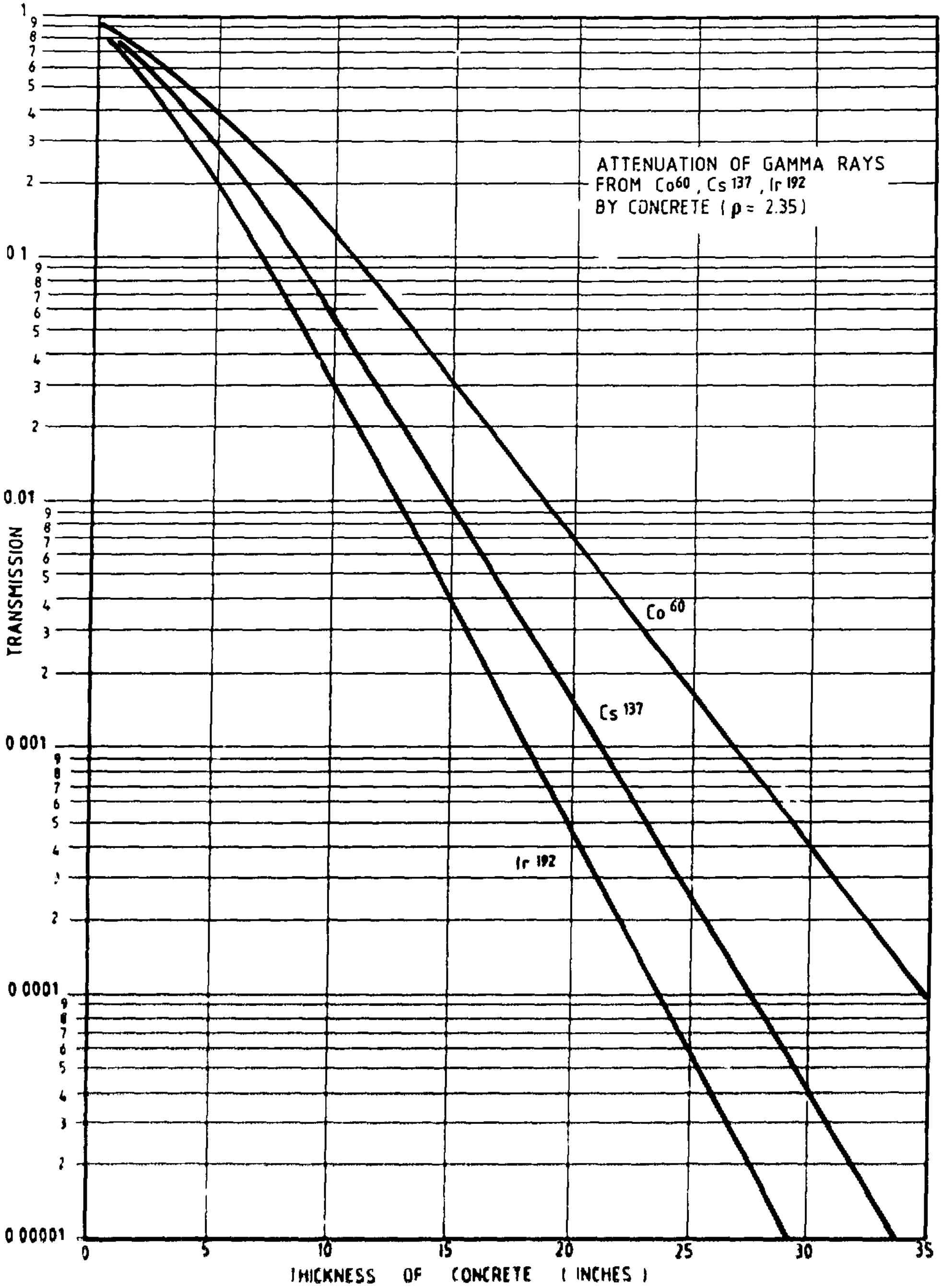

ATTENUATION OF GAMMA RAYS
FROM Co60, Cs137, Ir192
BY CONCRETE (ρ ≈ 2.35)
TRANSMISSION
1
0.1
0.01
0.001
0.0001
0.00001
9
8
7
6
5
4
3
2
0
5
10
15
20
25
30
35
THICKNESS OF CONCRETE (INCHES)
Co 60
Cs 137
Ir 192

Figure 12.15

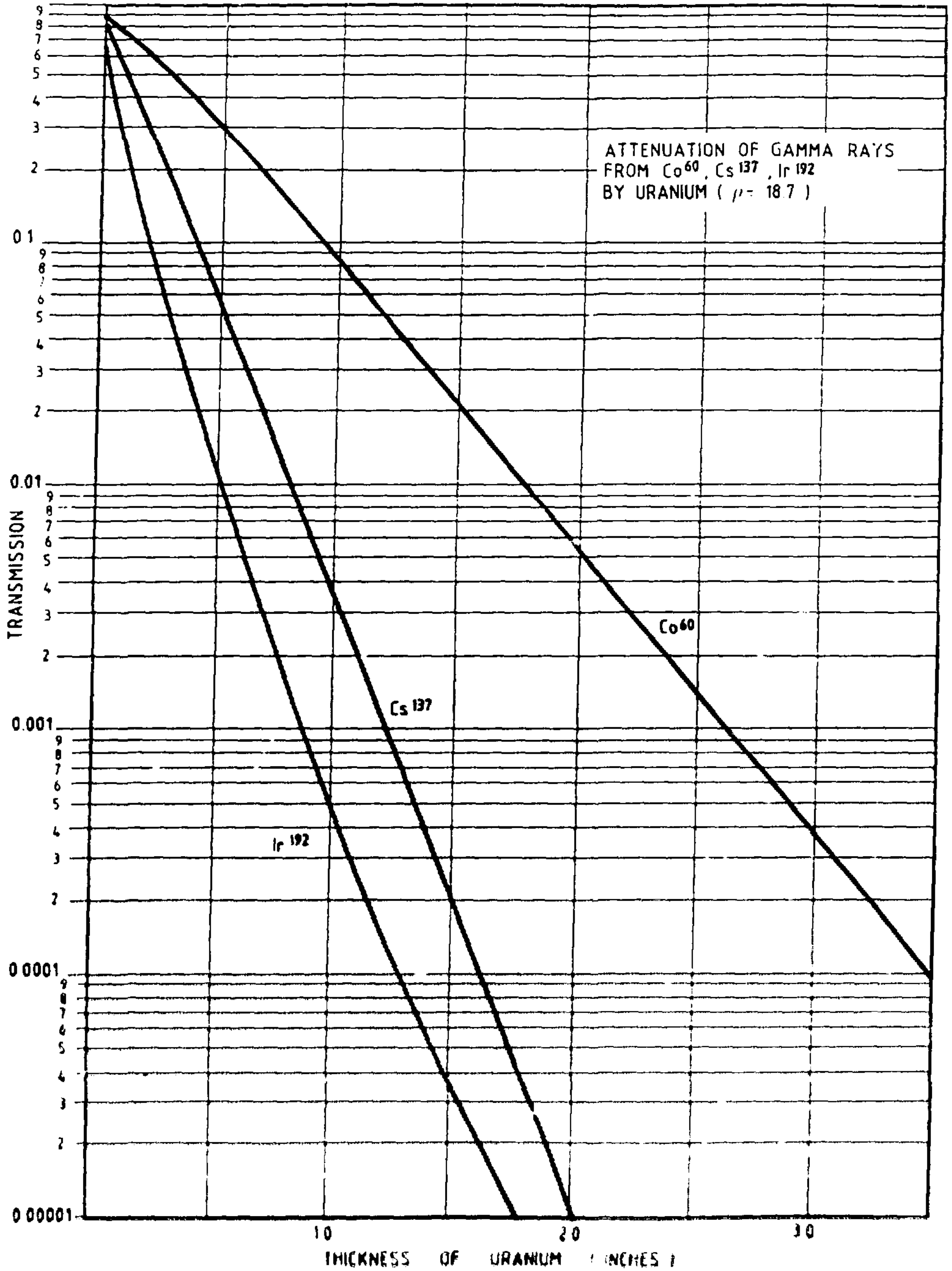

ATTENUATION OF GAMMA RAYS
FROM Co60, Cs137, Ir192
BY URANIUM (μ = 18.7)
TRANSMISSION
0.1
0.01
0.001
0.0001
0.00001
9
8
7
6
5
4
3
2
Co60
Cs137
Ir192
10
20
30
THICKNESS OF URANIUM (INCHES)

Figure 12.14

TABLE 12.5. INDUSTRIAL X-RAY SHIELDING REQUIREMENTS FOR CONTROLLED AREAS*

WUT **	Distance from the tube to occupied area (cm)										
40,000	150	210	300	420	600	840	1200	-	-	-	-
20,000	-	150	210	300	420	600	840	1200	-	-	-
10,000	-	-	150	210	300	420	600	840	1200	-	-
5,000	-	-	-	150	210	300	420	600	840	1200	-
1,250	-	-	-	-	150	210	300	420	600	840	1200
525	-	-	-	-	-	150	210	300	420	600	840
310	-	-	-	-	-	-	150	210	300	420	600
155	-	-	-	-	-	-	-	150	210	300	-

KV	HVL *** (mm)	TVL *** (mm)	Type of barrier	Thickness of Concrete (density 2.36gm/cc) **** (mm)										
100	15.2	50.8	Prim.	234	218	203	185	168	152	140	117	102	84	71
			Sec.	168	147	113	117	102	86	76	58	46	33	20
150	22.9	76.2	Prim.	338	395	292	269	246	226	206	183	165	147	128
			Sec.	231	208	185	163	140	117	94	74	56	47	30
200	27.9	91.4	Prim.	429	401	376	348	323	295	269	244	216	191	162
			Sec.	307	277	249	221	193	168	142	117	91	66	41
250	27.9+	96.5	Prim.	490	457	427	397	366	335	305	274	244	213	104
			Sec.	320	290	262	234	206	178	152	127	102	102	51
300	30.5	101.6	Prim.	551	521	490	460	429	399	368	338	307	277	246
			Sec.34	340	310	279	249	223	198	173	147	122	97	77

* For a design level of 100mr/weak. Add one tenth-value layer (TVL) for environs to reduce radiation to 10mr/week

** W = work load in MA-min/weak., U=use factor., T=occupancy factor. T is equal to 1 for controlled areas.

*** These values are approximate and are obtained at high filtration.

**** For other densities p, the tabular value should be multiplied by 2.36

ABLE 12.6. COBALT-60 SHIELDING REQUIREMENTS FOR CONTROLLED AREAS*

WUT**	Curies***(Approx.)	Distance from source to occupid area (cm)										
80,000	2,000	150	210	300	420	600	840	1200	-	-	- -	-
40,000	1,000	-	150	210	300	420	600	840	1200	-	-	-
20,000	500	-	-	150	210	300	420	600	840	1200	-	-
10,000	250	-	-	-	150	210	300	420	600	840	1200	-
5,000	125		-	-	-	150	210	300	420	600	840	1200
2,500	60		-	-	-	-	150	210	300	420	600	840
1,250	30		-	-	-	-	-	150	210	300	420	600
625	15		-	-	-	-	-	-	150	210	300	420
310	7		-	-	-	-	-	-	-	150	210	300

Type of barrier	HVL(mm) approx.	TVL(mm) approx.	Thickness of lead (mm)										
Primary	12	40	225	213	201	189	177	165	153	141	129	117	105
Secondary													
Leakage ****													
0.1%	12	40	105	93	82	71	60	47	34	20	6	0	0
0.05%	12	40	93	82	71	60	47	34	20	6	0	0	0
Scatter *****													
30°	10.2	34	122	111	101	91	80	70	60	50	40	30	20
45°	8.7	29	97	88	79	70	62	53	44	35	27	18	9
60°	7.5	25	77	69	62	54	47	39	32	24	16	9	3
90°	4.3	14.5	36	32	27	23	19	14	10	6	3	.3	0
120°	2	6.5	15	13	11	9	7	5	3	2	.5	0	0
150°	1.4	4.5	9	8	7	5	4	2.5	1.5	.8	.2	0	0

* For a weekly design level of 100mr. Add one tenth-value layer (TVL) for environs to reduce radiation to 10mr/week.

** W = work load in r/week at 1 m; U = use factor; T = occupancy factor.

*** Assuming use factor U and occupancy factor T equal to one.

**** Refers to leakage radiation of source housing; may be ignored if less than 2,5mr per hour at 1m in ON position.

***** For large field (20 cm dia) and a source-skin distance of 40 to 60 cm.

TABLE 12.7. COBALT-60 SHIELDING REQUIREMENTS FOR CONTROL AREAS*

WUT**	Curies***(Approx.)	Distance from source to occupied area (cm)										
80,000	2,000	150	210	300	420	600	840	1200	-	-	-	-
40,000	1,000	-	150	210	300	420	600	840	1200	-	-	-
20,000	500	-	-	150	210	300	420	600	840	1200	-	
10,000	250	-	-	-	150	210	300	420	600	840	1200	
5,000	125	-	-	-	-	150	210	300	420	600	840	1200
2,500	60	-	-	-	-	-	150	210	300	420	600	840
1,250	30	-	-	-	-	-	-	150	210	300	420	600
625	15	-	-	-	-	-	-	-	150	210	300	420
310	7	-	-	-	-	-	-	-	-	150	210	300

Type of barrier	HVL(mm) approx.	TVL(mm) approx.	Thickness of concrete (density 2.36gm/cc) (mm)										
Primary	66	218	1207	1146	1085	1024	960	899	836	775	711	650	587
Secondary													
Leakage****													
0.1%	66	218	587	526	465	396	329	259	185	112	36	0	0
0.05%	66	218	526	465	396	329	259	185	112	36	0	0	0
Scatter*****													
30°	64	208	777	714	653	589	523	462	401	338	277	213	150
45°	61	203	686	625	564	503	442	381	320	259	198	137	76
60°	58	193	610	551	493	434	376	312	254	196	137	76	13
90°	46	157	429	381	335	290	244	198	152	104	53	3	0
120°	43	147	381	338	295	251	208	165	119	76	30	0	0
150°	38	127	239	201	163	124	86	46	8	0	0	0	0

* For a weekly design level of 100mr. Add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10mr/week.

** W = work load in r/week at 1m; U = use factor; T = occupancy factor.

*** Assumes use factor U and occupancy factor T are equal to one.

**** Refers to leakage radiation of source housing; may be ignered if less than 2.5mr per hour at 1m in "ON" position

***** For large field (20cm dia) and a source-skin distance of 40 to 60cm.

TABLE 12.8. CESIUM-137 SHIELDING REQUIREMENTS FOR CONTROL AREAS*

WUT**	Curies***(Approx.)	Distance from source to occupied area (cm)										
24,000	2,000	150	210	300	420	600	840	1200	-	-	-	-
12,000	1,000	-	150	210	300	420	600	840	1200	-	-	-
6,000	500	-	-	150	210	300	420	600	840	1200	-	-
3,000	258	-	-	-	150	210	300	420	600	840	1200	-
1,500	125	-	-	-	-	150	210	300	420	600	840	1200
750	60	-	-	-	-	-	150	210	300	420	600	840
375	30	-	-	-	-	-	-	150	210	300	420	600

Type of barrier	HVL(mm) approx.	TVL(mm) approx.	Thickness of lead (mm)										
Primary	6.5	21	105	99	93	86	80	74	67	61	55	48	41
Secondary Leakage****													
0.1%	6.5	21	42	35	29	23	16	10	4	0	0	0	0
0.05%	6.5	21	35	29	23	16	10	4	0	0	0	0	0
Scatter*****													
35°	4.5	15	53	49	44	39	35	30	26	22	17	13	8
56°	3.8	13	41	37	33	29	25	21	17	14	10	7	4
90°	2.2	7	20	18	16	13	11	9	7	5	4	2	1
119°	1.3	4	10	9	8	7	6	5	3	2	2	1	0.3

* For a weekly design level of 100mm. Add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10mr/week.

** W = work lead in r/week at 1 m; U = use factor; T = occupancy factor.

*** Assumes use factor U and occupancy factor T are equal to one.

**** Refers to leakage radiation of sourcd housing; may be ignored if less, than 2.5mr per hour at 1m in "ON" position.

***** For large field (20cm dia) and a source-scatterer distance of 50cm.

12.5. SAFETY PROCEDURES FOR RADIOGRAPHIC TESTING

12.5.1. Operational Procedures

12.5.1.1. Introduction

Radiography is widely used in the inspection of boilers and pressure vessels, buildings, oil and gas pipelines, bridges, aircraft, ships and many others. In general, these applications can be classified into two categories, i.e. radiographic works performed in enclosed areas (exposure rooms) and radiographic works performed in open sites. Since the use of radioactive sources or X-ray equipments pose a potential health hazard to radiographic personnel and members of public, safety precaution must be observed at all times.

12.5.1.2. Preparation prior to commencement of work

The following jobs must be done before commencing any radiographic work.

(a) Duties of responsible user

The person who will supervise and be responsible for the use of radioactive sources or X-ray machines should:

(i) be aware of the hazards associated with the presence of radiation in the installation and if necessary obtain the advice of a qualified expert,
(ii) provide instructions concerning radiation hazards ,safe working practices and emergency procedures to employees who operate the radiographic equipment and also to those who may occasionally be exposed to radiation,
iii) ensure that all employees working with radiographic devices and all authorised visitors to areas where radiation may be present are supplied with necessary personnel monitoring devices,
(iv) ensure that radiographic devices are not handled by unauthorised personnel,
(v) follow and enforce all the requirements of any regulations and the conditions under which the radioisotope license is issued.

(b) Operating procedures manual

Each company or department should have an operating procedure manual for routine operations as well as emergency procedures. The manual should include:

(i) the name of the responsible user and his alternate, including the telephone numbers where they can be contacted,
(ii) routine operating procedures with particular reference to health and safety to be observed during all radiographic operations in the radiography rooms and in the field or other temporary locations,
(iii) procedures for the proper use, care and maintenance of radiography equipment through regular maintenance schedule and leak tests and of monitoring devices such as survey meters, dosimeters and film monitors,
(iv) source changing procedures,
(v) procedures for storage of sources and radiographic equipment,
(vi) transportation requirements for sources and radiographic equipment,
(vii) list of emergency equipment that should be available at every radiographic operation,
(viii) emergency procedures
(ix) methods of maintaining records

(c) Personnel monitoring

All personnel working with radiographic sources must wear appropriate personnel monitoring badges at all times during radiography. The film badge should be worn on the chest. In addition (depending on the operation) the worker may also wear a wrist badge. The film is normally worn for a period of four weeks and then replaced. The used film is returned for processing and dose assessment. The film badges should be stored in a radiation free area when not in use and must never be brought back home. Any accidental exposure or damage to the film badge due to mishandling shall be reported immediately to the safety officer in charge.

(d) Radiation survey meter

The following points shall be checked regarding the use of radiation survey meters.

(i) The response of the instrument should be appropriate to the type of radiation.
(ii) Only calibrated instruments for which a certificate of calibration has been issued by a competent authority shall be used
(iii) The instrument should cover a suitable range such that dose rates from 2 mR/h to 1R/h can be measured within ±20% of the true intensity.
(iv) The most important thing to remember is to ensure that the instrument's battery is in good working condition.

(e) Warning signals

Signals are used to warn people around the area about the presence of radiation.This should be in the form of lamps or audible signals or both. The light or audible signal shall be distinguishable for the following situations:

(i) When a sealed source is about to be exposed or when an X-ray machine is about to be energised and
(ii)While a sealed source is exposed or an X-ray machine is energised.

(f) Warning signs

Warning signs of adequate size and with appropriate radiation symbols must be made available. These signs are used to identify and define restricted areas. It is suggested that the name , address and telephone number of the person responsible for the site should be included on each warning sign.

(g) Equipment and facilities

(i) All radiographic devices must be conspicuously and permanently marked with the approved radiation warning signs.
(ii) The model number,serial number and source rating for the radioisotope contained in each camera should be stamped on the camera. When loaded the camera should bear a tag showing the type of radioisotope, its date of procurement and strength in curies at that time.
(iii) A camera should be so designed that :

1. numerous and elaborate precautions do not have to be observed to avoid excessive exposures to ionising radiation.
2. at no time during normal operation should it be necessary for a radiographer to expose any part of his body (excluding extremities) to a radiation field of more than 100mR/h.
3. the source capsule is fixed so that under no circumstances can it drop out of the camera.
4. the shielding is such that at no point on the surface of camera containing a radioactive source does the radiation level exceed 200mR/h with the camera in the closed position.
5. the outer casing will prevent the shielding material (such as lead) from shifting or escaping in the case of fire or accident.
6. it is capable of being locked preferably with the lock fixed on the body of the camera.
7. if it weighs 45kg or less it is provided with carrying handle(s) that enable the person(s) carrying it to remain farther than 150mm from its surface.
8. if it weighs more than 45kg, it is mounted on a carriage of adequate strength and stability.

iv) A camera should be provided with collimators to limit the beam of radiation to the size of the area being radiographed.
(v) A radiographic camera in which the source is manually positioned by means of a sliding rod should not be used.
(vi) When the source is extended by means of a teleflex cable the coupling of the source capsule to the cable should be such that the source will not detach itself if the camera is properly used and cables and couplings should be tested to withstand a tension of at least 450N.
(vii) Provision for electrical or mechanical signals to indicate the position of the source is a desirable feature.
(viii) A hose or tube through which the source moves pneumatically or mechanically should be capable of withstanding repeated flexures without suffering permanent distortion.
(ix) Source capsules or pencils designed and approved for use in one type of camera must not be used in any other type.
(x) The type and activity of the radioactive substance used should be selected in relation to the job to be performed.
(xi) The camera must be tested for proper mechanical function of shutter mechanism, source coupling , source positioning plungers, locking mechanisms and cleanliness of hose or tube through which the source moves.

12.5.1.3. Radiographic works in exposure rooms

Every radiographer must understand the working principles and operation of each radiographic unit that he will be using. The equipment should be checked before taking it out to the field and before using it to ensure that it is functioning satisfactorily. This will enable the radiographer to deal with emergencies with minimum delay and so limit personal radiation exposure.
(a) Before starting any radiographic work the radiographer must obtain the permission of the person responsible for the exposure room and shall inform him on the ;

(i) Type and strength of the radiation source (X or gamma ray :mA or Ci)
(ii) Model and serial numbers of the radiographic equipment
(iii) Number and names of radiographers involved
(iv) Period of work

However in practice the radiographer will be asked to provide all this information in a special log book issued by the person in- charge of the exposure room.

(b) Before performing the inspection a radiation survey must be made around the exposure room especially at the door and cable holes to ensure that there is no radiation leakage. The area must be cleared and some person designated to prevent unauthorised entry into the controlled area. A plan must be prepared to direct the beam towards the ground , unoccupied areas or areas that are adequately shielded. The radiographic set up must be completed before the shutter is opened.

(c) During radiation exposure ensure that the door is tightly closed. Occasional radiation survey must be carried out to ensure that the radiation level anywhere outside room does not exceed the permissible limit. The survey should also be made before entering the exposure room.

(d) After completion of work check with the survey meter whether the source has returned to its proper shielded position, remove the radiographic equipment and other accessories and store them in their proper storage area. For fixed installations (e.g. X-ray machines) the equipment only needs to be switched off. The warning signs and barriers should be removed. Inform the person in charge of the exposure room regarding the completion of the job. Carry out a careful inspection of equipment for any defects with special attention to cleanliness and lubrication of source guides, couplings etc. If anything is defective it should be repaired immediately without postponing it. The survey meter should be checked and batteries replaced if necessary.

12.5.1.4. Radiographic work in open sites.

12.5.1.4.1. Duties of radiographer

(a) Transportation of radioactive sources

The transportation of radioactive sources whether by public or private carrier must be in accordance with control regulations and is governed by the requirements of the agency having jurisdiction by statute over that particular mode of transport. Most radiography sources require approved packaging and for all modes of transport (including a radiography vehicle) must be approved. In addition to the above requirements the following conditions should be observed for in-use (radiography vehicle) transportation.

(i) The vehicle must be conspicuously marked with radiation warning signs
(ii) The source container must be conspicuously marked with radiation warning signs. The nature and amount of radioactive material present and the company's name and address must also be shown.
(iii) The source container must be placed securely in the interior of the vehicle or securely in a steel box.
(iv) Radiation levels at readily accessible places around the vehicle should not exceed 2.5mR/h.
(v) Radiation levels in any normally occupied position in the vehicle must not exceed 2mR/h.
(vi) Only radiation workers should travel in a vehicle carrying a radiographic source.
(vii) Emergency equipment and written procedures must be available to all personnel travelling with the source.

(b) On arrival at site the radiographer must obtain permission from the person responsible for the area and inform him on the :

(i) Type and strength of radiographic source.
(ii) Model and serial number of radiographic equipment.
(iii) Name of radiographer.
(iv) Type of radiation safety equipment to be used.
(v) Period of work.
(vi) A sketch of the site plan indicating the location of the work and intended boundary.

(c) After the location of the radiographic work has been identified the following requirements shall be satisfied:

(i) Boundaries shall be clearly defined with barriers of rope or other materials e.g.timber.
(ii) Warning lights shall be displayed to indicate that radiographic exposure is underway.
(iii) Warning signs shall be prominently displayed.
(iv) The area shall be kept under surveillance at all times during an exposure.

(d) Using a survey meter the radiographer shall check the exposure rate at the site boundary at frequent intervals to ensure that the boundary is correctly placed. If the dose rate exceeds the permissible limit the barrier should be adjusted.

(e) When operating radiation equipment the radiographer must take every effort to minimise the risk of over exposure. This can be achieved by observing three important parameters:

(i) Time (as short as possible).
(ii) Distance (as far as possible).
(iii) Shielding (use collimator or shielding materials whenever possible)

(f) On the completion of work the radiographer must ensure that all radiation equipment and radiation warnings or signs are removed from the site before leaving. The person in charge of the area shall be informed about the completion of the job

12.5.1.4.2. Types of open sites

(a) Fully open sites (field sites)

A fully open site (or field site) refers to the radiographic site where the radiation is not obstructed by any object except by those being radiographed. In other words the distance from the source is the only parameter to be considered. Warning lamps shall be used all along the previously determined circular boundary for permissible radiation levels. Unauthorised persons shall not be allowed to enter this barrier and notices bearing words such as 'DO NOT PASS THIS BARRIER< RADIOGRAPHY IN PROGRESS' must be displayed.

(b) Partly open sites

A partly open site refers to the radiographic site where the path of radiation is obstructed by foreign objects or materials acting as shielding. In this case the boundary is not necessarily circular as in field sites. The shape of the boundary is dependent upon the thickness and position of the obstruction.

12.5.1.5. Safety requirements for X-rays

12.5.1.5.1. Equipment specifications

(a) The control panel of an X-ray unit should be marked with a suitable warning sign, e.g. 'Caution - X-rays. This equipment will produce X-rays when energised'
(b) Effective means should be provided to prevent and unauthorised use of the equipment.
(c) There should be some easily discernible device on the control panel to give positive information as to whether or not the X-ray tube is energised.
(d) The tube housing should provide adequate protection to personnel. At the maximum specified rating the leakage radiation at a focal distance of 1m should not exceed 1 R/h.
(e) The unit should be provided with a cone or diaphragm to restrict the useful beam to the area of interest.
(f) An X-ray tube which can be continuously energised should be provided with lead shutters. The protection afforded by these devices should be at least equal to the tube housing and arranged so that it can be opened and closed only from the control panel.

12.5.1.5.2. Auxiliary protection devices

(a) all protection devices ,appliances and apparatus should be adequate for the purpose for which they are intended.

(b) protective lead-sheeting or mobile screens should be mounted in a manner so as to avoid 'creep' and to protect them from mechanical damage.

12.5.1.5.3. Building and installation specification

(a) In determining barrier thicknesses the protection provided should be such that :

(i) in areas occupied by radiation workers the radiation level does not exceed 100mR/week.
(ii) in areas occupied by non radiation workers or the general public the radiation level does not exceed 10mR/week.

(b) In planning an X-ray room careful consideration should be given to reducing to a minimum the number and size of all perforations in the protective barriers and openings of the room

(c) Doors into X-ray rooms should be so arranged that no one can enter such rooms during exposure without the operator's knowledge

(d) Warning lights and/or audible signals should be provided outside the X-ray room access doors to indicate when the X-ray tube is about to be energised.

(e) All doors or panels into an X-ray room should be provided with interlocking switches preventing operation of the X-ray tube unless the door or panel is closed.

(f) All means of exit should be so constructed that any person accidentally locked in can leave the enclosure without delay.

(g) If the operation of an X-ray machine has been interrupted by the opening of a door to the X-ray room, it should not be possible to resume operation by merely closing the door in question. To resume operation it must be necessary to reset manually a suitable device provided for this purpose and located at the operator's station.

(h) Effective means which can be reset from outside should be provided within the X-ray room for preventing or interrupting the operation of the X-ray machine.

Special precautions for open installations

(a) The control panel should be placed and operated from behind a fixed or temporary barrier of adequate protective thickness.
(b) During X-ray exposures all persons other than the control operator should be :

- (i) shielded from direct and / or scattered radiation by a barrier of adequate protective thickness, or
- (ii) excluded from the area around the radiographic site. (This area to be determined by a qualified person)

(c) The area as determined by the above procedure should be demarcated by roping off by suitable means.

(d) Audible signals should be provided and operated immediately prior to radiographic exposure.

(e) Visible warning signs should be provided and operated during radiographic exposure.

(f) Wherever practicable the useful beam should be directed away from the occupied spaces and the beam cross-section should be limited to the smallest area necessary for the work.

12.5.1.6. Establishment of radiographic boundary

(a) Initial calculations

A preliminary boundary can be estimated if the radiation intensity at a certain distance from the source is known. The safe working distance can then be determined by the inverse square law. This law is expressed as the equation :

$$I_1/I_2 = r_2^2/r_1^2$$

where,

I_1 = intensity at a distance r_1
I_2 = intensity at a distance r_2

Example 1 ; If the dose rate at 1 meter from a source is 5 R/h, what is the distance from the source which corresponds to a dose rate of 2.5 mR/h?

Let I_1 = 5 R/h = 5000mR/h
r_1 = 1 meter
I_2 = 2.5 mR/h
r_2 = ?

Substituting into the equation,

$$r_2 = r_1\sqrt{(I_1/I_2)} = 1\sqrt{(5000/2.5)}$$
$$r_2 = 44.7 = 45 \text{ meters.}$$

Example 2 : A 40 Curie source of Iridium 192 is used in a radiographic work. Given that the dose rate of Iridium 192 is 0.5R/h/Curie at a distance of 1 meter from the source. What is the dose rate received by a radiographer if he stands 30 meters away from the source?
The dose rate of Iridium 192 is 0.5 R/h/C at 1 meter: thus the dose rate of a 40 Curie source at 1 meter is 0.5x40R/h or 20 R/h.

$$I_1 = 20 \text{ R/h} = 20{,}000 \text{ mR/h}$$
$$r_1 = 1 \text{ m}$$
$$r_2 = 30 \text{ m}, I_2 = 20{,}000/900 = 22.2 \text{ mR/h}$$

Example 3: In example 2 if the radiographer wishes to be exposed to a dose rate of 2 mrem/hr how far from the source should he stand?

$$r_2 = \sqrt{(20000/2)} = \sqrt{10000} = 100 \text{ meters}$$

(b) After the safe working distance has been determined make a preliminary boundary and place radiation warning signs at the boundary.

(c) Energise the X-ray machine or expose the radioactive source.

(d) Check the dose rate at the boundary using a survey meter and adjust the boundary if necessary. The safe boundary is now established.

(e) For a fully open site, the boundary is circular.

(f) For a partly open site a preliminary boundary is calculated as described in (a) but the final boundary must be cross checked with a survey meter.

12.5.1.7. Storage of radiographic equipment on site

Sometimes radiography is conducted at site for a long period of time. In this case radiographers are resident in the area and the source or X-ray machine must be properly stored.

(a) Storage for radioactive sources

If radioactive sources are to be used a specially constructed storage pit is necessary and this shall be prepared before the sources are brought to site.

The responsibility over the safety of this pit shall be assumed by authorised persons. Sufficient radiation warning notices shall be displayed at the fence as to be clearly visible from all directions. The names and telephone numbers of the responsible persons should be included together with the company's name, address and telephone number.

(b) Storage for X-ray equipments

Storage facilities for X-ray equipment are less complicated than those for radiation sources. A small lockable store room is sufficient. This is because once the machine is switched off there will be no radiation emitted. Protection is only required against theft or vandalism.

12.5.2. Emergency procedures

12.5.2.1 Introduction

Industrial radiography is an important industrial use of ionising radiations and the wide range of accidents which have occurred illustrate why all users must exercise proper care to ensure that no unnecessary radiation exposure takes place. Although various safety rules and regulations have been imposed on the user of radioactive materials or X-ray sources, there is always the possibility of accidents. Thus it is very important for the employer or his appointed representatives (e.g. safety officers) to design emergency procedures which can help minimise radiation exposure of persons in the event of any unexpected accident.

In many cases radiography may be performed many miles away from the base. In such cases immediate contact with the supervisor may not be possible or even if possible the time required for the supervisor to reach the site may be quite long. Therefore radiographers must be fully trained and equipped to take immediate action to prevent unnecessary panic should an accident occur. For this matter radiographers must familiarise themselves with all emergency procedures outlined by their employer. It is the responsibility of the employer to ensure that each radiographer must have a copy of these emergency procedures. These procedures if possible should be detailed ,however, they may be in the form of general principles since the detailed procedures will depend on the actual conditions of each accident.

Emergency situations are most likely to arise when ionising radiations are actually being used. For this matter different actions are required for situations involving X-rays (which can be switched on and off) and gamma rays (which cannot be switched on and off.) Emergency procedures should be laid down to:

(a) ensure that external exposure to members of the public and emergency crew are kept to the lowest practical amount.
(b) ensure that during emergency operations there is no possibility of ingestion of radioactive material by any person.
(c) be specific in relation to the equipment, radioactive substance in use and possible modes of accident.

12.5.2.2. Administrative responsibility

The responsible user named on the licence must ensure that :

(a) Copies of the emergency procedures are distributed and explained to the operating personnel.
(b) All groups who use and/or store potentially hazardous amounts of radioactive substance should periodically meet to review the emergency procedures and modify them in the light of experience gained.
(c) Emergency equipment is readily accessible to all concerned.
(d) Names and telephone numbers of health authorities are available to operating personnel.
(e) Emergency measures taken in each accident are documented.

12.5.2.3. Radiation emergency planning

The time to think about a radiation accident with radiographic equipment is before it happens. This is why detailed emergency procedures should be prepared in advance and a copy should be available at the site of every radiographic operation. In handling any emergency situation the first rule is never to attempt to correct it unless a radiation detector in proper operating condition is available. If a suitable radiation detector is not available a restricted area should be set up and warning signs posted. The extent of this will depend upon the strength of the source and other factors such as shielding available. No further action should be taken until proper instruments become available. The second rule is think of steps that must be taken to remedy the trouble and should result in the minimum personal radiation exposure; for this the factors of time , distance and shielding must be used to the best advantage.

12.5.2.4. Emergency procedures involving X-ray equipment

Persons may be accidentally exposed to radiation from the X-ray machine. This can happen if the machine is unintentially energised while persons are within the 'no entry' barrier

Accidental exposure may also occur if persons entering the "no entry" barrier are unaware that the machine is in operation. As soon as the accident is realised the following actions must be taken :

(a) Action by radiographer

(i) SWITCH THE MACHINE OFF immediately

(ii) LEAVE EVERYTHING as it is until it can be seen by the supervisor or other higher authority.

(iii) ASK ANY PERSON WHO MAY HAVE BEEN EXPOSED TO REMAIN AT THE SITE. This will allow the competent authority to interview the persons involved and establish the extent of exposure received by them. If they cannot remain on site obtain their full names, addresses and telephone numbers so that they can be contacted later if necessary.

(iv) INFORM THE PERSON IN CHARGE OF THE AREA of the accident so that measures can be taken to restrict entrance to the area. This will ensure that the situation under which the accident occurred can be preserved.

(v) CONTACT THE SUPERVISOR OR THE SAFETY OFFICER AND INFORM him of the accident. If they cannot be contacted advice may be obtained from other competent authorities.

(b) Action by supervisor

As mentioned earlier in accidents involving ionising radiation the most important thing to do is to establish the extent of the exposure received by persons involved. As a matter of fact this is the reason why the X-ray machine and its surroundings should be left as it was as soon as the accident is realised. By knowing the exact position of the persons at the time of the accident and for how long the dose received by them may be estimated especially in cases where no personnel monitoring devices are worn. This estimation can be found by irradiating a film badge placed at the position of the person during the accident at exactly the same KV and exposure time. The following actions must be taken by the supervisor:-

If it is suspected that RADIOGRAPHERS ARE ACCIDENTALLY EXPOSED to radiation.

i. REMOVE THEM FROM WORKS involving ionising radiation until their exposures have been established.

ii. ASK THE COMPETENT AUTHORITY CONCERNED FOR ASSISTANCE IN ASSESSING THEIR DOSE.

iii. SEND THEIR FILM BADGES TO AN APPROVED LABORATORY.

in all cases :-

iv Make full investigation of the incident, taking written statements from the radiographer or any other members of public including details of where they were in relation to the X-ray machine and for how long. If it appears that the radiographer may have been overexposed, notify an employment medical adviser or appointed doctor immediately so that necessary medical examination can be carried out.

12.5.2.5. Emergency procedures involving radioactive source(s)

12.5.2.5.1. Source in use

Generally speaking, an emergency situation arises when the source is jammed in its guide tube (for a projector type container) or the source is accidentally separated from the shutter

Since work should be conducted within a predetermined barrier and constant monitoring of the dose is carried out using a survey meter, the presence of any unshielded source should be apparent immediately. In the event of this incident, the following action should be taken :-

(a) Action by radiographers

i. Using a survey meter, MEASURE THE DOSE RATE AROUND THE AREA AND ESTABLISH A NEW SAFE BARRIER (e.g. beyond which the dose rate is less than 0.25 mrem/hr.). The survey meter used should be capable of reading high radiation doses.

ii. RESTRICT ACCESS TO THIS BARRIER AND DISPLAY A WARNING LIGHT around it together with a radiation warning notice. If barrier materials are not available 'sentries' should be posted to ensure that no one passes through the barrier except those engaged in rescue operations. Detain any persons who may have been inside the barrier during the accident. If this is not possible, obtain their names, addresses and telephone numbers so that they can be contacted later if necessary.

iii. THINK AND PLAN CAREFULLY A COURSE OF ACTION while outside the barrier. Prepare all equipments required for the rescue operation, e.g long handling tongs, shielding materials, etc.

iv. INFORM THE PERSON IN CHARGE OF THE AREA WHERE THE WORK IS CONDUCTED, of the mishap and the proposed action to be taken.

v. ATTEMPT TO PLACE THE SOURCE INTO ITS CONTAINER QUICKLY if possible by using long handling tongs. NEVER TRY TO PICK THE SOURCE WITH BARE HANDS. The recommended maximum permissible times for rescue operation involving Ir-192 and Co-60 sources are given in Table 12.9. A second person must stand at the barrier to time the operation and shout when the permitted time is up.

vi. TRY TO ATTENUATE the radiation intensity using whatever materials are available (e.g. concrete block, sand, wood, etc.).

vii. CALL FOR ASSISTANCE FROM THE SUPERVISOR who will summon any other necessary help. In case he is not available, advice may be obtained from the competent authority (e.g. The Atomic Energy Licensing Authority)

TABLE 12.9. MAXIMUM PERMISSIBLE TIMES FOR RESCUE OPERATION INVOLVING Ir-192 AND Co-60 SOURCES

Source	Activity in Ci	Dose Rate at 1 meter (rem/hr)	Time allowed in minute (s)
Ir-192	1	0.48	120
	2	0.96	60
	5	2.40	25
	10	4.80	12
	20	9.60	6
	50	24.00	2
	100	48.00	1
Co-60	1	1.32	46
	2	2.64	23
	5	6.60	9
	10	13.20	4.6
	20	26.40	2.3
	50	66.00	0.9
	100	132.00	0.4

(b) Action by supervisor

Upon arrival at the scene, the supervisor's action depends on whether or not the source has been returned to its container.

If the source is already returned into its container :-

Ai. CHECK THE SHIELDING AND ITS FASTENER.

Aii. REMOVE PERSONNEL involved in the recovery operation from the radiation work until their doses have been established.

Aiii. SEND THE FILM BADGES WORN BY THE PERSONNEL INVOLVED to the approved laboratory (e.g. SSDL) for urgent examination.

Aiv. Repeat the procedure outlined in Section 12.5.2.4 (b)(iv).

If THE SOURCE IS STILL OUTSIDE ITS CONTAINER:-

Bi. CHECK THAT THE BARRIER, warning signals and notices are satisfactory, and the access to the radiation area is under control.

Bii. MAKE FURTHER ATTEMPTS TO RETURN THE SOURCE into its container. If this fails, a decision must be made either to continue the rescue operation or obtain an other container as a temporary shield for the source.

Biii. WHEN THE SECOND CONTAINER IS AVAILABLE, PLACE THE SOURCE INSIDE IT. The container must have adequate shielding properties so that it is capable of attenuating the radiation down to a permissible dose. At this stage, a decision must be made either to return the source to its original container with the aid of handling facilities at the base or to take disposal actions. In the latter case, it will be necessary to contact the Licensing Authority to obtain further advice.

Biv. The series of actions Ai - Aiv should now be set in motion.

12.5.2.5.2. Source not in use

(a) Accidents involving possible damage to a source container

This situation may occur as a result of road or other accidents. Before commencing any source rescue operation, efforts must be made to rescue any injured or trapped persons. The rescuers must be told about the presence of radioactive materials. Until measurements have been made with a survey meter, it should be assumed that the source is unsealed. Then carry out necessary actions as stated in Section 12.5.2.5.1.

(b) Fire involving radioactive sources

In the event of a fire, try to remove the container away from the scene. However, if this is not possible, abandon it, and tell the Fire Service of the presence of radioactive materials as quickly as possible. Then commence the series of actions mentioned in Section 12.5.2.5.1. (a) and (b).

(c) Missing or stolen source

In this case, the following action should be taken :-

i. BEGIN AN IMMEDIATE SEARCH using whatever detectors are available.

ii. If it cannot be found, INFORM THE police,THE SUPERVISOR, AND THE MAN IN CHARGE OF THE AREA. If a vehicle containing a source is missing the police and the supervisor must be informed immediately.

(d) Source lost in transport

If a source container has been loaded into a vehicle for transport and at the end of the journey it cannot be found, the police and the supervisor must be informed immediately. It may be necessary to retrace the exact route taken by the vehicle, making both a visual search for the source container and an instrumental search for the radiation from the source.

13. TOTAL QUALITY CONTROL

13.1 TOTAL QUALITY CONTROL

Total quality control is a system for defining, controlling and integrating all company activities which enable economic production of goods or services that give full customer satisfaction.

In the phrase , total quality control, 'quality' does not mean best or excellent, it means meeting the customer's requirements of suitability for the task at an economic price e.g. a different standard of performance is expected from a steel washer compared with a galvanised washer.

The word 'control' represents a management tool with four basic steps:

1. Setting quality standards.
2. Checking conformance with the standard.
3. Acting when the standards are not met.
4. Assessing the need for changes in the standards.

The objective of quality control is to provide the customer with the best product at minimum cost. This can be achieved by improvements in product design, consistency in manufacture, reduction in costs and improved employee morale. The factors affecting product quality can be divided into two major groups:

1. Technological - machines, materials and processes.
2. Human - operators, foremen and other personnel.

The later is the more important.

13.2. HISTORY OF QUALITY CONTROL

Quality control has its roots in the guilds of the Middle Ages where quality was assured by long periods of training. This training instilled in workers pride for the workmanship in their product.

Specialisation of jobs, as industry grew, meant workers no longer made the entire product. This resulted in a decline in workmanship and alienation of the work force. As products became more complicated it became necessary to inspect them after manufacture.

In the 1920's statistics were applied , initially at the Bell Laboratories in the USA, in the development of acceptance sampling as a substitute for 100% inspection. General acceptance of the techniques occurred during World War 2 when the early Military Standards containing quality control clauses were developed.

Subsequently Quality Control Institutes and Standards Associations were formed. The Institutes promoted the use of quality control techniques for production and service, through publications, conferences and training.

Standards Associations have promoted the development of universal standards which may be adopted as part of the quality control process.

13.3. THE NEED FOR QUALITY CONTROL

Quality Control is required because of changing buyer-producer relationships and major marketplace demands for quality. These changes can be seen in mounting product and service liability trends and consumer pressures which impact strongly on producers.

The social and economic demands for effective use of materials and production processes to turn out higher technology based products assure the need for quality assurance. Similarly the changing work practices in factories and offices and the need to compete in international markets require total quality control of all products and services.

Because the human factor is of great importance in the quality control operation, special attention must be paid to the personnel in the organisation. They need to be educated to the benefits of quality control, they need to feel involved in the quality control process and they must be able to communicate with other personnel on quality control. This allows them to develop a quality control spirit and improved morale necessary to the success of any quality control program.

Quality Circles have been developed in many factories to oversee the quality of products. These involve staff representatives at all levels who meet for short periods of time e.g. an hour, every week to discuss the quality control of their product and any changes necessary.

13.4. RESPONSIBILITY FOR QUALITY

The departments responsible for quality are listed in Figure 13.1. Quality is not the responsibility of any one person or department: it is everyone's job. It includes the assembly line worker, the typist, the purchasing officer and the managing director.

The responsibility for quality begins when marketing determines the customer quality requirements and continues through to the satisfied customer.

As can be seen from Figure 13.1 the responsibility for quality is delegated to all departments. Each has the authority to make quality decisions. Figure 13.1 shows the ideal place for an effective Quality Control department: independent, reporting directly to upper level management.

13.4.1. Inspection and Test Department

Inspection and test has the responsibility to appraise the quality of purchased and manufactured items and to report the results. These results can be returned to other departments so that corrective action can be taken when necessary.

In order to perform inspection, accurate equipment is necessary. This means it must be maintained and regularly calibrated.

It is necessary to continually monitor the performance of inspectors. Some defects are more difficult to find and require more patience. Inspectors vary in ability and the defect level affects the number of defects reported. Samples with known defects should be used to evaluate and improve the inspector's performance. The reliability of inspection can usually be quantified and is most often affected by the operator not the possible defects in the component presented for inspection. Education (training) is the most effective way of improving reliability.

13.4.2. Quality Control Department

The Quality Control Department does not have direct responsibility for quality. It assists or supports the other departments as they carry out their responsibilities. The relationship between the departments and quality control is similar to a line -staff organisational relationship.

Quality Control appraises the current quality, determines quality problem areas and assists in the correction or minimisation of these problem areas. The overall objective is the improvement of the product quality in co-operation with the responsible departments.

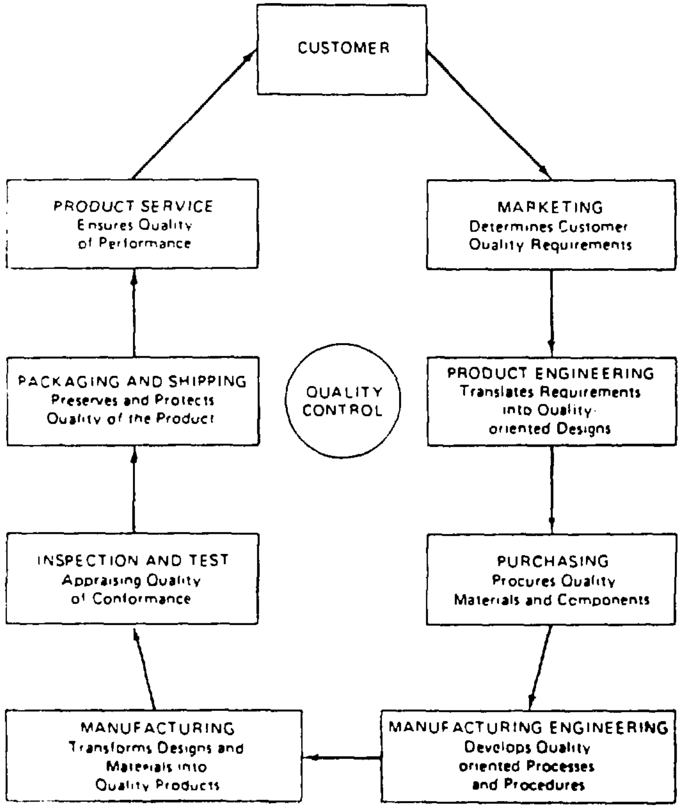


Figure 13.1 Departments responsible for quality

13.5. QUALITY ASSURANCE

Definition: All those planned and systematic actions necessary to provide adequate confidence that the item or facility will perform satisfactorily in service.

It involves a continuing evaluation of the adequacy and effectiveness of the overall quality control program with a view to having corrective measures initiated where necessary. For a specific product or service this involves verification audits and evaluation of quality factors that effect the production or use of the product or service.

IT IS QUALITY CONTROL OF THE QUALITY CONTROL SYSTEM!

Important functions -

- establishment of quality standards
- written procedures
- control of document flow
- maintaining identity and traceability of materials
- calibration of equipment
- retention of records

A quality assurance system is an effective method of attaining and maintaining the desired quality standards. It is based on the fact that quality is the responsibility of all functions. These interrelated functions can be broken down into 10 subsystems, as illustrated in Figure 13.2.

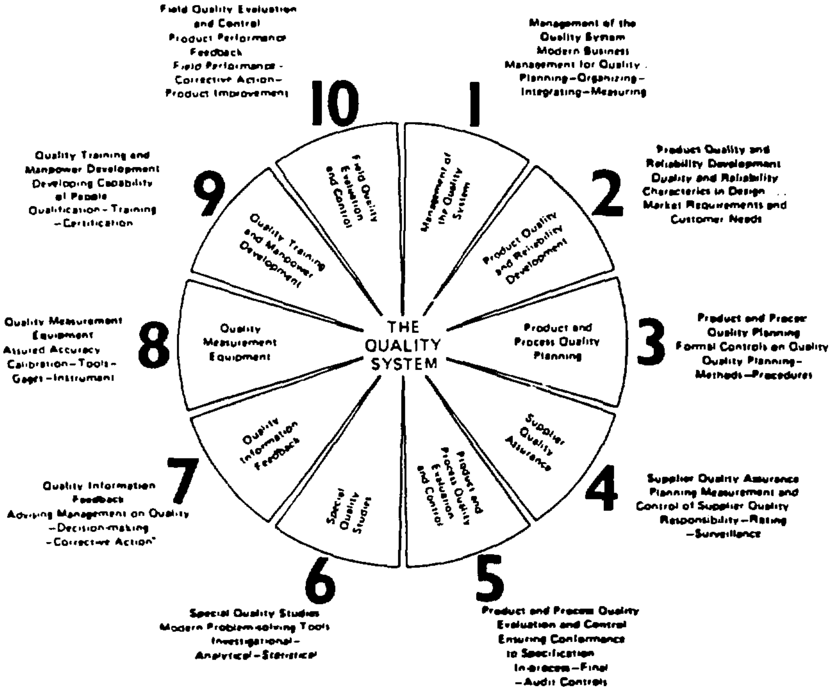


Figure 13.2 Major elements of a quality assurance system

The quality assurance system is an evaluation or audit of each one of these subsystems to determine how effectively the functions are being performed. Evaluations are usually conducted each year to determine which elements and subsystems need improvement. The overall rating provides a comparison with past performance or with other plants of a multiplant corporation.

Inspection alone does not assure quality or,more precisely, does not assure conformance to requirements of the contract or customer order. This applies not only to complex products such as satellites or nuclear submarines, but also to simple products such as nails or pipe fittings. Regardless of the product or service involved, the essentials of an effective quality assurance system include:

1. Independence of the quality assurance department from the design and production departments.
2. Standards of quality that reflect both the needs of the customer and the characteristics of the manufacturing process.
3. Written procedures that cover all phases of design,production, inspection, installation and service, with a program for continuous review and update of these procedures.
4.Control of the flow of documents such as order entry, order changes, specifications, drawings, route slips, inspection tickets and shipping papers.
5. Methods for maintenance of part identity which must establish traceability through the process.
6. Methods for timely detection and segregation of nonconforming material which must also include programs for corrective action.
7. Schedules for periodic calibration of inspection equipment.
8.Schedules for retaining important records.
9 Programs for training and qualification of key production and inspection personnel.
10. Systems for control of specifications incorporated into purchase orders, for control of the quality of purchased goods and for appropriate inspection of purchased goods

11. Systems for control of manufacturing , assembly and packaging processes, including inspection at key points in the process flow.
12. A system for periodic audit of any or all of the above by persons having no direct responsibility in the area being audited.

13.5.1. Independence of Quality Assurance Department

Responsibility for the development, operation and monitoring of an effective quality assurance program in a plant usually rests with the quality assurance manager. Companies having several plants may have a corporate quality assurance department that reviews and coordinates the system for the entire organisation. To be effective this department should be an independent staff department that reports directly to an upper level manager such as general manager, vice president or president. The quality assurance department should be free to devise and recommend specific systems and procedures and to require corrective action at their discretion.

13.5.2. Establishment of Quality Standards

No single quality level is necessary or economically desirable for universal use; the quality requirements of a paper clip are obviously quite different from those of a nuclear reactor. Many professional groups, trade associations and government agencies have established national codes and standards. However these codes and standards generally cover broad requirements , whereas a set of detailed rules for each product or class of products is required for the control of quality.

In most plants it is the responsibility of the quality assurance manager to interpret national codes and standards in terms of the purchase order and from these to devise process rules uniquely suited to the specific products and manufacturing methods used in that particular plant. The set of process rules thus devised may be known by various names: in these training notes it will be called an 'operating practice description'. There may be thousands of operating plant descriptions in plant files, each varying from the others as dictated code or customer requirements, limits on chemical composition or mechanical properties , or other special characteristics. Large plants may have computerised storage systems permitting immediate retrieval of part or all of the operating practice descriptions at key locations throughout the plant.

13.5.3. Written procedures

Written procedures are of prime importance in quality assurance. Oral instructions can be inadequately or incorrectly given and thus misunderstood and incorrectly followed. Clear and concise written instructions minimise the likelihood of misinterpretation.

Vague generalisations that do neither assign specific responsibilities nor determine accountability in case of error must be avoided. For instance, procedures should be specific regarding the type and form of inspection records, the identity of the individual who keeps the records, and where records are kept. Similarly a calibration procedure should not call for calibration at 'periodic intervals' but should specify maximum intervals between calibrations. Depending on the type of equipment , calibration may be performed at intervals ranging from a few hours to a year or more.

13.5.4. *Control of document flow*

The original purchase order, which is often less than one page in length, may generate hundreds of other working papers before the ordered material or part is shipped. All paperwork must be accurate and must reach each work station on time. In some industries where there may be an average of two or more specification or drawing changes per order, an effective system of material tracking that is separate and distinct from material identification is necessary

Control of document flow places direct responsibility on departments not usually associated with quality control. The sales office (which is responsible for entry of the customer order)

, the production planning group (which is responsible for scheduling work and tracking material) and the accounting department(which is responsible for billing and shipping) are all involved. Many large plants have computerised order systems, the heart of which is an 'active order file'. This computer file receives periodic inputs to update information on specifications, drawings, material sizes, shop operations, shipping and routing. In turn this file may be accessible from various terminals in the sales office, home office or plant, when information is needed on material location, order status and the like.

13.5.5. Maintaining identity and traceability of materials

In high speed manufacturing operations, particularly those involving hot work, identity markings on the raw material, such as paint marks, stencils or stamps, are usually destroyed during processing. In such instances , procedures must be devised for maintaining identity not by marking alone but also by location and count. These procedures sometimes must provide for traceability of individual units of products by a method suitable for the product and process and must include any additional identity that the customer may require. Ultimately both producer and customer must be confidant that the goods actually delivered are described accurately in the shipping papers , test reports and certificates of compliance. This confidence is of great importance in certain applications in the aerospace and nuclear industries.

13.5.6. Nonconforming material and corrective action

A system for detection and segregation of nonconforming material requires:

1. written inspection instructions that can be clearly understood;

2. identified, segregated holding areas for parts that have been rejected; and

3. a structured group (sometimes called a materials review board) to evaluate rejected material, make final judgment on its fitness for use , decide what is to be done with non-conforming material and prescribe corrective action for the cause of rejection.

In many instances rejected parts are only slightly out of tolerance and their usefulness is not impaired . Even so, all decisions of a materials review board to accept nonconforming material must be unanimous. (In the absence of unanimity, the problem may be referred to top management for a decision based on overall business judgment.) In some companies , the authority of the materials review board is limited to merely deciding whether or not nonconforming material is fit for use. However, in many companies the board also determines what is to be done with nonconforming lots-whether they are to be shipped 'as is', sorted, repaired or scrapped - and fixes the accountability for incurred losses. When corrective action is recommended by a materials review board, it is usually systems oriented - that is, intended to prevent recurrence of the nonconformity by avoiding its cause. In instances where a lot has been rejected because the acceptance number for a sampling plan has been exceeded, decisions concerning disposition of the lot often are made on the basis of costs, the solution that results in the least total cost to both producer and customer is adopted. Sometimes, material that is slightly out of tolerance and therefore not fit for use by one customer may meet the specifications of another customer.

13.5.7 Calibration of equipment

The quality assurance system must recognise that the accuracy and repeatability of measuring and testing equipment may be affected by continued use ; maximum intervals between calibrations should be specified in the written quality assurance procedures. Except perhaps for small hand instruments , such as micrometers, each testing machine or instrument should be plainly labelled with the last date of calibration. Calibration standards should be traceable to recognised industry or national standards of measurement. It is also desirable to maintain a central file of calibration records for each plant or department

13.5.8. Retention of records

A quality assurance system must designate which records are to be retained and must set down minimum time periods for retention of such records. It is usual for important documents to be retained for 25 years or more; the nuclear industry is required to maintain records for 40 years. Retention time , however, should be consistent with real needs as dictated by projected lifetime of products or by legal requirements. Besides satisfying certain contractual or other legal requirements , retained records can provide important cost benefits to both producer and customer. In one instance , extensive and costly testing of a 50 year old structure prior to repair was avoided when the fabricator was able to produce original drawings and material test reports.

13.5.9. Personnel training and qualification

National codes exist for the qualification of certain specialised workers , for instance welders and inspectors. When applicable, codes should be incorporated as minimum requirements for training and qualification of key personnel. All of these , however, must be supplemented by local written procedures for both on-the-job and classroom training. Quality assurance management must reduce complex procedures to the simplest form that will permit a trainee to understand exactly what the job is and how it is to be performed.

13.5.10. Control of purchased material

All specifications and orders for outside purchases of material whose performance may affect product quality should be subject to approval by quality assurance management. Inspection of incoming material should be incorporated into the quality assurance program. The main purpose of receiving inspection is to check for failures of vendor quality programs, but receiving inspection should not be expected to compensate for poor quality control by vendors. The purchaser should evaluate and periodically audit the quality assurance system of each major supplier to make sure that the purchased material can be expected to have the specified level of quality.

13.5.11. Periodic Audit (Quality Audit)

A periodic audit or quality audit of the system performance against written standards is needed to detect corner - cutting, noncompliance and intentional violations of established quality procedures. To be as unbiased as possible , such audits should be performed by persons not having responsibility in the area being audited. In companies having multiple plants , each individual plant may conduct its own internal audit , but in addition should be subject to audit by corporate staff personnel. The most important activities of corporate staff, aside from auditing, are review of the quality system with the highest level of plant management and follow up to approve corrective action for any discrepancies found during an audit.

Periodic review of the quality assurance system and reaffirmation of quality objectives by top management should be part of company policy. This will in part ensure long range viability of the business enterprise.

Quality audit

Definition. An independent evaluation of various aspects of quality performance to provide information with respect to that performance.

Quality audits are usually made .

- by companies to evaluate their own quality performance
- by buyers to evaluate the performance of their vendors
- by regulatory agencies to evaluate the performance of organisations which they are assigned to regulate

Purpose of audit to provide assurance that

procedures for attaining quality are such that if followed the intended quality will be obtained

- products are fit for use and safe for the user.
- laws and regulations are being followed.
- there is conformance to specifications.
- written procedures are adequate and are being followed.
- the data system is able to provide adequate information on quality.
- corrective action is being taken with respect to deficiencies.
- opportunities for improvements are identified.

For an internal quality audit typically the organisation is divided up into its component parts and each area is audited. The time taken depends on the size of the organisation. For a small NDT organisation one could audit the following

- documentation of NDT procedures
- control of stores
- receipt of job instructions
- purchasing of equipment and accessories
- maintenance of equipment and accessories
- calibration of equipment
- contract administration
- safety
- accounting
- office administration e.g. wages, leave, superannuation
- reports and records
- codes and standards
- organisational structure
- research and development

13.6. QUALITY CONTROL APPLICATIONS OF NON DESTRUCTIVE TESTING

Quality control of manufactured goods is accomplished by measuring dimensions, properties or other characteristics, comparing the measurements with predetermined standards and varying the manufacturing process as necessary to control these characteristics. Often direct measurements of characteristics can be accomplished only by destroying the parts. Obviously a product that has been destroyed cannot be sold. The commercial impact of this fact is two fold - costs were incurred to make the product, yet no profit can be made from its sale. However if the same information can be obtained without destroying the part , even if only as an indirect measurement, then the part can be sold for a profit after it has been tested. The commercial incentive to test non destructively is large when small quantities and large profit margins are involved and is crucial with one of a kind products.

Various methods have been developed for accurately and reliably measuring characteristics of parts without affecting their commercial value. Many of these are indirect methods , but they have gained wide acceptance as tools that can aid both management and production personnel in reducing costs and improving product quality. Also use of non destructive inspection has become necessary as a means of meeting certain legal and contractual requirements affecting the production and sale of a wide variety of manufactured products.

Factors that contribute to the reliable application of several of the major processes of non destructive inspection are considered later.

13.6.1 Quality of inspection

As with all production processes many quality consideration must be applied to the control of non destructive inspection processes to ensure that the information being supplied from them is accurate , timely and germane(i.e. relevant). One of the greatest problems of non destructive inspection has been misapplication which usually meant that the wrong information was supplied Thus non destructive inspection sometimes has had only limited usefulness as a production or technical tool. Also only when the capability of a non destructive process is known in quantitative terms can the inspection results be considered a measure of true product quality.

Successful application of non destructive methods to the inspection of manufactured goods requires that:

1. the test system and procedure be suited to both inspection objectives and types of flaws to be detected,

2. the operators have sufficient training and experience, and

3. the standard for acceptance appropriately defines the undesirable characteristics of a non conforming part.

If any of these prerequisites is not met , there is a potential for error in meeting quality objectives . For instance, with inappropriate equipment or with a poorly trained operator , gross errors are possible in detecting and characterising flaws . This is of particular concern if it means chronic failures to detect flaws that seriously impair service performance. With inadequate standards, flaws having little or no bearing on product performance may be deemed serious ,or significant flaws may be deemed unimportant.

It is necessary that the types of flaws that can be induced by each manufacturing operation are understood. only then is it practical to define the non destructive inspection that should be used. For instance, if a forging is inspected for internal forging cracks by radiography it is important to determine the direction of grain flow (and hence the most probable direction of cracking) because any cracks that are not aligned with the radiation beam will usually not be detected. Even when the direction of grain flow is known it may be difficult to orient the radiation beam properly but it is usually easy and effective to inspect the part ultrasonically.

As used in non destructive testing and quality control, the term 'defect' means a detectable lack of continuity or a detectable imperfection in a physical or dimensional attribute of a part. The fact that a part contains one or more flaws does not necessarily imply that the part is non conforming to specification or is unfit for use. Similarly the term ' non conforming ' means only that a part is deficient in one or more specialised characteristics. It should not be automatically assumed that a non conforming part is unfit for use. In many instances a non conforming part is entirely capable of performing its intended function even in its non conforming condition. In other instances a non conforming part can be reworked to make it conform to specifications. Of course sometimes a non conforming part can neither be used nor reworked and must be scrapped.

13.6.2. Human factors

Education of all levels of personnel engaged in non destructive inspection , including formal training and certification in accordance with government , technical society or industry standards, is probably the greatest single factor affecting the quality of non destructive inspection. All methods of non destructive inspection are highly dependent on operators for obtaining and interpreting data. Inadequate education of personnel jeopardises the reliability of inspection. This applies even to automated inspection which is controlled by the accept-reject criteria programmed into the process. Automatic data analysis techniques must be established, proven and monitored by competent non destructive inspection personnel. In general ,inspection should be performed by personnel who are trained to the national equivalent of ISO DIS 9712 Level 2 in the particular method being used. Supervisory personnel should have skill equivalent to ISO DIS 9712 Level 3.

The effects of human factors on the non destructive inspection process also must be considered. It has been found through independent statistical studies that different people have widely differing abilities to find all the flaws in a part, even when the same non destructive process and specific inspection procedure is used. This variability is usually more pronounced with small flaws. There is also a pronounced variation in the effect of factors such as heat, lighting , ventilation , fatigue and attitude on the performance of properly trained and qualified operators. As a result of these studies, confidence curves have been established showing the probability of detection versus defect size for each of the major non destructive inspection processes. Human factors should always be considered by the design engineer when setting maximum allowable defect sizes and by quality engineers when setting accept-reject criteria.

13.6.3. Acceptance limits

The setting of accept-reject criteria is important to the quality of non destructive inspection. Limits that are too strict unnecessarily increase both manufacturing and inspection costs, and often require special manufacturing techniques to meet the strict acceptability limits. Acceptance limits are usually indicated on the design drawing or specification. Often, however, these limits have been selected arbitrarily. It is a function of quality engineering to review acceptance criteria, ascertain that they are appropriate and can be met in production, and then approve them. It is often necessary, after production experience and reports of service usage have been obtained , to review acceptance limits to see if changes are needed. An acceptance limit that is too strict increases cost , but one that is too lax can contribute to failure to meet service requirements.

Fracture mechanics can be used to establish acceptance limits for critical parts , because it describes product performance in terms of the size of any flaws that might be present and can aid in establishing whether in service inspection is necessary. Fracture mechanics studies usually are undertaken only for critical parts because such studies are exacting and expensive. Inspection criteria should include probability/confidence limits for the inspection procedure because it is not the smallest defect that must be detected , but the largest defect that might be missed that ultimately determines the reliability of a part.

13.6.4. Inspection Standards

Inspection standards should be established so that decisions to accept, rework or scrap parts are based on the probable effect that a given defect will have on the service life or product safety. Once such standards are established non destructive inspection can characterise flaws in terms of a real effect rather than on an arbitrary basis that may impose useless or redundant quality requirements.

Most non destructive inspection methods rely on a reference standard to define acceptance limits or to estimate defect sizes. However there often is no recognised universal standard that can be used on diverse products or to satisfy varying inspection requirements of individual users. For instance, ultrasonic inspection is widely used to inspect adhesive - bonded structures, yet the variety of designs, materials and adhesives that are used do not permit a standard reference panel that is universally acceptable to be produced. Under normal circumstances , producer and consumer agree in advance as to the design of the reference standard and to the procedure for using it.

13.6.5. Effect of manufacturing operations

It is difficult to define the best point in a sequence of manufacturing operations at which inspection should be performed. Obviously, there should be some type of final inspection after all manufacturing operations have been completed . However, final inspection is often far from optimal as regards either quality of inspection or overall economy of manufacture In many instance it is easier, more reliable and more economical to perform limited inspection at each of several points in the manufacturing sequence rather than performing all inspection at the end of the sequence

In general, the principles listed below should be followed when choosing the point of inspection.

1. Inspect raw material for flaws that may have been missed by the supplier's inspection and that can interfere with manufacturing operations or will reduce performance of the finished part.

2. Perform intermediate inspection following each operation or series of operations that have a significant probability of introducing serious flaws.

3. Perform intermediate inspection when the part shape affords easiest access to the region to be examined.

4. Limit the extent of non destructive inspection to detection of flaws having a size , type and location that will significantly affect subsequent manufacturing operations or service performance.

5. Use different inspection methods to detect different types of flaws particularly when no single method yields an optimal balance between inspection costs and sensitivity to the various types of flaws that may be present.

6 Perform final non destructive inspection only to detect those flaws that could have been introduced after the last previous inspection or to serve as a check (audit) of intermediate inspection.

Characteristically, non destructive tests are easiest to perform and most effective when applied to incoming stock or at intermediate points in the manufacturing process rather than at final inspection. From the standpoint of manufacturing economy it is foolish to expend time and effort processing parts that already contain flaws that exceed allowable limits. Consequently it is desirable to find non conforming parts and remove them from the normal process flow as soon as possible after the non conformance is introduced. Of course, each set of operations will be different from all others and each situation should be studied to determine where in the manufacturing sequence non conformance can be detected with greatest effectiveness and least cost. Points of greatest effectiveness may not coincide with points of least cost so trade offs to achieve optimal balance may have to be made. In some instances, a highly sensitive non destructive test method cannot be economically justified. Usually a less costly method can be substituted but with an accompanying reduction in sensitivity.

13.6.6. *Quality Manuals*

A Quality Manual is a document which lays down the basic policies and principles on which the Inspection Group functions and provides the coordinating links with the other more detailed collections of operating procedures , resource information and data upon which the Inspection Group's quality depends. It is a working document describing the reality of the group's operations for use by both management and staff.

Typical elements of a Quality Manual are:

1. Table of contents
2. Amendment of records
3. Introduction
4. Management of quality system
5. Description of group and its function
6. Staff
7. Equipment
8. Testing environment
9. Test methods
10. Operational procedure
11. Control of test items
12. Test records
13. Diagnostic and corrective actions
14. Test reports
15. Subcontracting
16. Occupational health and safety
17. Propriety rights and confidentiality
18. Accreditations held

14. ORGANISATION AND ADMINISTRATION OF NDT

The responsibilities of the owner or manager of an NDT company are:

14.1. RESPONSIBILITY FOR FINANCIAL STABILITY

Primarily the manager has to be concerned about the profitability of his company. To achieve that he must have a complete understanding of his operating costs so that he knows the direct cost of every job he undertakes and how to apportion his indirect costs as an overhead to every job. A cost analysis has to be carried out to determine the total cost of a service or product.

14.1.1. Cost accounting

Total cost comprises three elements:

i) Material cost, i) Labour costs (wages), and ici) Expenses i.e. the cost of services provided including the notional cost of owned assets.

Each of these elements can be further divided into two parts :
i) Direct costs, *and* i) Indirect costs.

Direct costs are those costs which can be identified as having been directly incurred in carrying out an inspection on behalf of a client and can therefore be allocated directly to a cost unit or cost centre. Indirect costs cannot be conveniently allocated (i.e. directly charged) but can be apportioned or absorbed by cost units or cost centres. Indirect expenses are known as 'Overheads' or 'On Costs'. These overheads may be divided on a functional basis. For example, in the case of a company manufacturing a product as (1) Works at Factory costs, (2) Administration and office costs, (3) Selling costs , and (4) Distribution costs.

The total cost can be tabulated as follows:

Total costs

Direct costs
Indirect costs (overheads)

Direct Materials
Direct Labour
Direct Expenses
Indirect Materials
Indirect Labour
Indirect Expenses

Manufacturing Expenses
Adm. Expenses
Selling Expenses
Distribution Expenses

14.1.1.1. Direct Materials

Raw materials , semi finished materials or components which become part of a product are known as ' direct materials . ' They go into the product e.g.cloth in garments, timber in furniture, leather in shoes, pig iron in a foundry, spare parts and components of assembled products such as cycles, radios, cars etc. It also includes primary packing materials such as cartons, polystyrene foam, adhesive tape, staples etc. However if a material forms part of a product but is of negligible value , it may be treated as ' indirect material'. The cost of direct materials includes not only invoices but also expenses directly incurred in acquiring them, such as carriage inward, customs duty, clearing charges etc. Where it is not practical or convenient to charge these purchase expenses to direct materials, they may be included as production overheads.

14.1.1.2. Direct Labour

All labour expended in construction or altering or shipping a product may be regarded as ' direct labour' and remuneration paid to it as ' direct wages '. This includes the time workers engaged in actual production or in carrying out an operation or a process It does not include services of attendants, servicemen, supervisors etc. However if the time is spent by a supervisor or inspector on a particular job it may be treated as direct labour. Any direct labour cost which is insignificant such as trainees may be considered as indirect labour.

14.1.1.3. Direct Expenses or Chargeable Expenses

These are expenses other than direct labour which are specifically incurred for a product or process. These expenses are:

(1) Hire charges, repairs and maintenance of special equipment hired for a job,(2) Cost of special drawings, designs, moulds and patterns (3) Experimental expenses of a job (4) Cost of special process required for a job (5) Cost of defective work in trial projects related to a job (6) Excise duty (7) Royalties, and (8) Travel expenses connected to a job.

14.1.1.4. Overheads

Overheads are the aggregate of indirect material, indirect labour and indirect expenses.

14.1.1.5. Indirect Materials

Materials which do not form part of a product are indirect materials, e.g. consumable stores, lubricants, cotton waste, chemicals added in the production process, stores required by service and maintenance departments. The direct material which is of very small value may also be treated as ' indirect material ' e.g. thread in dress, nails in wooden box etc. Costs of indirect materials cannot be allocated to cost units but are apportioned on some equitable basis.

14.1.1.6. Indirect Labour

Wages paid to persons who facilitate or assist the direct labour in a manufacturing process are known as ' indirect labour costs '. Examples are services of supervisor, inspectors, instructors, repairers and servicemen, stores personnel, drawing office personnel, clerks and typists in the office, service department personnel, trainees, apprentices, time office staff, etc. Indirect wages are apportioned on the basis of the benefit received indirectly by cost centres.

14.1.1.7. Indirect Expenses

These include expenses which cannot be allocated but can be apportioned to or absorbed by cost units, such as rent, tax, depreciation on buildings and furniture, insurance, welfare expenses, depreciation on plant and machinery, power and fuel, advertising, show room expenses, research and development expenses, office expenses etc.

Overheads are analysed and grouped into:

1) Production overheads
2) Administration overheads
3) Selling and distribution overheads

Again when marginal costing principles are to be applied they are subdivided into

1) Fixed overheads
2) Semi-fixed overheads
3) Variable overheads

14.1.1.8. Cost Sheet

A cost sheet or a statement of cost is prepared to present total costs by different stages. A typical cost sheet could be:

	Total cost	per unit cost
Direct material consumed	*	*
Direct wages	*	*
Direct expenses	*	*
	--------	--------
Prime cost	*	*
Add Factory overheads	*	*
	--------	--------
Works cost	*	*
Add Admin. overheads	*	*
	--------	--------
Cost of production	*	*
Add selling and distribution overheads	*	*
	--------	--------
Cost of sales	*	*

14.1.1.9. Methods of collecting and presenting costs

The methods of collecting and presenting costs vary with the type of production to be costed. The methods employed fall into two groups:

a) Specific Order Costing

1) Job costing
2) Batch costing
3) Contract costing

b) Operation costing

1) Process costing
2) Service costing

The basic costing method adopted thus depends on the nature of activity being carried out by the organisation. Given this basic method there is then a choice open as to the way in which the information is to be presented for control purposes. ' Marginal costing' may be employed or ' actual costs may be ascertained and variance accounting may be adopted.

14.1.1.10. Example of simplified costing of NET test

Cost of equipment including installation charge	*
Operating crew Level 1	*
Level 2	*
Power consumption	*
Direct expenses	*

Calculation of total cost

1 (a) Wages	*
(b) Power	*
(c) Consumables	*
(d) Repairs and maintenance	*

Prime cost	*

Add Factory overheads	
Depreciation @ 5%(?)	*
Share of factory expenses(salary, lighting, rent etc.)	*
Return on investment @ 10%(?)	*

Works cost	*
Add Admin. overheads @ 1% of cost of equipment	*
(Distributed on the operating hours available)	*

Cost of production	*
Add selling and distribution overheads	*

TOTAL COST	*

The total cost per annum divided by the anticipated annual production gives the unit cost of ultrasonic testing e.g. cost per film, cost per hour of ultrasonic testing etc.

14.2. RESPONSIBILITY FOR SAFETY

He is responsible for the safety of his staff and of the public. This means that he must be aware of and implement:

- Government regulations with regard to hygiene, buildings, scaffolding, use of radioactive equipment, use of electrical equipment, etc.
- Proper care and handling of hazardous materials(toxic and inflammable).
- Provision and use of safety equipment.

14.3. RESPONSIBILITY FOR PLANNING

He must identify his short term and long term aims and objectives e.g. is he going to specialise in only one type of NET or cover all methods, specialise in only one industry or try to be general. What does he want his organisation to be doing in 1 year's time, 5 year's time ,10 year's time etc. What is the market place doing i.e. trends which can give him business opportunities. What staff does he have ? What are their strengths and weaknesses ? Is training required or will he steal staff from other organisations when required?

14.4. RESPONSIBILITY FOR ORGANISATION

He is responsible for effective management systems leading to locating work, costing and submitting bids, programming work(staff, equipment), ensuring successful completion, correct reporting, correct invoicing , ensuring payment of all accounts, chasing bad debts , buying new equipment, carrying out research and development to produce new test procedures, hiring and firing of staff, maintaining equipment, conducting quality audits, exercising technical control,etc.

14.5. RESPONSIBILITY FOR QUALITY ASSURANCE MANUAL

He is responsible for the development of the Quality Assurance Manual for his organisation. This Manual should

- detail all the policies ,procedures and practices of the organisation and give cross references to other organisation documents.

- be a working document for all his staff.

- contain instructions for its own review and updating as practices or policies change.

- be the basis for self audit of the organisation by management.

- describe procedures for training staff and monitoring their performance

- describe the job duties , authority and responsibilities of each of the key technical and managerial positions in the staff structure .

- describe procedures for monitoring the validity of results produced by new staff or by new techniques.

- detail the recording and reporting system so that there is a traceable link between the test and the report to allow repeatability.

- indicate which calibration records must be kept and by whom. For example , records of
    - UT equipment
    - UT probes
    - intensity of black light
    - colour intensity of penetrants
    - efficiency of used emulsifiers

- system checks with reference testpieces

- state who is responsible for check viewing of radiographs and how many radiographs have to be checked and where the result of the check is recorded. e.g.
    - repetitive work -2% checked
    - general jobbing work - 20% checked

- state who is responsible for visits to site to check ultrasonic work and where the records of the visits have to be recorded.

- *state who is responsible for checks on developer strength and temperature.*

- state who is responsible for checks for compliance with the sensitivity requirements of codes.

- state who is responsible for routine checks of the field strength in magnetic particle testing using portable flux indicators or magnetic field meters.

14.6 RESPONSIBILITY FOR TEST METHOD MANUAL AND FOR ENSURING THAT TEST METHODS ARE FOLLOWED

The Test Method Manual should contain copies of all standard test procedures. In addition all staff performing a test must have a copy of the relevant code, standard or test procedure and procedures must be followed exactly. Any modifications to standard procedures are only acceptable if the effects of the modifications have been documented and can be justified technically. Any variations must be noted and acknowledged in test documents. Procedures must also be in place to update codes and standards.

Any internal test procedures, procedures which are not covered by codes, must be documented and verified.

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