

# ULTRASONIC TESTING OF STEEL CASTINGS

by

**J . D . Lavender**

**Research Manager. Quality Assurance Group**

**Steel Castings Research & Trade Association  
Sheffield. England**

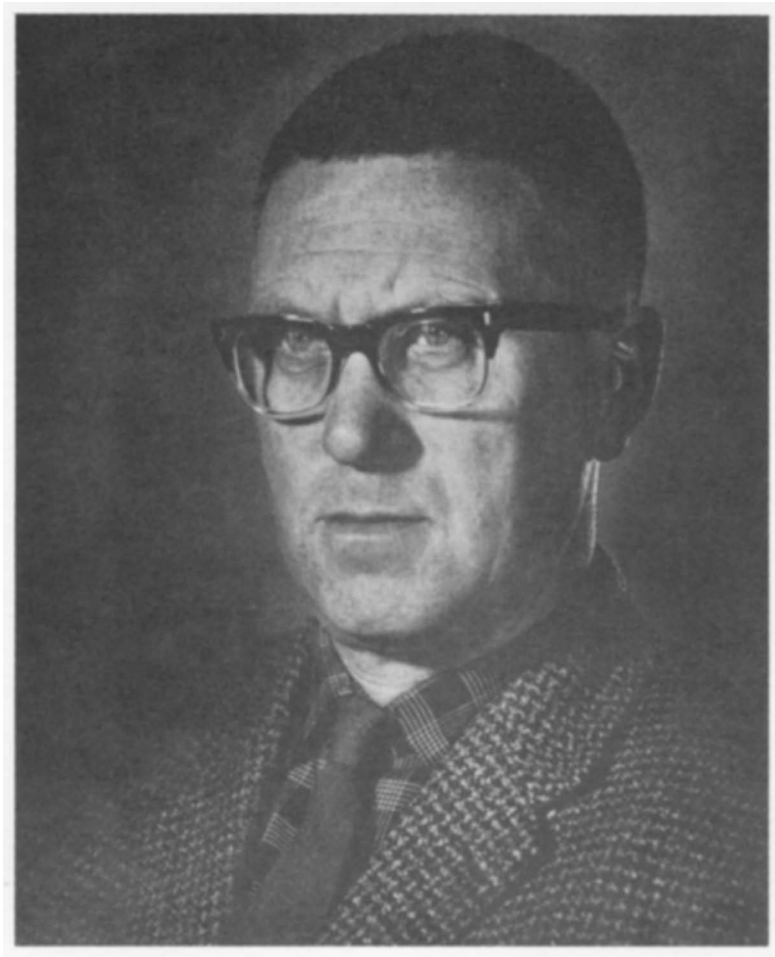
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J. D. Lavender was educated at Ecclesfield Grammar School, Nr. Sheffield. He received the Associateship of the Institution of Metallurgists in 1954 and became a Fellow in 1972. He is a member of the Institute of Physics and of the British Institute of Nondestructive Testing. He was employed by Brown-Firth Research Laboratories from 1940 to 1946 on radiography of non-ferrous and ferrous alloys, X-ray crystallography and metallography of low and high alloy steels.

In 1954 he became foundry metallurgist with Firth-Vickers Stainless Steels in Sheffield, and in 1957 moved to the Steel Castings Research and Trade Association (S.C.R.A.T.A.) as a senior investigator of nondestructive testing. He was made section head in 1964 and research manager of quality assurance in 1972. Mr. Lavender has presented the S.C.R.A.T.A. Exchange Lecture at the National Technical and Operating Conference of the Steel Founders' Society of America in 1969 and 1975.

## PREFACE

Ultrasonic flaw detection is a method of non-destructive testing that is finding increasing acceptance in the United States. This growth in the application of ultrasonics is intimately tied to the field of fracture mechanics and the scientifically based approaches to designing against failure. Ultrasonic flaw detection, as opposed to the more widely used radiography, permits the inspector to pinpoint accurately the location of the flaw and to determine its shape and size. These factors play an important role in fracture mechanics where the maximum safe stresses can be calculated for a given flaw size and location. Conversely, for a given flaw type, size and operating stress field, the maximum flaw size that can be tolerated safely can be determined. Thus the unique ability of ultrasonic inspection to assess flaw location and flaw geometry is vital to engineering approaches of fracture-safe design.

Further insight into the growth of nondestructive testing is gained by a historical review of developments. Radiography was developed early and achieved industrial status when a set of radiographs called, "Gamma Ray Radiographic Standards for Steam Pressure Service" was issued in 1938 by the Bureau of Engineering, U.S. Navy. Numerous ASTM specifications relative to radiography in steel casting production have been issued since then. Ultrasonics, in contrast, received its first major boost towards industrial application for steel castings in Britain when a study on its use and development possibilities was undertaken in 1958. ASTM specification A-609, "Standard Specification for Longitudinal Beam Ultrasonic Inspection of Carbon & Low Alloy Steel Castings"

was published in 1970. This specification was followed in 1974 by the ASME Boiler & Pressure Vessel Code, Section V, T524.2, "Angle Beam Examination of Steel Castings." Other specifications of international importance are the Westinghouse Specification 600964, "Ultrasonic Testing of Steel Castings," and the Central Electricity Generating Board United Kingdom Standard 66011, "Turbine Castings (chromium, molybdenum, vanadium steel) ."

Increased acceptance and utilization of ultrasonic inspection are to be expected for the future. These trends are apparent from the extensive activity going on now in the United States and abroad. Three standards, in addition to ASTM A-609, are currently considered. These are the British ISO Standard-"Draft Proposal for an International Standard for the Ultrasonic Inspection of Steel Castings," the German standard-"Introduction of Ultrasonic Testing and Standards and General Conditions of Delivery for Steel Castings," and a new proposed ASTM specification which will be similar to Westinghouse Specification 600964.

This booklet is published to present basic information on the nature of ultrasonic inspection principles with specific guidelines on flaw detection in steel castings. This information and the favorable economic aspects of flaw detection by ultrasonic means are presented for technical personnel and managers of casting producers and particularly the technical staff of casting users who control the level to which ultrasonic inspection will find acceptance in the future.

**PETER F. WIESER**

Research Director

By direction of the  
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H. J. SHEPPARD, Chairman

A. G. LINLEY

F. H. HOHN

L. H. LONG, JR

P. J. NEFF

A. J. WHITTLE

R. A. MILLER

# THEORY OF ULTRASONIC FLAW DETECTION

## THE CHARACTERISTICS OF SOUND WAVES

Sound is produced when a body vibrates and is propagated only within a medium. Sound waves are classified in terms of frequency, which is the number of vibrations per second or Hertz; the frequency scale relating the sonic and ultrasonic ranges is shown in Fig. 1.

The basic formula, to which reference is made throughout the whole study of ultrasonic examination, is:

$$c = f \times \lambda$$

where  $c$  = velocity, mm/s

$f$  = frequency, Hz

$\lambda$  = wavelength, mm

The relationship between frequency and wavelength for the transmission of ultrasonic waves in steel is given in Fig. 2.

Sound waves must have a medium in which to travel and the velocities with which they are transmitted through a particular medium depends on its elastic constants and on its density, as given by the following formulae:

Thin rod velocity -

$$c = \sqrt{\frac{E}{\rho}}$$

Longitudinal wave velocity

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

Transverse wave velocity

$$c = \left[ \frac{E}{\rho} \frac{(1)}{2(1 + \sigma)} \right]^{1/2} \sqrt{\frac{G}{\rho}}$$

where

$c$  = wave velocity, mm/s

$E$  = Young's modulus of elasticity, dynes/mm<sup>2</sup>

$G$  = shear modulus of elasticity, dynes/mm<sup>2</sup>

$\rho$  = density, g/mm<sup>3</sup>

$\sigma$  = Poisson's ratio

Values of sound velocity, density and acoustic impedance of materials associated with ultrasonic examination are given in Table I. The wavelengths of longitudinal and transverse waves in steel are given in Table II.

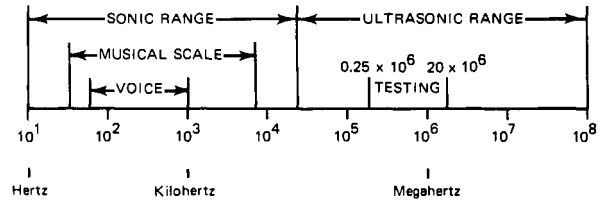


Figure 1—Frequency scale relating the sonic and ultrasonic ranges, Hertz.

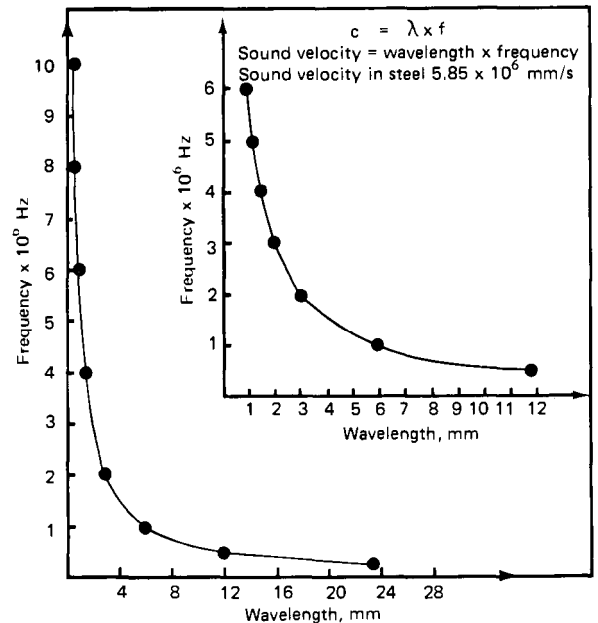


Figure 2—Relationship between frequency and wavelength for the transmission of ultrasonic waves in steel.

TABLE I  
Values of Wavelength in Steel for  
Acoustic Impedance for a Number of Media

Material	Sound velocity (longitudinal) mm/s x 10 <sup>3</sup> (C)	Density gm/mm <sup>3</sup> x 10 <sup>-3</sup> (ρ)	Acoustic impedance c.g.s. units x 10 <sup>4</sup> (ρC.)
Steel	5.85	7.8	4.56
Oil	1.38	0.92	0.127
Water	1.49	1.0	0.149
Air	0.33	0.0013	0.000043
Glycerine	1.90	1.26	0.239
Plexiglass	2.70	1.20	0.324

**TABLE II**

**Values of Wavelength in Steel for Longitudinal and Transverse Waves**

Longitudinal wave velocity, $5.85 \times 10^3$ mm/s		
Transverse wave velocity, $3.23 \times 10^3$ mm/s		
Frequency, MHz	Wavelength, mm	
	Longitudinal	Transverse
$\frac{1}{2}$	11.6	6.5
$1\frac{1}{4}$	4.7	2.6
$2\frac{1}{2}$	2.3	1.3
5	1.2	0.6

**TYPES OF ULTRASONIC WAVES**

There are two wave types normally associated with ultrasonic examination :

- Longitudinal waves (Fig. 3).
- Transverse waves (Fig. 4).

The longitudinal waves are produced by a voltage applied to a piezo-electric transducer. The mechanical vibrations produced are related to this voltage, and are propagated as ultrasonic waves.

Transverse waves are normally obtained by initially producing longitudinal waves which are then refracted in accordance with Snell's Law as they pass from a Plexiglass wedge into the steel. The design of the Plexiglass wedge, which forms part of the probe, is such that the longitudinal wave does not enter the specimen. Fig. 5 shows the conversions which occur when a longitudinal wave is transmitted from one isotropic medium (A) into a second isotropic medium (B).

**PRODUCTION OF ULTRASONIC WAVES**

There are two main types of transducers which are used to produce ultrasonic vibrations :

- Naturally occurring, or artificially produced anisotropic single crystals, e.g. quartz, lithium sulphate, Rochelle salt.
- Ceramics, e.g. barium titanate, lead zirconate.

These transducers are frail and must therefore be placed in a suitable housing which incorporates a voltage lead, a suitable backing material to damp mechanical vibration, and a sturdy cover to protect the whole device.

This device is called a probe; several probes are illustrated in Figs. 6, 7 and 8.

**COUPLANTS**

In order to transmit ultrasonic energy efficiently into the specimen, the probe must be coupled to the casting surface by means of a liquid, e.g. glycerine, oil, grease, water.

The reflected energy which arises when a longitudinal wave meets a boundary between two media is a function of their relative acoustic impedances ( $\rho_1 c_1$  and  $\rho_2 c_2$  where  $\rho$ =density and  $c$ =sound velocity). The amount of energy reflected at a boundary is given by the formula (restricted to longitudinal waves, normal to the boundary).

$$R = R_0 \left[ \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \right]^2$$

where  $R$  = the reflected energy  
 $R_0$  = the incident energy

Typical values of  $\rho.c.$  are given in Table I. The use of values of  $\rho.c.$  in this formula shows that at an air/steel interface, 100 % of the ultrasonic energy is reflected, while 88% is reflected at a water/steel interface.

**GEOMETRY OF THE ULTRASONIC BEAM**

In order to use the probes for flaw detection, a pulse of sound waves from the probe must be transmitted at regular intervals through the steel ; the time intervals between successive pulses must be long in comparison with the time taken for the echoes to return to the probe.

The ultrasonic beam, which is produced as each pulse of energy is supplied to the transducer, has a certain geometry. This geometry, which covers the beam spread and the near and far zones, is dependent on the ultrasonic frequency, the transducer diameter and on the way in which the transducer is damped.

- Beam spread

The solid angle of beam spread  $2\theta$  at 10% of maximum axial intensity is given by the formula

$$\sin \theta = \frac{1.22\lambda}{D}$$

where  $\theta$  = half the angle of beam spread, degrees  
 $\lambda$  = wavelength, mm  
 $D$  = transducer diameter, mm

The above formula applies only to the far zone. The relationship between beam spread and frequency for 10, 15, and 23 mm diameter probes is given in Fig. 9. The maximum intensity of the beam lies on the axis and decreases rapidly with increase in angle from the probe axis; with further increase in angle, alternate maximum and minimum intensity values occur, which are called side lobes, Fig. 10.

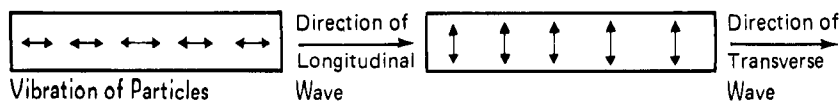
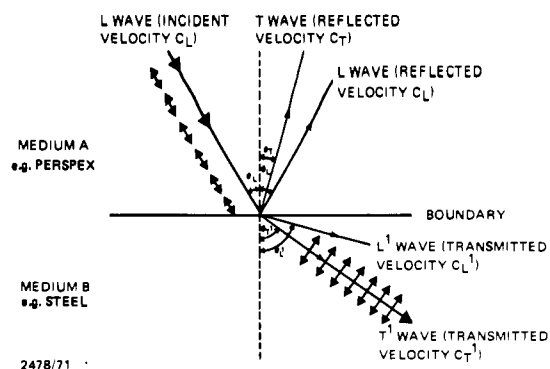


Figure 3—Longitudinal waves.

Figure 4—Transverse waves.



$$\text{Snell's Law} \\ \frac{\sin \theta_L}{C_L} = \frac{\sin \theta_T}{C_T} = \frac{\sin \theta_{L'}}{C_{L'}}$$

$C_L$  = Velocity of longitudinal wave in medium A  
 $C_T$  = Velocity of transverse wave in medium A  
 $\theta_L$  = Angle of incidence longitudinal wave A  
 $\theta_T$  = Angle of reflection transverse wave A  
 $\theta_{L'}$  = Angle of refraction longitudinal wave B  
 $\theta_{T'}$  = Angle of refraction transverse wave B  
 $C_{L'}$  = Velocity of longitudinal wave in medium B  
 $C_{T'}$  = Velocity of transverse wave medium B

Figure 5—Conversions occurring when a longitudinal wave is transmitted between two isotropic media.

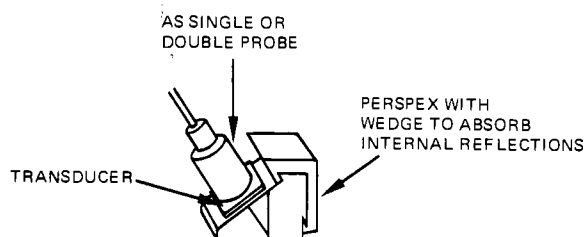


Figure 6—Construction of a longitudinal wave probe (single or double).

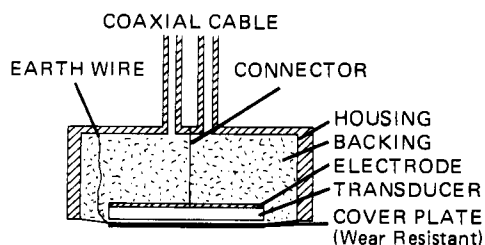


Figure 7—Combined double longitudinal wave probe.

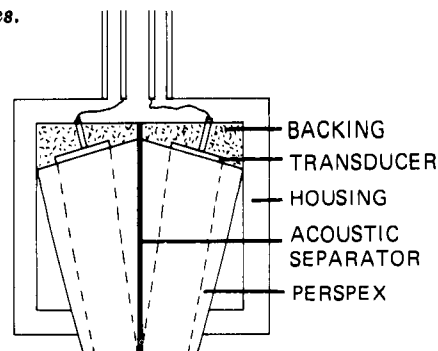


Figure 8—Transverse wave probe.

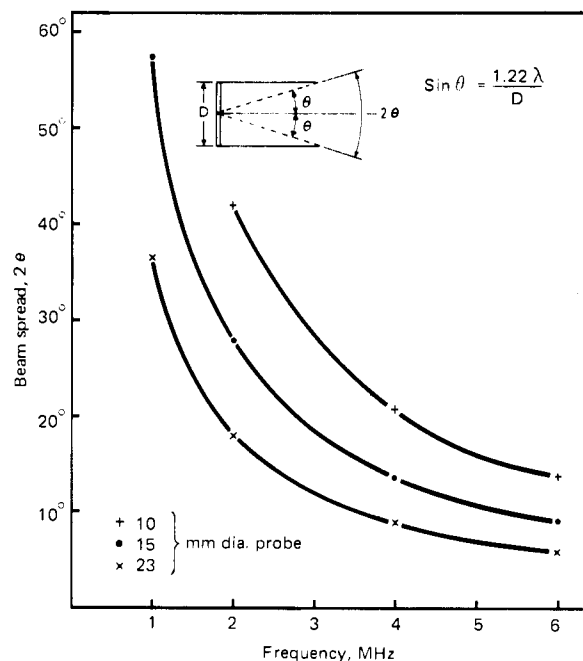


Figure 9—Relationship between frequency, probe diameter and beam spread in steel.

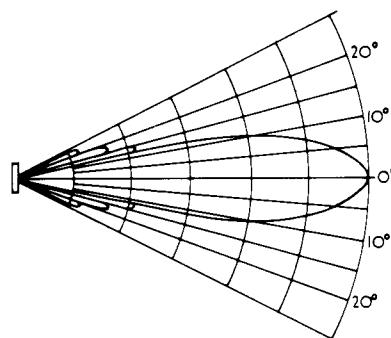


Figure 10—Polar diagram illustrating beam spread and ultrasonic intensity.

(b) Near zone; transition zone; far zone

The complex variations in sound intensity which occur close to the transducer cause interference effects. This interference is confined to the near zone, in which the beam is essentially parallel. Note that the near zone is affected by the Plexi-glass block, shear and combined double probes. The near zone is defined by a distance N, beyond which the beam diverges:

$$N = \frac{D^2}{4\lambda} \text{ mm}$$

where D = transducer diameter, mm  
λ = wavelength, mm

This relationship for a number of media is plotted in Figs. 11a and 11b. In the far zone, the intensity of the beam follows the inverse square law. A diagrammatic representation of the variation in intensity within the near and far zones is given in Fig. 12; a transition zone separates these two zones.

The interference and variation of intensity within the near zone makes flaw size estimation impossible and such measurements should only be made in the far zone: Claydon has carried out extensive work on this problem.

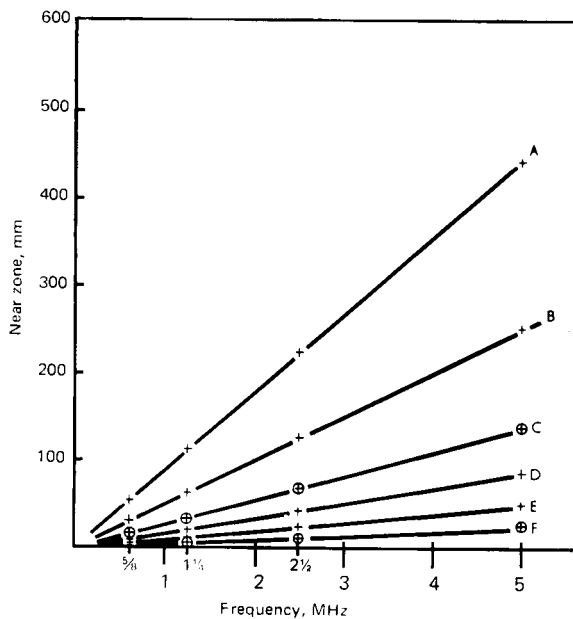


Figure 11a—Relationship between frequency and near zone for two probe diameters in water, plexiglass and steel.

- A Near zone in water, 23mm probe
- B Near zone in plexiglass, 23mm probe
- C Near zone in steel, 23mm probe
- D Near zone in water, 10mm probe
- E Near zone in plexiglass, 10mm probe
- F Near zone in steel, 10mm probe

$$N = \frac{D^2}{4\lambda}$$

N = Near zone, mm  
D = Probe diameter, mm  
λ = Wavelength, mm

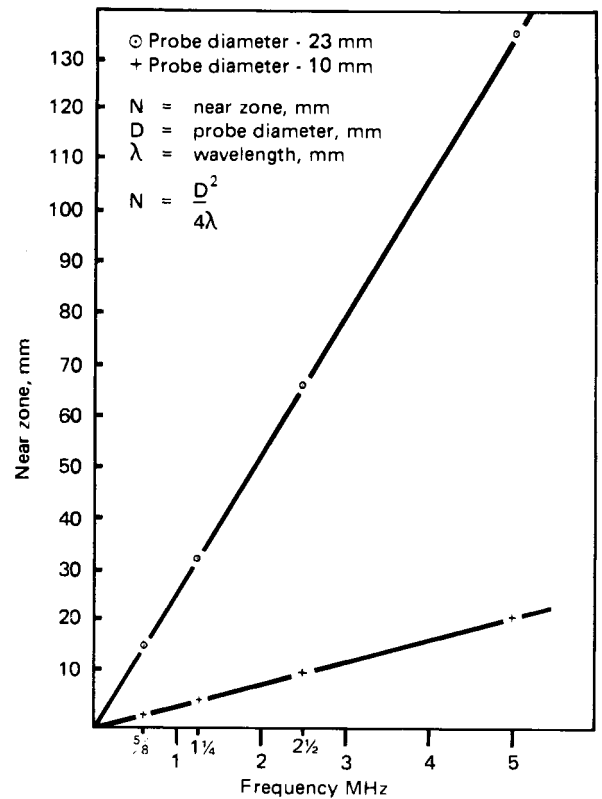


Figure 11b—Relationship between frequency and near zone in cast steel for two probe diameters.

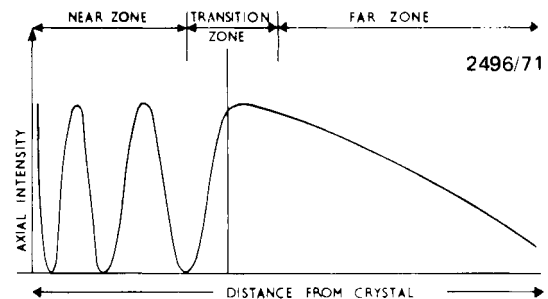


Figure 12—Variation in intensity within the near and far zones.

# CALIBRATION OF THE ULTRASONIC INSTRUMENT

## CALIBRATION AND REFERENCE BLOCKS

Ultrasonic instruments and their probe systems are not built to a universally recognized specification. In order to have a means of comparing the probe and instrument characteristics, it is advisable to use one or more reference blocks to calibrate the instrument (Fig. 13). This calibration is particularly important under working conditions to ensure that the correct sensitivity levels are maintained. It may also be an advantage to prepare additional reference blocks of thickness, shape and surface finish appropriate to the needs of the operator.

## LONGITUDINAL WAVE PROBES

The first operation (Figs. 14a-d) is used for steel thickness measurements between 0 and 200 mm and automatically sets the initial pulse at the zero point on the screen. It is necessary to re-calibrate each longitudinal wave probe for the zero point in a similar manner.

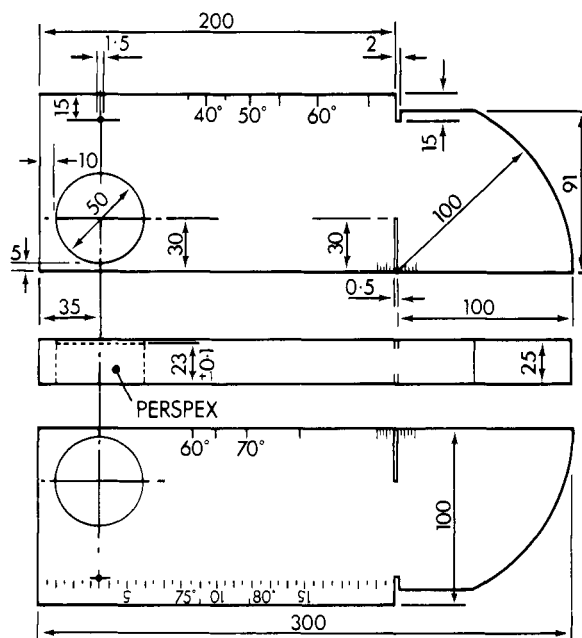
### 1. Calibration of the time base in terms of steel thickness

The probe is placed in position A on the test block and by controlled movement of the horizontal shift (or delay if no horizontal shift is provided) and the fine time base control, a series of echoes are obtained at the screen positions of 25, 50, 75 and 100 scale divisions (Fig. 14a). These movements of the two instrument controls automatically set the zero point. If the echoes will not coincide with appropriate scale divisions, the time base is not linear and a graphical calibration should be prepared, or the supplier of the instrument approached if the error is excessive.

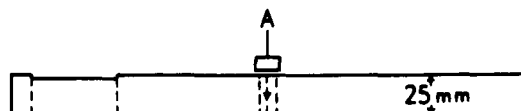
The following operations (Figs. 14b-14d) may require adjustment of the time base and other controls.

For greater accuracy in the range of less than 10 mm, a 4-5 MHz probe should be used, because a higher frequency probe has a smaller dead zone. Place the probe in positions D and E, as shown in Figures 14d and 14e.

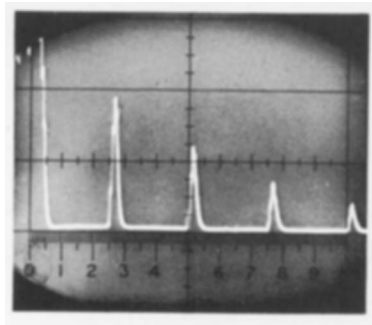
*Figure 14a—Position of Probe A gives 0-100mm thickness range, 25 subdivisions on the screen scale represent 25mm of steel thickness.*



*Figure 13—A2—calibration block BS.2704:1966 (all measurements in mm) (Perspex = Plexiglass).*



Position of probe A gives the 0-100mm thickness range.





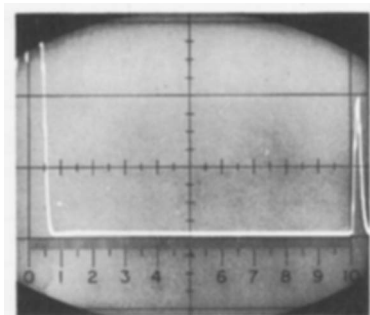
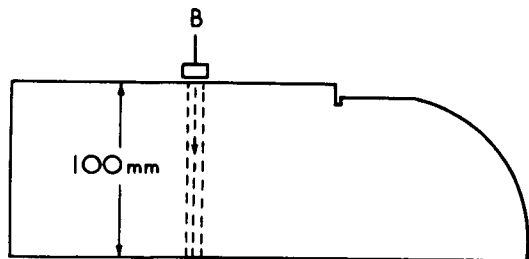


Figure 14b—Position of Probe B is a check on the performance described in 14a. 100 subdivisions on the screen represent 100mm steel thickness.

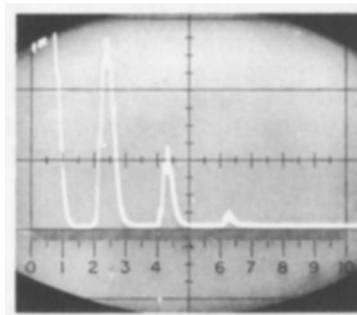
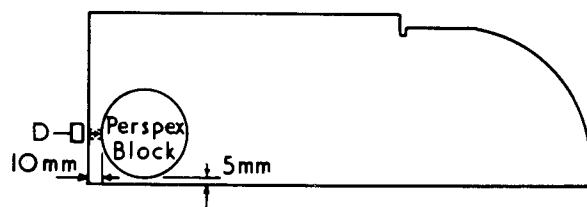


Figure 14d—Probe D gives the 10mm thickness range, 20 screen subdivisions represent 10mm of steel thickness (Perspex=Plexiglass).

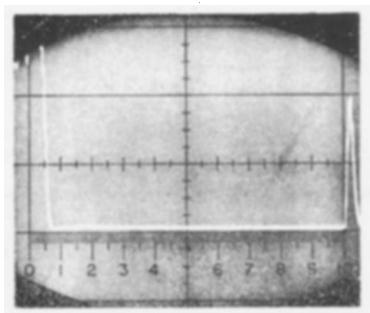
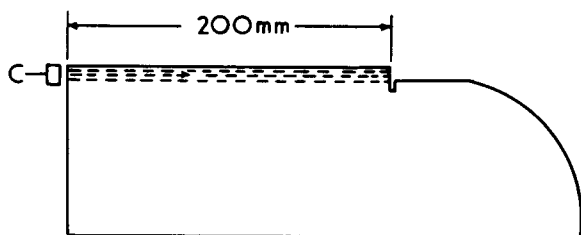


Figure 14c—Position of probe C gives the 0-200mm thickness range. 100 screen subdivisions represent 200mm of steel thickness.

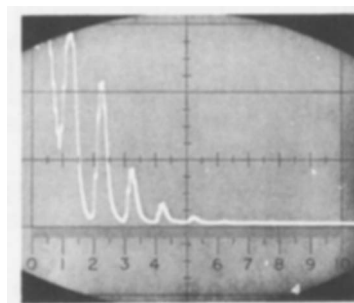
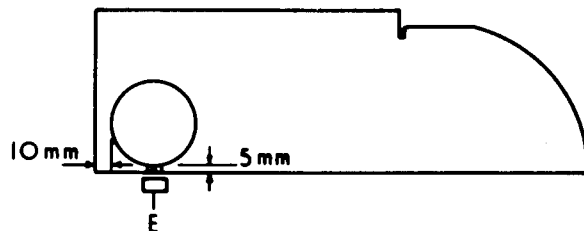


Figure 14e—Probe E gives a check on the probe in position A, 10 screen subdivisions represent 5mm steel thickness.

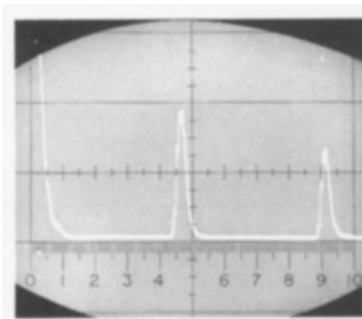
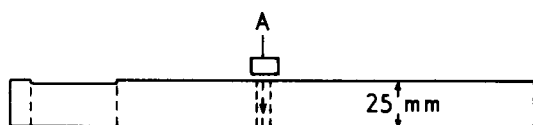


Figure 14f—Position A gives multiple echoes from the bottom surface.

## 2. Check on linearity of amplifier

The amplification is linear when the ratio of the height of any two consecutive echoes remains constant when the degree of sensitivity is altered (Fig. 14f). A quantitative value of amplifier linearity may be determined and reference should be made to BS.4331: Part 1: 1968.

In order to ensure that an apparatus has adequate penetrating power, operation 3 (a) should be carried out.

## 3. Assessment of-

### (a) Penetrating power

The sensitivity control is set at a minimum and the probe placed on the metallized surface of the Plexiglass block (Fig. 15a). The thickness of the Plexiglass is calculated to correspond to 50 mm of steel. A measure of the penetrating power can then be obtained by slowly increasing the sensitivity control to a maximum and noting the number of bottom echoes which appear. A low penetrating power apparatus may only give 2-4 bottom echoes, a high penetrating power apparatus 6 - 10 bottom echoes.

### (b) Relative sensitivity

The sensitivity control is initially set at a minimum and the probe moved until an echo from the 1.5 mm diameter hole is obtained on the screen. The height of this echo at a given setting of the sensitivity control constitutes a relative measure of sensitivity (Fig. 15b).

The dead zone, which is dependent on the instrument and probe characteristics, should be assessed for each probe, since flaw indications cannot be received in this zone.

## 4. Check of the dead zone

The distance from the probe to the Plexiglass at positions D and E is 10 mm and 5 mm, respectively. The ability to see one or both of these echoes is a measure of the dead zone (Figs. 16a, b).

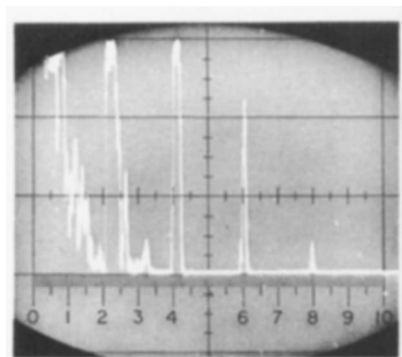
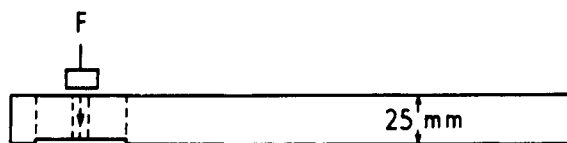


Figure 15a—Multiple echoes appear when the probe is placed on the metallized surface of the plexiglass (e.g. 4 echoes as shown here).

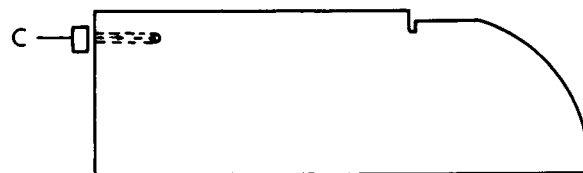


Figure 15b—Probe in position C will give an echo from 1.5mm hole.

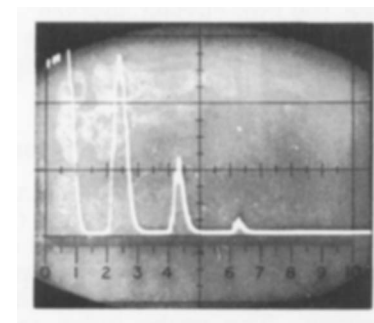
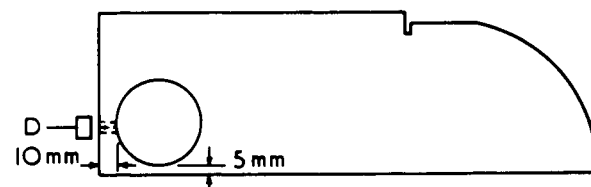


Figure 16a—A clear indication, absence of echoes, upon placing probe in position D, indicates a dead zone of 10mm length.

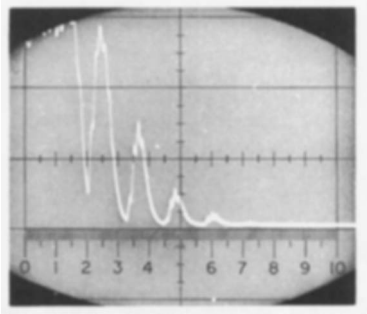
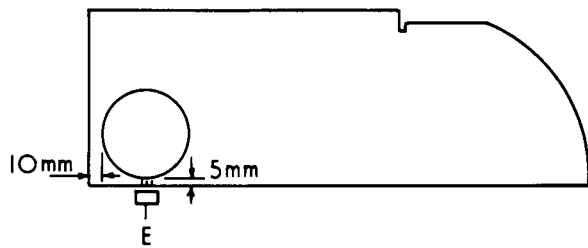


Figure 16b—Blurred indication, upon placing the probe in position E, indicates a dead zone length of 5mm.

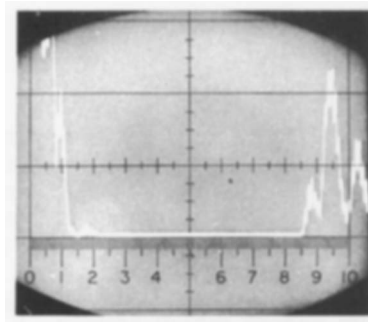
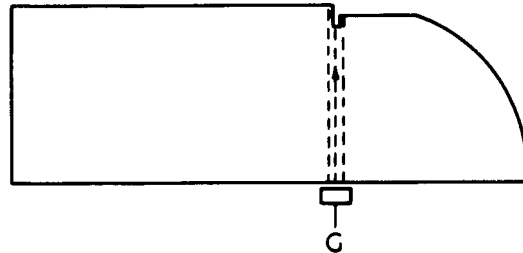


Figure 17a—Trace obtained from probe position G showing bad resolving power,  $1\frac{1}{4}$  MHz

## 5. Check on the resolving power

The probe is moved in order to obtain 3 bottom echoes at 85, 91 and 100 divisions (Figs. 17a and b). Three separate echoes on the screen will indicate a probe system with good resolving power ; when the echoes are not separate, but merge together giving a blurred effect, the equipment is said to have bad resolution. A quantitative value of resolution may be determined and reference should be made to BS.4331:Part 1:1968.

## TRANSVERSE WAVE PROBES

The first three of the following operations are essential because the probe index and the beam spread must be found by practical measurement and not assumed to be correct from probe markings and theoretical considerations. The results can then be used for the assessment and location of flaws.

### 1. Determination of probe index

The probe index is given on the probe ; in order to check that the position marked on the probe is correct, place the probe in position H (Fig. 18). Move the probe until maximum amplitude is received from the 100 mm curved surface. The central mark on the graduated scale will be the position at which the beam leaves the Plexiglass and enters the steel, i.e. the probe index.

### 2. Determination of the angle of refraction

Move the probe until maximum signal amplitude is obtained from the Plexiglass cylinder (Fig. 19). The reference block has calibrated scales engraved at  $40-70^\circ$  and the relevant angle of refraction marked on the probe should coincide with the correct scale position. The probe index which has been previously determined should be marked on the probe in order to obtain the correct results.

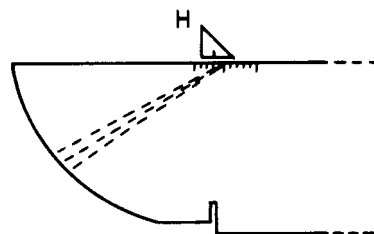


Figure 18—Probe H in position to determine probe index.

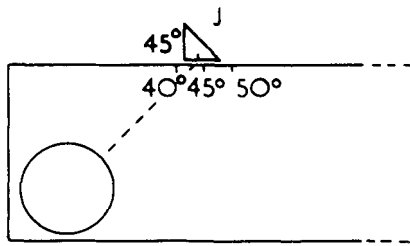


Figure 19—Probe J in position to determine the angle of refraction.

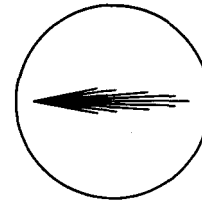
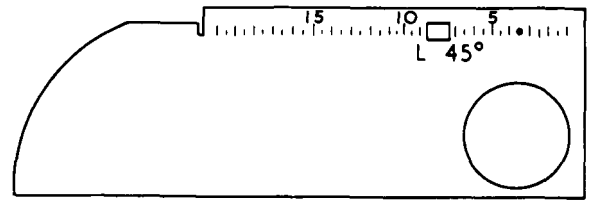


Figure 21—Position probe at position L to plot a horizontal polar diagram.

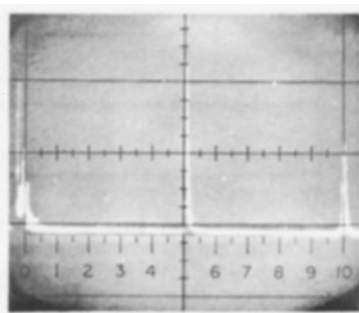
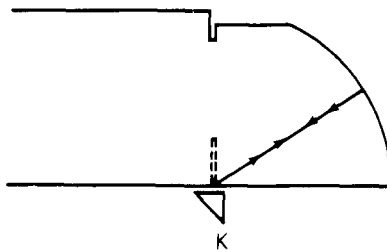


Figure 20—Position probe at K to find the zero point of the trace for a shear wave probe. 50 subdivisions on the screen represent 100mm of steel thickness.

### 3. Correction of the zero point

The presence of the Plexiglass in the transverse wave probe causes a time lag between the moment at which the signal leaves the transducer and the moment it leaves the wedge. This time lag must be corrected for and the zero point set on the cathode ray screen. Obtain an echo at a maximum amplitude on the screen from 100 mm radius (Fig. 20). Adjust the echo by movement of the horizontal shift and the fine time base control in order to obtain two echoes on the screen at 50 subdivisions and 100 subdivisions; the zero on the scale will then correspond to the moment the beam leaves the Plexiglass wedge.

It is necessary to recalibrate each transverse wave probe for the zero point in a similar manner.

A beam plot is used to verify the position of the beam in a cast section. It is used in conjunction with a second Plexiglass slide on which a drawing is produced showing the geometric shape of the component. Flaw size, shape and position may be assessed using this method, and reference should be made to the Test Procedure. The above method may also be used to assess the beam spread from both single and combined double probes. A horizontal polar diagram is shown in Fig. 21.

The scale on this part of the block is calibrated every 25 mm and the hole diameter is 1.5 mm. Obtain an echo on the screen by placing the probe at a suitable distance from the hole, e.g. for a 45° angle probe, the distance would be 25 mm. Rotate the probe from one side to the other and note the echo amplitude at various angles of probe position. A horizontal polar diagram can be plotted, as previously described. It is suggested that in order to plot a more accurate diagram, a similar check should be carried out at multiples of a given distance.

#### 4. Assessment of sensitivity

Obtain an echo at a convenient height on the screen by placing the probe 25 mm away from the 1.5 mm hole (Fig. 22). Move the probe back 50, 75 and 100 mm away from the hole and note the new echo amplitude. Note that to carry out a similar measurement using a 70° probe, the above figures, excepting the diameter of the hole, must be multiplied by 2.75. For a 60° probe the figures must be multiplied by 2.

The sensitivity of the equipment can now be specified in terms of echo height and distance from the 1.5 mm hole.

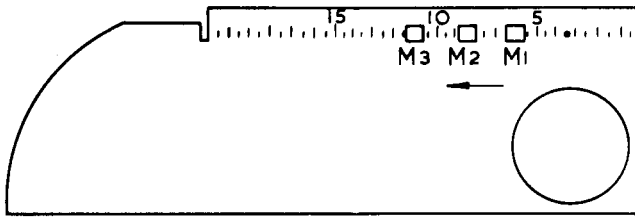


Figure 22—Move the probe from  $M_1$  to  $M_2$  to  $M_3$  in order to assess instrument severity.

#### MEASUREMENT OF STEEL THICKNESS

Ultrasonics, using longitudinal waves and conventional flaw detection equipment, can readily be used for thickness measurement. A frequency range of 2-5 MHz is recommended.

The accuracy of the technique, which should be of the order of 2 - 5% steel thickness, depends on two main factors:

- (a) the surface roughness, and
- (b) whether or not the two surfaces are parallel. The value of 2 - 5% accuracy will fall off where steel thicknesses less than 6mm are to be measured.

The first technique which is described is the one recommended by the Procedure and may be used with any ultrasonic instrument provided the instrument is correctly calibrated.

##### 1. Direct calibration method

This technique is widely used because of its simplicity, and depends on the time base linearity of the instrument. It consists of initially calibrating the instrument on the A2 calibration block (Fig. 13), details of which are given in the preceding pages under the heading, Calibration of the Time Base in Terms of Steel Thickness.

Once this operation is complete, a check may be made by the use of the B.S.C.R.A. reference block, ignoring the echo from the drilled hole. A rule

measurement in two directions on this block can be directly related to the position of each bottom echo on the graduated cathode ray screen.

The next two techniques (2 and 3) are specific to certain types of equipment.

##### 2. The "resonance" method

In this technique, a unit attached to the ultrasonic equipment enables a pulse at a continuously variable repetition frequency to be transmitted into the specimen. From the received signal, the thickness of material can be obtained.

##### 3. The use of a calibrated time marker

This technique depends on two factors, firstly, a linear time base on the instrument and, secondly, the sound velocity of the longitudinal wave in the material. Since this sound velocity is a variable factor, the method is not recommended, but is described in order to illustrate the use of the "time marker."

For a given material, the distance on the screen between the initial pulse and the reference echo, or between consecutive reference echoes, represents the time interval for the pulse to travel the total distance from the transducer to the bottom of the material and back to the transducer. Certain commercial instruments have a calibrated time marker circuit coupled to the time base, which enables accurate time measurements to be made.

The thickness of the material is then calculated from the formula:

$$s = v \times t$$

$$s = \text{thickness, mm}$$

$$v = \text{sound velocity, mm/sec}$$

$$t = \text{time interval, sec}$$

$$\begin{aligned} \text{e.g. number of bottom echoes} &= 6 \\ \text{number of time markers} &= 20 \end{aligned}$$

Assume the marker time interval is 5 micro seconds (1 micro second =  $10^{-6}$  seconds). The total time for sound to travel 12 times the steel thickness is therefore 100 micro seconds.

$$\begin{aligned} \text{Time required to travel the thickness of the material} &= 100/12 \text{ micro seconds} \\ &= 8.33 \text{ micro seconds} \end{aligned}$$

$$\begin{aligned} \text{Velocity of longitudinal wave} &= 5.85 \times 10^6 \text{ mm/sec}^* \\ s &= v \times t \\ s &= (5.85 \times 10^6) (8.33 \times 10^{-6}) \text{ mm} \\ s &= 48.7 \text{ mm} \end{aligned}$$

$$\begin{aligned} \therefore \text{thickness of material} &= 48.7 \text{ mm} \end{aligned}$$

Reference is also made to ultrasonic thickness measuring devices, but direct reading methods using conventional flaw detection equipment is to be preferred.

\* In order to obtain correct results, this method requires accurate knowledge of the velocity of sound in the material undergoing testing.

# FORMATION OF CASTING DEFECTS

## ULTRASONIC AND RADIOGRAPHIC CORRELATION

The use of non-destructive testing for the examination of steel castings has increased considerably during the past few years. The most striking advance has been in the application of ultrasonic examination as a quality control technique in the steel foundry. Ultrasonic examination to assess the presence and nature of internal flaws in steel castings has many advantages over radiography, these including such factors as capital and running costs, safety in operation, portability and, a most important point, ultrasonic examination is independent of section thickness. The Atlas of Some Steel Castings Flaws, therefore, places a particular emphasis on the use of ultrasonics for the detection of casting flaws. Its purpose is to illustrate and describe typical casting flaws and discuss how they may be detected by ultrasonics. In order to clarify the ultrasonic indications, appropriate radiographs, micro-sections, and diagrams have been included.

Ultrasonic examination requires an experienced operator to obtain the maximum economic benefits. It is essential that the operator be given every facility so that he can estimate the possible location of flaws before carrying out an examination, i.e. he should be provided with a drawing showing location of feeder heads, gating systems, etc. and should have all the information on the history of the casting.

### FLAWS DUE TO INADEQUATE FEEDING (SHRINKAGE FLAWS)

#### 1. Description of flaws

Shrinkage flaws are cavities formed during solidification, which occur as a result of liquid to solid contraction. The flaws are not normally associated with gas but a high gas content will magnify their extent.

Shrinkage flaws may occur in steel castings where there is a localized variation in section thickness; they may, however, occur in parallel sections where penetration of the liquid feed metal is difficult. The shrinkage flaws which occur in steel castings may be considered as falling into three types, namely :

- (a) Macro-shrinkage
- (b) Filamentary shrinkage
- (c) Micro-shrinkage

#### (a) Macro-shrinkage

A large cavity formed during solidification is referred to as a macro-shrinkage flaw. The most common type of this flaw is piping, which occurs due to lack of sufficient feed metal. In good design, piping is restricted to the feeder head.

#### (b) Filamentary shrinkage

This is a coarse form of shrinkage but of smaller physical dimensions than a macro-shrinkage cavity. The cavities may often be extensive, branching and interconnected. Occasionally the flaw may be dendritic. Theoretically, filamentary shrinkage should occur along the center line of the section but this is not always the case and on some occasions it does extend to the casting surface. Extension to the casting surface may be facilitated by the presence of pin or worm holes.

#### (c) Micro-shrinkage

This is a very fine form of filamentary shrinkage due to shrinkage or gas evolution during solidification. The cavities occur either at the grain boundaries, (intercrystalline shrinkage), or between the dendrite arms (interdendritic shrinkage).

Typical locations at which shrinkage cavities are most likely to occur are illustrated in Fig. 23. Localized changes of section thickness represent hot spots which cannot be fed adequately in most cases. Shrinkage cavities will form, therefore, unless special precautions are taken. In-

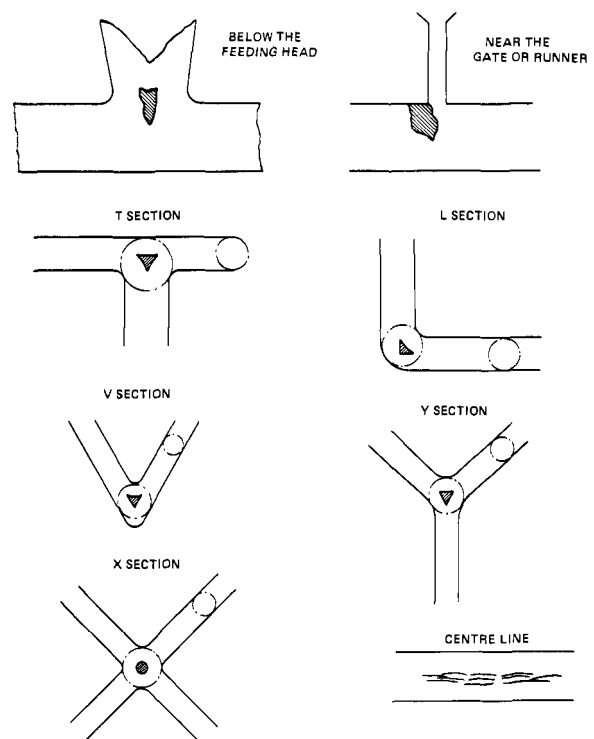


Figure 23—Formation of shrinkage flaws.

scribing circles in the junction and in the adjacent sections, and determining the ratio of the circle diameters, provides a relative measure of the hot spot severity and hence susceptibility to shrinkage formation. If the technique is applied to L, T, V, and Y sections, it will be seen that crosses and acute angle junctions are to be avoided in favor of T and L junctions.

## 2. Detection of flaws

### (a) Macro-shrinkage

The technique used for the detection of this flaw is dependent on the casting section thickness. Where the section exceeds 3 inches a normal single probe is satisfactory, while for section thicknesses of less than 3 inches it is advisable to use a combined double probe. The presence of the flaw is shown by a complete loss in back wall echo, together with the appearance of a new flaw echo. The position of the flaw echo on the oscilloscope screen indicates the depth of the flaw below the surface. An angle probe should be used to confirm the results obtained from the scan using a normal probe.

### (b) Filamentary shrinkage

The presence of filamentary shrinkage is best detected with a combined double probe if the section thickness is less than 3 inches. The flaw echoes which are obtained reveal the extent of the flaw and also the flaw depth. It is suggested that an initial scan on expansive rough surfaces is best carried out with a large combined double probe (say 23 mm in diameter); final assessment and flaw depth measurement are achieved by a small diameter combined double probe (say 10 - 15 mm in diameter).

### (c) Micro-shrinkage

A fine "grass" type of oscilloscope indication is typical of this flaw. The extent to which the flaw occurs may be assessed by a consideration of the number of back wall echoes which occur at any given frequency. Where it is difficult to obtain one or a number of back wall echoes at 4 - 5 MHz due to random scattering of the ultrasonic beam, and since this could give the impression of a large cavity type of flaw, it is advisable to reduce the frequency to 1 - 2 MHz. This reduction in frequency will indicate that no large cavity does in fact exist if a back wall echo can be obtained.

## FLAWS ASSOCIATED WITH HINDERED CONTRACTION DURING COOLING

### 1. Description of flaws

#### (a) Hot tears

These are cracks which are discontinuous and generally of a ragged form, resulting from stresses developed near the solidification temperature when the metal is weak. The stresses arise when the contraction is restrained by a mold or

core or by an already solid thinner section. Typical examples are illustrated in Fig. 24. Hot tears occur at or near to changes in section, e.g. re-entrant angles and joints between sections. They are not fully continuous and commonly exist in groups, often terminating at the surface of the casting.

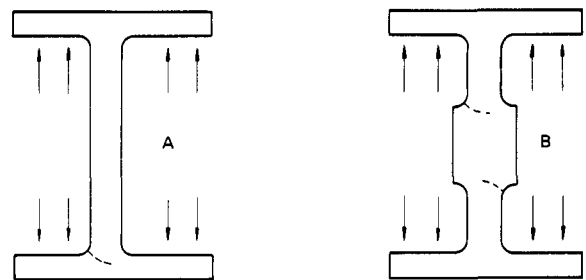
### (b) Cracks or stress cracks

These are well defined and approximately straight cracks formed when the metal is completely solid. They are revealed as clearly defined, smooth, dark lines.

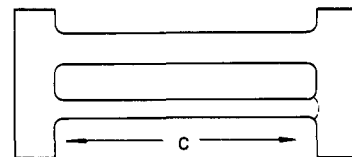
## 2. Detection of flaws

### (a) Hot tears and cracks

The location of a hot tear can rarely be determined accurately using a normal probe because of the orientation of the flaw. The most satisfactory technique is the use of a transverse wave probe. Since the tears usually exist in groups, the extent is assessed by passing the beam underneath the flaw (Fig. 25). The location of a hot tear is found most easily by magnetic crack detection and its depth by the ultrasonic angle probe. A cold crack may be detected in a similar manner (Fig. 26).



HOT TEAR DUE TO MOULD RESISTANCE ALONG DIRECTIONS A & B



HOT TEAR DUE TO CASTING RESISTANCE ALONG LENGTH C



HOT TEAR DUE TO CHANGE IN SECTION D

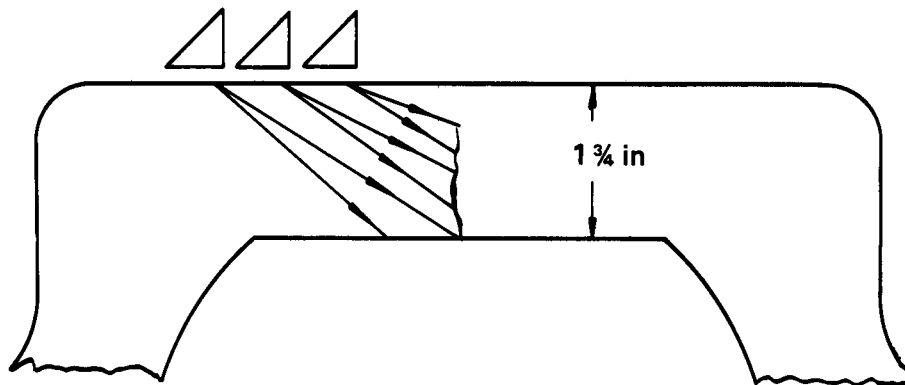
Figure 24—Formation of hot tear flaws.



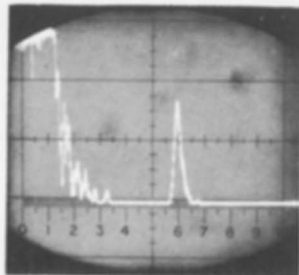
Oil Refinery Casting



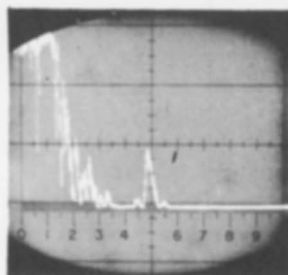
Transverse wave probe placed for examination



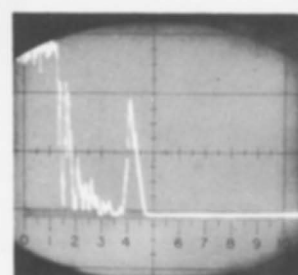
Direction of ultrasonic beam  
15 mm diameter 2½ Mc/s transverse wave probe



Trace showing  
echo from the  
base of the crack  
1 div. = ¼ in steel



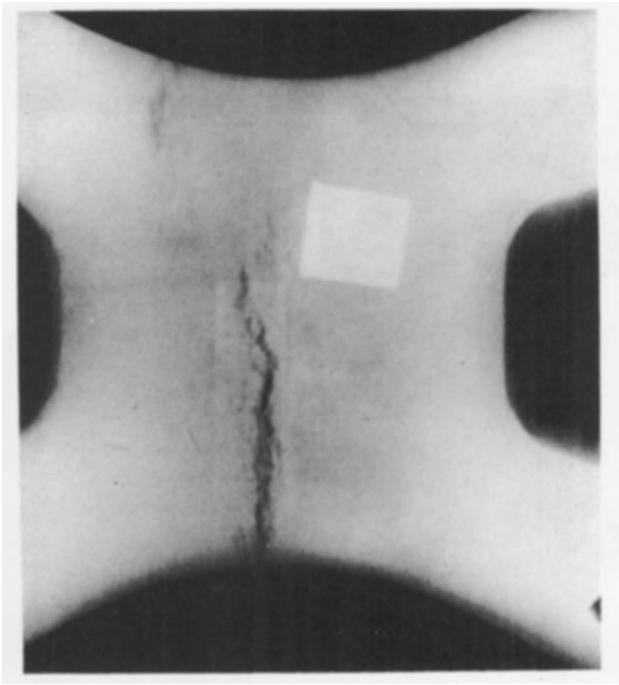
Trace showing  
echo on the  
crack



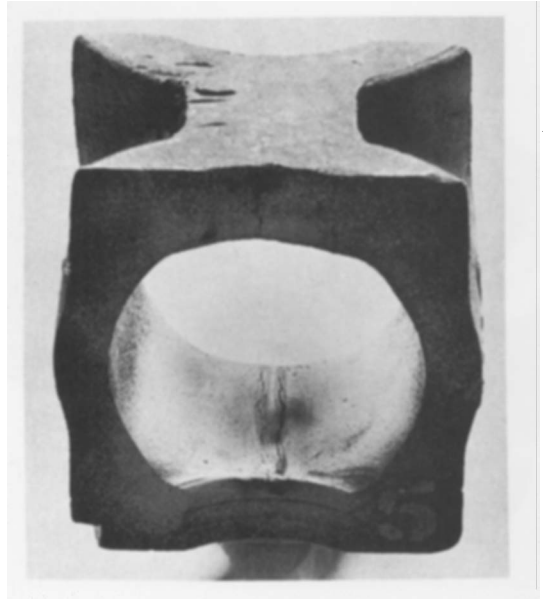
Trace showing  
echo near the  
top of the flaw

Figure 25a—Hot tear (Mc/s=MHz)



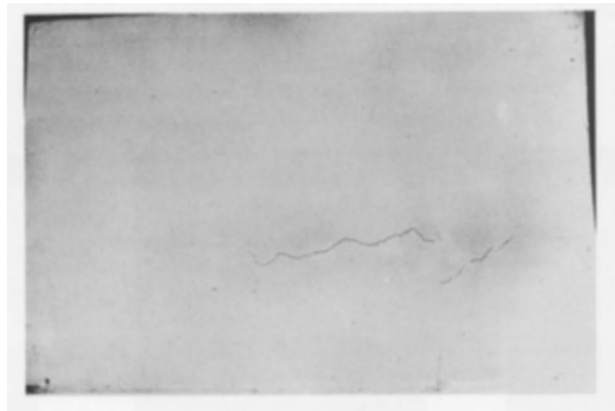


Radiograph showing hot tear resulting from stresses developed near the solidification temperature

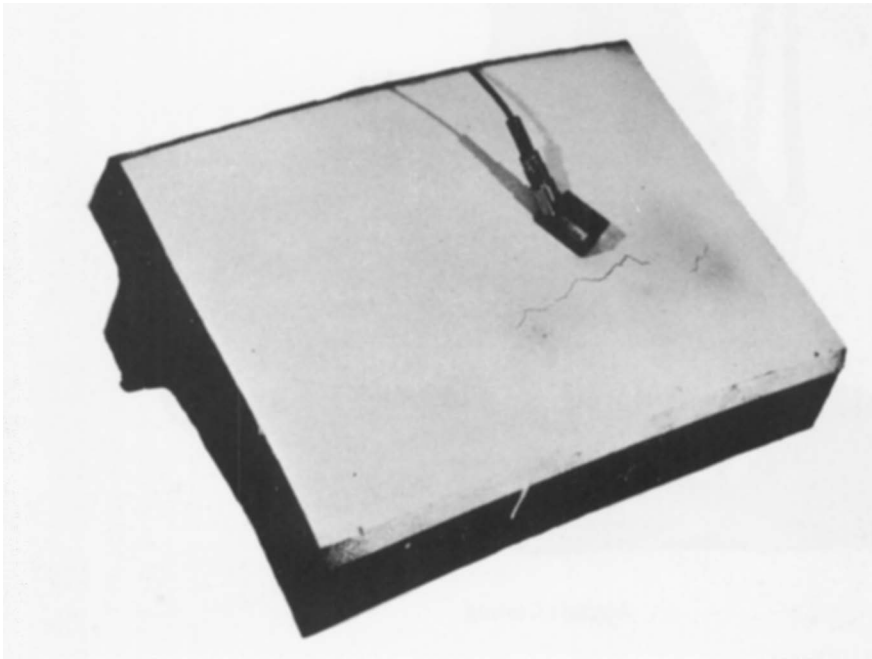


Section showing hot tear revealed by magnetic crack detection

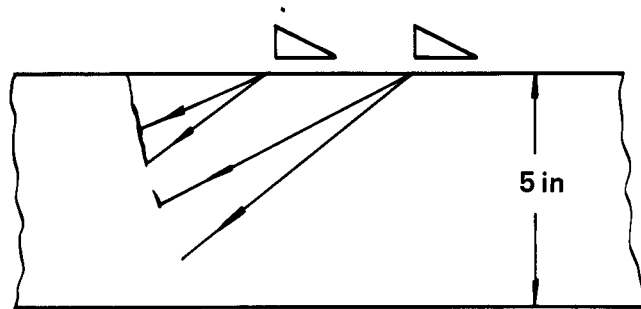
*Figure 25b—Hot tear (cont'd)*



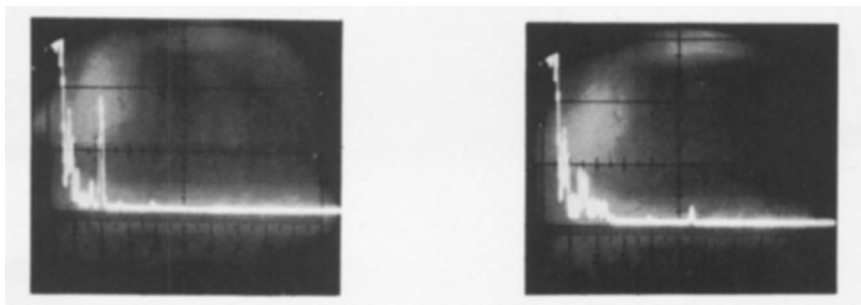
*Figure 26b—Crack (cont'd)*  
Crack revealed by magnetic crack detection



Section from a Large Roller Bearing  
Transverse wave probe placed for examination



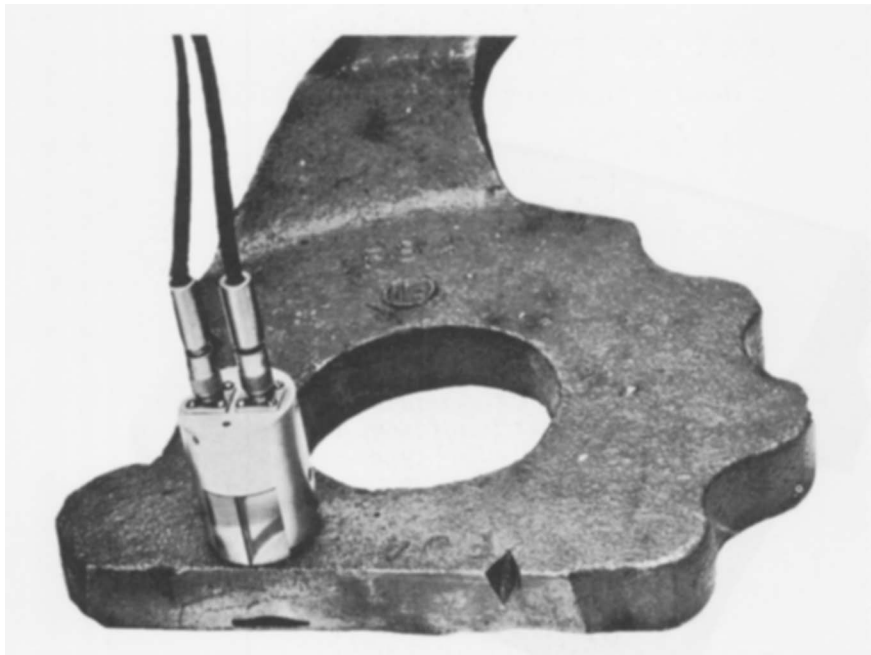
Direction of ultrasonic beam  
23 mm diameter 2½ Mc/s 70° transverse wave probe



Trace showing  
flaw is close  
to surface  
1 div. = ¼ in steel

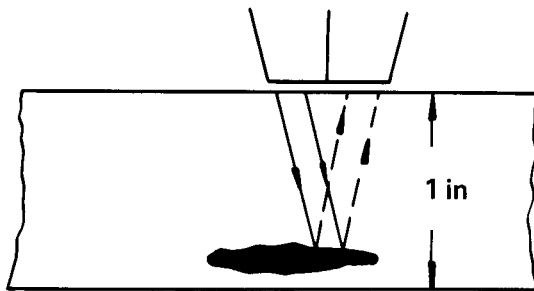
Trace showing the  
bottom of the flaw,  
its depth may be  
calculated after  
calibration on a  
reference block

*Figure 26a—Crack*

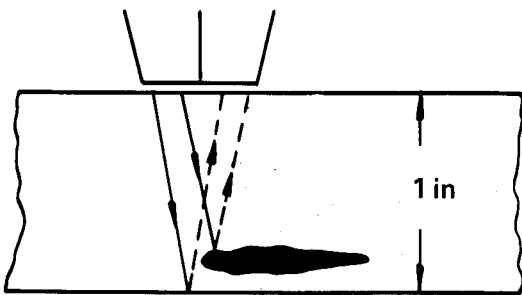
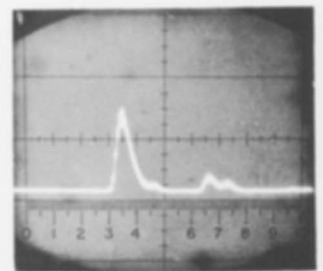


Aircraft Casting

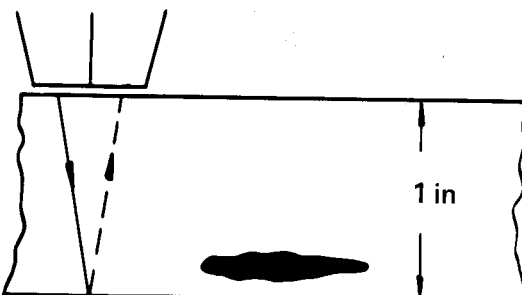
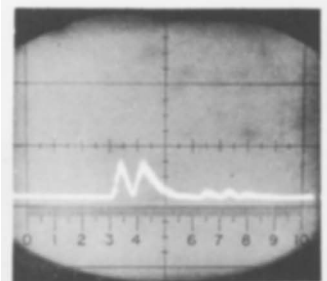
Direction of ultrasonic beam  
23 mm diameter 2½ Mc/s combined double probe



Trace showing  
flaw echo, no  
back wall echo,  
a large flaw



Trace showing  
appearance of  
large flaw ¾ in  
below top surface  
and reduced back  
wall echo



Trace showing  
2 back echoes  
indicating sound  
material  
1 div. = ¼ in steel.

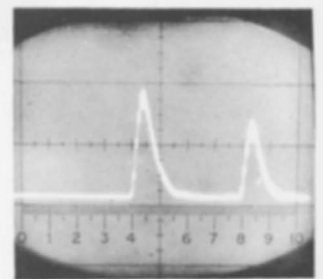


Figure 27a—Large airlock

## FLAWS DUE TO GAS AND ENTRAPPED AIR

### 1. Description of flaws

#### (a) Airlocks

When molten metal is poured into a mold, air may be entrained in the metal stream which may appear in the subsequent casting as a cavity or several cavities just below and parallel to the casting surface.

#### (b) Gas holes

These flaws are discrete cavities usually greater than 1/16 inch diameter, which are caused by the evolution of dissolved gases from the metal during solidification. A particular type of gas hole is a blow hole, which is due to gas evolved from the mold or core rather than the metal. A wormhole is another form of gas hole, which occurs as a tube-like cavity usually normal to the casting surface and almost extends to the surface.

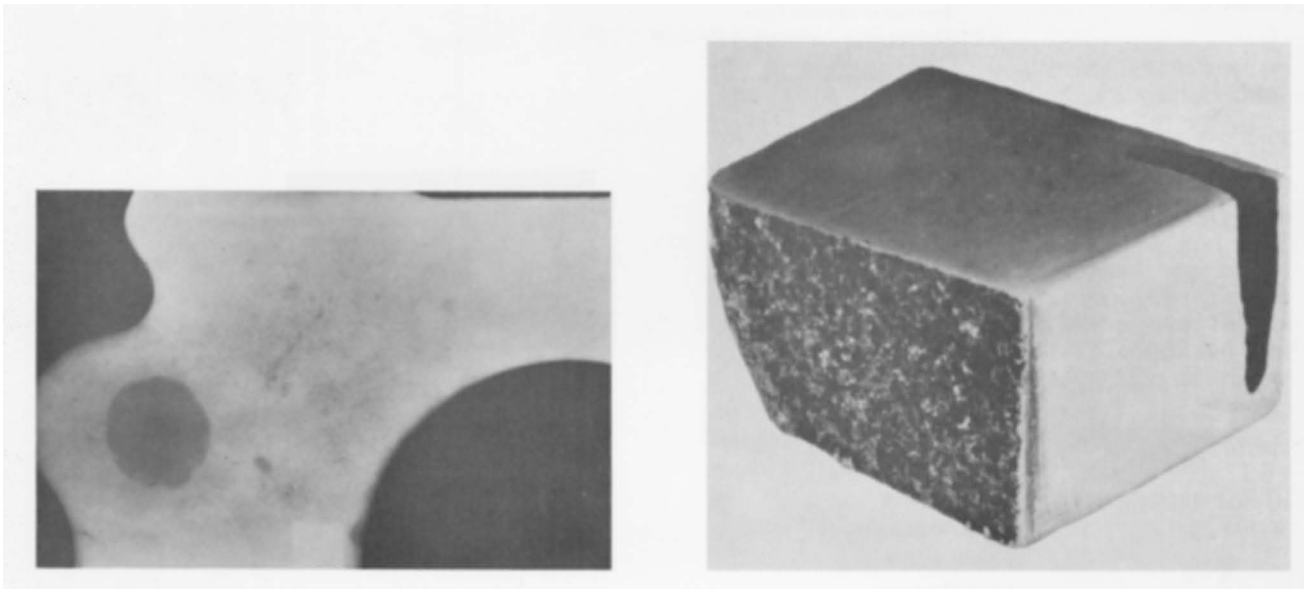
### 2. Detection of gas cavity flaws

#### (a) Airlocks

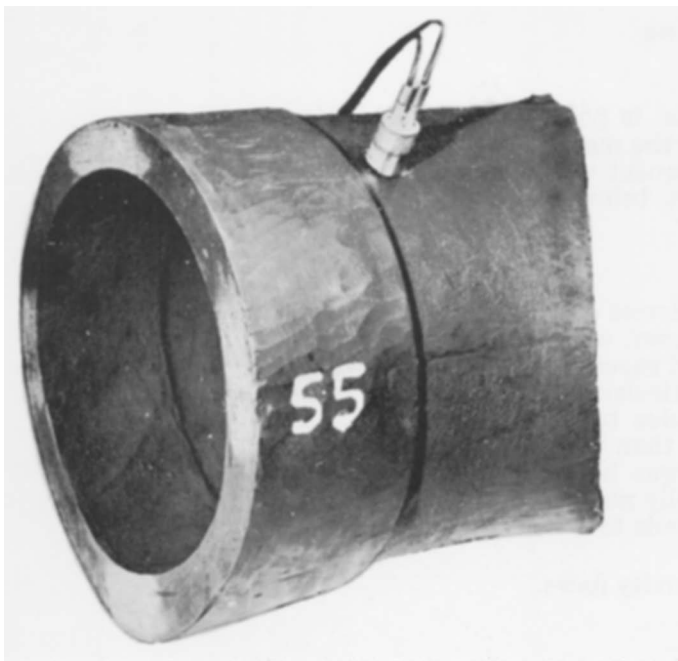
Since airlocks tend to lie just below the casting surface and parallel to it, their presence is best detected by a normal or combined probe (Fig. 27).

#### (b) Gas holes

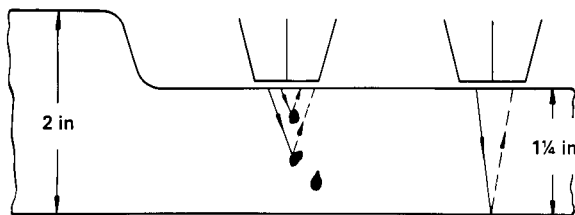
A combined double probe is also recommended for the detection and assessment of gas holes, i.e. blowholes and wormholes. The gas hole type of flaw, where there are many similar flaws associated, is typified by a loss in back wall echo with a number of flaw echoes (Figs. 28 and 29). It is often advantageous to use angle probes to assess the size and severity of such flaws,



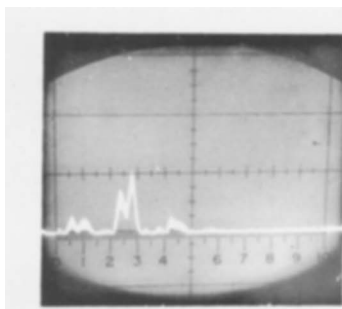
*Figure 27b—Large airlock (cont'd)*



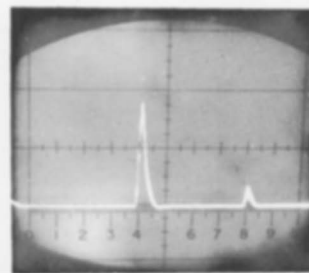
Steam Cylinder for Turbine Industry



Direction of ultrasonic beam  
23 mm diameter 2½ Mc/s combined double probe

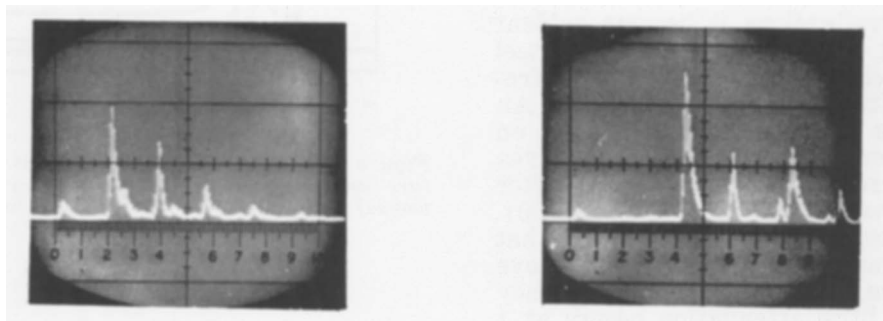
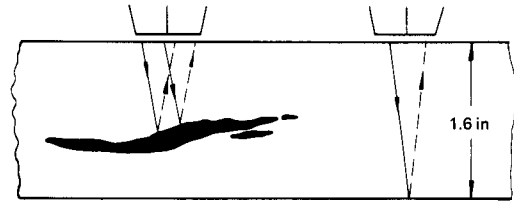
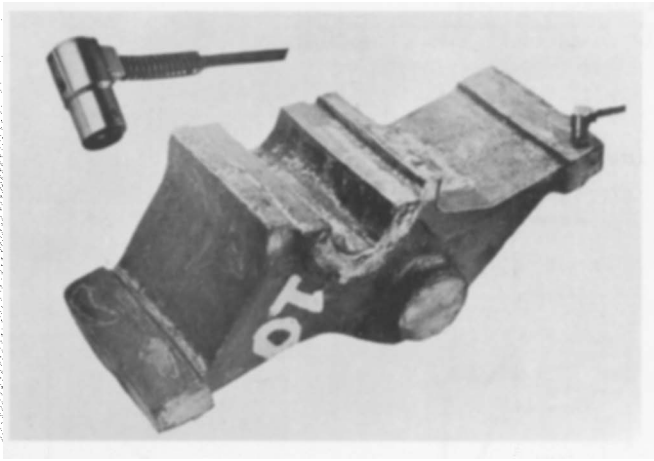


Trace showing  
large flaw echoes,  
no back wall echo,  
∴ large flaws



Trace showing  
2 back echoes,  
sound material.

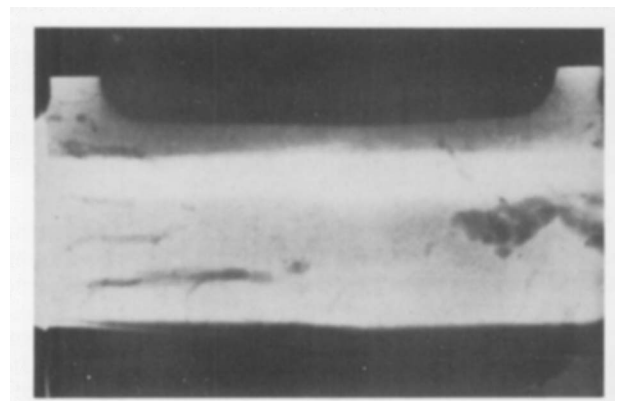
*Figure 28—Gas holes - blowholes*



Trace showing flaw echoes, no back wall echo, large flaw

Trace showing 3 back wall echoes, sound material.  
1 div. = 0.4 in steel

*Figure 29a—Wormholes*



*Figure 29b—Wormholes (cont'd)*

# ULTRASONIC ATTENUATION CARBON, LOW ALLOY AND AUSTENITIC STEELS

## INFLUENCE OF STRUCTURE ON ULTRASONIC ATTENUATION

### 1. Carbon, low alloy and martensitic steels

These steels undergo a transformation during cooling in the solid state, i.e. from austenite to ferrite.

During early investigations it became evident that heat treatment of carbon and low alloy steel vitally affected the choice of an optimum test frequency for penetration and test sensitivity. An investigation of the effect of heat treatment on ultrasonic attenuation in 0.3% carbon steel waves revealed a sharp decrease in grain coarseness after heat treatment above 1580°F (860°C) (Fig. 30). It may also be interpreted from the graph that when the material has not been heat treated above the AC3 temperature, the attenuation is frequency dependent, that is, little attenuation occurs at 1 MHz with a sharp increase occurring as the frequency is increased from 2 - 10 MHz. Practical experience in the examination of cast components to various steel specifications has led to the production of a series of histograms, Figs. 31a and 31b indicating which steels may and may not be examined by ultrasonic techniques.

Steels are graded into the following types: low carbon (less than .08% C), plain carbon, low alloy and 13% chromium steels. After heat treatment, these steels exhibit a small grain size compared with the wavelength of the ultrasonic beam ( $\lambda > G$ ).

Two methods of assessing the attenuation characteristics of a casting are outlined in Table III. This assessment is necessary to determine whether a given steel casting is acceptable for ultrasonic examination. In a situation where values in Table III are not obtained, the steel should be re-heat treated and re-checked in order to ascertain the significance of the original heat treatment given to the casting.

The possibility of using ultrasonic attenuation values to assess mechanical properties has been studied. Grain size related properties were found to correlate with the attenuation characteristics. A reasonable correlation was obtained between Charpy Izod impact energy (Figs. 32a, 32b), the 15 ft\*lbs transition impact temperature (Fig. 32c) and ultrasonic attenuation. It may be possible to correlate other related properties affected by grain structure, e.g. fracture toughness.

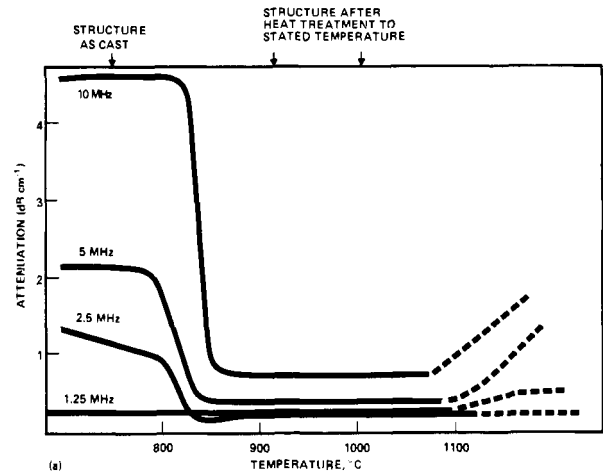


Figure 30—Relationship between heat treatment temperature and attenuation in a .3 carbon steel (longitudinal waves). A similar graph is obtained for transverse waves.

TABLE III  
Signal Strength Ratio Requirements for Testing

METHOD 1			
Probe	Type	Frequency MHz	Minimum dB reading
Combined double	Longitudinal	1 - 2½	20
		4 - 6	25
Single	Longitudinal	1 - 2½	25
		4 - 6	35
Combined double	Transverse	1 - 6	20
		1 - 6	20

The attenuation assessment is obtained by the difference in signal strength between the grass and the first back wall echo or corner. Acceptable attenuation shall be within the above range for the type of probe and frequency. This may be measured by adjusting the attenuator such that the grass and then the first back wall echo from the longitudinal wave probe or the corner echo from the transverse wave probe reach the same height on the screen and taking the difference between the two attenuator readings.

#### METHOD 2

The attenuation assessment shall be carried out by obtaining at least four back wall echoes on the cathode ray screen with a longitudinal wave probe from a parallel section of the casting under examination. The fourth back wall echo shall be at least 50% of the screen height. For metal thickness up to and including 250 mm a frequency of 4 - 6 MHz shall be used. For metal thicknesses above 250 mm a frequency of 1 - 1½ MHz shall be used.

A clear indication of full screen height of a corner echo of the casting shall be obtained with a transverse wave probe.

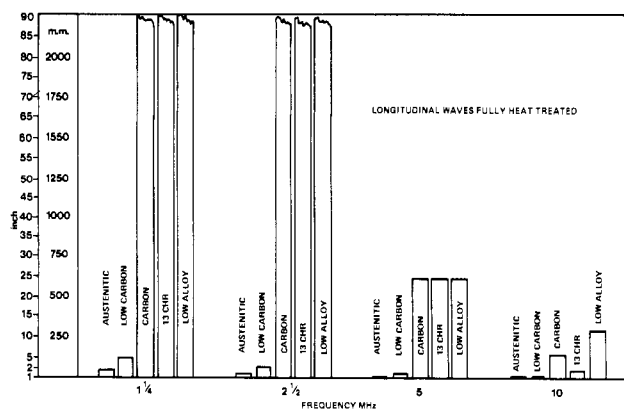


Figure 31a—Maximum thickness which can be ultrasonically tested for five different materials in the heat treated condition with longitudinal waves.

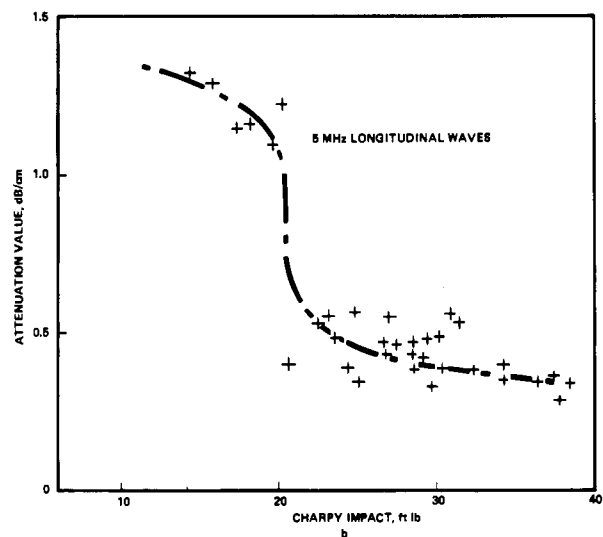


Figure 32b—Relationship between attenuation value for impact strength for as-cast, normalized and annealed conditions using longitudinal waves.

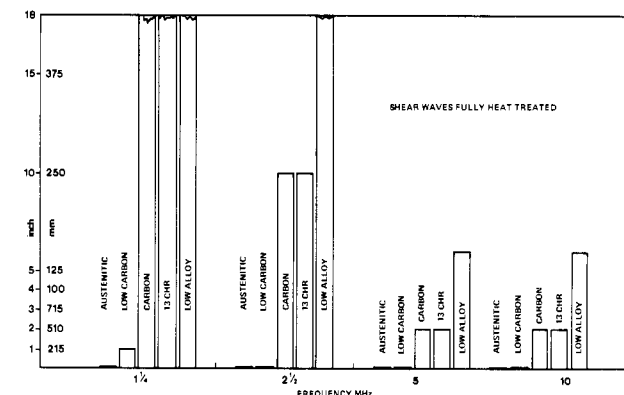


Figure 31b—Maximum thickness which can be ultrasonically tested for five different materials in the heat treated condition with transverse waves.

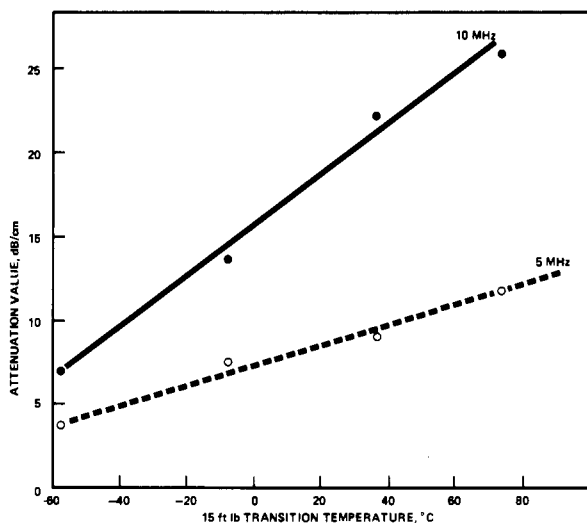


Figure 32c—Relationship between attenuation value and 15 ft•lb transition temperature.

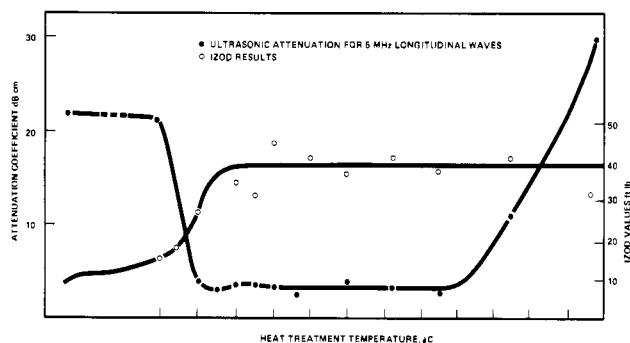


Figure 32a—Relationship between attenuation value, izod results and heat treatment temperature for a .3 carbon steel.



## 2. Austenitic steels

These steels do not have a transformation during cooling in the solid state. Their grain size is equal to, or larger than the wavelength of the ultrasonic beam. This fact introduces a loss of a transmitted pulse due to scattering which severely reduces the possibility of ultrasonic flaw detection. Flaw detection is also affected by the anisotropy of the cast structure, the sound velocity, attenuation and elastic moduli, of individual grains which all vary with the direction of grain growth.

The influence of grain orientation alone is shown in the columnar structure of an 18% Chromium, 12% Nickel Austenitic Steel, Figs. 33a and 33b. A variation in transmission and sound velocity occurs at different orientations to the columnar axis (Table IV). If the grain size of cast austenitic steels is less than 2 - 4 mm it may be possible to obtain some information when using 1 MHz probes.

The effects of orientation, grain size and metal composition on ultrasonic attenuation require further research in order to establish the reason for this phenomenon.

### MEASUREMENT OF ULTRASONIC ATTENUATION

Measurement of ultrasonic attenuation in cast steel components will provide useful information in the assessment of the grain size and thereby on the effect of heat treatment. The grain size of as-cast steel is large and high attenuation is caused by the ultrasonic beam being scattered by the large grains. An increase in background noise (grass) occurs which reduces the sensitivity of the ultrasonic technique. In the fully heat treated condition, when the temperature of the heat treatment exceeds the transformation temperature, the as-cast grain structure is recrystallized. The grain size of fully heat treated material is small and its ultrasonic attenuation is low,

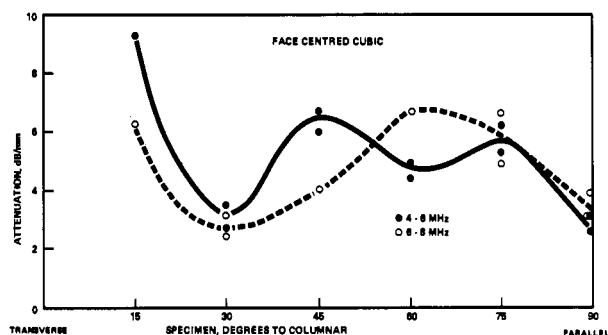


Figure 33b—Anisotropy in austenitic alloy structure.

TABLE IV  
Attenuation and Velocity Values in  
18/12 Austenitic Steels

Cast No.	C	Si	Mn	S	P	Cr	Ni	Type
VHF 773	0.15	0.81	0.78	0.027	0.021	17.30	11.98	FCC
Columnar axis				Attenuation dB/cm			Velocity cm/sec	
Parallel				2.36			$5.96 \times 10^5$	
Perpendicular				4.72			$6.54 \times 10^5$	

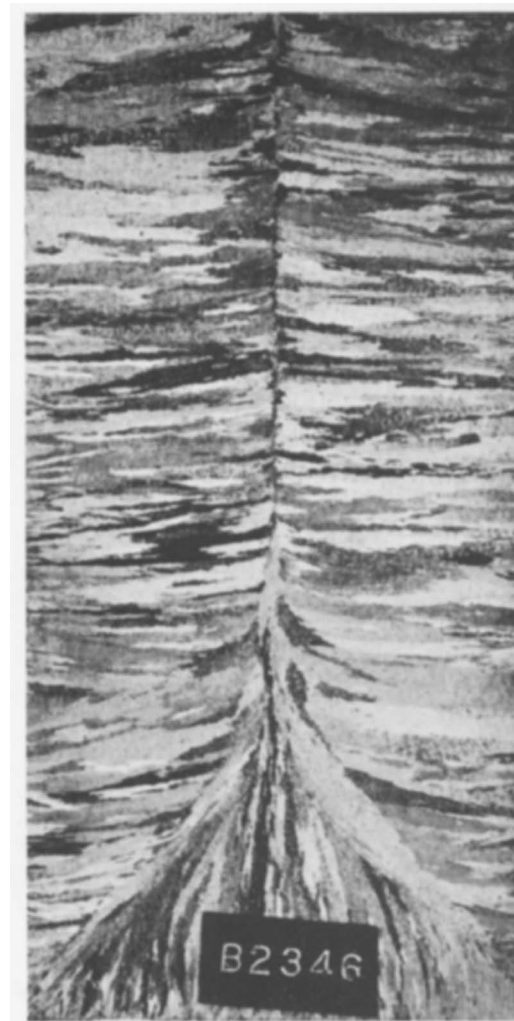


Figure 33a—Columnar structure in an austenitic alloy.

The predominant factor in attenuation measurement is the relationship between the ultrasonic wavelength and the grain size. These are related as follows:

High attenuation occurs when  $\lambda < D$

Low attenuation occurs when  $\lambda > D$

where  $\lambda$  = wavelength

$D$  = grain diameter

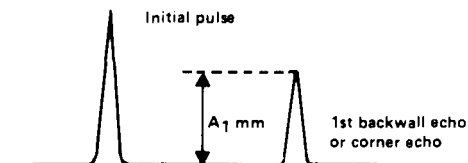
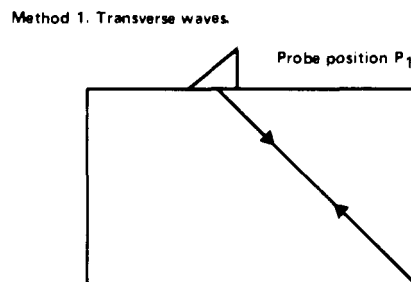
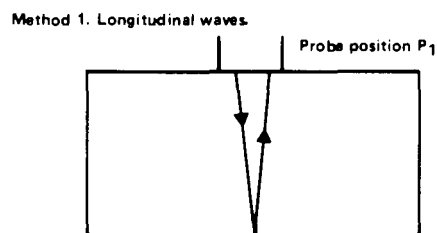
The operator must consider the following factors before carrying out the ultrasonic attenuation measurements :

- (a) The frequency of the transducer; as high an ultrasonic frequency as practicable should be used i.e. between 4 and 6 MHz, for longitudinal waves and 2 - 5 MHz for transverse waves.
- (b) More critical results are obtained by the use of transverse waves than longitudinal waves.
- (c) The path distance when longitudinal waves are used should be between 50 - 200 mm.
- (d) The path distance for transverse waves should be between 10 and 100 mm.
- (e) The roughness of the input surface.
- (f) The roughness of the back surface.
- (g) The analysis of the cast steel.
- (h) The nominal heat treatment.
- (i) The position of ingates, risers, feeder heads and test bars.
- (j) The position of ingates, risers, feeder heads and test bars.
- (k) The couplant.
- (m) The examination must be carried out on sound material. In excess of 50 mm the presence of microshrinkage is unlikely to affect the results.

Three methods of measurement are applicable:

### 1. Method 1

This is a practical shop floor method which uses contact coupling with longitudinal and transverse waves. Fig. 34 is comparative and will locate variations of heat treatment within a single casting. Attenuation is compared from a series of dB values.



where  $a$  =  $Y_1$  dB  
 $a$  = attenuation value in dB  
 $Y_1$  = attenuator reading in dB when the first backwall or corner echo is at an amplitude of  $A_1$  mm

Figure 34—Comparative method of attenuation measurement.

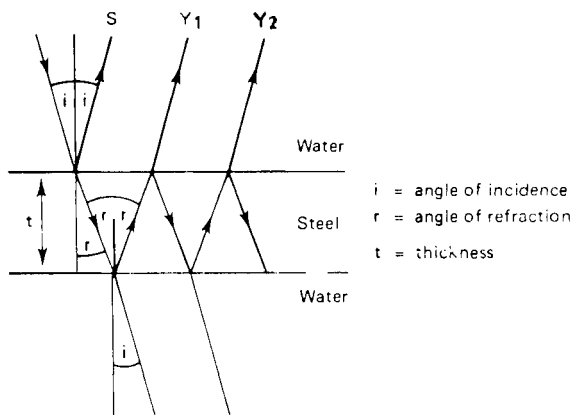
## 2. Method 2

This is a practical shop floor method which uses contact coupling with longitudinal waves. Fig. 35 will give a quantitative value. It may be used to compare one casting with another provided the same probe, the same thickness and the same geometric configuration is assessed on each casting. The attenuation may be expressed in dB/mm.

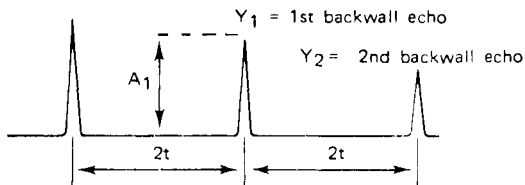
## 3. Method 3

This is a water immersion technique more suitable for laboratory conditions. Fig. 36 will give an accurate assessment of attenuation. It is usual to produce a standard machined test piece.

Method 3. Longitudinal waves - water immersion



where S = Surface reflection



Method 3

1. Take attenuator reading ( $Y_1$  dB) with first backwall echo amplitude  $A_1$  mm.
2. Adjust attenuator until second backwall echo reaches amplitude  $A_1$  mm, note attenuator reading ( $Y_2$  dB).

$$\text{where } a = \frac{1}{2t} [Y_1 - Y_2 - R]$$

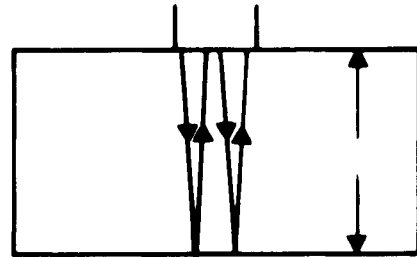
$a$  = attenuator values  
 $t$  = thickness

$Y_1 - Y_2$  = attenuator reading of two consecutive echoes in dB

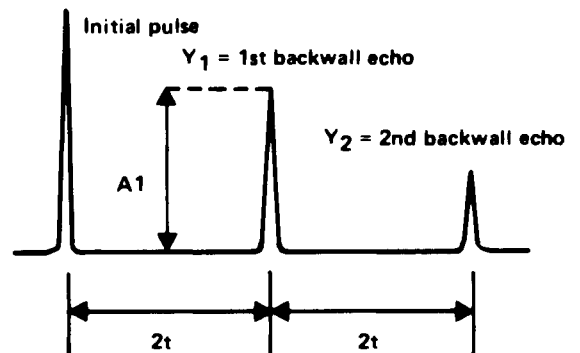
$R$  = reflection coefficient at water/steel interface 1.1 dB  
 $i$  = incident angle  
 $r$  = refracted angle

Figure 36—Qualitative, immersion method of attenuation measurement.

Method 2



Probe position  $P_1$



Method 2

1. Take attenuator reading ( $Y_1$  dB) with first backwall echo at amplitude  $A_1$  mm.
2. Adjust attenuator until second backwall echo reaches amplitude  $A_1$  mm. Note attenuator reading ( $Y_2$  dB).

$$\text{where } a = \frac{1}{2t} (Y_1 - Y_2)$$

$a$  = attenuator value

$t$  = thickness

$Y_1 - Y_2$  = attenuator reading of two consecutive echoes in dB

Figure 35—Quantitative method of attenuation measurement.

## SIZING OF FLAWS AND ACCEPTANCE STANDARDS

Customers may specify their own or other standards for ultrasonic inspection. Internationally, however, the only standards that are widely recognized are ASTM A609 "Standard Specification for Longitudinal Beam Ultrasonic Inspection of Carbon & Low Alloy Steel Castings", and the ASME Boiler & Pressure Vessel Code, Section V, T524.2, "Angle Beam Examination of Steel Castings".

Two steps are important in working to these standards. The first step consists of specifying rejection levels for discontinuities. The second step consists of specifying one of the following methods of recording discontinuities :

- 1) Method based upon flat bottom holes and back wall echoes produced from test blocks
- 2) Method based upon back wall echoes from test blocks
- 3) The DGS system, using theoretical curves based upon flat bottom holes and back wall echoes
- 4) Method based upon back wall echo/defect echo ratio, to quantify the actual flaw size and shape. This method uses either the 6 or 20 dB technique or the maximum echo amplitude from the flaw.

To establish the ultrasonic technique completely a knowledge of its accuracy in both sizing and indicating the flaw type is essential. The flaw size, type and accuracy are dependent upon the casting thickness, or whether the casting walls are planar (linear) or rounded. A review of the allowable flaw sizes in current specifications (Table V) shows the averaged value of the minimum flaw size to be detected by magnetic particle, dye penetrant, radiographic and ultrasonic techniques. The flaw type is specified in terms of its shape (linear, planar, or rounded).

The critical flaw size to be detected is 10 mm for a linear flaw, and 4 mm for a rounded flaw. The ultrasonic technique should be able to detect each of these flaw sizes with an accuracy of  $\pm 20\%$ , i.e. between 8 - 12 mm for a 10 mm linear and between 3-5 mm for a 4 mm rounded flaw. The accuracy would be severely reduced and may not be practical should the critical flaw size be reduced to a value of, for example, 1 mm. A second important aspect is how far apart two flaws would be located before they could be resolved: the value is of the order of 10 mm. However, further research is essential to determine the accuracy of the ultrasonic technique in many different situations.

The currently available ultrasonic methods of assessing flaw size are the maximum amplitude and beam spread techniques.

The use of flat bottomed hole test blocks or the German DGS system are irrelevant in this context since they express the value of an equivalent flaw size. The actual flaw may be very much greater than the flat bottomed hole to which the

flaw is stated to be equivalent. They should be used, if at all, for equipment calibration and setting sensitivity levels.

The use of the methods which are described and the accuracy of their use depend primarily on the structure of the cast component and its ultrasonic attenuation. This factor determines the test frequency MHz of the resolving power of the method. Other important factors to be considered are the equipment characteristics, setting sensitivity, casting production, shape, surface roughness and the ability of the ultrasonic operator.

### Beam Spread and Maximum Amplitude Techniques

The above techniques use straight and angle -- probes with the 6 and 20 dB echo and maximum amplitudes of the beam, Figs. 37a and 37b.

The geometry and intensity within the beam in both the horizontal and vertical directions are used to define the flaw depth and to quantify the flaw in terms of shape and size.

**TABLE V**  
**Average Minimum Flaw Size to be Detected by NDT Techniques**

Technique	Type of flaw	
	Linear	Rounded
Magnetic particle	4 mm	2 mm
Dye penetrant	4 mm	3.5 mm
Radiography	15 mm	3.0 mm clusters
Ultrasonics	10 mm	4 mm

The two methods (6 dB and 20 dB) use, initially, the axis or maximum intensity of the beam and then a selected sound pressure level or isobar to locate the flaw boundary. The flaw is located, maximized and recorded, the probe is then moved towards the edge of the flaw until its echo loses height to a prescribed amount, i.e. 6 or 20 dB (1/2 to 1/10 in. amplitude). The position of the edge of the flaw relative to the probe is plotted by reference to the known beam profile. The distance at which the flaw lies and a datum mark on the probe is, in turn, related to a fixed datum on the component.

The maximum amplitude technique simply plots a defect in relation to either the maximum echo height or a series of different maximum echo heights at various positions across the detected flaw. The method is simple and its degree of accuracy may be completely adequate for cast steel examination. A simple comparison of the techniques is given in Figs. 38a and 38b.

The sensitivity setting for ultrasonic examination is to establish a 1-3 mm grass structure level on the screen, when the probe is positioned on the cast surface. Once a flaw is detected, its size, position and type are ascertained by probe

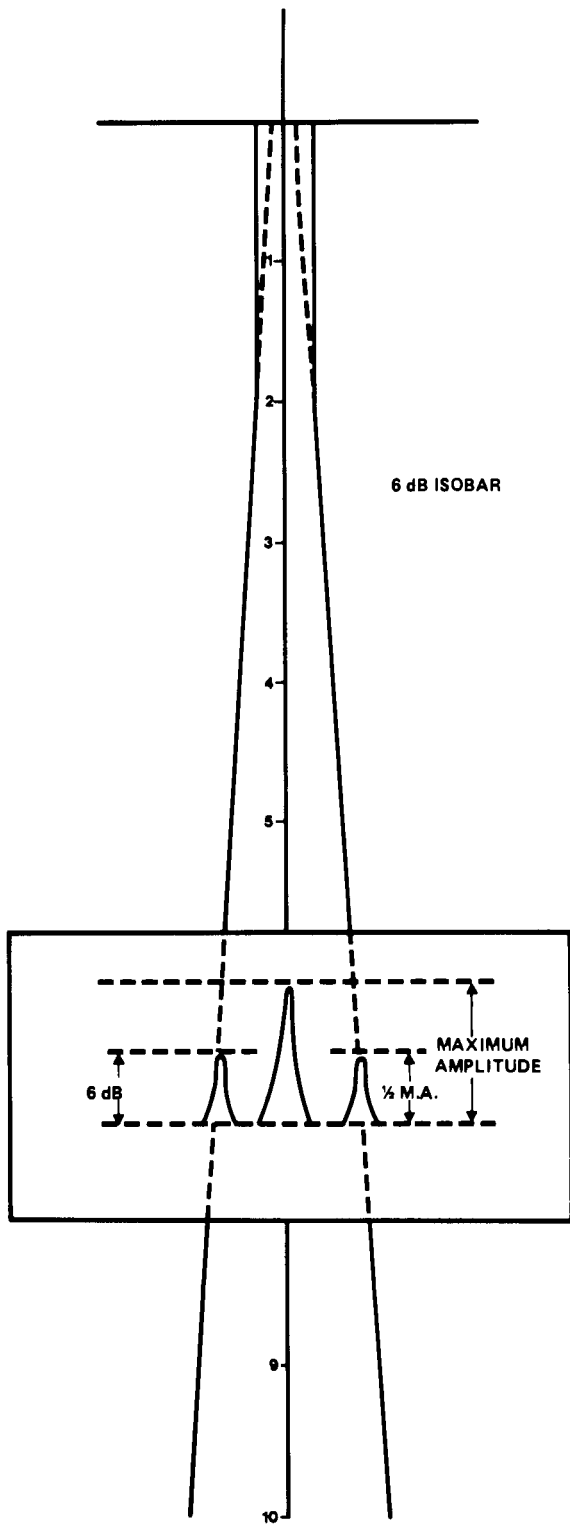


Figure 37a—20mm diameter 2½ MHz combined double probe. Beam spread showing maximum and 6 dB amplitudes.

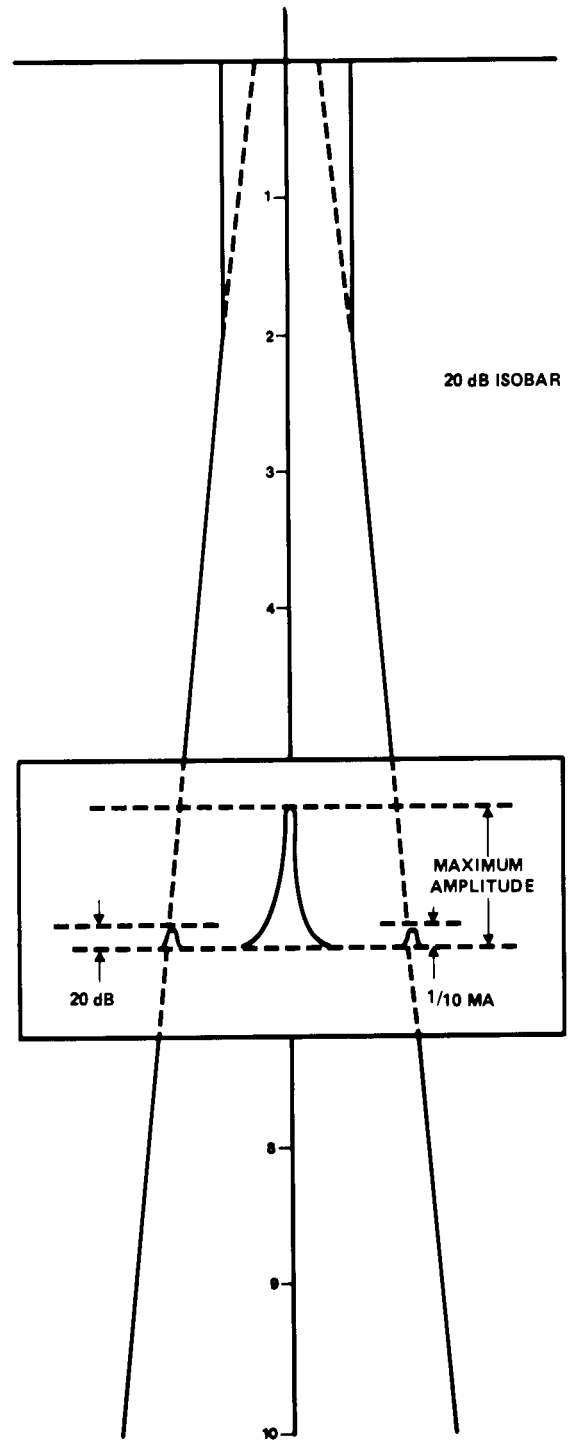
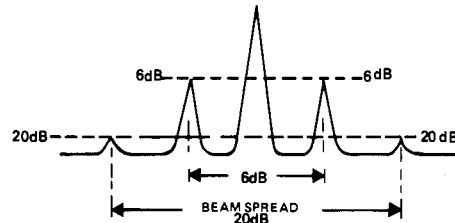
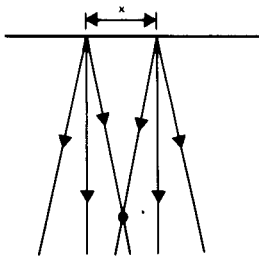


Figure 37b—20mm diameter 2½ MHz combined double probe. Beam spread showing maximum and 20 dB amplitudes.

# POINT FLAW, < PROBE DIAMETER

Using beam spread techniques  
 Probe movement =  $x$  mm  
 which = beam spread



Using maximum amplitude  
 technique flaw is point size  
 Probe movement =  $0$  mm  
 Flaw is point size

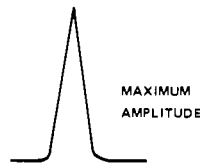
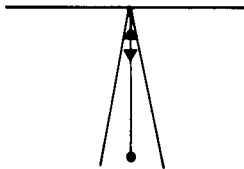
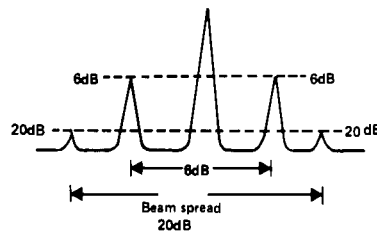
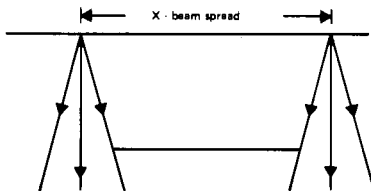


Figure 38a—Defect sizing for straight and angle beam testing, when flaw is less than probe diameter.

# FLAW > PROBE DIAMETER

Using beam spread techniques  
 Probe movement =  $x + \text{beam spread}$   
 Flaw size =  $x - \text{beam spread}$



Using maximum amplitude technique  
 Probe movement =  $x$  mm  
 and is flaw size

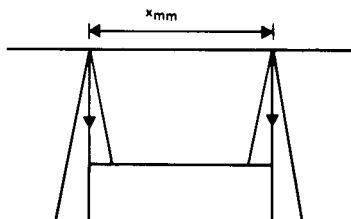


Figure 38b—Defect sizing for straight and angle beam testing, when flaw is greater than probe diameter.

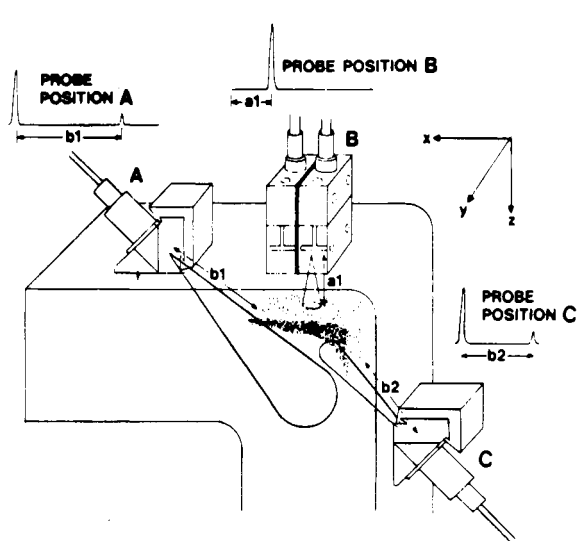


Figure 39a—The determination of the size of a shrinkage cavity in an L section using a 5 MHz longitudinal combined double probe and a 45° 10mm diameter transverse wave probe.

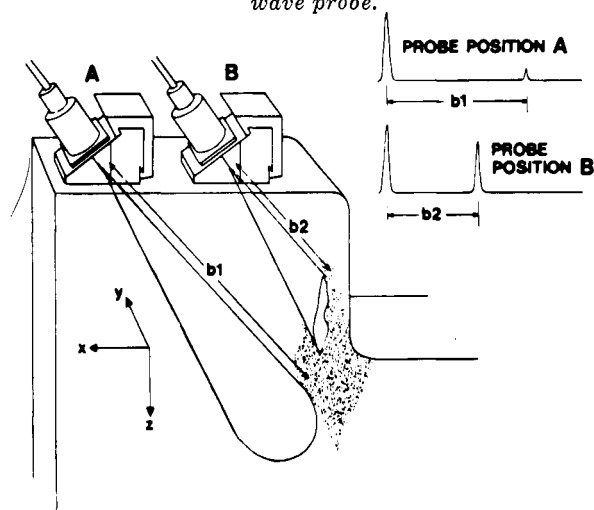


Figure 39b—The determination of the size of a shrinkage cavity in a T section using a 2-5 MHz longitudinal combined double probe and a 10mm diameter transverse wave probe. The flaw size X-Y axis is assessed by probe movement. The flaw depth is measured by the echo position on the cathode ray screen.

movement, using one of the techniques described above.

A two dimensional x - Y axis picture of the flaw may be drawn on the cast surface by assessing the ratio of the flaw echo to the back echo on the oscilloscope screen. A complete loss of back wall echo with corresponding increase in height of the flaw echo, indicates a significant flaw. Reference should be made to Figs. 39a and 39b. The third dimension, depth or Z axis is obtained from the position of the flaw echo on the graduated screen.

Transverse wave probes must be employed when the beam is required to enter the casting at an angle relative to the orientation of the flaw. Fig. 39c shows the detection of a hot tear in an L section using a 45° transverse wave probe where the flaw position is favorable and results in a maximum reflection when the probe is in position B. The X - Y axis is measured by probe movement

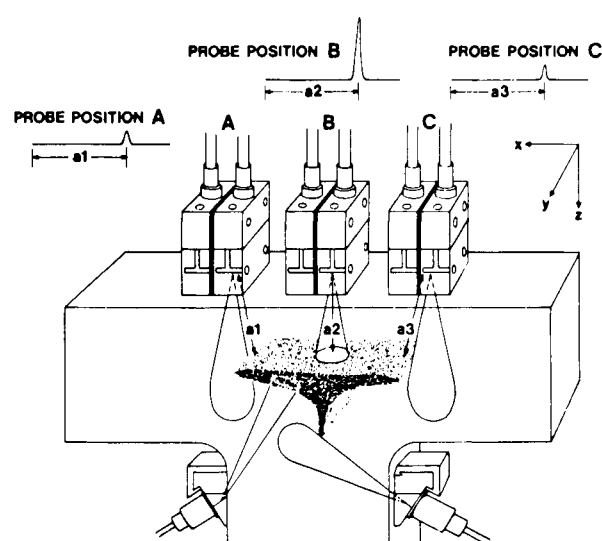


Figure 39c—The determination of flaw size and depth of a hot tear in an L section using a 45° 15mm diameter 5 MHz transverse wave probe. The length of the tear Z axis is measured by both probe movement and beam spread.

upon the cast surface. The depth of the tear, that is, the Z axis is obtained by measurement of the beam direction. Due to both the orientation and position of the flaw, longitudinal wave probes will be of little value.

Visual aids such as those relating to the substitution technique will help the operator to position and diagnose flaw echoes.

A further important procedure for the flaw size estimation is transverse wave probe manipulation. The probe has four degrees of freedom: a swivel movement about the flaw; a circular rotary movement around the flaw; a lateral movement along the flaw and a 90° transverse movement towards and away from the flaw. The extent, size and position of each flaw echo on a graduated cathode ray screen as each probe movement is carried out should be noted. These flaw indication echo changes relate directly to the flaw size and position in the cast section.

Figs. 40a and 40b give an example of probe manipulation techniques for the identification and size estimation of a flaw. In this context a linear planar flaw (crack) being bi-directional is only detectable with lateral probe movement along the flaw, a rounded flaw (gas cavity) is detectable over a very small probe movement from any direction.

It should be appreciated that while it is desirable to scan at a high sensitivity level, minor flaws may be detected, probe movement will ascertain if their size is significant.

### Surface Flaws

In order to detect near surface flaws it is essential to use a combined longitudinal and a combined transverse double probe which are obtainable with different focussing systems. This enables maximum reflection to be obtained from a flaw at different depths, so helping the operator to assess the flaw size at any given position in the

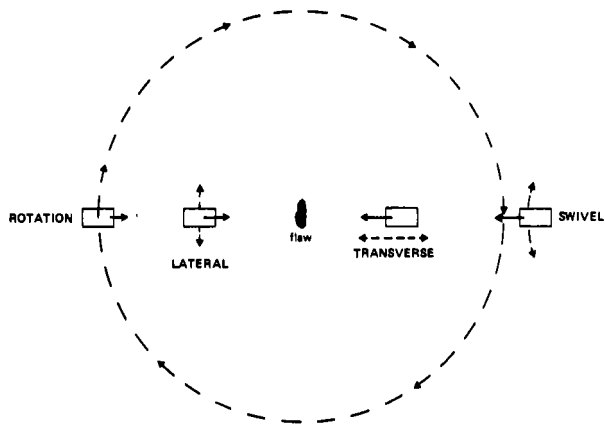


Figure 40a—Scanning system using angle probes.

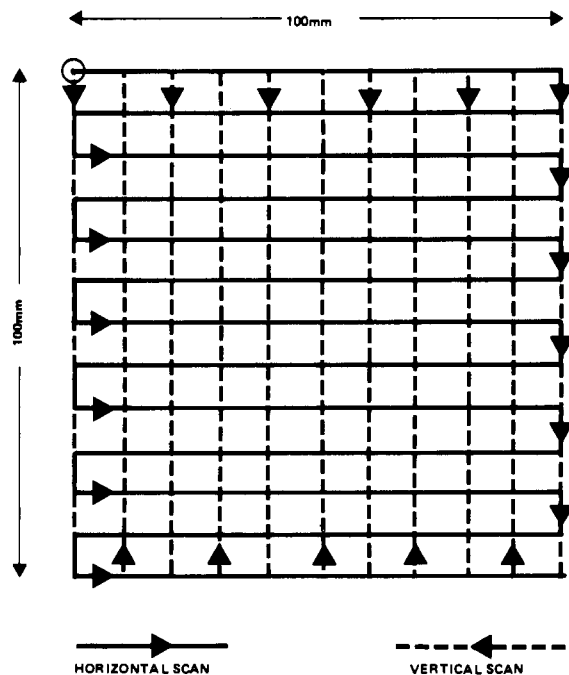


Figure 40b—Scanning system using normal straight beam probes.

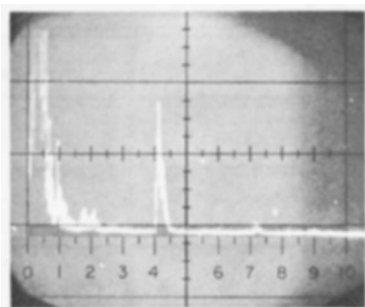
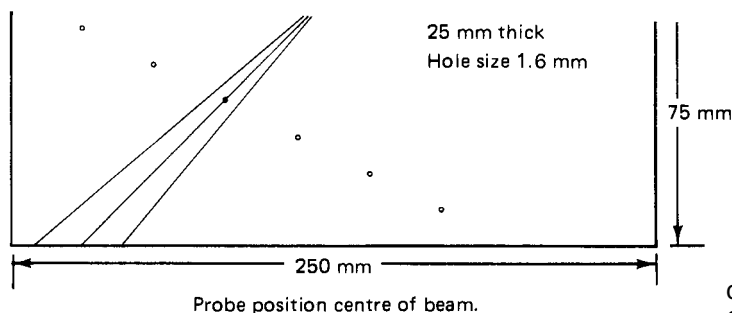


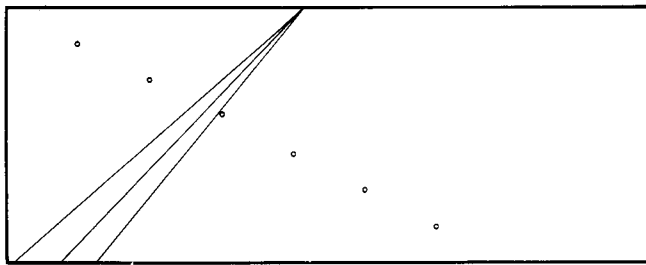
Figure 41

cast section. Cross noise occurs with combined double probes which may mask the reflection from near surface flaws. New electronic systems to overcome this problem have been investigated.

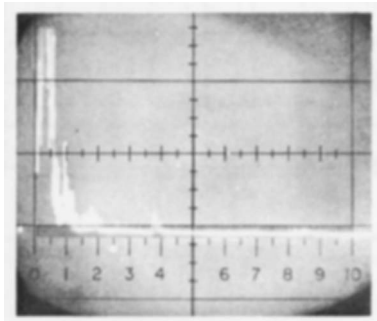
### Beam Spread From Transverse Wave Probes

- Determine the probe index
- Calibrate the time base in terms of steel thickness.
- Move the probe until maximum amplitude is obtained from the hole (Fig. 41). Mark the position of the probe index on the block.
- Move the probe forward until the amplitude is reduced to approximately 1/8 (20 dB) of the original value. Mark the position of the probe index on the block (Fig. 42).
- Repeat (d) above move the probe backward (Fig. 43).
- Repeat the exercise with holes at different depths.
- Plot the beam spread on a Plexiglass sheet (Fig. 44).



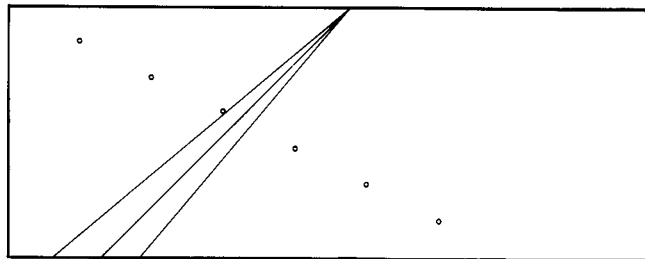


Probe position rear edge of beam.

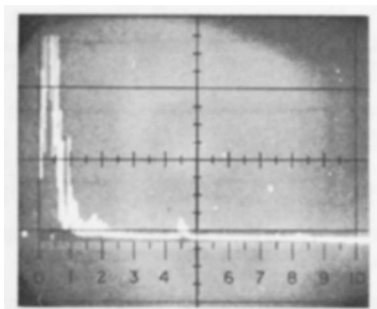


Beam position 36mm steel thickness.

*Figure 42*

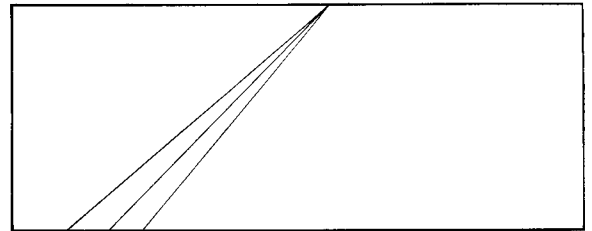


Probe position front edge of beam.

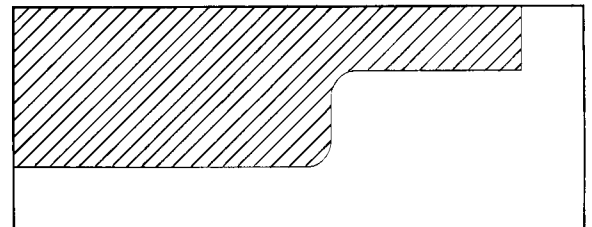


Beam position 44mm steel thickness.

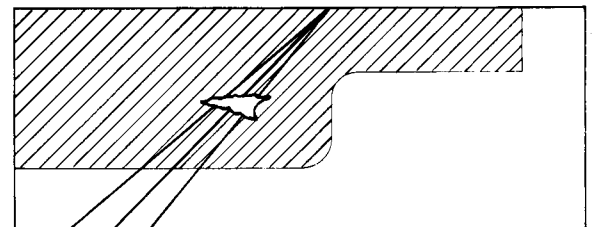
*Figure 43*



*-Beam spread plotted on plexiglass slide.*



*Geometric shape of component on plexiglass slide.*



*Two slides fitted together give beam position in component.  
Note flaw position, size and depth may be assessed  
using this method.*

*Figure 44*

# PRODUCTION AND ECONOMICS OF AN ULTRASONIC TECHNIQUE

One of the main advantages of using ultrasonics in place of radiography is a decrease in the cost of and an increase in the speed of inspection ; this is of particular value to steel foundries not having x-ray facilities for radiography of thick sections in excess of 50 - 100 mm (approx. 2 - 4 in.). These facts were demonstrated in the early 1960's during work on the application of ultrasonic methods to the examination of steel castings.

The standard of acceptance for the integrity castings, usually specified by the user, are the ASTM radiographic standards. The substitution of ultrasonics therefore requires, in many instances, that flaws detected by the operator should be assessed in ultrasonic flaw severity in terms of ASTM radiographic standards. This has partly been achieved by a current project and the results described later indicate that direct correlation may be obtained between ultrasonic examination and the ASTM radiographic standards for the shrinkage flaws in the 50 - 100 mm (approx. 2 - 4

in.) thickness range.

The ultrasonic/radiographic substitution technique is completely dependent on the production of a written procedure for the examination of the casting. This procedure is outlined in Fig. 45. The main features are the use of longitudinal and shear wave beam spread diagrams (Figs. 46-46d) calibration values and the use of a full size casting drawing. Full details of the scanning procedure and calibrations are essential in order to ensure complete coverage. It is no longer possible to use incompetent untrained operators who do not understand the full significance of the highly skilled and important job which they undertake. Neither should the casting be examined by slopping couplant all over the cast surface and expecting the examination to be complete within 20 minutes. The technique requires trained, competent operators who fully understand steel casting production and who have the full co-operation of management .

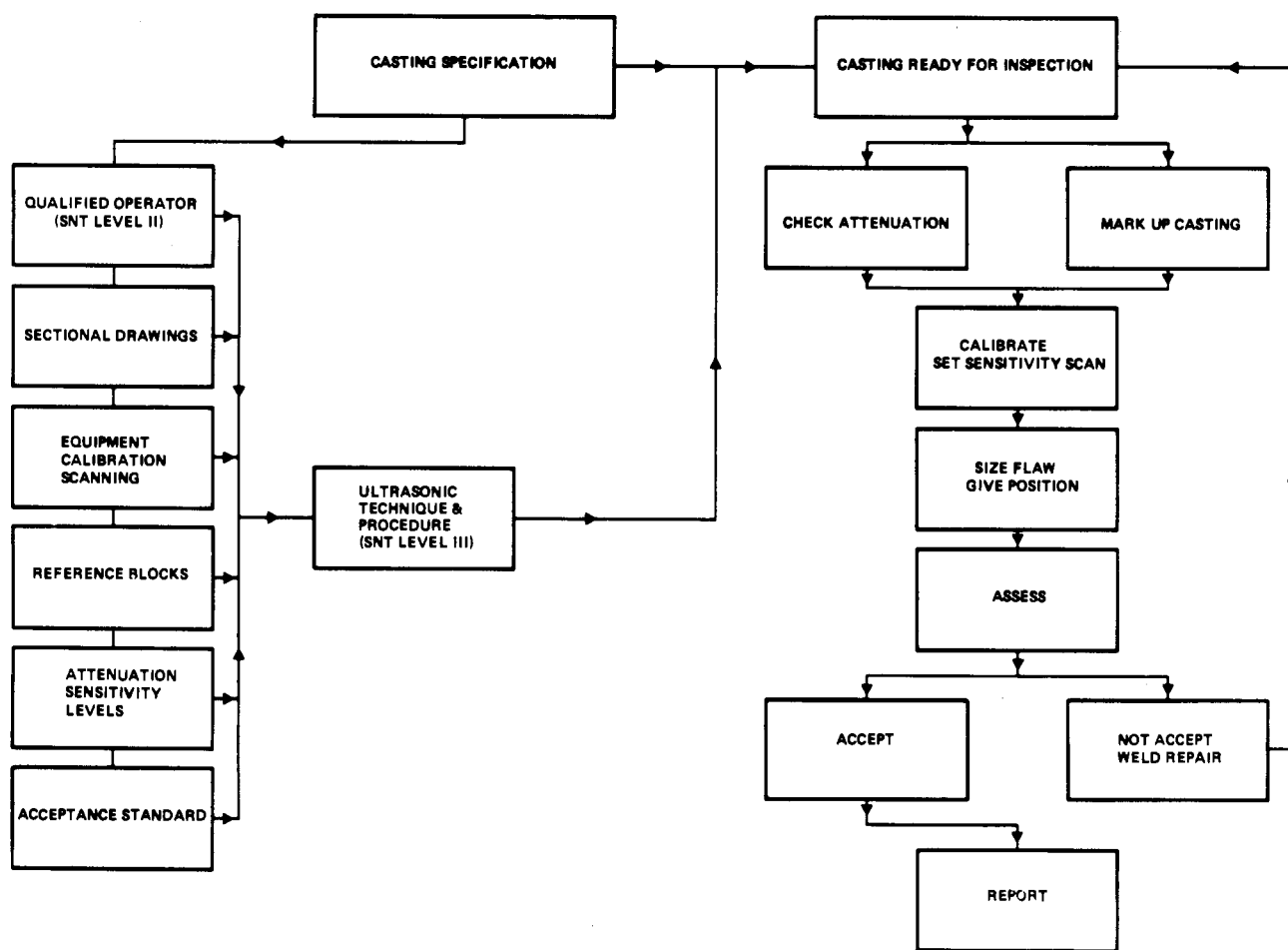


Figure 45—Procedure for ultrasonic inspection.

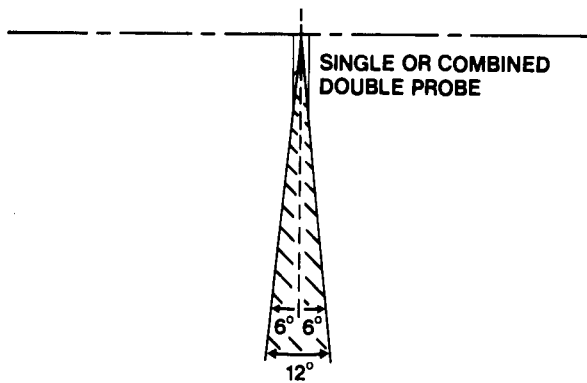


Figure 46a—Theoretical beam spread (straight)

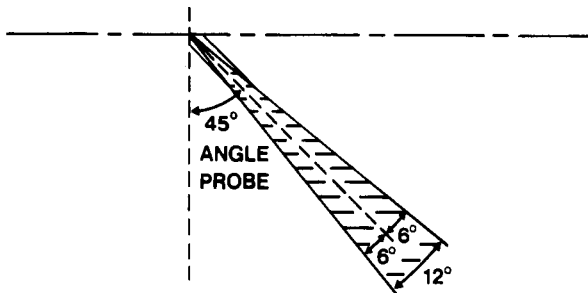


Figure 46b—Theoretical beam spread (45°)

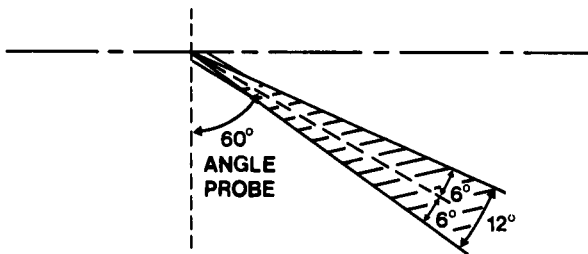


Figure 46c—Theoretical beam spread (60°)

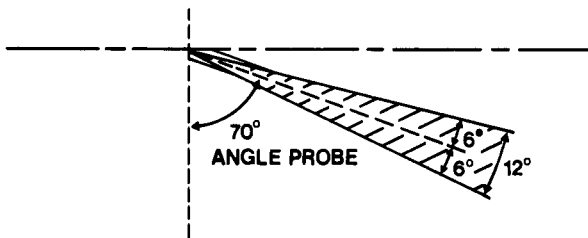


Figure 46d—Theoretical beam spread (70°)

A successful exercise of substituting radiography by ultrasonics was carried out on a valve casting weighing 2 tons; its dimensions were as follows: 500 mm (20 in.) diameter x 1200 mm (4 ft) long, barrel thickness 80 mm (3 1/2 in.) valve seat 200 mm (8 in.). A photograph and sectional diagram of the valve casting is shown in Fig. 47.

Originally, full radiography was specified and used. The technique is detailed in Table VI, Figs. 48a - 48c.

The second stage was to radiograph the valve seat and butt weld ends only, substituting an ultrasonic technique for the barrel section. In the final stage the butt weld ends only were radiographed. This required a further ultrasonic technique to be substituted for the more difficult valve seat examination, Table VII, Figs 49a - 49d.

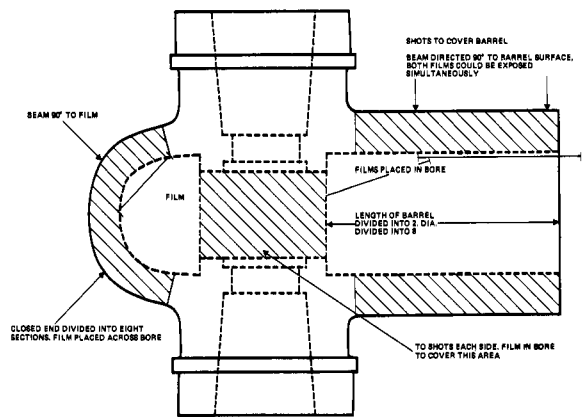
The commercial implication of the substitution was evidently favorable, Table VIII. The cost for full radiography was \$560 (\$1120). By substituting ultrasonic testing on the barrel the cost was reduced to \$340 (\$680), a substantial decrease. A further lowering in cost to \$240 (\$480) was also possible by using an ultrasonic technique on the valve seat. This latter substitution is a more difficult examination due to the complex shape of the valve seat and makes further demands on the ultrasonic operator.

**TABLE VI**  
**Radiographic Technique for a**  
**Valve Casting (Figs. 48a - 48c)**

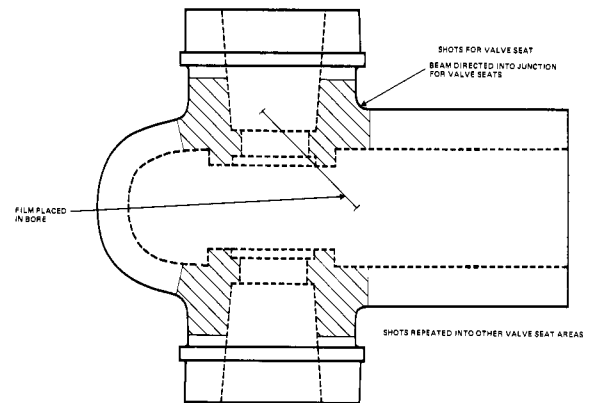
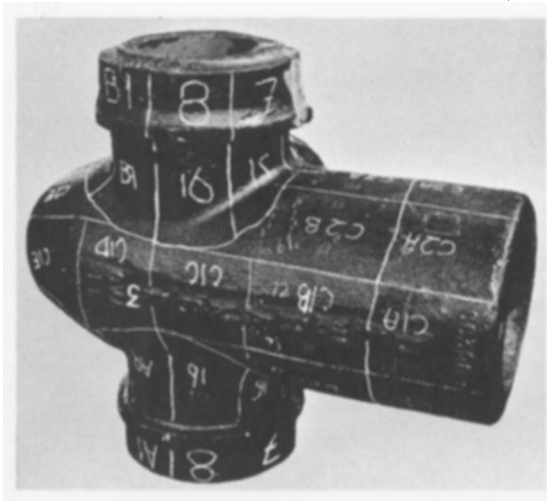
	Shot	Area covered	No. of shots	No. of films and size
Technique 1 Full radiography	A	Barrel and end cap	28	28 (17 x 14)
	B	Valve seat	12	24 (12 x 10)
	C	Butt weld end	16	16 (17 x 14)
		Total number of shots	56	
Technique 2 Butt weld end, valve seat	B	Valve seat	12	24 (12 x 10)
	C	Butt weld end	16	16 (17 x 14)
		Total number of shots	28	
Technique 3 Butt weld end	C	Butt weld end	16	16 (17 x 14)
		Total number of shots	16	

**TABLE VII**  
**Ultrasonic Technique for a Valve Casting**  
**(Figs. 49a - 49b)**

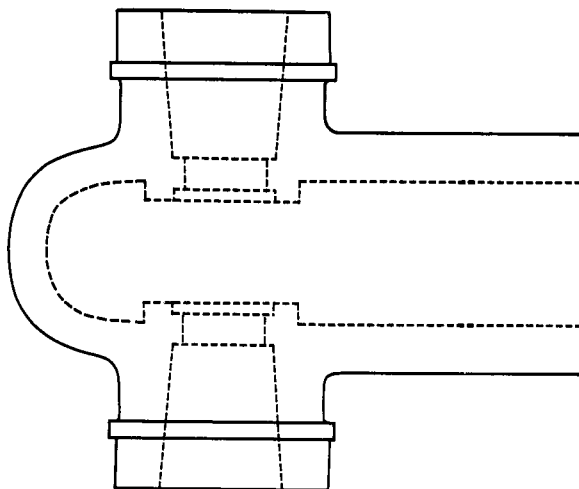
	Scan	Section	Probes
Technique 1	A <sub>1</sub>	Barrel and end cap	2½ MHz combined double normal longitudinal
	A <sub>2</sub>	Barrel and end cap	2½ MHz single 45° shear
	A <sub>1</sub>	Barrel and end cap	2½ MHz combined double normal longitudinal
	A <sub>2</sub>	Barrel and end cap	2½ MHz single 45° shear
	B <sub>1</sub>	Valve seat	5 MHz combined double normal longitudinal
	B <sub>2</sub>	Valve seat	2½ MHz single 45° shear
	B <sub>3</sub>	Valve seat	2½ MHz single 70° shear



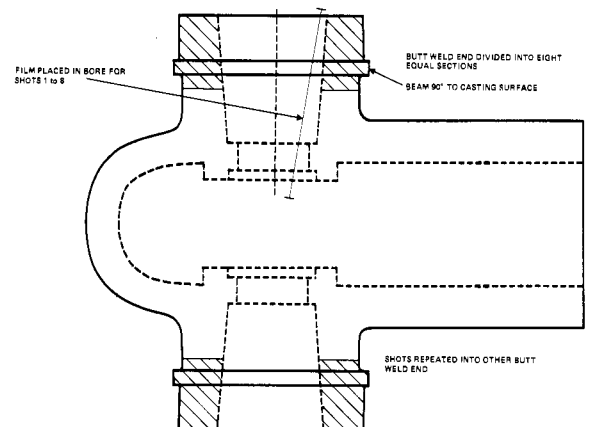
*Figure 48a—Radiographic technique - barrel and end cap*



*Figure 48b—Radiographic technique - valve seat*



*Figure 47—Valve casting*



*Figure 48c—Radiographic technique - butt weld ends*

This example shows that the substitution of ultrasonics for radiography can result in substantial economies. In this connection the following factors are essential :

(a) The NDT Manager must be fully conversant with ultrasonic technology, ASNT Level III.

(b) The ultrasonic operator should be trained and certified to ASNT Level II- steel castings.

(c) A written ultrasonic procedure, Fig. 45, must be produced by an ASNT Level III person which, together with the ultrasonic technique, shows that the whole volume of the casting has been completely examined. Where changes in section occur full use must be made of the whole range of longitudinal and shear wave probes.

An ultrasonic test report must be produced upon test completion and cover the following:

- 1) Procedures (techniques, calibration, reference blocks, sensitivity setting, acceptance standards)
- 2) Results (location and size of recordable flaws, description of flaw type where possible)
- 3) Conclusions (acceptability of flaws relative to standards)

## REFERENCES

1. Atlas of Some Steel Casting Flaws as shown by Non Destructive Testing, Steel Castings Research and Trade Association, Sheffield, England, 1968.
2. Recommended Procedure for the Ultrasonic Examination of Steel Castings, Steel Castings Research and Trade Association, Sheffield, England, 1971.
3. ASTM A609, "Standard Specification for Longitudinal Beam Ultrasonic Inspection of Carbon & Low Alloy Steel Castings".
4. ASME Boiler & Pressure Vessel Code, Section V, T524.2, "Angle Beam Examination of Steel Castings".

**TABLE VIII**  
**Costs Involved in High Energy Radiography**  
**and Ultrasonics of a Valve Casting**

Description	No. of shots	No. of films	Time	Radiography Cost	Time	Ultrasonics Cost
Full radiography	56	68	24 hours	£560 \$1120		Nil
TOTAL COST £560 (\$1120)						
Radiography						
(1) Butt weld ends				£280		
(2) Valve seat	28	40	12 hours	\$560		
Ultrasonics						
(1) Barrel					10 hours	£60 \$120
TOTAL COST £340 (\$680)						
Radiography						
(1) Butt weld ends	16	16	6 hours	£160 \$320		
Ultrasonics						
(1) Barrel						£80
(2) Valve seat					15 hours	\$160
TOTAL COST £240 (\$480)						

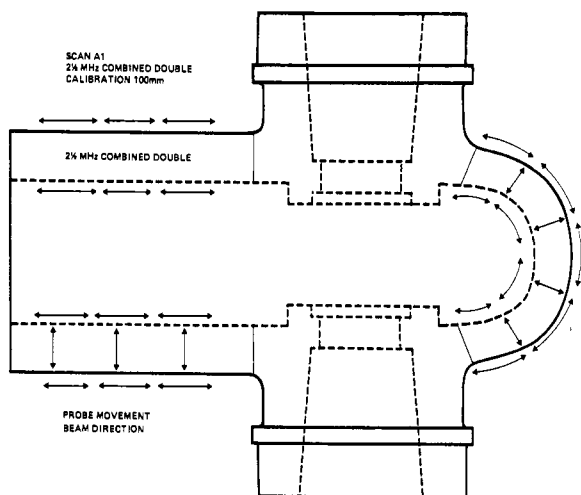


Figure 49a—Ultrasonic technique - barrel and end cap  
(normal probes)

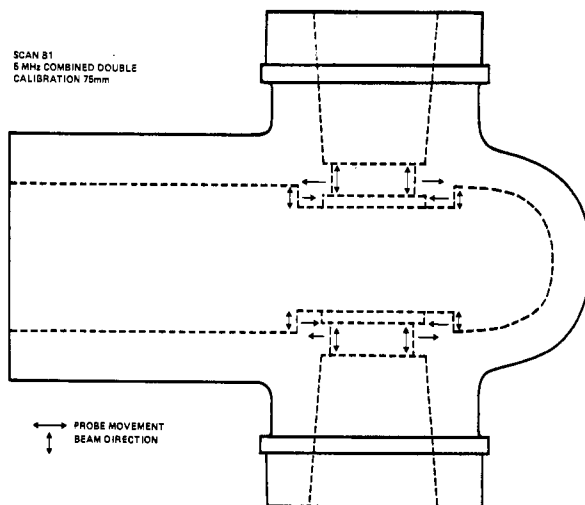


Figure 49c—Ultrasonic technique - valve seat  
(normal probes)

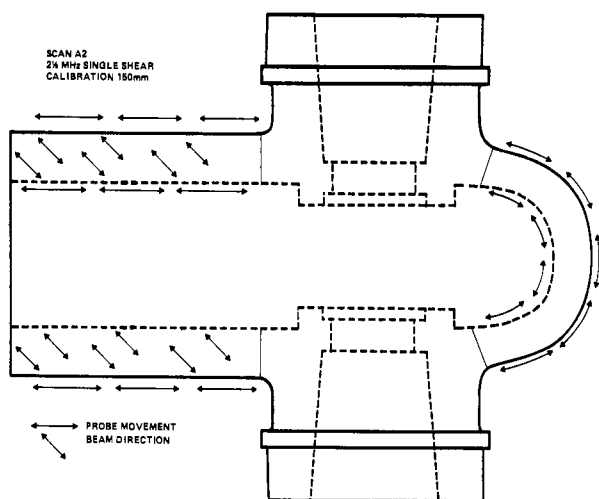


Figure 49b—Ultrasonic technique - barrel and end cap  
(angle probes)

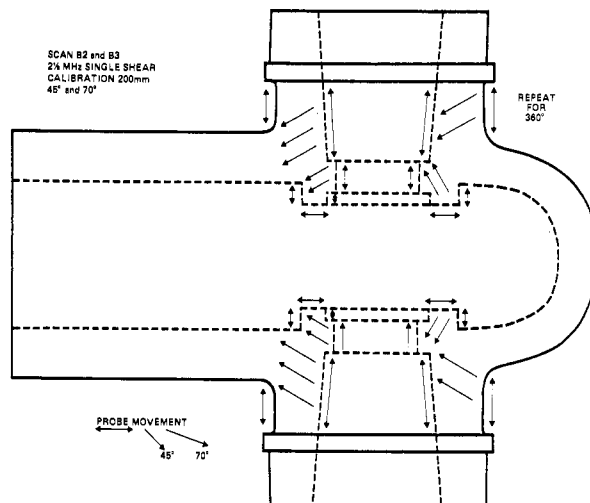


Figure 49d—Ultrasonic technique - valve seat  
(angle probes)