Designation: E 494 – 95

An American National Standard

Standard Practice for Measuring Ultrasonic Velocity in Materials[1]

This standard is issued under the fixed designation E 494; 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.

This specification has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This practice covers a test procedure for measuring ultrasonic velocities in materials with conventional ultrasonic pulse echo flaw detection equipment in which results are displayed in an A-scan display. This practice describes a method whereby unknown ultrasonic velocities in a material sample are determined by comparative measurements using a reference material whose ultrasonic velocities are accurately known.

1.2 This procedure is intended for solid materials 5 mm (0.2 in.) thick or greater. The surfaces normal to the direction of energy propagation shall be parallel to at least ± 3°. Surface finish for velocity measurements shall be 3.2 μm (125 μin.) rms or smoother.

NOTE 1—Sound wave velocities are cited in this practice using the fundamental units of meters per second, with inches per second supplied for reference in many cases. For some calculations, it is convenient to think of velocities in units of millimeters per microsecond. While these units work nicely in the calculations, the more natural units were chosen for use in the tables in this practice. The values can be simply converted from m/sec to mm/μsec by moving the decimal point three places to the left, that is, 3500 m/s becomes 3.5 mm/μsec.

1.3 Ultrasonic velocity measurements are useful for determining several important material properties. Young's modulus of elasticity, Poisson's ratio, acoustic impedance, and several other useful properties and coefficients can be calculated for solid materials with the ultrasonic velocities if the density is known (see Appendix X1).

1.4 More accurate results can be obtained with more specialized ultrasonic equipment, auxiliary equipment, and specialized techniques. Some of the supplemental techniques are described in Appendix X2. (Material contained in Appendix X2 is for informational purposes only.)

NOTE 2—Factors including techniques, equipment, types of material, and operator variables will result in variations in absolute velocity readings, sometimes by as much as 5%. Relative results with a single combination of the above factors can be expected to be much more accurate (probably within a 1% tolerance).

1.5 *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 limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 597 Test Method for Pulse Velocity Through Concrete[2]

E 317 Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Systems Without the Use of Electronic Measurement Instruments[3]

E 797 Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method[3]

E 1316 Terminology for Nondestructive Examinations[3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this practice, see Terminology E 1316.

4. Summary of Practice

4.1 Several possible modes of vibration can propagate in solids. This procedure is concerned with two velocities of propagation, namely those associated with longitudinal (v_l) and transverse (v_t) waves. The longitudinal velocity is independent of sample geometry when the dimensions at right angles to the beam are very large compared with beam area and wave length. The transverse velocity is little affected by physical dimensions of the sample. The procedure described in Section 6 is, as noted in the scope, for use with conventional pulse echo flaw detection equipment only.

5. Apparatus

5.1 The ultrasonic testing system to be used in this practice shall include the following:

5.1.1 *Test Instrument*—Any ultrasonic instrument comprising a time base, transmitter (pulser), receiver (echo amplifier), and an A-scan indicator circuit to generate, receive, and display electrical signals related to ultrasonic waves. Equipment shall allow reading the positions of A_k, A_s, A_t, A_l (defined in 6.1.4 and 6.2.4), along the A-scan base line within ±0.5 mm (0.020

[1] This practice is under the jurisdiction of ASTM Committee E-7 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Testing Procedure.

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[2] *Annual Book of ASTM Standards*, Vol 04.02.

[3] *Annual Book of ASTM Standards*, Vol 03.03.

in.). For maximum accuracy, the highest possible frequency that will present at least two easily distinguishable back echos, and preferably five, shall be used.

5.1.2 *Search Unit*—The search unit containing a transducer that generates and receives ultrasonic waves of an appropriate size, type and frequency, designed for tests by the contact method shall be used. Contact straight beam longitudinal mode shall be used for longitudinal velocity measurements, and contact straight beam shear mode for transverse velocity measurements.

5.1.3 *Couplant*—For longitudinal velocity measurements, the couplant should be the material used in practice, for example, clean light-grade oil. For transverse velocity measurements, a high viscosity material such as resin or solid bond shall be used. In some materials isopolybutene, honey, or other high-viscosity materials have been used effectively. Most liquids will not support transverse waves. In porous materials special nonliquid couplants are required. The couplant must not be deleterious to the material.

5.1.4 *Standard Reference Blocks*:

5.1.4.1 *Velocity Standard*—Any material of known velocity, that can be penetrated by the acoustical wave, and that has an appropriate surface roughness, shape, thickness, and parallelism. The velocity of the standard should be determined by some other technique of higher accuracy, or by comparison with water velocity that is known (see Appendix X2.5 and Appendix X4). The reference block should have an attenuation similar to that of the test material.

5.1.4.2 For horizontal linearity check, see Practice E 317.

6. Procedure

6.1 *Longitudinal Wave Velocity*—Determine bulk, longitudinal wave velocity (v_l) by comparing the transit time of a longitudinal wave in the unknown material to the transit time of ultrasound in a velocity standard (v_k).

6.1.1 Select samples of each with flat parallel surfaces and measure the thickness of each to an accuracy of ±0.02 mm (0.001 in.) or 0.1%, whichever is greater.

6.1.2 Align the transducer over each sample and obtain a nominal signal pattern (see Fig. 1) of as many back echoes as are clearly defined. The time base (sweep control) must be set the same for both measurements.

6.1.3 Using a scale or caliper measure the distance at the base line between the leading edge of the first back echo and the leading edge of the last back echo that is clearly defined on the known and unknown sample. For better accuracy, adjust the amplitude of the last back echo by means of the gain control to approximately the same height as the first back echo, after the position of the leading edge of the first back echo has been fixed. This allows more accurate time or distance measurements. The position of the leading edge of the last back echo is then determined. The signal has traversed a distance twice the thickness of the specimen between each back echo. The signal traversing the specimen and returning is called a round trip. In Fig. 1 the signal has made six round trips between Echo 1 and Echo 7. Count the number of round trips from first echo used to the last echo measured on both samples. This number will be one less than the number of echoes used. Note that the sample thickness, number of round trips, and distance from front to last back echo measured need not be the same.

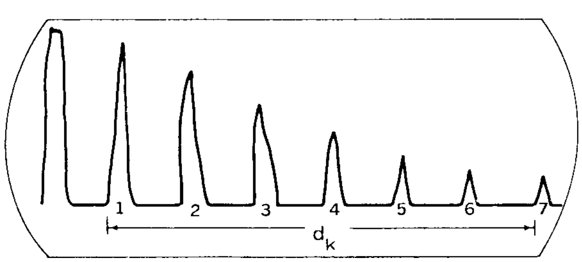

FIG. 1 Initial Pulse and 7 Back Echoes

6.1.4 Calculate the value of the unknown velocity as follows:

$$v_1 = (A_k\, n_l\, t_l\, v_k)/(A_l\, n_k\, t_k) \tag{1}$$

where:

A_k = distance from first to *N*th back echo on the known material, m (in.), measured along the baseline of the A-scan display,
n_l = number of round trips, unknown material,
t_l = thickness of unknown material, m (in.),
v_k = velocity in known material, m/s (in./s),
A_l = distance from the first to the *N*th back echo on the unknown material, m (in.), measured along the baseline of the A-scan display,
n_k = number of round trips, known material, and
t_k = thickness, known material, m (in.).

NOTE 3—The units used in measurement are not significant as long as the system is consistent.

6.2 *Transverse Velocity*—Determine transverse velocity (v_s) by comparing the transit time of a transverse wave in an unknown material to the transit time of a transverse wave in a material of known velocity (v_t).

6.2.1 Select samples of each with flat parallel surfaces and measure the thickness of each to an accuracy of ±0.02 mm (0.001 in.) or 0.1 %, whichever is greater.

6.2.2 Align the transducer (see Fig. 1) over each sample and obtain an optimum signal pattern of as many back echoes as are clearly defined. The time base (sweep control) must be the same for both measurements.

6.2.3 Using a scale or caliper measure the distance at the base line between the leading edge of the first back echo and the leading edge of the last back echo that is clearly defined on the known and unknown sample. For better accuracy, adjust the amplitude of the last back echo by means of the gain control to approximately the same height as the first back echo, after the position of the leading edge of the first back echo has been fixed. This adds high frequency components of the signal which have been attenuated. Then determine the position of the leading edge of the last back echo. Count the number of round trips from first echo used to the last echo measured on both samples. This number will be one less than the number of echoes used. Note that the sample thickness, number of round trips, and distance from first to last back echo measured need not be the same.

6.2.4 Calculate the value of the unknown velocity as follows:

$$v_s = (A_t\, n_s\, t_s\, v_t)/(A_s\, n_t\, t_t) \quad (2)$$

where:
A_t = distance from first to Nth back echo on the known material, m (in.), measured along the baseline of the A-scan display,
n_s = number of round trips, unknown material,
t_s = thickness of unknown material, m (in.),
v_t = velocity of transverse wave in known material, m/s (in./s),
A_s = distance from the first to the Nth back echo on the unknown material, m (in.), measured along the baseline of the A-scan display,
n_t = number of round trips, known material, and
t_t = thickness, known material, m (in.). (See Note 3).

7. Report

7.1 The following are data which should be included in a report on velocity measurements:

7.1.1 *Longitudinal Wave*:
7.1.1.1 A_k = __________m (in.)
7.1.1.2 n_l = __________
7.1.1.3 t_l = __________m (in.)
7.1.1.4 v_k = __________m/s (in./s)
7.1.1.5 A_l = __________m (in.)
7.1.1.6 n_k = __________
7.1.1.7 t_k = __________m (in.)
7.1.1.8 v_l (using Eq 1) = ___m/s (in./s)
7.1.2 *Transverse Wave*:
7.1.2.1 A_t = __________m (in.)
7.1.2.2 n_s = __________
7.1.2.3 t_s = __________m (in.)
7.1.2.4 v_t = __________m/s (in./s)
7.1.2.5 A_s = __________m (in.)
7.1.2.6 n_t = __________
7.1.2.7 t_t = __________m (in.)
7.1.2.8 v_s (using Eq 2) = ___m/s (in./s)
7.1.3 Horizontal linearity
7.1.4 Test frequency
7.1.5 Couplant
7.1.6 *Search unit*:
7.1.6.1 Frequency
7.1.6.2 Size
7.1.6.3 Shape
7.1.6.4 Type
7.1.6.5 Serial number
7.1.7 Sample geometry
7.1.8 *Instrument*:
7.1.8.1 Name
7.1.8.2 Model number
7.1.8.3 Serial number
7.1.8.4 Pertinent control settings

8. Keywords

8.1 measure of ultrasonic velocity; nondestructive testing; ultrasonic properties of materials; ultrasonic thickness gages; ultrasonic velocity

APPENDIXES

(Nonmandatory Information)

X1. FORMULAS

X1.1 Using the technique of this practice will give results in some instances which are only approximate calculations. The determination of longitudinal and transverse velocity of sound in a material makes it possible to approximately calculate the elastic constants, Poisson's ratio, elastic moduli, acoustic impedance, reflection coefficient, and transmission coefficient. In this Appendix, the formulas for calculating some of these factors are as follows (see Note X1.1):

X1.1.1 *Poisson's Ratio*:

$$\sigma = [1 - 2(v_s/v_l)^2]/2[1 - (v_s/v_l)^2]$$

where:
σ = Poisson's ratio,
v_s = ultrasonic transverse velocity, m/s (or in./s), and
v_l = ultrasonic logitudinal velocity, m/s (or in./s).

X1.1.2 *Young's Modulus of Elasticity:*

$$E = (\rho\, v_s^2 (3v_l^2 - 4v_s^2)]/(v_l^2 - v_s^2)$$

where:
ρ = density, kg/m^3 (or lb/in.^{3}),
v_l = longitudinal velocity, m/s (or in./s),
v_s = transverse velocity, m/s (or in./s), and
E = Young's modulus of elasticity, N/m^2 (or lb/in.^{2}) (see Notes X1.2 and X1.3).

X1.1.3 *Acoustic Impedance* (see Note X1.3):

$$z = \rho\, v_l$$

where:
z = acoustic impedance (kg/m^2· s (or lb/in.^{2}· s)).

X1.1.4 *Shear Modulus* (see Note X1.3):

$$G = \rho\, v_s^2$$

X1.1.5 *Bulk Modulus* (see Note X1.3):

$$K = \rho\, [v_l^2 - (4/3)v_s^2]$$

X1.1.6 *Reflection Coefficient for Energy (R)*:

$$R = (Z_2 - Z_1)^2/(Z_2 + Z_1)^2$$

where:
Z_1 = acoustic impedance in Medium 1, and
Z_2 = acoustic impedance in Medium 2.

X1.1.7 *Transmission Coefficient for Energy (T)*:

$$T = (4Z_2 Z_1)/(Z_2 + Z_1)^2$$

NOTE X1.1—The dynamic elastic constants may differ from those determined by static tensile measurements. In the case of metals, ceramics, and glasses, the differences are of the order of 1 %, and may be corrected by known theoretical formulas. For plastics the differences may be larger, but can be corrected by correlation.

NOTE X1.2—Conversion factor: 1 $N/m^2 = 1.4504 \times 10^{-4} lb/in.^2$.

NOTE X1.3—When using pounds per cubic inch for density and inches per second for velocity, results must be divided by *g* (acceleration due to gravity) to obtain results in pounds per square inch for *E*, *G*, or *K* and also to obtain results for *Z* in pounds per square inch per second. Acceleration due to gravity (*g*) = 386.4 in./s · s.

X2. IMPORTANT TECHNIQUES FOR MEASURING ULTRASONIC VELOCITY IN MATERIALS

X2.1 Introduction

X2.1.1 Several techniques are available for precise measurement of ultrasonic velocity in materials. Most of these techniques require specialized or auxiliary equipment.

X2.1.2 Instruments are available commercially which automatically measure sound velocity or time interval or both. There is a growing list of manufacturers who make ultrasonic instruments, including pulser, receiver, and display designed specifically for making these measurements automatically or which can be used for these measurements even though designed primarily for other measurements (for example, thickness gages).

X2.1.3 Various methods have been introduced to solve the problem of the accurate measurement of time interval or number of waves in the specimen. It would be beyond the scope of this Appendix to attempt to include all these techniques. However, it is considered of value to those using this practice to know some of these techniques. This Appendix will be useful to those who have more refined equipment or auxiliary equipment available and to those who wish more accurate results.

X2.1.4 This Appendix will include some techniques that are only suitable for the laboratory. It is only under strictly controlled conditions such as are available in the laboratory that the greatest accuracy can be achieved. Such measurements may be slow and require very carefully prepared specimens. A list of references **(1-28)**[4] is provided for more detailed information.

X2.2 Special Features Built Into the Ultrasonic Equipment

X2.2.1 Ultrasonic equipment is available that provides means adequate for the measurement of acoustic wave propagation with respect to time.

X2.3 Precision Oscilloscope

X2.3.1 An auxiliary precision cathode ray oscilloscope can be used to observe the echo pattern. Using the precision calibrated horizontal display of the oscilloscope, the transit time between successive multiple back reflections is determined. Calculate velocity as follows:

$$\text{Velocity (m/s (or in./s))} = [2 \text{ thickness (m or in.)}]/[\text{Time (s)}]$$

X2.4 Electronic Time Marker

X2.4.1 An accessory is frequently available that displays one or more visual marks, usually a step, on the display of the basic instrument. It is usually superimposed on the standard echo pattern. The mark is moved using a calibrated control. The control reads time directly in microseconds.

X2.4.2 The technique is to align the step on the display, first with the first back reflection, and then, using the second marker, if available, with the second back reflection. Based on control readings at both instances, the elapsed time for a round trip through the specimen is determined. (Calculation is the same as in X2.3).

X2.5 Ultrasonic Interferometer (Velocity Comparator)

X2.5.1 The measurement of ultrasonic velocity is carried out by comparing transmission times of a pulse in a specimen and in the comparison travel path. The ultrasonic velocities in liquids (for example, water) are well known and consequently the velocity in the specimen can be determined with an accuracy of about 0.1 %.

X2.5.2 In practice, the echo in the specimen is made to coincide with the echo from the interferometer travel path which is obtained by altering the latter to the point of interference. The ultrasonic velocities of the specimen and interferometer liquid are in the ratio of their lengths and these two quantities must be exactly measureable.

X2.5.3 A normal probe is clamped to the open tank by means of a clasp on one side. The frequency of the probe should be equal to that which is required for the specimen. The attenuation member must be inserted between the interferometer probe and the cable. It serves to change the height of the interferometer echo independently of other conditions of test.

X2.5.4 A reflector dips into the tank containing the liquid and is held on an adjustable mechanism so that it cannot be tilted. This mechanism can be moved to and fro rapidly by disengagement. The fine adjustment is carried out by means of a spindle. One complete revolution of the spindle changes the travel path by 1 mm. One scale division of the spindle knob represents 1⁄100 mm (0.0004 in.).

X2.5.5 The tank must be filled with liquid in which the ultrasonic velocity is known. In the case of water at 20°C, velocity = 1483.1 m/s. The temperature coefficient is $\Delta v/\Delta t = +2.5$ m/s ·° C. A check of the temperature in the case of water is therefore absolutely necessary (see Appendix X4).

X2.5.6 Mixtures can also be used, for example, water alcohol (18% weight percentage), whose temperature coefficient is zero at room temperature.

X2.5.7 Calculate velocity as follows:

$$\text{Velocity}_x \text{ (m/s)} = \frac{\text{Velocity}_{water} \text{ (m/s)} \times \text{Thickness}_x \text{ (m)}}{\text{Distance}_{in\ water} \text{ (m)}}$$

or

[4] The boldface numbers in parentheses refer to the list of references appended to this practice.

$$\text{Velocity}_x \text{ (in./s)} = \frac{\text{Velocity}_{water} \text{ (in./s)} \times \text{Thickness}_x \text{ (in.)}}{\text{Distance}_{in\ water} \text{ (in.)}}$$

X2.6 Pulse Velocity Through Concrete (see Test Method C 597)

X2.6.1 Frequency of pulse generator 10 to 50 kHz—Repetitive pulses at rate not less than 50/s.

X2.6.2 Press the faces of the search units against the faces of the concrete after establishing contact through a coupling medium. Wetting the concrete with water, oil, or other viscous materials may be used to exclude entrapped air from between the contact surfaces of the diaphragms of the search unit and the surface of the concrete. Measure the length of the shortest direct path between the centers of the diaphragms and the time of travel on the A-scan display by aligning the strobe marker pulse opposite the received wave front and reading the calibrated dial, or by counting the number of cycles of the timing wave between the transmitted and received pulse.

X2.7 Pulse Echo Twin-Probe Method

X2.7.1 This method uses a single-probe housing containing two elements: one a sender, the other a receiver.

X2.7.2 Since ultrasonic velocity measurements are principally measurements of time, based on the thickness of a specimen, and since many thickness measuring instruments successfully measure thickness to a high degree of accuracy using this method it seems appropriate to include this method of velocity measurement in the practice.

NOTE X2.1—With the twin-probe method the pulse-echo transit time is a non-linear function of specimen thickness, which may introduce significant errors when that technique is used for velocity measurements. The non-linearity is discussed in Practice E 797. Errors in velocity measurement can be minimized by use of a calibration block having both velocity and thickness nearly equal to that of the specimen to be measured. Single transducer systems are generally more suitable for precision velocity measurements.

X2.7.3 All instruments where the twin-probe method of thickness measurement is recommended, including A-scan display units as well as meter read-out units, have precisely calibrated scales. The parallax problem is removed from many of the A-scan display units since the scale is engraved on the inside face of the display or is integral with the output signal. Parallax is not a major problem with meter read-out units or digital read-out units.

X2.7.4 Most twin-probe thickness measuring instruments use the first echo for measurement read-out. Thus the test ranges are usually fixed and precisely calibrated. There is no need to produce several back echoes to obtain an average transit time.

X2.7.5 Specimens with curved surfaces present less measuring problems as the first back echo is more representative of depth or time than a later back echo, say the fifth from a tube wall. In small diameter tubing the error may be greater than for equivalent flat specimens.

X2.7.6 *Procedure*:

X2.7.6.1 Calibrate the instrument and probe on a steel step block of known velocity. By adjustment of sweep delay and range controls, ensure that thickness readings for two or more thicknesses (high and low) occur at their proper distances (Fig. X2.1). The instrument and probe are properly calibrated for (1020 or 1095) steel at 5900 m/s (2.32×10^5 in./s).

X2.7.6.2 Measure the thickness of part with unknown velocity without changing sweep or range controls on the instrument. Check the actual thickness of the test area with calipers or a micrometer.

X2.7.6.3 Calculate unknown velocity as follows:

$$V_x = V \text{ steel} \times \frac{\text{actual thickness}}{\text{indicated thickness}}$$

where:
V_x = unknown velocity.

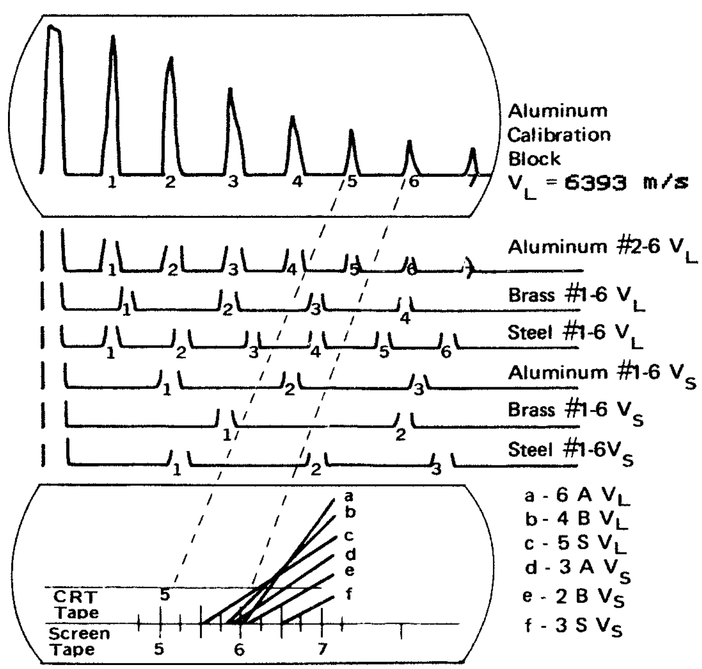

FIG. X2.1 Instrument Setup to Avoid Errors Due to Parallax

X2.8 Harmonic Wave Method (Zero Method)

X2.8.1 Wall thickness measurement by means of ultrasonic, echo-sounding instruments will become inaccurate if only a few echoes can be utilized because of either high absorption, corrosion, or unfavorable radiation geometry. In such cases, the accuracy of the results can be improved by the tuning of the wall thickness meter to the harmonic waves of the echo frequency (harmonic wave method).

X2.8.2 Up to now the interferometer method has been used for the precision measurement of sound propagation. Further development of the harmonic wave method can replace the rather complicated and time-consuming interferometer method in all those cases where the ultimate accuracy of the latter is not required. Under normal conditions, a measuring accuracy of 0.5 % or better can be obtained with the so-called "zero-method."

X2.8.3 A modification of the method utilizes bursts of radio frequency (rf) radiated from a transducer into a long buffer rod and then into the sample, which is a few wavelengths thick. The buffer rod is long enough to contain the entire rf bursts, while the burst is long enough to occupy the three round-trips in the specimen. Thus the burst interferes with itself as it reverberates within the specimen. One characteristic echo pattern occurs when the round-trip distance in the specimen is equal to an odd number of half-wavelengths; an even number gives a different pattern. The two patterns alternate as the rf frequency is changed. One plots phase versus frequency in units of cycles versus MHz. One cycle of phase occurs for each repetition of one of the characteristic patterns; between the two patterns there is ½ cycle of phase. The slope of the phase versus frequency line is the delay time t in microseconds, and for a specimen of thickness L, the velocity is

$$v = 2L/t$$

X2.9 Phase Comparison Method

X2.9.1 This method consists of superimposing the echoes of two pulses which have made different numbers of round trips. If the echoes are made exactly in phase by a critical adjustment of frequency, the expression for phase angles may be written as:

$$\gamma - [(2L\,W_n)/v] = -2\,\pi n$$

where:

v = velocity of propagation,
W_n = 2 π times resonant frequency (f_n),
L = thickness,
n = number of waves, and
γ = phase angle due to the seal between the transducer and the specimen.

Consequently, the velocity is expressed by:

$$v = (2L\,f_n)/[n + (\gamma/2\pi)]$$

X2.9.2 It has been experimentally proven that size and shape effects are reduced to effectively zero whenever there are at least 100 wave lengths of sound in the specimen thickness. High frequencies (10 to 20 MHz) are generally used to minimize this effect.

X2.9.3 The main advantage of the phase comparison method is the fact that the absolute velocity can be determined very accurately without the error introduced from coupling, since the transducer coupling effect can be evaluated. This method also makes it possible to measure the velocity on a very small specimen with linear dimensions as small as 2 mm (0.08 in.).

X2.10 Pulse Superposition Method

X2.10.1 This method uses an rf pulse applied to the transducer at the intervals approximately equal to the round-trip delay time of waves traveling in the specimen. In order to observe the superimposed echoes just after the last applied pulse, a few applied pulses are omitted periodically. When the echoes are brought into phase adjusting the time spacing T between signals, a maximum in the resulting pulse amplitude occurs. In this condition, the following equation is satisfied:

$$\delta = (T/p) - (L/f)\,[m/p - (\gamma/2\pi)]$$

where:

δ = round trip delay time,
f = rf frequency in the pulse,
m = an integer which may take on both positive and negative values, and
γ = a phase angle associated with wave reflected at the transducer end, and
p = an integer (1, 2, 3. . .).

Since T is approximately some multiple of the round-trip delay time δ, the applied pulse occurs once for every round trip delay for $p = 1$. Usually, a number of measurements of T at different frequencies between f, the resonance frequency of the transducer, and 0.9 f_r are made to obtain the difference in T between f_r and another frequency f. The negative value of ΔT that is smallest in magnitude corresponds to $n = 0$; except for specimens of very low mechanical impedance, the delay time is then given by $\delta = T + (\gamma/2\pi f)$. The velocity in the sample is $V = 2\,L/\delta$, where L is the sample length.

X2.10.2 The advantage of this particular method is that the coupling to the transducer is taken into account so that this method is well suited to measurements aimed at pressure and temperature variations. With this method, the effect of coupling between transducer and specimen can be made negligibly small. So far as the accuracy of this method is concerned, it is within a few parts in 10^5 in ideal conditions, while that of the phase comparison in X2.9 is within one part in 10^4. In this method, however, it is possible to send a strong signal into the specimen, so that the velocity measurement can be made even if the attenuation is high.

X2.10.3 The limitation of both techniques is expected to depend on various factors besides porosity, such as grain size and grain boundary conditions.

X2.11 Phase Velocity by Pulse-Echo-Overlap Method

X2.11.1 In this method, pairs of echoes are compared by driving the x-axis of a viewing oscilloscope at a frequency equal to the reciprocal of the travel time between the echoes. By choosing the correct cyclic overlap for the rf within the echoes by the ΔT method explained in X2.10, accurate measurement of ultrasonic phase velocity can be made. When corrections for the phase advance due to ultrasonic diffraction are applied to the travel times between various pairs of echoes, the accuracy of the average round-trip travel time is improved. Delay times are accurate to 0.2 ns or better, which may be as low as 5 parts in 10^6 in some cases. For dispersive materials, the group delay may be obtained by overlapping the rectified and detected envelopes of Gaussian (bell curve)-shaped rf bursts, which have narrow bandwidths. Thus, group velocity may be measured. In nondispersive materials (most solids), broadband digital pulses may be used instead of rf bursts.

X2.12 Sonic Resonance

X2.12.1 The dynamic resonance method, or the sonic method, has been developed to the point that this technique can be considered a standard method of obtaining sonic velocity and elastic constants of solids. The flexural, transverse, and torsional resonance frequencies of a solid body are determined. From these values, the velocities can be computed.

X2.12.2 The advantage of this method is its convenience and simplicity of the measurement without losing a high degree of accuracy. It is possible by this method to determine the elastic moduli of very porous aggregate compounds.

X2.12.3 The disadvantage of this method arises only from the limitation on the size of the specimen to be examined. When the length becomes shorter than 3 in. (76 mm), the torsional fundamental resonance frequency of a material of high elastic moduli exceeds 40 kHz, so that special equipment and experimental techniques are required to obtain accurate results. Moreover, all three dimensions (length, width, and thickness) are critically involved in the calculation of the elastic moduli from the resonance frequency. From a practical point of view, it is quite difficult to fabricate small specimens with a uniform cross-section dimension.

X2.12.4 Another problem to be considered is the shape correction factor in the equation relating to the elastic moduli to the resonance frequency. It has been recommended that for rectangular specimens, the ratio of length to either cross-sectional dimension should not be less than three to one. When accurate values within 0.1 % are required, the ratio is preferably not less than six to one. Therefore, it becomes difficult to determine the elastic moduli of specimens in massive structure.

X2.12.5 The sonic resonance technique has been used for measurements up to 3000°C.

X2.13 Momentary Contact Pressure Coupling Technique

X2.13.1 Measurements of longitudinal and shearwave velocity from room temperature to beyond 2000°C have been made by the technique developed by Carnevale and Lynnworth **(1)**.[4] In this technique, measurements are made by momentarily pressure-coupling 1-MHz longitudinal and shear-wave pulses through a specimen and measuring the transit time (and amplitudes too, if attenuation is to be determined). Measurement of longitudinal and shear-wave velocity is accurate to about 1 %. The test specimen is a cylinder at least five wavelengths in diameter by several centimetres long. Dimensional requirements are easily met. Accordingly, sample preparation and moduli determinations are relatively simple. The momentary-contact method is also applicable to measurement of thickness of tubing, centerline "pipe" flaws in billets, internal temperature and other characteristics of materials at high temperature, typically 1000°C.

X2.14 Notched-Bar and Stepped-Wire Techniques

X2.14.1 These techniques are applicable to bulk specimens typically 1 to 3 cm in diameter by several centimetres long, or to slender specimens less than or equal to 3 mm in diameter by several centimetres long. Specimens are typically tested from room temperature to the highest temperature of interest.

X2.14.1.1 The *bulk* specimen is an extension of the buffer rod, but of smaller diameter. The diameter change creates a first echo. The free end creates the second echo. With suitable geometry, a longitudinal wave can be partly mode-converted within the specimen, yielding both longitudinal and shear wave echoes, from which both moduli and Poisson's ratio are determined. The upper temperature limit is usually imposed by heat conduction into the buffer, or by attenuation in the buffer at the test frequencies normally employed, approximately 1 to 10 MHz.

X2.14.1.2 The *slender* specimen may be an extension of the lead-in wire buffer, but more often one uses a given buffer (for example, tungsten wire, 1 mm in diameter by 1 m long) with a variety of different specimens. This technique is especially convenient for fibers of diameter much less than 1 mm, and also for whiskers of this diameter, and lengths less than 1 cm. Using a Joule-Wiedemann magnetostrictive transducer, extensional and torsional pulses of approximately 0.1 MHz center frequency are launched simultaneously and propagate nondispersively and without mode conversion down the buffer. But due to their velocity difference, these modes are clearly separated by the time they reach the specimen. Therefore one can readily arrange to determine both velocities and therefore Young's and shear moduli and Poisson's ratio. At high temperature, the slender buffer produces only a small heat loss. The specimen itself rapidly follows the furnace temperature. In some cases, electrical self-heating of the specimen has been used to determine sound velocity under cyclic conditions, and at the melting point of refractory wires.

X2.15 Continuous Wave (CW) Phase-Sensitive Techniques

X2.15.1 A system for measuring phase in a specimen on a cw basis consists of a lock-in amplifier, an input transducer, and an output transducer arranged for transmission through the specimen. The amplifier contains a cw frequency source for the input transducer. As frequency is varied, the phase meter of the phase-lock amplifier registers zero (null) for every 180° phase change. Thus every other zero-crossing is a cycle of phase ϕ. A plot is made of phase in cycles versus frequency in megahertz. The slope of this curve is the group delay t_g in microseconds from which the group velocity is found by the formula:

$$v_g = L/t_g$$

X2.15.2 To study materials with this system, the ideal specimen is either an unbounded plate tested through its thickness, or a thin wire (diameter of d) tested along its length. In the first case, sidewall effects are nonexistent. In the second case, sidewall effects give rise to the first longitudinal mode only, and it is nondispersive as long as λ is much greater than d. With specimens of aspect ratio nearer unity (for a cube, this ratio is exactly unity), the multiplicity of modes in the structure can obscure the material parameters. Then the measurement becomes merely qualitative. Comparative measurements on specimens of identical shape and size could be made, however.

X2.15.3 The method is very useful in highly attenuating specimens in which echoes cannot be observed, that is, for a material loss of 20 dB or higher in one pass through the specimen. Then the phase is monotonic in frequency, offering unambiguous readings. Both dispersive and nondispersive materials can be tested. Nondispersive materials show no variation of t_g with frequency (that is, ϕ is a straight line versus frequency), and then the group velocity is equal to the phase velocity.

X2.16 Alternative Method for Measuring Velocities of Materials

X2.16.1 An alternative method to that used in this recommended practice, but in which provisions have been made to (*1*) eliminate errors due to parallax, (*2*) minimize errors due to imperfect sweep linearity, and (*3*) use one mode velocity in the calibration block as the known velocity for all measurements, is included as a useful technique for measuring ultrasonic velocity in materials.

X2.16.2 Velocity is distance traveled per unit of time; therefore, time (which is displayed on the ultrasonic pulse echo instrument screen as horizontal displacement) equals distance divided by velocity. Calibrating time with multiple reflections of a piece of T thick material (distance or length ultrasonic, L) of known longitudinal velocity (V_l) gives distance divided by velocity:

$$L_u/V_l = \text{time}$$

Setting an equal time in another material whose t thickness can be measured, we can drop the reference to time. This permits us to measure velocity by the ratio of distance to velocity:

$$L_u/V_l = L_m/V_x \text{ or } V_x/V_l = L_m/L_u.$$

Since these are ratios, we can state velocities in centimetres per second and lengths in inches or other units as long as we keep both velocities in the same units and both lengths in the same units. The equation can be simplified to:

$$V_x = V_l\, L_m/L_u$$

where:

V_x = velocity in a measured sample (longitudinal or shear depending on which search unit is used on the measured sample),
V_l = known longitudinal velocity in the calibration block (a straight beam longitudinal wave search unit is used to calibrate time),
L_m = measured length of physical path through the measured sample, and
L_u = ultrasonic length of equal time path through the calibration block.

Restated in the general terms of the figure, the velocity is:

$$V_x = V_l\,[nt/(NT + \text{reading})]$$

where:

n = number of measured sample back reflections,
t = thickness of the measured sample,
N = number of calibration back reflections before the n back reflections, and
T = thickness of the calibration block reading in direct calibrated distance units from the Nth indication to the nth indication.

This measurement may be accomplished in the following steps:

X2.16.2.1 Measure thickness T of the calibrated sample and thickness t of the sample to be measured using a micrometer or caliper with capability to accurately read ±0.0025 mm (0.0001 in.).

X2.16.2.2 Rub a pencil on the fine scale (for example, 1 mm or 1/32-in. divisions) on an engraved scale (such as the steel scale in a combination square set). Lift the calibration from the scale with a strip of transparent tape. Attach to the display of the instrument as shown in Fig. X2.1. Attach a second scale tape to the screen cover. (Superimposing the two scales eliminates errors in reading caused by misalignment of the indication scale and your eye.)

X2.16.2.3 Attach a straight beam search unit to the instrument. The search unit wave mode determines what velocity will be measured. For example, a γ cut quartz, whose major motion is face shift parallel to the contact surface, will produce a straight beam shear wave. Couple the search unit to the sample to be measured with oil or glycerin (the more viscous liquid, isopolybutene, provides improved coupling for shear wave measurement). Adjust instrument controls to provide the largest number of clear back reflections with the reject (clipping, threshold) control adjusted to provide maximum amplitudes. Measurements should not be attempted on less than two back reflections and it is rarely necessary to use more than ten back reflections. Five back reflections provide good accuracy for velocity measurement. Mark the sweep line at the left edge of the nth indication with a grease pencil (5t) to dark indication if the sweep is adjusted as shown on the top screen in Fig. X2.2.

X2.16.2.4 Read the number (N) of back reflections between the initial pulse and the grease pencil mark. Delay the Nth back reflection to position its left edge at the first whole inch mark on the scale. Sweep control adjust the $N + 1$ back reflection to position its left edge at a distance equal to the thickness (T) of the calibrated sample from the N back reflection. (Delay and sweep must be readjusted two or three times to attain N position at the first even inch mark on the scale and T spacing on the scale between N and $N + 1$ back reflections.) Mark amplitudes of N and $N + 1$ on the screen with a grease pencil and connect the two points with a straight line.

X2.16.2.5 Couple the search unit to the sample to be measured. Adjust sensitivity (gain) to set the amplitude of back reflection n on the N to $N + 1$ amplitude line. Read distance from the first even inch mark to the sweep line point at the left edge of back reflection n; this is the reading.

X2.17 Through Transmission—Pulse Echo

X2.17.1 The through-transmission technique is suitable for usage in situations involving specimen surfaces that are not ideally flat and parallel and also materials that are highly attenuating. This technique, which utilizes more than one

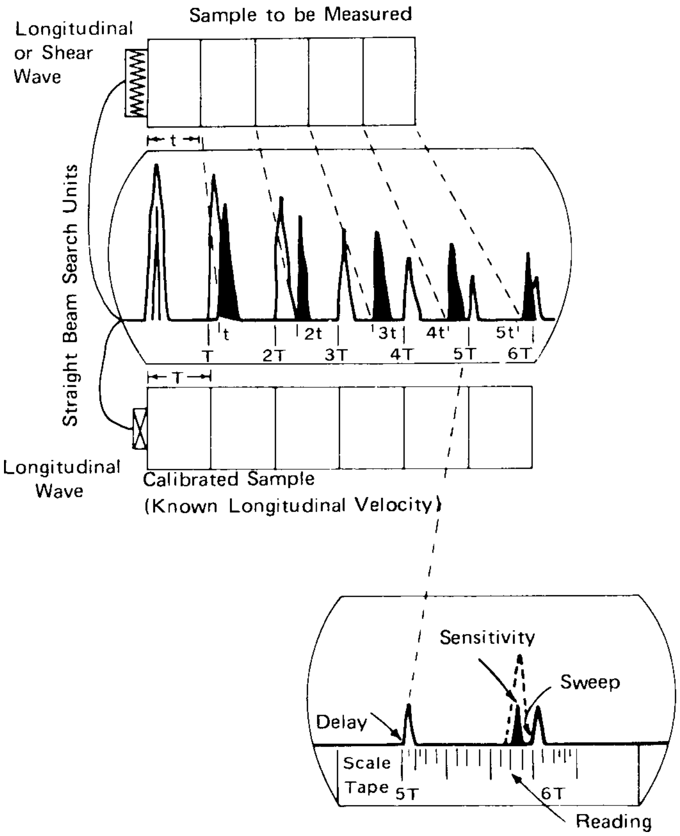

FIG. X2.2 Instrument Setup for Reading

transducer, does not require back reflections on a linear time axis.

X2.17.2 In the through-transmission method, if one can receive the pulse from the transmitting transducer, then a velocity measurement is possible provided the thickness can be determined.

X2.17.3 By adding an oscilloscope, one can measure more accurate time readout. The method here is to view the output pulses on the expanded r-f component of the pulse which can be used as a reference point to locate the pulse on the time axis which has been appropriately calibrated by a standard.

X2.18 Velocimetry Methods Independent of Thickness

X2.18.1 Most ultrasonic velocimetry methods are based on an equation of the form:

$$V = x/t$$

where:

V = velocity,

x = ultrasonic path length (that is, x = thickness, for through-transmission, or x = twice the thickness, for pulse-echo), and

t = transit time.

In contrast to these methods, there are several other methods for measuring V without requiring knowledge of x. Thus, they may be appropriate when it is not convenient to determine x; for example, when only one surface is accessible.

X2.18.2 *Critical Angle Reflectivity*—This method is based on Snell's law. It involves measuring one of several critical angles, depending on which wave type (longitudinal, shear, Rayleigh, etc.) is of interest. Denoting the velocity of interest as V_2, Snell's law gives V_2 in terms of the velocity V_1 and the measured initial angle of incidence θ_{1c} in an adjacent medium (usually water) as follows:

$$V_2 = V_1/\sin\theta_{1c}$$

This method has been described in greater detail by Rollins **(2)** and by Becker **(3)**.

X2.18.3 *Differential Path or Differential Angle*:

X2.18.3.1 This method, of limited use **(4)**, is also based on Snell's law, and may be considered when it is not convenient to measure χ or θ_{1c}. It may be understood by applying Snell's law twice, for two different angles of incidence. Let the incident angles be denoted θ_{1a} and θ_{1b}. Consider the two refracted rays of like mode in Medium 2, which will travel along different paths at refracted angles θ_{2a} and θ_{2b}. They will be reflected after traveling in Medium 2 for intervals t_p and t_q, respectively (t_p and t_q are transit time one way). Again denoting the velocity in Medium 1 as V_1, if we define A |Cc $\sin\theta_{1a}/V_1$ and B |Cc $\sin\theta_{1b}/V_1$, it may be shown that, for isotropic media,

$$V_2 = \sqrt{\frac{1 - (t_p/t_q)^2}{B^2 - A^2\,(t_p/t_q)^2}}$$

As a special simplifying case, we may let $\theta_{1a} = 0$ (normal incidence). Then $A = 0$ and

$$V_2 = (1/B)\sqrt{1 - (t_p/t_q)^2}$$

X2.18.3.2 The practical difficulty stems from trying to measure t_q directly. Of perhaps academic interest, one might determine t_q by timing the modulation of a laser beam by the echoes, where the laser in effect monitors at least one surface of the specimen. This would, of course, be limited to wedges or specimens, or both, that were optically transparent, and would be a relatively complicated measurement in any event.

X2.18.3.3 In principle, one can also determine V_2 in terms of the transit time t_p measured at normal incidence, and the distance $2W$ along the specimen surface between a pair of symmetrical "pitch-and-catch" wedge transducers, when the distance between these transducers is adjusted for the maximum echo amplitude. It may be shown that

$$\frac{V_s^2}{\sqrt{V_1^2 - V_2^2\sin^2\theta_{1b}}} = \frac{W}{t_p\sin\theta_{1b}}$$

Now, if the wedges are such that $\theta_{1b} = 45°$, this simplifies to

$$\frac{V_2^2}{\sqrt{2V_1^2 - V_2^2}} = \frac{W}{t_p}$$

For a specific wedge velocity V_1, and measurements of W and t_p, the unknown V_2 may be estimated by an iterative calculation, or by interpolation from graphical or tabular data such as is shown in Table X2.1. The accuracy of this method generally is not nearly as good as more conventional velocimetry methods. It is seen to depend on the relative values of V_1 and V_2, as well as on the angle of incidence. The errors stem in part from the uncertainty in determining W.

X2.18.4 *Reflection Coefficient*—In this method, V_2 is derived in terms of the sound pressure reflection coefficient R **(5)**. One can measure R at normal incidence, at the interface

TABLE X2.1 Calculated Values of W/t_p for Incident Angle of 45°

V_2, m/s	W/t_p, m/s			
	V_1 = 2500 m/s	5000 m/s	7500 m/s	10 000 m/s
0	0	0	0	0
1000	0.295	0.143	0.0947	0.0709
2000	1.37	0.59	0.384	0.286
3000	4.81	0.764	0.885	0.651
4000	...	2.74	1.63	1.18
5000	...	5.00	2.67	1.89
6000	...	9.62	4.12	2.81
7000	...	49.00	6.15	3.99
8000	...	...	9.19	5.49
9000	...	...	14.43	7.43
10 000	...	...	28.3	10.00

between a first medium (liquid or solid) of known characteristic impedance Z_1 and the second medium. That is, one measures $R = -E_{coupled}/E_{free}$, where the E's are the echo amplitudes observed when the two media are coupled and then uncoupled, respectively, for a wave in Medium 1 impinging on Medium 2. Provided the density ρ_2 in Medium 2 is known or measurable, the velocity V_2 may be determined as follows:

$$V_2 = (Z_1/\rho_2)(1 + R)/(1 - R)$$

X2.18.5 *Velocity Ratios*— In some instances, it may be useful to determine the ratio of two velocities over a common path **(6)**. This is sometimes easier to do than to determine just one velocity, when the path length x is known **(7)**. The velocity ratio for longitudinal and shear waves is simply the reciprocal of the corresponding transit time ratio as follows:

$$\frac{V_T}{V_L} = \frac{t_L}{t_T}$$

X2.18.5.1 Poisson's ratio σ may be written in terms of these ratios as follows:

$$\sigma = \frac{1 - 2(V_T/V_L)^2}{2 - 2(V_T/V_L)^2}$$

X2.18.5.2 Conversely, the velocity ratio may be expressed in terms of σ as follows:

$$\frac{V_T}{V_L} = \sqrt{\frac{1 - 2\,\sigma}{2(1 - \sigma)}}$$

X2.18.5.3 In the case of specimens such as round wires or thin rods whose diameter is small compared to wavelengths, such that, instead of the propagation of longitudinal waves, extensional waves propagate at a velocity of $V_E = \sqrt{E/\rho}$, where E = Young's modulus and ρ = density, and torsional waves propagate at $V_T = \sqrt{G/\rho}$, where G = shear modulus, the thin rod velocity ratio is as follows **(8)**:

$$\frac{V_T}{V_E} = 1\sqrt{1 + \sigma}$$

X3. ACOUSTIC VELOCITY IN ENGINEERING MATERIALS

TABLE X3.1 Acoustic Velocity in Engineering Materials

Material	Density kg/m^3	Longitudinal Velocity		Shear Velocity	
		(m/s)	×10^3(in./s)	(m/s)	×10^3(in./s)
Aluminum	2700	6300	250	3130	124
Beryllium	1850	12 400	488	8650	340
Bismuth	9800	2180	85	1100	43
Brass	8100	4370	173	2100	83
Bronze	8860	3530	139	2230	88
Cadmium	8600	2780	109	1500	59
Columbium	8580	4950	194	2180	85
Copper	8900	4700	185	2260	88
Gold	19 300	3240	127	1200	47
Hafnium	11 300	3860	152	2180	82
Inconel	8250	5720	225	3020	119
Iron, electrolytic	7900	5960	235	3220	128
Iron, cast	7200	3500 to 5600	138 to 222	2200 to 3200	87 to 131
Lead	11 400	2160	85	700	27
Lead antimony	10 900	2160	85	810	32
Magnesium	1740	5740	227	3080	122
Monel	8830	6020	237	2720	107
Nickel	8800	5630	222	2960	118
Plastic (acrylic resin)	1180	2670	105	1120	44
Platinum	21 450	3960	155	1670	65
Fused quartz	2200	5930	233	3750	148
Silver	10 500	3600	141	1590	62
Silver nickel	8750	4620	182	2320	91
Stainless steel (347)	7910	5790	226	3100	122
Stainless steel (410)	7670	5900	232	3300	130
Steel	7700	5900	232	3230	127
Tin	7300	3320	130	1670	65
Titanium	4540	6240	245	3215	126
Tungsten	19 100	5460	214	2620	103
Uranium	18 700	3370	133	1930	76
Zinc	7100	4170	164	2410	94
Zirconium	6490	4310	169	1960	77

X3.1 The values given in this appendix have been gathered from a number of sources. The values should not be taken as exact values because of the effects of variations in composition and processing as well as the conditions of test. They are, in general, sufficiently accurate for most practical applications.

TABLE X3.2 Densities and Ultrasonic Velocities of Some Ceramic Materials

Material	Condition	Density (kg/m^3)	%Theoretical	Longitudinal Velocity		Transverse Velocity	
				(m/s)	Frequency (MHz)	(m/s)	Frequency (MHz)
Alpha silicon carbide	Sintered	3190	99+	12 180	20	7680	20
		3100		11 182		7510	
		3000					
		2900	90	11 020		6950	
Aluminum oxide	Sintered	3660	92	9850	50	5900	20
	Extruded & sintered	3700		10 200^{A}		5890^{A}	
		3700		9970^{B}		5930^{B,C}	
		3700		9970^{B}		5910^{B,D}	
Zirconium oxide	Sintered	5700	98	7040	30	3720	10
	Thermally aged	5680		7050		3760	
Silicon nitride	HIP	3200	99+	10 800	50	6010	20
Reinforced silicon nitride	30 vol % SIC whiskers	3200	99+	10 800	50	6250	20
Reinforced silicon nitride	25 vol % SIC fibers	2490	77	7600^{E}	5	4700^{E,F} 4300^{E,G}	5
$YBa_2Cu_3O_{7-x}$(superconductor)	Single phase untextured	5940	93	5120	20	3040	5

^{A} Propagation parallel to extrusion axis.
^{B} Propagation perpendicular to extrusion axis.
^{C} Polarization parallel to extrusion axis.
^{D} Polarization perpendicular to extrusion axis.
^{E} Propagation perpendicular to fiber axis.
^{F} Polarization parallel to fiber axis.
^{G} Polarization perpendicular to fiber axis.

X4. VARIATION OF THE ACOUSTIC VELOCITY IN WATER WITH TEMPERATURE

TABLE X4.1 Variation of the Acoustic Velocity in Water with Temperature

Temperature, °C	Velocity (m/s)	Velocity $\times 10^3$(in./s)	Temperature, °C	Velocity (m/s)	Velocity $\times 10^3$(in./s)
15.0	1470.6	57.89	20.2	1483.6	58.40
15.2	1471.1	57.91	20.4	1484.1	58.42
15.4	1471.6	57.93	20.6	1484.6	58.44
15.6	1472.1	57.95	20.8	1485.1	58.46
15.8	1472.6	57.97	21.0	1485.6	58.48
16.0	1473.1	57.99	21.2	1486.1	58.50
16.2	1473.6	58.01	21.4	1486.6	58.52
16.4	1474.1	58.03	21.6	1487.1	58.54
16.6	1474.6	58.05	21.8	1487.6	58.56
16.8	1475.1	58.07	22.0	1488.1	58.58
17.0	1475.6	58.09	22.2	1488.6	58.60
17.2	1476.1	58.11	22.4	1489.1	58.62
17.4	1476.6	58.13	22.6	1489.6	58.64
17.6	1477.1	58.15	22.8	1490.1	58.66
17.8	1477.6	58.17	23.0	1490.6	58.68
18.0	1478.1	58.19	23.2	1491.1	58.70
18.2	1478.6	58.21	23.4	1491.6	58.72
18.4	1479.1	58.23	23.6	1492.1	58.74
18.6	1479.6	58.25	23.8	1492.6	58.76
18.8	1480.1	58.27	24.0	1493.1	58.78
19.0	1480.6	58.29	24.2	1493.6	58.80
19.2	1481.1	58.31	24.4	1494.1	58.82
19.4	1481.6	58.33	24.6	1494.6	58.84
19.6	1482.1	58.35	24.8	1495.1	58.86
19.8	1482.6	58.37	25.0	1495.6	58.88
20.0	1483.1	58.38			

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