Designation: E2192 – 13

Standard Guide for
Planar Flaw Height Sizing by Ultrasonics[1]

This standard is issued under the fixed designation E2192; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This guide provides tutorial information and a description of the principles and ultrasonic examination techniques for measuring the height of planar flaws which are open to the surface. The practices and technology described in this standard guide are intended as a reference to be used when selecting a specific ultrasonic flaw sizing technique as well as establishing a means for instrument standardization.[2]

1.2 This standard guide does not provide or suggest accuracy or tolerances of the techniques described. Parameters such as search units, examination surface conditions, material composition, etc. can all have a bearing on the accuracy of results. It is recommended that users assess accuracy and tolerances applicable for each application.

1.3 This guide does not purport to provide instruction to measure flaw length.

1.4 This standard guide does not provide, suggest, or specify acceptance standards. After flaw-sizing evaluation has been made, the results should be applied to an appropriate code or standard that specifies acceptance criteria.

1.5 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory requirements prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E1316 Terminology for Nondestructive Examinations

E543 Specification for Agencies Performing Nondestructive Testing

2.2 *ASNT Standards*[4]

SNT-TC-1A Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT-CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

2.3 *AIA Standards*[5]

NAS-410 Nondestructive Testing Personnel Qualification and Certification

3. Terminology

3.1 *Definitions*—Related terminology is defined in Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *corner reflection*—the reflected ultrasonic energy resulting from the interaction of ultrasound with the intersection of a flaw and the component surface at essentially 90 degrees.

3.2.2 *doublet*—two ultrasonic signals that appear on the screen simultaneously and move in unison as search unit is manipulated toward and away from the flaw. During tip-diffraction flaw sizing, the flaw tip signal and flaw base signal (corner reflector) will appear as a doublet.

3.2.3 *far-surface*—the surface of the examination piece opposite the surface on which the search unit is placed. (For example, when examining pipe from the outside surface the far-surface would be the inside pipe surface).

3.2.4 *focus*—the term as used in this document applies to dual crossed-beam search units that have been manufactured so that they have a maximum sensitivity at a predetermined depth or sound path in the component. Focusing effect may be obtained with the use of dual-element search units having both refracted and roof angles applied to each element.

3.2.5 *near-surface*—the surface of the examination piece on which the search unit is placed. (For example, when examining pipe from the outside surface the near-surface would be the outside pipe surface).

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[1] This guide is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Method.

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[2] This Standard Guide is adapted from material supplied to ASTM Subcommittee E07.06 by the Electric Power Research Institute (EPRI).

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org

[5] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA22209-3928, http://www.aia-aerospace.org.

***A Summary of Changes section appears at the end of this standard**

3.2.6 *sizing*—measurement of the through-wall height or depth dimension of a discontinuity or flaw.

3.2.7 *30-70-70*—term that is applied to the technique (and sometimes the search unit) using an incident angle that produces a nominal 70° L wave in the examination piece. Provided that a parallel far-surface exists, the 30° shear wave, produced simultaneously at the near surface, reflects as a 30° shear wave and generates a nominal 70° L wave as a result of mode conversion off the far-surface. The 70° L wave reflects off a planar flaw and is received by the search unit as a 70° L wave.

4. Summary of Guide

4.1 This guide describes methods for the following flaw sizing techniques.

4.1.1 Far-surface creeping wave or mode conversion method,

4.1.2 Flaw-tip-diffraction method,

4.1.3 Dual element bi-modal method, and

4.1.4 Dual element, (focused) longitudinal wave or dual element, (focused) shear wave methods.

4.2 In this guide, ultrasonic sound paths are generally shown diagrammatically by single lines in one plane that represent the center of the ultrasonic energy.

4.3 Additional information on flaw sizing techniques may be found in the references listed in the Bibliography section.

5. Significance and Use

5.1 The practices referenced in this document are applicable to measuring the height of planar flaws open to the surface that originate on the far-surface or near-surface of the component. These practices are applicable to through-wall sizing of mechanical or thermal fatigue flaws, stress corrosion flaws, or any other surface-connected planar flaws.

5.2 The techniques outlined describe proven ultrasonic flaw sizing practices and their associated limitations, using refracted longitudinal wave and shear wave techniques as applied to ferritic or austenitic components. Other materials may be examined using this guide with appropriate standardization reference blocks. The practices described are applicable to both manual and automated examinations.

5.3 The techniques recommended in this standard guide use Time of Flight (TOF) or Delta Time of Flight (ΔTOF) methods to accurately measure the flaw size. This guide does not include the use of signal amplitude methods to determine flaw size.

5.4 Generally, with these sizing methods the volume of material (or component thickness) to be sized is divided into thirds; the inner ⅓, the middle ⅓ and the near ⅓. Using the far-surface Creeping Wave Method the user can qualitatively segregate the flaw into the approximate ⅓ zone.

5.5 The sizing methods are used in ⅓ zones to quantitatively size the crack, that is, Tip-diffraction for the far ⅓, Bi-Modal method for the middle ⅓, and the Focused Longitudinal Wave or Focused Shear Wave Methods for the near ⅓ . These ⅓ zones are generally applicable to most sizing applications, however, the various sizing methods have applications outside these ⅓ zones provided a proper reference block and technique is demonstrated.

6. Basis of Application

6.1 The following items are subject to contractual agreement between the parties using or referencing this standard.

6.2 *Personnel Qualification*

6.2.1 If specified in the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, NAS-410, or a similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

6.3 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in Specification E543. The applicable edition of Specification E543 shall be specified in the contractual agreement.

6.4 *Procedures and Techniques*—The procedures and techniques to be utilized shall be as specified in the contractual agreement.

6.5 *Reporting Criteria/Acceptance Criteria*—Reporting criteria for the examination results are not specified in this standard, they shall be specified in the contractual agreement.

6.6 *Reexamination of Repaired/Reworked Items*—Reexamination of repaired/reworked items is not addressed in this standard and if required shall be specified in the contractual agreement.

7. Ultrasonic Flaw Sizing Methods

7.1 *30-70-70 Mode Conversion or Far-surface Creeping Wave Method*—The far-surface Creeping Wave or 30-70-70 Mode Conversion method (as illustrated in Fig. 1) provides qualitative additional depth sizing information. This method has considerable potential for use when approximating flaw size, or, determining that the flaw is far-surface connected.

7.1.1 *Excitation of Creeping Waves*—The excitation of refracted longitudinal waves is always accompanied by refracted shear waves. In the vicinity of the excitation, the separation between these two wave modes is not significantly distinct. At the surface, a longitudinal wave cannot exist independently of a shear wave because neither mode can comply with the boundary conditions for the homogeneous wave equation at the free surface alone; consequently, the so-called headwave is formed. The headwave is always generated if a wave mode with higher velocity (the longitudinal wave) is coupled to a wave mode with lower velocity (the direct shear wave) at an interface. The longitudinal wave continuously energizes the shear wave. It can be concluded that the longitudinal wave, which in fact "creeps" along the surface, is completely attenuated a short distance from the location of the excitation. (See Fig. 2 for generation of the near-side creeping wave). With the propagation of the near-surface creeping wave and its continuous conversion process at each point it reaches, the energy

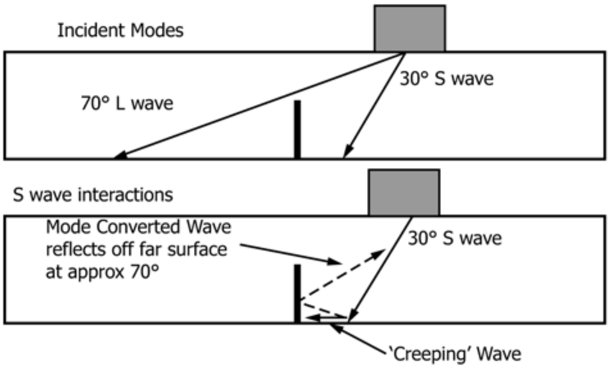


FIG. 1 Wave Generation for the Far-surface Creeping Wave/30-70-70 Mode-Conversion Search Unit

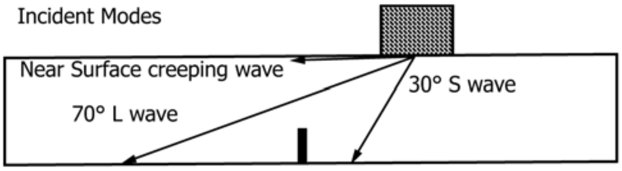
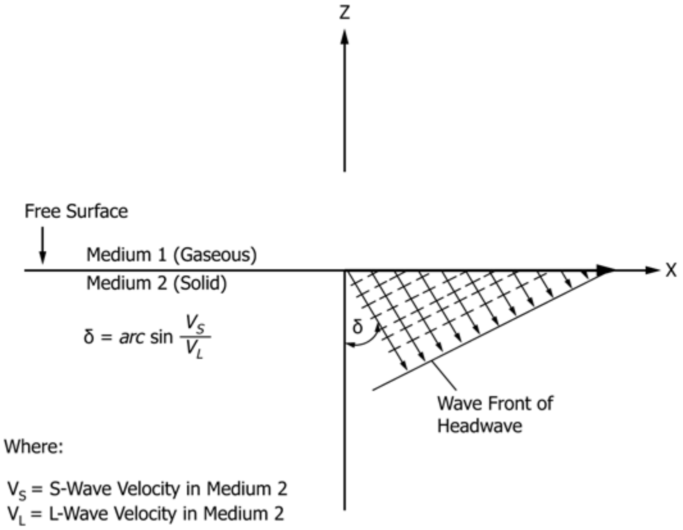


FIG. 2 Near-Surface Creeping Wave Occurs for a Short Distance in Association with the Incident Longitudinal Wave

converted to shear is directed into the material as shown in Fig. 3. Thus, the wave front of the headwave includes the head of the creeping wave, direct and indirect shear waves.

7.1.2 *Far-Surface Creeping Wave Generation*—When the headwave arrives at the far-surface of the component, the same wave modes will be generated which were responsible for generating the shear wave energy, due to the physical law of reciprocity. Thus, the indirect shear wave and part of the direct shear wave will convert into a far-surface creeping wave and a 70-degree longitudinal wave. The far-surface creeping wave will be extremely sensitive to small surface-breaking reflectors and the longitudinal wave will be engulfed in a bulk longitudinal beam created by beam spread. Additionally, these reflection mechanisms are responsible for a beam offset so that there is a maximum far-surface creeping wave sensitivity at about 5 to 6 mm (0.20 to 0.24 in.) from the ideal conversion point on the far surface. The sensitivity range of the far-surface creeping wave extends from approximately 2 to 13 mm (0.080 to 0.52 in.) in front of the index point. The far-surface creeping wave, as reflected from the base of a far-surface notch or flaw, will convert its energy into a headwave since the same principles apply as established earlier for the near-surface creeping wave. The shear wave will continue to convert at multiple V-paths if the material has low attenuation and noise levels.

7.1.3 *Typical Echoes of the Far-Surface Creeping Wave/30-70-70 Mode Conversion Technique*—When the search unit approaches a far-surface connected reflector, three different signals will occur in sequence: (*1*) 70-degree longitudinal wave direct reflection; (*2*) 30-70-70 mode-converted signal; and (*3*)



$\delta = arc\ sin \frac{V_S}{V_L}$

Where:

V_S = S-Wave Velocity in Medium 2
V_L = L-Wave Velocity in Medium 2

FIG. 3 Generation of S-Waves (Headwaves) by an L-Wave with Grazing Incidence

A far-surface creeping wave signal, as a result of mode conversion of the indirect shear wave.

7.1.3.1 *Direct Longitudinal Wave Signal*—If the flaw extends to within approximately 10 to 16 mm (0.375 to 0.625 in.) of the scanning surface (near surface), the direct longitudinal wave will reflect from the upper extremity of the flaw face, which is very similar to the high-angle longitudinal wave sizing method discussed later.

7.1.3.2 *Mode Converted Signal*—If the flaw exceeds a height of 10 to 20 % of the wall thickness, an indication from the mode converted signal will occur at a typical wall thickness-related position. This mode converted signal results from the headwave or direct shear wave, which mode converts the 70-degree longitudinal wave that impinges on the reflector at its highest part; it is reflected as a 70-degree longitudinal wave back to the search unit as depicted by position 1 in Fig. 4. The presence of the mode-converted echo is a strong indication of a flaw with a height greater than 10 to 20 % of the wall thickness. In the case of smooth or at least open flaws, amplitude versus height function curves can give a coarse estimate of flaw height.

7.1.3.3 *Far-Surface Creeping Wave Signal*—If a far-surface connected reflector is within the range of sensitivity (as described above), the far-surface creeping wave will be reflected and mode converted into the headwave or shear wave directed to the search unit (Fig. 5). Since the far-surface creeping wave is not a surface wave, it will not interact with weld root convexity and will not produce an indication from the root as shown by position 1 in Fig. 6. However, if the search unit is moved too far toward the weld centerline, the direct shear wave beam could result in a root signal, but there is at least 5 mm (0.2 in.) difference in positioning as shown in Fig. 6. The far-surface creeping wave signal is a clear, sharp signal with a larger amplitude than the mode converted signal. It does not have as smooth an echo-dynamic behavior as does the mode converted signal, and it cannot be observed over as long a distance as shown in Fig. 7.

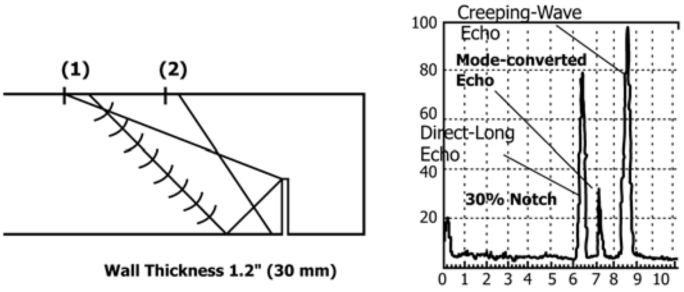
7.2 *Tip-Diffraction Method*—Ultrasonic diffraction is a phenomenon where ultrasound tends to bend around sharp corners or ends of an object placed in its path, as illustrated in Fig. 8. While the flaw tends to cast a shadow, diffraction occurs at the flaw tips and ultrasonic energy is bent to fill part of the shadow region. Sharp edges are diffraction centers tending to radiate spherical or cylindrical wave fronts as though they were actually ultrasonic point or line sources. If the screen signals correlating to these diffraction centers are identified, it is possible to determine their positions relative to the thickness of the component. The tip-diffraction method relies on this principle. Although the tip-diffraction concept sounds simple, there are many other signals that may complicate screen interpretation. This is due to the fact that the ultrasound/planar flaw interaction is very complex. When ultrasound strikes a flaw, specular reflection from the main plane of the flaw and texture reflections from flaw surface facets occur in addition to diffraction and mode conversions. There are two standardization and measuring techniques for tip-diffraction sizing: (*1*) The Time of Flight (TOF) technique that measures the arrival time of the tip-diffracted signal from the top of the flaw and locates the top of the flaw with respect to the near surface; and (*2*) The Delta Time of Flight (ΔTOF) technique that measures the difference in arrival time of the tip-diffracted signal and the corner reflector signal at the far surface.

7.2.1 *Time of Flight (TOF) Sizing Technique*—The TOF sizing technique is a tip-diffraction technique that takes advantage of uniquely locating the flaw tip. The signal from the flaw tip is peaked (maximized), and its arrival time or sound path is measured without regard to the arrival time of other signals. This time of flight or sound path is then a direct measurement of the remaining ligament (material) above the flaw, or the distance from the flaw tip to the examination surface. This technique is illustrated in Fig. 9. Note that here the second half-V path is possible also. When the search unit is moved away from the flaw, the tip echo may again be obtained after the tip-diffracted signal reflects off the opposite surface of the component. With the second half-V path technique, the tip signal will occur later in time than the signal from the flaw corner reflector.

NOTE 1—It is very important that the user be extremely conscious of the weld geometry when using the second half-V path since, for example, the counterbore can exaggerate flaw height.

NOTE 2—Longitudinal waves should not be applied when practicing the second half-V path technique as this can cause mode conversions that may interfere with the ability to interpret the instrument display.

7.2.2 *Delta Time of Flight (ΔTOF) Technique*—The ΔTOF Technique is applied by observing the arrival time difference between the flaw corner reflector signal and the diffracted signal from the flaw tip while both are simultaneously present on the ultrasonic instrument display. While using this technique, the ultrasonic beam diameter must be greater than the projected height of the flaw (actual height multiplied by the



1—Mode-Converted Signal
2—Far-Surface Creeping-Wave Signal

FIG. 4 Search Unit Index Point Position

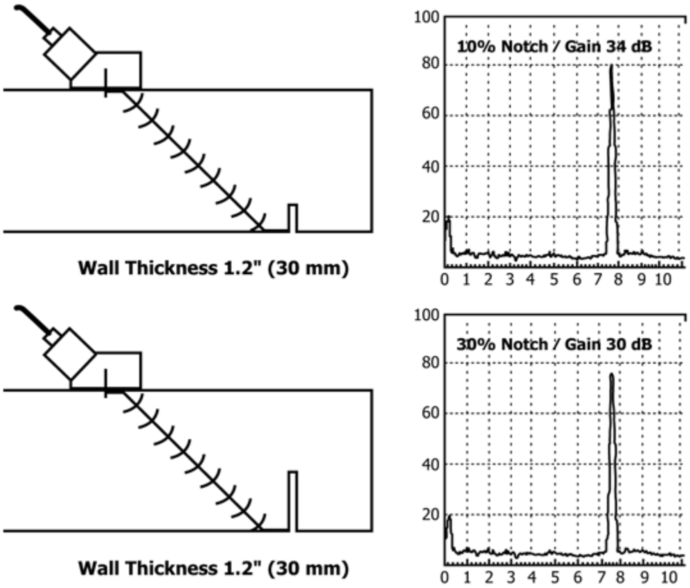
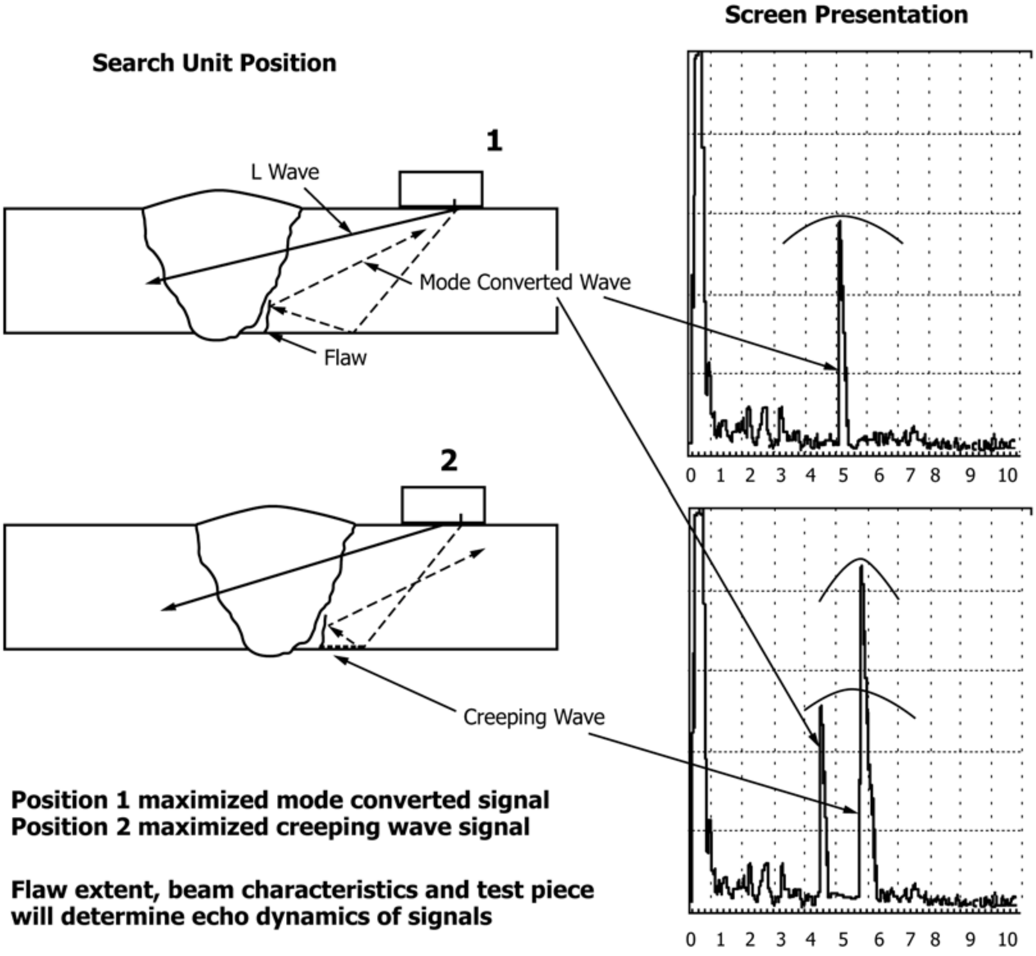


FIG. 5 Generation of Far-Surface Creeping Wave Signal



1—Flaw indication maximized for mode-converted wave signal
2—Flaw indication maximized for creeping-wave signal

FIG. 6 Far-Surface Creeping Wave Search Unit Position Related to Index Point

sine of the refracted beam angle) and the flaw must be essentially perpendicular to the examination surface. In this situation, the tip-diffracted signal will occur earlier in time due to its shorter sound path. The tip signal amplitude is very small

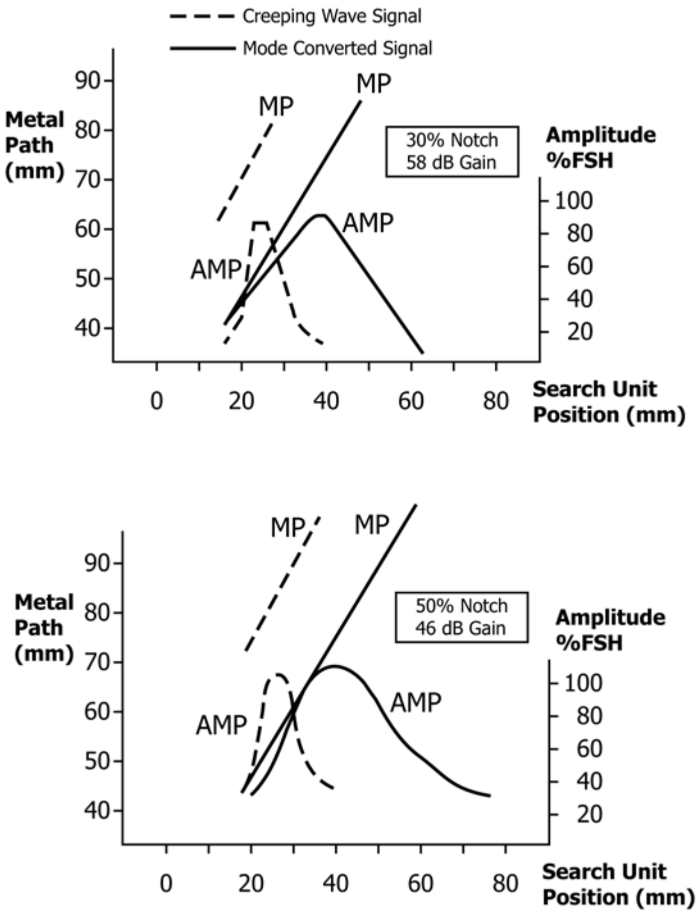


FIG. 7 Echo-Dynamic Behavior of Mode-Converted Echo Signal and Far-Surface Creeping-Wave Signal

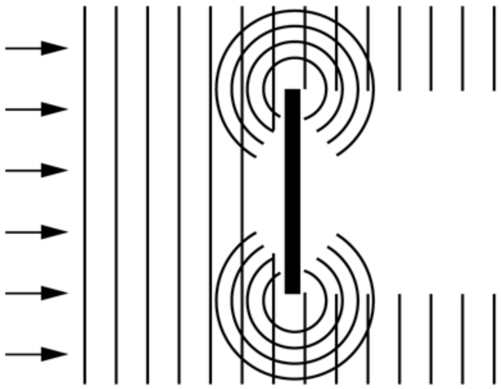


FIG. 8 Corners or Ends of Reflectors are Diffraction Centers and Tend to Radiate Spherical or Cylindrical Waves

in comparison to the flaw corner reflector signal; and the flaw tip and corner signals are out of phase due to one signal being diffracted and the other reflected twice. To measure flaw height, it is necessary to note the difference in the time of arrival between the two signals, then apply the following formula:

$$h = \frac{v(\delta t)}{2cos\theta}$$

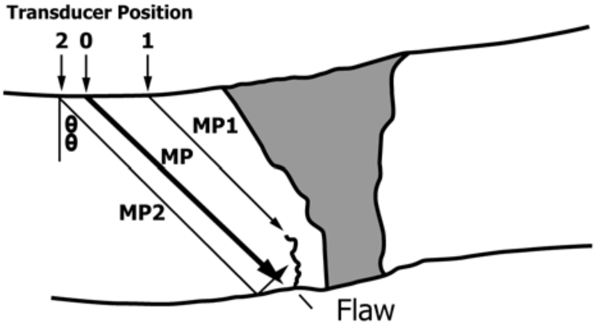


FIG. 9 Various Metal Paths (MP) from Different Search Unit Positions Used in the TOF Technique

where:

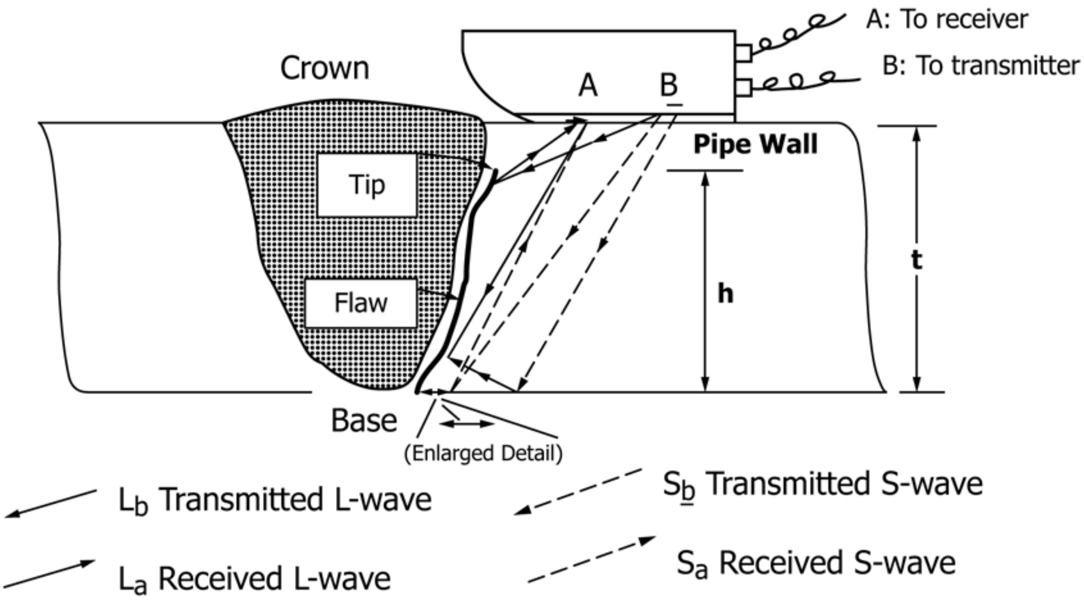
h = flaw height,
v = ultrasonic velocity in the material,
δt = difference in arrival time, and
θ = refracted beam angle.

Alternately, the ultrasonic instrument may be standardized to read directly in flaw height. This standardization method will be addressed in the standardization section. Separation between the doublets should remain constant as the signals move across the screen. The echo dynamic of the doublet is asynchronous; however, since it is the fixed interval between the doublet arrival times that is measured, it is not necessary to maximize the response from either signal. This technique allows measurement when the weld crown is wide, preventing maximization of the tip signal. It may also be possible to note a tip signal after reflection from the back surface (second half-V path). The principles are the same as for the first half-V path except that the tip signal will appear later in time than the corner reflector signal. Whether using the first or second half-V path, accuracy of the height measurement depends on the flaw orientation. If the flaw is vertical, then the measurement is accurate. If the flaw is oriented toward the search unit, the first half-V path measurement will overestimate the height and the second half-V path measurement will underestimate the height. The opposite occurs for flaws oriented away from the search unit.

7.2.3 *Application Considerations*—For all of the physics involved in tip diffraction, the method relies on the user's ability to uniquely identify the location of the flaw tip. The signal need not originate singly from diffraction, since reflection can also occur very near the flaw tip. In fact, reflection is the mechanism that will primarily be observed when using notched reference blocks. It is reasonable to expect some reflection to occur at an actual flaw tip. The associated rough texture will often act as a good scattering center. It should be noted, however, that this may not be true in every case and the amplitudes of the signals received may be 20-30 dB below the flaw corner-reflector signal amplitude. Each component and material type examined should be considered as a separate examination problem. The flawed area should be adequately scanned so that all signals, which occur in the region, can be identified. Care should be taken to define the tip signal since some geometries or weld flaws produce signals that can be readily confused with the true tip signal. Some flaws produce multiple tip signals that must be resolved. The ability of the operator to distinguish between tip and corner signals can be compromised if several cracks are clustered in the same area. In areas of clustered cracks, corner reflections will dominate and mask tip signals. In cases of clustered cracks, the depth of the peaked signal may be the only reliable means to distinguish the tip signals from the corner signals. The tip-diffraction methods can be valid for a wide range of flaw heights. The prerequisites are that the tip of the flaw and the tip signal be distinguishable from other signals. For very shallow flaws, the tip signal may be masked by the flaw corner-reflector signal due to poor resolution. A search unit with a shorter pulse duration will improve this limitation. Broadband search units have been noted for their short pulse durations; however, due to dispersion in austenitic stainless steel weld metal, it may be beneficial to select a narrow-band search unit with greater penetrating characteristics. This argument holds true for very deep flaws also. When the flaw is located in the weld region or very near the weld region, longitudinal waves may be considered for the tip-diffraction method. Longitudinal waves may help locate weak tip-diffracted signals in highly attenuative stainless steel but reflection from the component far surface should be avoided due to mode conversion. A very important factor in the sizing of planar flaws using the tip-diffraction method is signal pattern recognition. To size with this method, the user must be able to identify two signals: (*1*) a signal that is diffracted from the flaw tip and (*2*) a second signal that is reflected from the base of the flaw. The task of identifying the two signals is complicated by the high-amplitude noise signals and geometric signals from the component surface. Some ultrasonic instruments allow the user the option of using the un-rectified or rectified display (RF display) signals. In many cases, an RF display facilitates in distinguishing the tip signal from noise signals by identifying the phase of the signals. The signal from the tip of the flaw must always peak when the search unit is moved forward from the point where the corner signal is maximized (for first half-V path) or backed up from the point where the corner signal is maximized (for second half-V path). This distance traveled is directly related to flaw height. The examiner must become accustomed to the search unit movement as it relates to flaw height by becoming familiar with the characteristics observed when sizing notches of known heights.

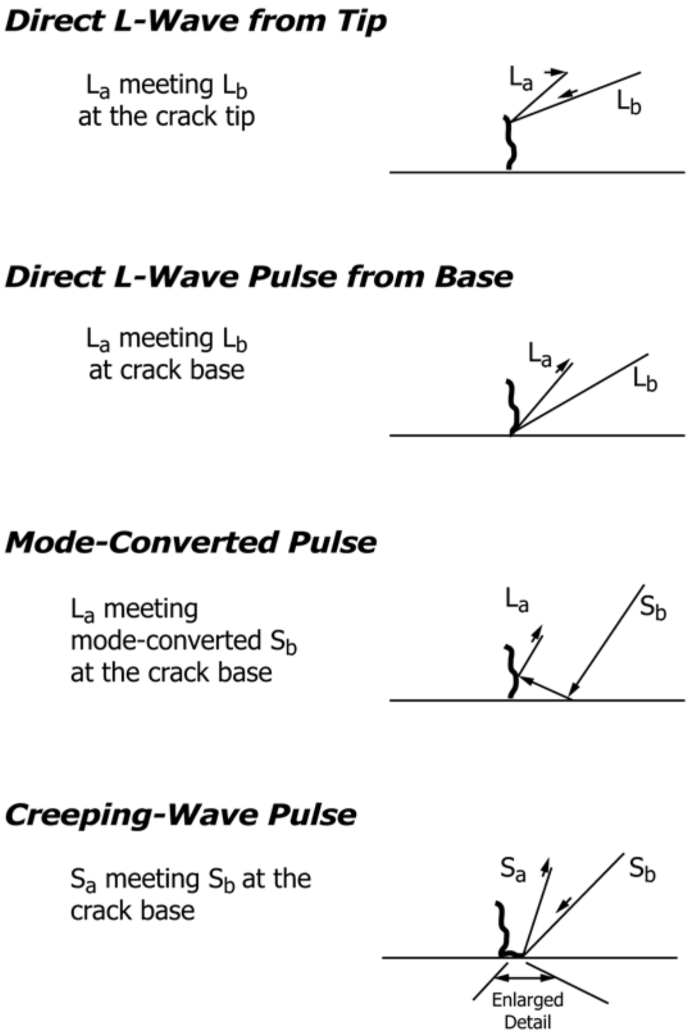
7.3 *Dual-Element Bi-Modal Method*—The Bi-Modal Sizing Method is based on the use of a dual-element search unit. This dual-element search unit is designed to insonify the entire wall thickness by transmitting and receiving high-angle refracted longitudinal waves as well as low-angle shear waves. For this reason, the Bi-Modal sizing methods that feature the dual-element search unit are applicable to far-surface connected planar flaws from 10 to 90 % through-wall. The TOF technique requires that the first signal, the longitudinal wave, be maximized or peaked and the peaked first signal is measured along the instrument time base which is standardized in through-wall depth. The ΔTOF technique is particularly useful because the flaw height-related separation between the direct longitudinal wave and mode-converted signal can be measured before the search unit is restricted by the weld crown. For the ΔTOF technique, both measurements are independent of signal amplitudes. A20 % far-surface notch and an 80 % far-surface notch are sufficient to standardize the time base for components in the thickness range of 10 to 40 mm (0.4 to 1.6 in.). Flaw height may then be read directly on the screen in percent of wall thickness. The extent of the flaw is indicated by the signals that are observed in the left half of the instrument screen. The further the direct longitudinal wave is peaked, or the greater the separation of the signals from the mode-converted signal, or peaks from mid-screen, the deeper the flaw. Signals originating from the interaction of shear waves with the base of the flaw, with or without mode conversion, are confined to the right half of the instrument screen and merely indicate that the flaw is far-surface connected.

7.3.1 *Wave Propagation Through the Material*—It is acknowledged that shear waves cannot interact effectively with the upper extremities of tight and branched, medium to large flaws that are located near the sound-scattering fusion lines of austenitic welds. These may not produce readily recognizable tip-diffracted signals for flaw sizing purposes. The Bi-Modal search unit is designed specifically for austenitic weld examination, however, this is also applicable to carbon steel materials. As shown in Fig. 10, the Bi-Modal search unit transmits one longitudinal wave, and two shear waves and receives two longitudinal waves (one from the tip of the flaw and one from the base of the flaw), one mode-converted signal from the flaw face, and one far-surface Creeping wave signal from the base of the flaw when the search unit is operated in its normal dual element mode. Depending upon search unit design, either element can be used as the transmitter or the receiver. The directivity patterns of the Bi-Modal search units are quite broad due to the relatively small active element size and low operating frequency in the region of 3 MHz. Therefore, the high-angle longitudinal waves and the low-angle shear waves insonify the entire component wall thickness. Four associated signals that move together on the instrument screen can be expected when the search unit is scanned over a far-surface connected flaw with broad back-and-forth movements, (Fig. 11). This follows from the premise that while the longitudinal waves interact effectively with both extremities of the flaw (the tip and the base), the shear waves interact only with the flaw base. The first signal originates from the upper tip of the flaw. If each element were a transmitter, the longitudinal wave energy from the two elements would converge to this area. The usually weak tip-diffracted signal is enhanced while the background of irrelevant indications is suppressed by restricting the longitudinal wave beams to the upper flaw tip area. The next signal can sometimes be observed from a flaw and is usually observed from a far-surface notch as a result of the longitudinal wave from the transmitter reflecting at the flaw base and being received as a longitudinal wave by the receiver. The third signal is usually the strongest because it results from the mode-converted shear wave from the face of the flaw. The reflection of the incident shear wave at the flaw opening results in the fourth signal which is analogous to the far-surface creeping wave signal. The echo-dynamic curve is broadest for the longitudinal wave signal and narrowest for the creeping wave signal as shown in Fig. 12. The mode-converted signal peaks shortly after the flaw is insonified. It follows from geometrical considerations that the echo-dynamic curves for



Subscript 'a' denotes travel to the receiver and subscript 'b' denotes travel from the transmitter. Enlarged detail note refers to Fig. 11.

FIG. 10 Bi-Modal Search Unit Longitudinal Wave and Shear Wave Signals



Subscripts as in Fig. 10.

FIG. 11 Interaction of the Incident L-Wave and S-Wave from a Bi-Modal Search Unit with a far-surface Connected Flaw Resulting in Four Associated Signals

the longitudinal wave signal and the far-surface creeping wave signal are nearly synchronous for a large flaw (that is, the rise in the amplitude of one signal is in unison with the amplitude rise of the other). When the center of the incident longitudinal wave beam is directed toward the flaw tip, the center of the incident shear wave beam is directed toward the flaw base, and the amplitude of the longitudinal wave signal, as well as that of the far-surface creeping wave signal, is maximized. Upon moving the search unit closer to the flaw, the longitudinal wave signal will again recede into the background of irrelevant indications. To determine the arrival time of this signal, the user typically moves the search unit toward the flaw until the amplitude drops.

7.3.2 *Principles of Bi-Modal TOF Technique*—Weld crown permitting, the search unit may be moved toward the weld far enough to peak the longitudinal wave signal. Fig. 13 shows that the relationship between the signal arrival time in screen divisions and the flaw height in percent of wall thickness is very nearly linear and independent of wall thickness.

7.3.3 *Principles of the ΔTOF Technique*—The longitudinal wave signal may be considered as a satellite of the mode-converted signal since their separation, measured in screen divisions, is practically independent of the axial coordinate of the search unit relative to that of the flaw. Figs. 14 and 15 illustrate the nearly linear relationship between normalized flaw height and this signal separation. The most useful feature of the Bi-Modal sizing method is that the flaw height can be measured anywhere along the length of the flaw as long as both the longitudinal wave and the mode-converted signals are seen moving in unison on the screen, allowing height measurements to be made even when a wide weld crown is present. A second ΔTOF measurement may sometimes be used to confirm the flaw height. This second measurement is obtained by noting the difference in arrival time of the longitudinal wave signal and the longitudinal wave signal reflected from the flaw base. These two signals also move in unison and form a linear relationship when the flaw is oriented vertically.

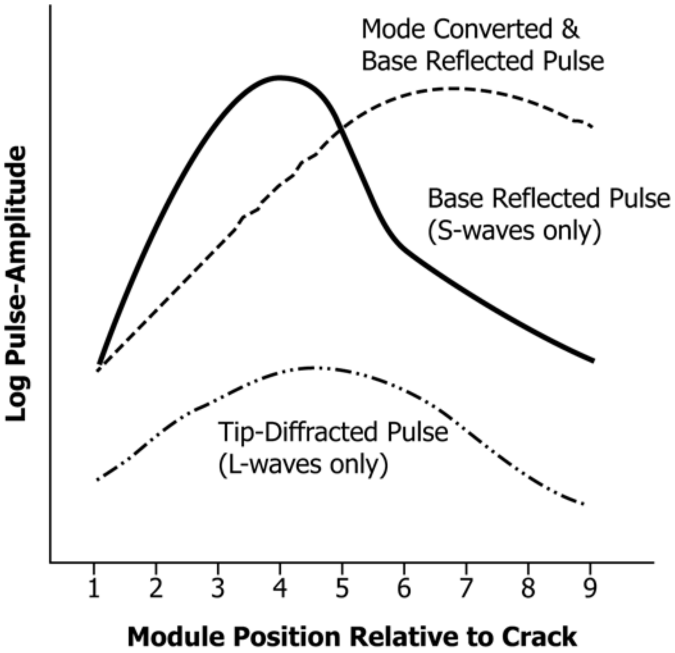


FIG. 12 Asynchronous Echo-Dynamic Curves for a 50 % Deep far-surface Notch

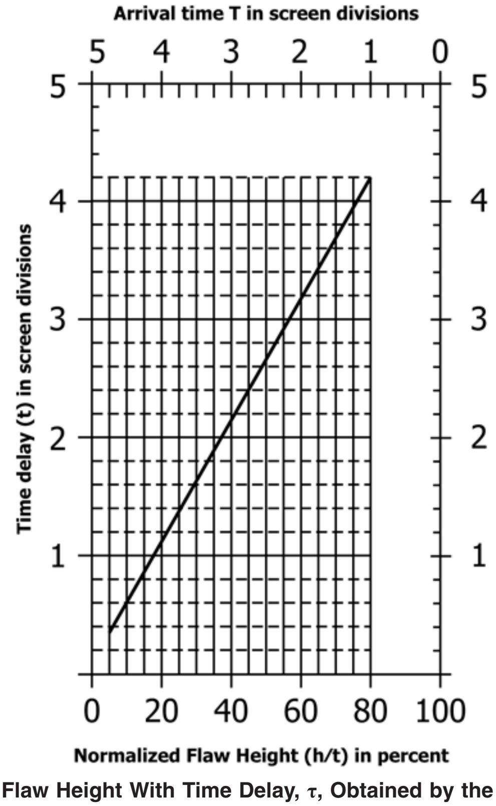


FIG. 13 Correlation of Normalized Flaw Height With Time Delay, τ, Obtained by the Bi-Modal Time of Flight Technique

7.4 *Focused Longitudinal Wave or Dual-Elements Focused Shear Wave Methods*—The dual-element focused longitudinal or dual-element focused shear wave flaw sizing techniques are essentially the TOF or sound-path measurement techniques with the use of focused longitudinal or shear wave search units, generally greater than 50 % from the far surface in depth. These techniques are particularly suitable for sizing flaws which are mid-wall to very deep. The use of high beam angles results in this technique being the most accurate for very deep flaws. As with the tip-diffraction method, the signal from the flaw tip is maximized or peaked and its time of flight or sound path is recorded without regard to the arrival time of other signals. The focused longitudinal wave and focused shear wave sizing techniques are used to measure the remaining ligament

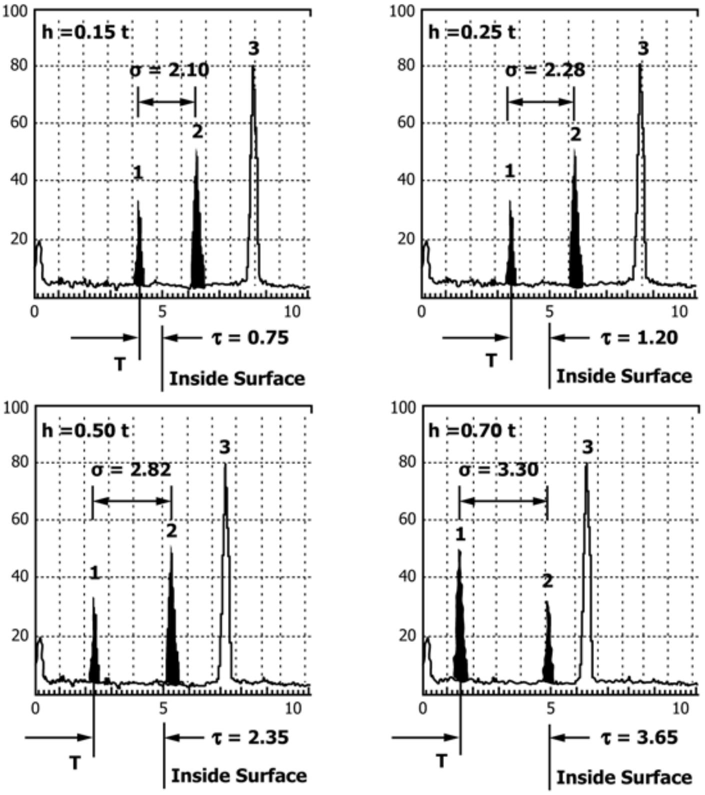


FIG. 14 Relationships Among Normalized Flaw Height, *h/t*, Doublet Separation, σ and Time Delay, τ

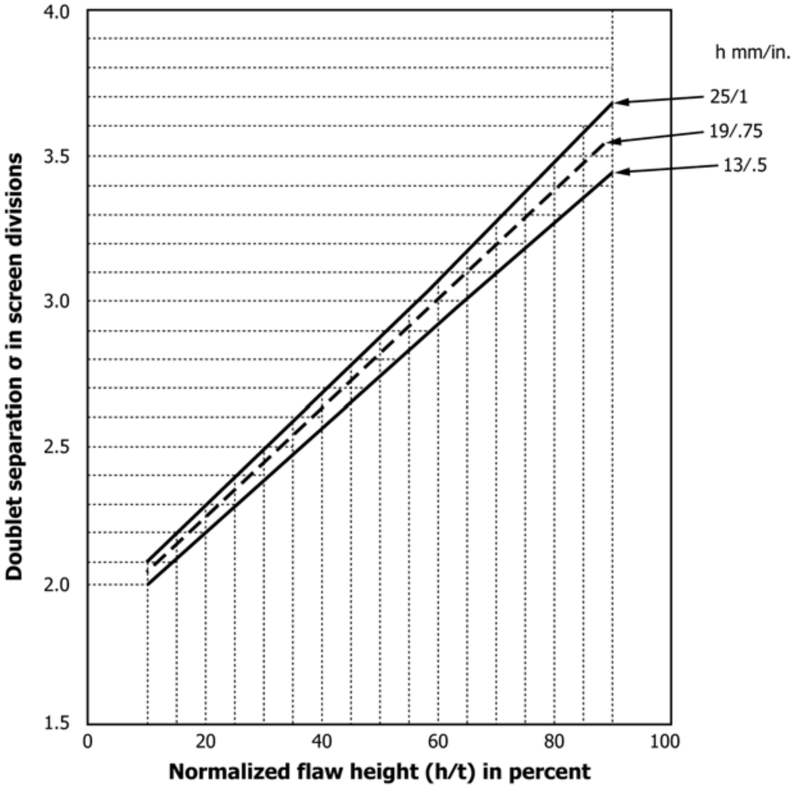


FIG. 15 Correlation of Normalized Flaw Height With Doublet Separation, σ, Obtained by the Bi-Modal ΔTOF Technique

of good material between the flaw and the scanning surface. Actual flaw height is obtained by subtracting the remaining ligament from the local wall thickness. Occasionally, the signal associated with the upper extreme of a flaw is due to beam reflection rather than diffraction. This is most prevalent when a flaw follows the weld fusion line toward the outside surface of the weld and is oriented away from the weld and the search unit is placed on the weld reinforcement and directed at the flaw. In this case instead of a diffracted wave returning to the search unit, the upper extreme of the flaw face reflects ultrasonic energy back to the search unit. The result is a high-amplitude signal with a long or broad echo-dynamic pattern. Due to an obliquely oriented flaw, a flaw height measurement obtained in this manner tends to undersize the flaw when the location of the peak reflection is used as the tip location. The user must compensate by moving the search unit toward the flaw until the signal drops by about 3 dB or by finding the slight rise in amplitude along the leading edge of the echo-dynamic pattern, which is due to the diffracted wave from the flaw tip.

NOTE 3—A limitation of this method with a focused longitudinal wave search unit is that associated shear waves (if not properly identified) may cause confusion and could result in mode-converted signals that may produce erroneous measurements.

Search unit frequency, refracted angle, element size, and focal depth are factors for determining the effective range of the technique. Common search unit frequencies are 2 MHz and 4 MHz, with the lower frequency preferred for coarse grain materials, for example, austenitic. The effectiveness of sizing with high-angle longitudinal waves is strongly dependent on the selection of a search unit that produces a beam shape appropriate to the application. When sizing a flaw in thin-wall material, select a beam angle that does not penetrate very deeply into the component. For thicker-wall material, increase the penetration depth by reducing the frequency to increase beam spread or by reducing the incident angle for a lower central refracted angle, that is, a 60-degree or a 45-degree longitudinal wave or shear wave search unit. It is essential to measure the focal depth of the search unit using a reference block that contains a series of known reflectors at different depths.

8. Ultrasonic Flaw Sizing Standardization Requirements

8.1 *Far-Surface Creeping Wave Method*—The far-surface Creeping Wave Sizing Method depends upon pattern recognition of the three potential signals that may be observed, for example, 70-degree L wave, the mode converted signal or the far-surface creeping wave signal. By observing the absence or presence of these three signals, the echo dynamics of the signal, and the time of flight of the 70-degree L wave signal, a user can classify a far-surface connected crack into the far ⅓, middle ⅓, or the near ⅓ zone of the material thickness to be inspected.

8.1.1 *Search Unit*—The pattern of the three signals strongly depends on several search unit parameters. Before attempting to apply this method with a new search unit, the sound wave patterns should be evaluated using known notch reflectors at various depths, 20 %, 40 %, 60 %, and 80 %. There may be significant variations between search units with identical faceplate parameter values, even if they are from the same manufacturer. Generally, a single-element search unit is suitable for most applications.

8.1.1.1 *Beam Angle*—The primary intent when sizing with the far-surface Creeping Wave method is to produce different beams at the far surface and utilize the responses from these beams to categorize flaw height. This goal is met by using 70-degree longitudinal waves or refracted longitudinal waves at 55 degrees and higher.

8.1.1.2 *Frequency*—To limit beam spread and its degradation of sizing accuracy, higher frequencies than those commonly used during examination are suggested. Narrow-band search units will avoid the beam spread caused by the low-frequency components of the spectrum. A frequency of 2 MHz seems ideal for austenitic material, while 4 MHz seems more effective for carbon steel materials.

8.1.1.3 *Elements*—Specially designed search units with single- or dual-element search units may be used. It is very difficult to eliminate internal wedge reflections and entry surface noise with a 70-degree, single-element search unit. These single-element problems can only be avoided with long wedge paths. This can lead to increased beam size and make search unit movement difficult. Element size is significant. Very small elements will have excessive angular beam spread, and very large elements may produce beams with too much penetration. The optimal size will probably be a function of wall thickness, with larger elements being acceptable for greater thickness. Generally, a 10 mm or a 0.375 in. diameter or square search unit will work for most applications.

8.1.1.4 *Contact Area*—The search unit contact area or "footprint" should be as small as practical. With dual search units, small search unit width is necessary for proper coupling of both elements to the scanning surface. Short length is desirable for adequate coupling in pipe weld conditions of diametrical weld shrinkage, especially if the shrinkage is made more severe by grinding of the weld crown. If the search unit is too long, there may be entry angle variations with strong effects on the refracted angle.

8.1.2 *Instrument*—A pulse-echo ultrasonic instrument capable of generating and receiving frequencies in the range of at least 1 to 5 MHz should be suitable for sizing with the far-surface Creeping Wave or 30-70-70 mode conversion method. The instrument should exhibit adequate resolution and high filtering capabilities.

8.1.3 *Reference Block*—Standardization for the far-surface Creeping Wave technique requires special far-surface notch reference blocks. The block must have a set of notches located at various depths from the far surface. The simplest design is a flat plate or pipe section with far-surface notches located at increments of 10 % or 20 % depths, for example, 10 %, 20 %, 40 %, 60 %, 80 %. The user should become familiar with the absence or presence of the 70-degree L wave signal, the time of flight of the 70-degree L wave signal, the amplitudes and echo-dynamic patterns of the mode-converted signal and the far-surface creeping wave signal as different depth notches are encountered. If these notches are used to familiarize the user with various signals that may be encountered, the block should equal the thickness of the component to be examined.

8.1.4 *System Standardization*—The far-surface Creeping Wave or 30-70-70 mode conversion technique does not depend on the arrival time of the flaw tip signal, so the system does not have to be standardized accurately for distance. The same search unit used for the refracted longitudinal wave sizing method may be used for the far-surface Creeping Wave technique. Use a notched block for standardization following these steps:

8.1.4.1 Adjust the delay to display the initial pulse at the left side of the screen.

8.1.4.2 Place the search unit near the end of the reference block. Observe the 70-degree mode converted L wave signal and creeping wave signals.

8.1.4.3 Peak the creeping wave signal, and adjust delay and range controls to position the 70-degree mode converted L wave and creeping wave signals at 4 and 5 screen divisions respectively.

8.1.4.4 Adjust the creeping wave signal amplitude to 80 to 100 % full screen height. Then increase the instrument amplitude by 8 dB. This reference level is now the primary scanning and evaluation level.

8.1.4.5 Place the search unit to peak the creeping wave signal from the 20 % notch. Record echo dynamic movement of the 70-degree mode converted L wave signal as the search unit is scanned toward and away from the far-surface connected notch.

8.1.4.6 Place the search unit to peak the creeping wave signal from the 40 % notch. Record the echo dynamic movement of the 70-degree mode converted L wave signal as the search unit is scanned toward and away from the far-surface connected notch. If present, record the amplitude of the 70-degree L wave signal.

8.1.4.7 Place the search unit to peak the creeping wave signal from the 60 % notch. Then record echo dynamic movement of the 70-degree mode converted L wave signal as the search unit is scanned toward and away from the far-surface connected notch. If present, record the amplitude of the 70-degree L wave signal. Increase the gain to bring the 70-degree L wave signal up to at least 40 % full screen height (FSH). Peak the longitudinal wave signal and record the horizontal screen division position, for example, 2.5 divisions.

8.1.4.8 Place the search unit to peak the creeping wave signal from the 80 % notch. Then record echo dynamic movement of the 70-degree mode converted L wave signal as the search unit is scanned toward and away from the 80 % notch. Record the amplitude of the 70-degree L wave signal. Increase the gain to bring the 70-degree L wave signal up to at least 40 % FSH. Peak the L wave signal and record the horizontal screen division position, for example, 1.8 divisions.

8.1.4.9 A typical sequence of recordings is shown below. These values will be relative to the search unit design and frequency, and material type and thickness.

Notch Depth	70° L Wave	Creeping Wave Signal	70-degree Mode Converted L Wave Signal
20 %	none	2.5 divisions	yes
40 %	none	3.5 divisions	yes
60 %	2.5 divisions	4.5 divisions	yes
80 %	1.8 divisions	5.5 divisions	yes

8.2 *Tip-Diffraction Method*—The tip-diffraction method depends primarily on the arrival time of the flaw tip signal and, in some cases, on the arrival time of the flaw base or corner signal. Consequently, it is important to standardize the screen accurately for sound path, however, it is always acceptable to standardize the screen to read directly in depth as a function of a percent of component thickness. This approach is generally more convenient.

8.2.1 *Search Units*—When selecting a search unit for sizing planar flaws using the tip-diffraction method, the following guidelines should be considered: (*1*) A very high signal-to-noise ratio is desired. This characteristic is governed by the frequency, diameter, and wave mode; (*2*) High-resolution search units (higher frequency, shorter pulse length) will aid in sizing very shallow flaws because the tip and base signals are close together and nearly coincident in time; (*3*) High-resolution search units work well with the time of flight (TOF) technique; (*4*) Large beam spread may be beneficial when sizing suspected midrange flaws with the delta time of flight technique because this technique requires viewing of the tip and base signals simultaneously; (*5*) The characteristics of the search unit selected should be thoroughly investigated with reference blocks before attempting any sizing techniques; (*6*) Longitudinal waves can enhance the tip signal but may produce spurious mode-converted indications; (*7*) The distance from the front of the search unit to the beam index point should be minimal in order to maximize the diffracted signal from the flaw tip when a wide weld crown is present; and (*8*) Beware of reflections that may occur from within the search unit wedge. These can occur in the area of interest on the display and can increase the difficulty of identifying the tip signal. Various search unit designs with different element sizes and arrangements can be used. It must be pointed out that the individual search unit design parameters greatly influence their effectiveness. For the Tip-diffraction method using delta time of flight technique, a search unit that is highly damped to a maximum pulse length of one and one half to two cycles at the -6 dB points is desirable. This will improve resolution for sizing very shallow flaws, that is, less than 10 % wall thickness. Search unit characteristics must be documented adequately prior to use if examination repeatability is necessary.

8.2.1.1 *Beam Angle*—Refracted beam angles in the range of 40 to 60° can generally be used with the tip-diffraction method. Due to the long sound paths involved in the second half-V path technique, it is preferable to use refracted angles in the range of 40 to 52° from the perpendicular. Higher beam angles require longer metal path distances and the energy may be attenuated to an almost nonexistent level.

8.2.1.2 *Frequency*—Search units may have either single or dual elements in the nominal frequency range of 2 to 5 MHz. Favorable results have been obtained with nominal frequencies of 4 and 5 MHz when the sizing is limited to the first half-V path and height of the flaw is minimal. To maintain penetration of shear waves through large-grain base metal structures, low frequencies such as 2.25 MHz are desirable. However, this low frequency does result in a sizeable amount of beam spread, which reduces the accuracy of the sizing method. Occasionally, tip-diffracted signals are detected with lower frequencies (for example, 1.5 MHz). The tip signal should be noted if identified during the flaw detection process. The flaw depth should then be measured using higher frequencies.

8.2.1.3 *Propagation Mode*—Either shear or longitudinal waves may be used for the tip-diffraction sizing techniques when using the first half-V path technique. Due to the high attenuation of stainless steel, longitudinal waves may present higher amplitude tip-diffracted signals, but decreased resolution. Longitudinal waves are impractical with the second half-V path technique since the search unit also produces a shear wave which may cause confusion. Also, the longitudinal wave tends to mode convert to shear wave as the ultrasonic beam reflects at the opposite surface. The large amount of mode conversion reduces the signal-to-noise ratio even more. Additionally, the presence of many spurious signals from the various mode converted signals may present the user with more opportunities to select the wrong signal and misidentify it as the flaw tip.

8.2.2 *Instrument*—A pulse-echo instrument capable of generating and receiving frequencies in the range of at least 1 to 5 MHz is suitable for sizing with the tip-diffraction method. Avoid screen displays showing signals that have minimal filtering. Horizontal linearity should be within 2 % of full screen width. The ability to view the full, unrectified RF waveform is helpful during sizing. It is recommended that ultrasonic instruments capable of displaying the RF waveform be used.

8.2.3 *Reference Blocks*—The reference block (or blocks) should contain special reference reflectors (for example, notches having various depths) that pertain to the standardization for specific sizing technique(s). To standardize the time base, use 25 mm (1 in.) thick, flat plate of material similar to the component to be examined. This plate should have notches from 10 to 90 % deep in steps of 10 %. The most desirable reference block is the same thickness as the component containing the flaw to be sized, but standardization can be accomplished with any known thickness.

8.2.4 *System Standardization*—The tip-diffraction method depends primarily on arrival time differences between the pulses from the base of the flaw and the flaw tip. It is, therefore, important that the screen be standardized accurately for sound path. Sound path standardization may be accomplished in exactly the same fashion as the standardization for flaw detection if it is limited to second half-V path. The horizontal sweep is standardized in inches or mm of sound path along the beam path. Any reference block used for sweep distance standardization may be used, for example, IIW, DSC, etc. There is an alternative sweep standardization which is simple and results in higher accuracy. In this case, the horizontal sweep is standardized in depth. A reference block consisting of a series of far-surface connected notches is required (see Fig. 16).

8.2.4.1 *Standardization for the Time of Flight (TOF) Technique* To standardize for direct flaw depth measurements when using the time of flight (TOF) technique:

NOTE 4—The first 5 steps are a simple technique to establish a coarse standardization.

(1) Select a suitable reference block with at least two notches of known depths, bracketing the flaw depth range of interest, for example, 20 % and 80 % deep notches.

(2) As a ranging technique, place the search unit to obtain the far-surface corner of the end of the reference block.

(3) Peak this half-V path signal and using the delay control adjust this signal to 5 horizontal screen divisions.

(4) Move the search unit from the end of the block to peak the near-surface signal at the edge of the reference block and, using the range control, adjust this full-V path signal to 10 screen divisions.

(5) Alternate between the delay and range controls to set the far-surface corner to 5 divisions and the near-surface corner to 10 divisions.

(6) Locate the base signal or corner signal of the 80 % far-surface notch. Move the search unit forward to peak the tip-diffracted signal from the tip or edge of the notch. Using the delay control adjust this signal to 1 horizontal screen division.

(7) Locate the 20 % far-surface notch to obtain the base or corner signal. Move the search unit forward to peak the tip-diffracted signal from the tip or edge of the notch. Using the fine range control adjust the peaked signal to 4 screen divisions.

(8) Alternate between the delay and range controls to set the 80 % tip signal to 1 screen division and the 20 % tip signal to 4 divisions.

Screen Divisions	Depth from Far-Surface
0	100 %
1	80 %
2	60 %
3	40 %
4	20 %
5	0 %

8.2.4.2 *Standardization for Delta Time of Flight Technique (Direct Flaw Depth Measurement)*—Standardize the ultrasonic instrument as in 8.2.4.1, record the screen divisions of separation for the base and tip-diffracted signals for each of the notches. They will be approximately as follows:

Notch Depth	Divisions of Separation
20 %	0.5 Divisions
40 %	1.0 Divisions
60 %	1.5 Divisions
80 %	N/A

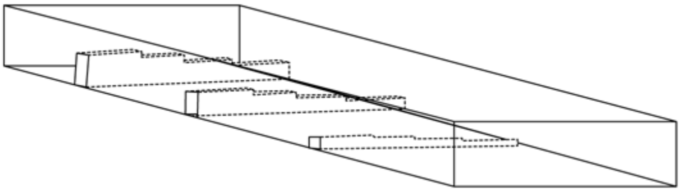


FIG. 16 Sizing Reference Block

With the deeper notches, that is, 60 % and 80 %, the tip and the base signal may not be seen on the instrument screen due to limited beam spread of the search unit.

8.3 *Bi-Modal Technique:*

8.3.1 *Search Unit*—The Bi-Modal search unit consists of two moderately damped search units, one mounted behind the other (tandem design) on a plastic wedge with two refracting wedge angles. Both elements are bi-modal, that is, each is capable of transmitting and receiving both a longitudinal wave and a shear wave signal. The roles of the two elements can be interchanged.

8.3.1.1 *Beam Angles*—In the transmit-receive mode of operation, one element transmits a high-angle longitudinal wave beam as well as a low-angle shear wave. The other element is directed to receive all sound waves emanating from the upper and lower extremities of a far-surface connected flaw.

8.3.1.2 *Mode of Propagation*—The search unit transmits and receives both longitudinal and shear wave signals.

8.3.2 *Instrument*—A pulse-echo, ultrasonic instrument capable of generating and receiving frequencies in the range of at least 1 to 5 MHz with linear and stable time base should be suitable for sizing with the multi-pulse observation sizing method. An RF display mode is not required, but is desirable.

8.3.3 *Reference Block*—Standardization for this sizing method also requires special reference blocks. As with the other sizing methods referenced in this document, the reference block must have a set of planar notches located at various depths from the far surface. Using additional blocks, the user should become familiar with the echo-dynamic patterns of the various signals expected from components of known thickness.

8.3.4 *System Standardization*—A reference block containing far-surface notches as in Fig. 16 or Fig. 17 is necessary to standardize the time base of the ultrasonic instrument. Each notch in a 25 mm (1 in.) thick reference block increases by 5 mm (0.2 in.) or 20 % depth increments.

8.3.4.1 Standardization for the Time of Flight technique should be conducted as follows:

(1) Position the Bi-Modal search unit at the edge of the reference block to display the three primary signals, that is, the refracted L wave signal, the mode converted shear wave signal, and the far-surface Creeping wave signal.

(2) As a ranging technique, using the range control, separate the second and third signals by approximately 2.0 screen divisions.

(3) Position the Bi-Modal search unit to peak the refracted L wave signal from the 80 % far-surface connected notch. Adjust the delay control to position this to 1 horizontal screen division.

(4) Position the Bi-Modal search unit to peak the refracted L wave signal from the 20 % far-surface connected notch. Adjust the range control to position this to 4th horizontal screen division.

(5) Alternating between delay and range controls ensure the signal from the 80 % notch is at screen division 1 and the 40 % notch signal is at the screen division 4.

(6) The instrument is now standardized such that 5 screen divisions equals 0 % and 0 screen divisions equals 100 % through-wall depth.

8.3.4.2 Standardization for the Delta Time of Flight technique should be conducted as follows. With the Time of Flight standardization set, record the separation in horizontal screen divisions between the refracted L wave and mode converted signals. Approximate values are shown below:

20 % Notch	2.1 Screen Divisions
40 % Notch	2.5 Screen Divisions
60 % Notch	2.9 Screen Divisions
80 % Notch	3.3 Screen Divisions

8.4 *Dual-Element Focused Longitudinal or Focused Shear Wave Methods*—As with the tip-diffraction TOF technique, high-angle focused longitudinal wave or focused shear wave methods also depend primarily on the sound path travel of the flaw tip signal. It is important that the screen be standardized accurately for sound path distance; however, it is always possible to standardize the screen to read directly in depth. The depth approach is preferred.

8.4.1 *Search Units*—The focal depth of the longitudinal wave and shear wave search units depends on several search unit parameters. Before attempting to apply this sizing method with a new search unit, it is essential to determine the focal depth of the search unit with known reflectors at known depths. Results between search units having identical faceplate parameter values may vary significantly even if they are from the

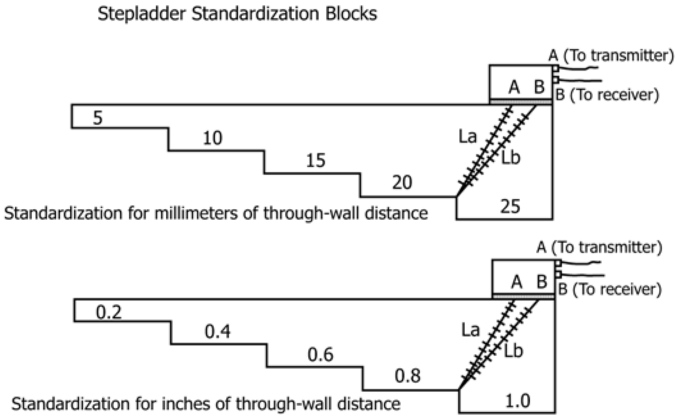


FIG. 17 A Bi-Modal Search Unit Positioned on the Reference Block for Maximum L-wave Signal Amplitude from the Fourth Step

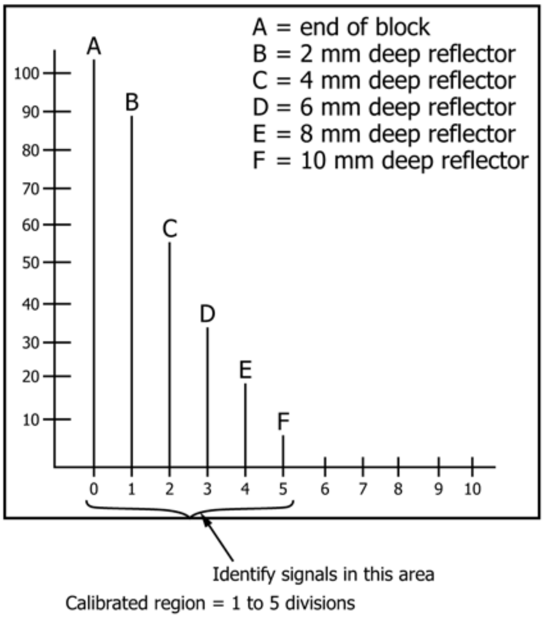


FIG. 18 Focused Longitudinal Wave or Focused Shear Wave Standardization

same manufacturer. Search unit selection should be based on the component thickness and depth of penetration. The objective is to insonify a layer of the component thickness under the near surface without penetrating to the opposite surface.

8.4.1.1 *Beam Angle*—The primary intent when sizing with the focused longitudinal or focused shear wave techniques is to limit the penetration of the beam into the component in order to avoid confusion from unidentifiable ultrasonic signals. Focused search units should only be used with the first half-V path technique. Dependent upon the examination volume (near ⅓ thickness), 45, 60, 70 degree L-waves or shear waves, and near-surface Creeping Waves may be used.

8.4.1.2 *Frequency*—To limit beam spread and its negative effect on sizing accuracy, it is desirable to use higher frequencies than those commonly used during flaw detection. Narrowband search units should be used to limit the beam spread caused by the low-frequency components of the spectrum. Ideally, the transmitting element should have a tuning circuit that will optimize the effects of possible pulser impedance variations on the frequency spectrum. If the frequency is too high, then the penetration depth will be inadequate for locating any but the deepest flaws. A search unit of 4 or 5 MHz should permit quantitative sizing of flaws that reach to the near ⅓ thickness of the near surface. Lower frequencies of 2 and 3 MHz are acceptable dependent upon the depth of penetration desired.

8.4.1.3 *Elements*—Either single or dual-element search units may be used. Note that it is very difficult to eliminate internal wedge reflections and entry surface noise when using a single-element search unit for high-angle longitudinal wave examination. These single-element problems can only be avoided with the use of larger wedges, however, this can lead to increased beam size and difficult search unit manipulation. Element size is an important consideration. Very small elements will have excessive angular beam spread, and very large elements may produce beams with too much penetration. The optimal size will probably be a function of depth of penetration and wall thickness, with larger elements being acceptable for greater thicknesses.

8.4.1.4 *Contact Area*—The search unit contact area or "foot print" should be small. With dual-element search units, small search unit width is necessary for proper coupling of both elements to the surface. Short length is desirable for adequate coupling in conditions of diametrical weld shrinkage, especially if the shrinkage is made more severe by grinding of the weld crown.

8.4.1.5 *Focal Depth or Focal Sound Path*—Dual-element search units focus at a point directly beneath or only slightly ahead of the housing to maximize the signal. This is the point at which the sound beams would cross or Beam Crossover Point. This may result in insufficient access to deep flaws if the weld crown is present. The exit point-to-front of search unit distance should be as small as practical and the crossover point distance should be as long as practical. The focal sound path is generally noted for each type of focused dual-element search unit. The more important measurement is the focal depth of the search unit. This can be calculated by the following formula:

$$FD = FS\left(\text{Cos of the refracted angle of the search unit}\right)$$

where:

FD = focal depth, and
FS = focal sound path.

8.4.2 *Instrument*—A pulse-echo ultrasonic instrument capable of generating and receiving frequencies in the range of at least 1 to 5 MHz should be suitable for sizing using the high-angle longitudinal wave method. Horizontal linearity should be within 2 % of full screen width. The system should exhibit adequate resolution and high filtering capabilities.

8.4.3 *Reference Block*—Standardization for the focused longitudinal wave or focused shear wave sizing techniques requires special reference blocks. The block must have a set of planar or rounded reflectors located at various depths from the examination surface. An example is a flat plate or pipe section with far-surface notches located at increments of 2 mm depth below the near surface, that is, 2 mm, 4 mm, 6 mm, etc. (or if in inch units, 0.10 in., 0.20 in., 0.30 in., 0.40 in., etc.). Alternatively, a reference block with side-drilled holes located at increments of 2 mm (or inch equivalent) in depth below the near surface can be used. The signals noted from the holes are due to reflection rather than diffraction, and the central part of the ultrasonic beam is apparently bent as it propagates into the component, resulting in the beam interacting with the holes at various depths. The beam may reflect off of the side of the hole at the 2 mm depth and near the top of the hole at the 10 mm depth. This is dependent upon the refracted angle of the search unit and the depth of the hole. Starting with the notch or hole located 2 mm (or inch equivalent) in depth below the near surface, set the ultrasonic response from the notch tip at 1 horizontal screen division. Standardize the instrument screen so that each horizontal division represents 2 mm (or inch equivalent) of depth into the component. The beam entry point is placed at the extreme left side of the screen. It is also useful to observe the response from either a near-surface notch or the end of the block. These signals appear at the same horizontal position as a 100 % through-wall flaw. When a planar flaw signal is obtained and maximized, its distance below the near surface will be indicated by the time-of-flight (sweep position), or depth from the near surface. This dimension is subtracted from the local thickness of the component to determine the flaw height. If notches are used, the block should be of the same thickness as the component. If the reference block is used only for establishing the screen distance standardization, its thickness is not important provided that it is a known thickness and it is thick enough to fully characterize the ultrasonic beam.

8.4.4 *System Standardization*—The focused longitudinal wave or focused shear wave techniques depend primarily on the time of flight or sound path. The instrument must be standardized accurately for distance or depth. Standardization may be performed using a notched block.

8.4.4.1 Adjust the delay to display the initial pulse at the left side of the screen.

8.4.4.2 Obtain a signal from the end of the reference block with the index point placed very near the block end. This will not be a corner reflection from the bottom of the block; it will be a reflection from the top part of the end of the block. Verify that the correct signal is obtained by finger-damping near the top of the end face.

8.4.4.3 Adjust the delay and range controls to place the end-of-block signal at 0 horizontal divisions.

8.4.4.4 Place the search unit index point directly above the reference notch or hole located at 2 mm (or inch equivalent) from the near surface. Move the search unit backward, slowly. With focused L waves, one or more signals from the associated shear wave component may appear. Continue to move back until a separate signal appears. This will be the focused longitudinal wave or focused shear wave signal. It can be recognized by the fact that it usually travels more along the screen baseline than the mode converted signals.

8.4.4.5 When the focused L wave or focused shear wave signal is maximized, visually verify that the search unit index point is in the proper position to detect the reflector with a high beam angle. Adjust the delay control to place this signal at 1 division.

8.4.4.6 Obtain and maximize the high-angle longitudinal wave or shear wave signal from the notch or hole located at the desired depth below the near surface, for example, 12 mm or typically 0.5 in. if using inch reference blocks. Adjust the range control to place this signal at 5 screen divisions.

8.4.4.7 Continue with the other notch or hole signals until they are too far from the near surface to be detected with a signal-to-noise ratio of at least 3. Increase instrument gain as necessary.

8.4.5 The screen setup should now be as follows:

Reflector Signal	Horizontal Divisions
End of block	0
2 mm deep	1
4 mm deep	2
6 mm deep	3
8 mm deep	4
10 mm deep	5 (may not be detectable: dependent on search unit)

(For inch standardization, select accordingly). See Fig. 18.

The standardized region of the screen is from 1 division to the position of 10 mm below the surface. As a general rule, do not attempt to size cracks outside this standardized range. Instrument gain will likely need to be increased to obtain the last one or two signals. Also, the near-surface notch signal would be well over 100 % full screen height. Note that the area of the screen where the mode converted shear wave signals appear from the far surface is to the right half of the screen outside the standardization region.

9. Sizing Applications

9.1 *Far-Surface Creeping Wave or Mode Conversion Technique*—Once the flaw's existence has been verified with the detection and characterization techniques, the next decision is to estimate the vertical extent of the flaw as measured from the far surface. The far-surface Creeping Wave or Mode Conversion Method will place the flaw into ⅓-depth zones. The far-surface Creeping Wave method will provide a qualitative estimate of the flaw depth. The technique also confirms that a flaw is surface connected by the presence of the Creeping Wave signal. The component thickness is divided into ⅓ thickness zones; far ⅓, middle ⅓ and the near ⅓ volume or zone. Using the far-surface creeping wave, the user can approximate the flaw depth into one of the ⅓ zones. Once the flaw is qualitatively sized, for example, 20 to 30 % deep, then the other sizing methods and techniques are used to provide a finite flaw depth estimate, for example, 23 % through-wall. Generally, the following steps are used for evaluation with the far-surface creeping wave to approximate the flaw depth. However, the standardization performed on the reference blocks addressed in Section 8 is used for comparison with signals observed on an actual far-surface connected flaw. If only the far-surface creeping wave signal is observed, the flaw is approximated to less than 10 to 15 % depth. If the far-surface creeping wave signal and the mode converted signal, are observed, the flaw is approximated to greater than 15 to 20 %

depth. If the far-surface creeping wave signal, the mode converted signal, and a 70-degree L wave are observed, the flaw is approximated to greater than 40 to 50 % depth.

NOTE 5—These estimates are a typical evaluation from a far-surface-notch reference block. These estimates will vary with type of search unit, frequency, size, material thickness and type. Another key point is to observe the echo dynamics of the mode converted signal. A broad echo dynamic movement of the mode converted signal would confirm the presence of a 70-degree L wave signal to verify a deep flaw greater than 40 to 50 % through wall.

9.2 *Tip-Diffraction Technique*—Tip-diffraction sizing may be performed using the first or second half-V path techniques, and the user may choose either the Time of Flight (TOF) or the Delta Time of Flight (ΔTOF) techniques. The results should be the same if the flaw is vertical and the actual material thickness is known. If more than one of these combinations of methods is used and different results are obtained, the user must determine whether to accept the results of one method or disregard all results and attempt sizing with one of the other two methods. If the flaw is not vertical, the ΔTOF technique will provide inaccurate results; therefore if the flaw is suspected to be oriented other than essentially vertical, the user should choose the TOF technique. Experience has shown that occasionally the second half-V path, TOF technique may exaggerate the flaw height as the ultrasonic beam may be redirected slightly at the reflection. This leads to the conclusion that the first half-V path technique is more accurate and the second half-V path data is used only for confirmation of flaw height in the middle to outer ⅓ volume of material.

9.2.1 *First Half-V Path Technique:*

9.2.1.1 *Time of Flight Technique*—After the specific area containing the far-surface connected planar flaw is identified, position the search unit to obtain a signal from the flaw base at half-V path. Move the search unit forward to obtain the diffracted signal from the flaw tip. If the signal is observed, peak the diffracted wave signal from the flaw tip, then measure the sound-path distance to the signal. This distance reveals the amount of material above the flaw tip. The flaw height is then determined by subtracting this dimension from the local material thickness. Fig. 19 shows the display of a first half-V path TOF standardization and the ultrasonic beam paths related to that standardization.

9.2.1.2 *Delta Time of Flight Technique*—After the specific area containing the planar flaw is identified, position the search unit to obtain a signal from the flaw base at half-V path. Move the search unit toward the flaw and back again and look for evidence of a tip-diffracted signal moving in unison with the flaw base signal (a doublet). If the doublet is observed, measure the time difference between the two signals, (the tip signal and the flaw base signal). The separation indicates the height of the flaw, according to the standardization. Fig. 20 shows the instrument display of a first half-V path Delta Time of Flight Technique standardization and a sketch of the ultrasonic beam paths relative to the far-surface notches in the reference block.

9.2.2 *Second Half-V Path Technique:*

9.2.2.1 *Time of Flight (TOF) Technique*—After the specific area containing the planar flaw is identified, position the search unit to obtain a signal from the flaw base at half-V path. Move the search unit away from the flaw to obtain the diffracted wave signal from the tip of the flaw after reflecting from the far surface. If the signal is observed, peak the diffracted wave signal from the flaw tip, then measure the distance to the signal. Subtracting the local wall thickness from this measurement reveals the flaw height. Fig. 21 shows the display of a second half-V path Time of Flight (TOF) Technique standardization and the ultrasonic beam paths related to that standardization. This technique may be effective for wide weld crowns which would not allow for effective use of the first half-V path technique. If the tip signal is not observed but there is the presence of a second half-V path corner reflector signal, this would indicate the presence of a very deep flaw. This signal would only provide qualitative information that the flaw was very large. This may occur in highly attenuative material, such as with austenitic stainless steel, or when the tip signal cannot be resolved from the upper corner reflector signal. If both the tip and the upper corner signal are present, which can occur with less attenuative material, then both a quantitative and a confirming qualitative signal are attained as illustrated in Fig. 22.

9.2.2.2 *Delta Time of Flight Technique*—After the specific area containing the planar flaw is identified, position the search unit to obtain a signal from the flaw base at half-V path. Move the search unit back to obtain a tip-diffracted signal from the top of the flaw. Manipulate the search unit back and forth and look for a doublet. If the doublet is observed, measure the time difference between the two signals. The separation indicates the height of the flaw, according to the standardization. Fig. 23 shows the instrument display of a second half-V Delta Time of Flight standardization and a sketch of the ultrasonic beam paths related to that standardization.

9.3 *Bi-Modal Method*—Flaw sizing on the basis of time of flight or the delta time of flight techniques should be performed as follows:

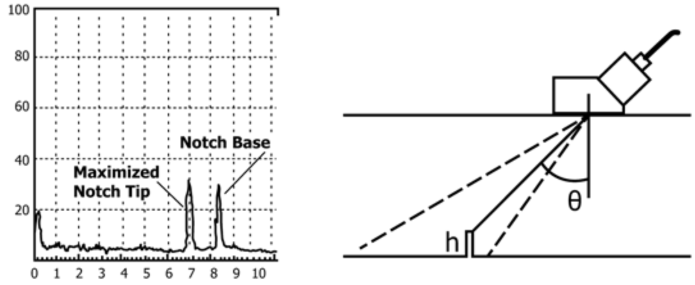


FIG. 19 Example of First Half-V Path Time of Flight (TOF) Standardization

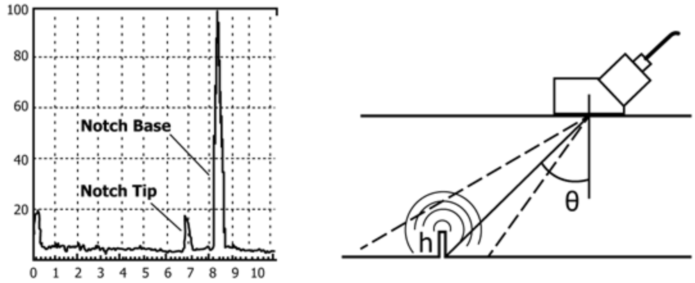


FIG. 20 Example of First Half-V Path Delta ΔTOF Standardization

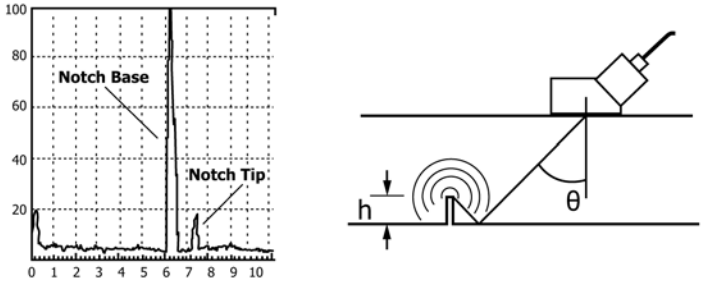


FIG. 21 Example of Second Half-V Path Time of Flight Standardization

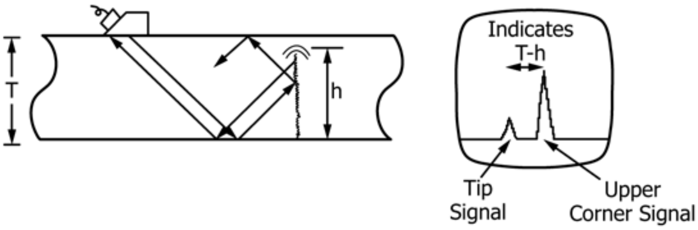


FIG. 22 Example of the Presence of Both the Tip Signal and the Upper Corner Signal

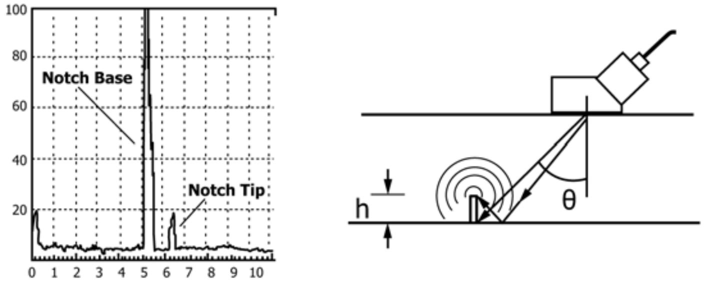


FIG. 23 Example of Second Half-V Path Delta Time of Flight Standardization

9.3.1 Connect the search unit to the instrument operated in the transmit-receive mode.

9.3.2 Standardize the instrument for the appropriate wall thickness using the nomograms prepared from Fig. 13 or the table prepared from the nomograms. Check the standardization by observing the initial pulse at t = 0 from the edge of a block and a tip-diffracted signal from the reference block.

9.3.3 Using the notches in the most appropriate reference block, review the echo-dynamic behavior of the various signals that are expected from all flaw sizes.

9.3.4 Scan a component volume void of flaws from both opposing directions and observe the irrelevant indications, both statically and dynamically, to the left of mid-screen. Adjust the gain so that the average background noise is approximately 10 % of full screen height.

9.3.5 Scan over the flawed area with broad back-and-forth movements. Look for the mode-converted and creeping wave signals to the right of mid-screen. If the flaw is perpendicular to the surface, only two signals separated by about 2.2 screen divisions and peaking between divisions 5 and 7 should be observed. The longer the signal duration, the deeper the flaw.

9.3.6 Scan the area from the opposite direction with broad movements and look for signals only to the right of mid-screen. If the signal patterns are essentially the same when the flaw is viewed from the two directions, it is likely that the flaw has grown perpendicular to the surface and is oriented vertically.

9.3.7 Look for a tip-diffracted longitudinal wave signal to the left of mid-screen, from both sides of the component. If the amplitudes of the tip-diffracted signals are comparable and smaller than that of the appropriate reference signal, then it is still likely that the flaw is oriented vertically. The separation measured between the tip-diffracted longitudinal wave signal and the mode-converted signal along the component from each side of the flaw yields the first two estimates of flaw height according to the appropriate curve in Fig. 15. The more extensive the flaw, the larger the distance between the signals.

9.3.8 Move the search unit toward the flaw far enough to maximize the tip-diffracted longitudinal wave signal (weld crown permitting). The time between the peaked tip-diffracted signal and the mid-screen mark yields a third estimate of height in percent of local wall thickness.

9.3.9 If possible, repeat these measurements from the other direction and profile the flaw from both directions. If a longitudinal wave signal from the flaw base is received, then relative arrival time measurements between the tip-diffracted longitudinal wave signal and the longitudinal wave signal from the flaw base provide additional confirmation of flaw height.

9.4 *Focused Longitudinal Wave and Shear Wave Method*—Longitudinal waves are not strongly affected by weld metal. Given a suitable surface, ideally a flush-ground and blended weld crown, this method can work as well through weld metal as through base metal.

9.4.1 *Signal Presentation*

NOTE 6—Instrument gain for investigating the flaw should be set such that the noise level from an unflawed area is low in amplitude but visible, that is, 10 to 20 % full screen height. The examiner should only be concerned with the noise level in the part of the screen that is standardized. Noise at the extreme left and right sides of the screen will have no effect.

Select the area of the component where the flaw is located. Scan the area and look for signals in the standardized area of the screen. Signals near 2 divisions should be expected to have higher amplitude and signal-to-noise ratio than those occurring deeper into the wall (a strong signal at 2 divisions indicating a through-wall flaw). The screen may display the longitudinal wave extremity signals and the shear wave flaw opening signals moving in unison. As the search unit is scanned toward the flaw, the shear wave signal will appear late in time at high amplitude, and the high-angle longitudinal wave signal will appear earlier in time (in the standardized region), probably with less amplitude. If signals were obtained in either of the previous investigations, return to the unflawed area of the weld and try to reproduce them. If similar signals are obtained in the unflawed area, the recorded signals were probably not flaw-related; if the signals cannot be reproduced in the unflawed area, they were probably flaw-related. Time permitting, repeat the investigation at several points along the flaw. If the flaw is large enough to penetrate into the beam center, the signal-to-noise ratio should be sufficient to resolve the indications. In the shallower, less intense areas of the beam, it is possible to miss the tip signal. The distinction between the high- and low-intensity areas can be very clear, particularly for search units with a very high refracted angle and relatively low beam spread. When evaluating a signal in a low-intensity area of the beam, the user should confirm the result using another sizing technique. When a large beam is used (large due to high angular beam spread or large elements), the tip signals may exhibit extensive travel across the time-base. Such signals are difficult to maximize accurately and therefore should be used non-quantitatively. Use a smaller beam or a different sizing method to obtain a numerical value for the flaw height.

9.4.2 *Calculation of Flaw Height*—If no relevant signals were obtained in the standardized region, then the high-angle longitudinal wave method has not found any evidence that the flaw penetrates near the near surface. If relevant signals were present in the standardized region but excessive signal travel precluded accurate definition of their sweep positions at maximum amplitude, then a quantitative value for flaw height cannot be obtained. The only conclusion is that the flaw was deep enough to approach the near surface to within the standardized depth range. If accurately maximized signals are obtained, calculate the indicated height by the formula:

$$h = t - 0.1\text{ in.}\,(s - 2)$$

where:

h = height,
t = wall thickness at the flaw location, and
s = sweep position of the maximized recordable signal, expressed as the number of major sweep positions.

NOTE 7—The 2 in the parenthesis results from placing the beam center entry point at 2 major sweep divisions. The constant in front of the parenthesis is shown in inches. This would be converted to the applicable value in mm if metric standardization was used.

Compare the height measurements obtained from both sides of the flaw. They should be almost equal. For weld inspection, the measurement made from the weld side may be slightly lower if the flaw follows the weld fusion line because the received signal will be a reflected wave from the top of the flaw face instead of the extreme tip. If the heights are very different (more than two wavelengths), then one of the signals may have been a misinterpreted noise signal. If confirmation is achieved, the conservative approach should be taken. Compare the height measurements obtained from different points along the length of the flaw. A flaw profile can be constructed from these measurements. If the profile shows large height changes with a small position change (small compared to the flaw length), suspect that some of the measurements are incorrect.

10. Use of Complementary Methods for Flaw Sizing

10.1 *General Guidelines for Complementary Methods*—The various sizing methods have certain limitations that prohibit their application to all flaw sizes. By understanding each method in detail with its limitations, the methods must be combined to complement one another so that the user is more confident of the flaw size measurement obtained from several methods than of a flaw size obtained from only one method. The methodology described in this document assumes that all of the necessary search units are available to the user to combine the methods in the prescribed manner. The extent to which complementary flaw sizing methods may be useful in a field environment will depend on the physical conditions of the component, the flaw morphology, the search unit selection and the time constraints imposed. Fig. 24 shows the optimum ranges of applicability for the three most important sizing methods.

10.2 *General Guidelines for Flaw Sizing Evaluations*—To provide optimum conditions for flaw sizing in welds, the weld crown should be ground flush with the weld for the entire flaw length. Prior to attempting to size a planar flaw, the user must first verify its location and extent. This is typically accomplished with the original equipment used for detection. The next step involves searching for evidence of an extremely large flaw. The initial approach is to use the creeping wave technique. The two methods of determining that a planar flaw is large (High-Angle Longitudinal Wave Method and obtaining a signal from the second half-vee path corner reflection) should both be attempted to provide greatest confidence. If neither of these show that the flaw is large, the tip-diffraction method should be attempted with the first half-V path technique. The Mode Conversion and Bi-Modal Methods should add confidence to the results obtained. It is recommended that whatever results are obtained, the user must confirm them using a complementary method. Additionally, if the results show that the flaw is small, the user should also prove that it is not large by using a High-Angle Longitudinal Wave technique. This is important since flaws can be multifaceted and a lower facet may provide signals indicating flaws less than 50 % through-wall while there are other facets that may be virtually 100 % through-wall. It is very important that large flaws are not missed and that small flaws are not called large. Flaw height determinations should also be made at several locations along the flaw length to increase confidence levels and to increase the chances of finding the deepest point of the flaw. In the case where two or more methods produce different estimations of flaw height, the user should be knowledgeable enough to select the correct data. This requires understanding of the theory behind each method as well as the limitations. The diagram shown in Fig. 25 presents a flaw evaluation and sizing flow chart with five possible sequences for estimating flaw height.

10.3 *Principles for Flaw Sizing*—The activities as listed should be accomplished.

10.3.1 Verify location and extent of flaw.

10.3.2 Approximate the flaw depth with the far-surface Creeping Wave or Mode Conversion Method.

10.3.3 Search for evidence of a very large flaw:

10.3.3.1 Focused Longitudinal Wave or Focused Shear Wave Method,

10.3.3.2 Second Half-V Path Corner Reflection, and

10.3.3.3 Tip-Diffraction.

10.3.4 Search for evidence of a small flaw:

10.3.4.1 Tip-Diffraction, and

10.3.4.2 Bi-Modal Method.

10.3.5 If evidence of a large flaw exists:

10.3.5.1 Confirm with complementary method, and

10.3.5.2 Prove that a small flaw does not exist.

10.3.6 If evidence of a small flaw exists:

10.3.6.1 Confirm with complementary method,

10.3.6.2 Confirm that a large flaw does not exist, and

10.3.6.3 Confirmation may also be achieved by a different angle of approach or by the opposite direction of approach.

10.3.7 If two or more methods exhibit differing results:

10.3.7.1 Eliminate those results with lowest confidence based on range of applicability or repeatability or result,

10.3.7.2 In case of doubt, take value with greater height, and

10.3.7.3 Be aware of possible indications from weld fabrication flaws.

11. Keywords

11.1 evaluation; examination; flaw-height sizing; flaw sizing; nondestructive testing; ultrasonic

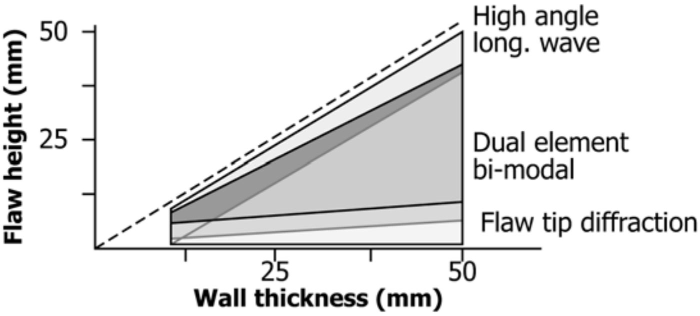


FIG. 24 Optimum Ranges of Applicability for Flaw Sizing Methods

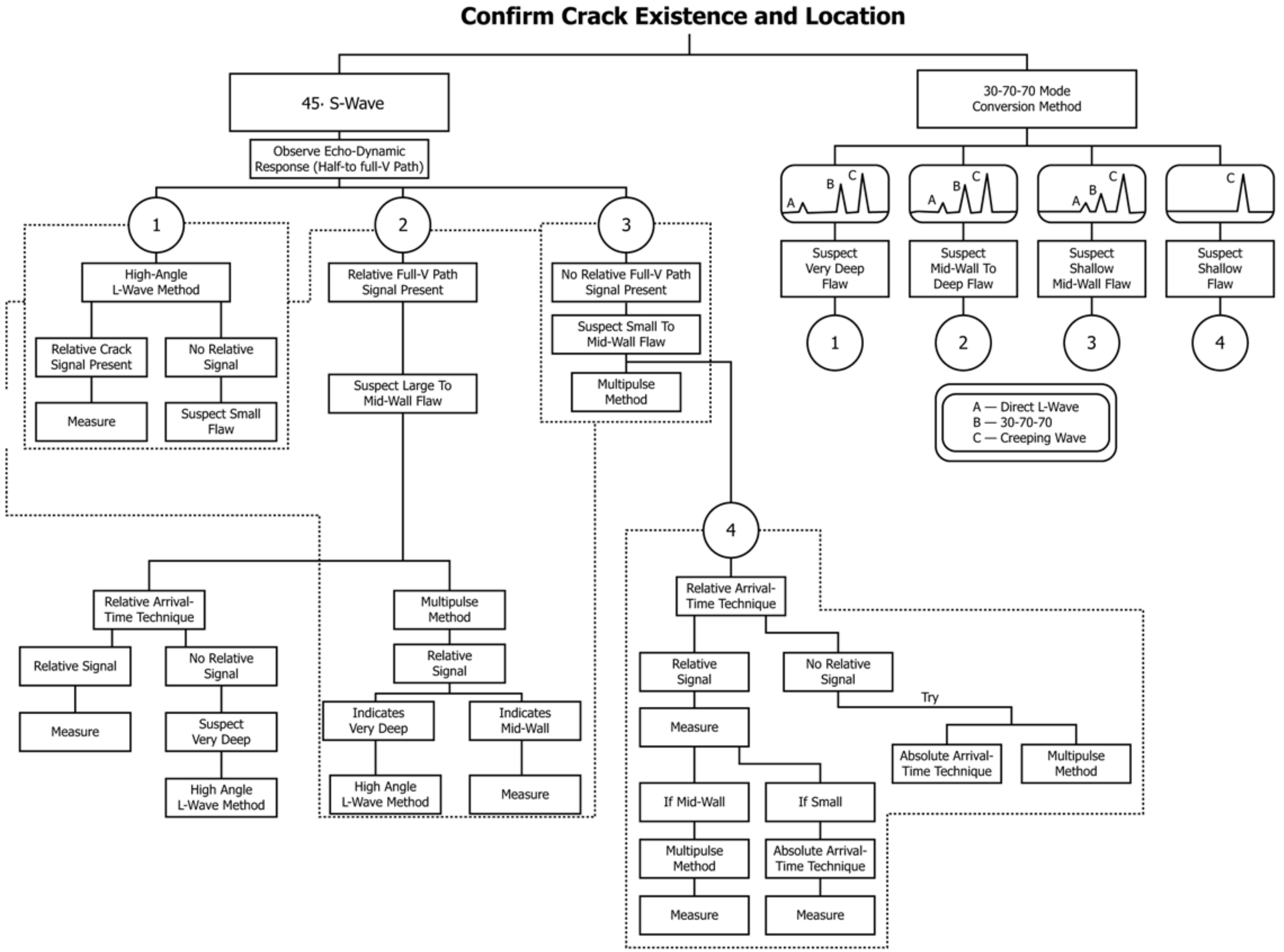


FIG. 25 Guide to Confirm Flaw Existence, Location, and Depth Sizing

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SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue (E2192 - 08) that may impact the use of this standard. (June 1, 2013.)

(1) Added 1.5
(2) Deleted definition in 3.2
(3) Added Section 6 Basis of Application as applicable to this document
(4) Added references made in Section 6 to Section 2 Referenced Documents
(5) Renumbered paragraphs due to insertion of new section