U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

EPOCH 2002 USERS' GUIDE FOR ULTRASONIC VELOCITY MEASUREMENTS IN GLACIER ICE

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ABSTRACT

This report is an instruction manual in the set-up, calibration, and operation of the Panametrics Epoch 2002 ultrasonic testing workstation. Detailed procedures for sample preparation and measurement of differential p-wave velocities in fine-grained glacier ice are also outlined in this document. Measurement of the speed of propagation of elastic waves through ice in two mutually perpendicular directions, down and across the drilling axis of an ice core, yields information on the degree of orientation of ice crystals within the core and thus indicates the progress of fabric development as the ice recrystallizes in a stress field. Differential ultrasonic velocity measurements can be used both as a rapid screening method to track the progress of fabric development with increasing depth in an ice sheet or glacier and also to indicate zones of anomalous flow within the ice body. Additionally, measurement of both p- and s-wave velocities in a core allows computation of all elastic moduli.

INTRODUCTION

The Epoch 2002 is a self-contained, ultrasonic flaw-detection system. It is designed to generate, detect , and process ultrasonic signals with the use of appropriate transducers. The internal microprocessor will accept a known velocity and convert ultrasonic input data contained in a preset gate to a "distance-to-reflector" display utilizing this known velocity. The digital oscilloscope display screen on the Epoch shows information in decibels (vertical) and distance (horizontal) in English or metric units rather than in more conventional oscilloscope units of voltage (vertical) and time (horizontal). In the application discussed in this manual, measuring ultrasound velocity in ice, the Epoch is utilized in a reverse sense in that the depth readout is slewed to a known, premeasured path length, i.e. the distance between the transducer faces, and the velocity is calculated from the observed travel time. For more details on the specifications of the Epoch, refer to Table 1.

The Epoch has three modes of operation: (1) in manual mode, its functions are accessed via the soft keypad to the right of the digital oscilloscope screen, (2) in external mode, these same key commands can be issued from a remote computer keyboard via the RS-232 interface on top of the Epoch case, and (3) in external-program mode, the Epoch can be driven from a remote computer which is running a program designed to drive the Epoch. This is also accomplished via the RS-232 interface. An example of such a program, written in QuickBasic for the IBM-PC-XT, is provided by Panametrics along with the Operation and Programmers' Manuals (Part Nos. 20M02 and 20SF32). At this time (July, 1992), a communication protocol for Epoch to Macintosh has not yet been established, and communications are limited to those types of computers which utilize IBM handshake protocols. This manual assumes that the operator is using the Epoch in manual mode.

This particular Epoch 2002 (SN 2002-1409) has been tested and modified by Panametrics to withstand extended periods of operation at -20°C. To accomplish this, precision at high temperatures was sacrificed. This unit will self compensate at low temperatures but may drift out of calibration at ambient operating temperatures above 32°– 38° C. During the course of testing and calibration of this unit at Panametrics, a one-way, thru mode of signal input and detection utilizing two, single-element transducers was shown to maximize the signal strength at the receiving transducer. Attenuation tests show that this system can propagate and detect a 2.25Mhz P-wave signal through a maximum 20– 25 cm of polycrystalline ice in high energy, thru modes of operation.

This manual makes frequent reference to the softkeys on the front of the Epoch control panel. All references to softkeys in this manual are in bold type and are followed by reference numbers which are keyed to the legend in Figure 1. The reader is urged to have Figure 1 at hand when reading this manual to gain rapid familiarity with the function of each softkey. Not all keys will be used routinely in the normal course of ice measurement. This manual is intended as a guide for using the Epoch to measure P-wave velocities in ice. The reader should refer to the Panametrics Operation Manual (Part No. 20M02) for instructions in other applications.

Table 1. Manufacturer's Specification sheet for EPOCH 2002.

Display	5" (127) diagonally measured CRT
Graticule	Electronically generated 2.25" x 3.125" (57 x 80mm) – approximate size
Sensitivity	110dB max. readout to 0.1dB resolution with automatic reference sensitivity feature that displays + or - deviation from reference sensitivity.
Reject	Absolutely linear to 70% of full scale.
Units	English or metric by rear panel switch selection.
Velocity	0.025 to 0.6 in / µs (635 to15240m/s)
Zero Offset	0 to 200 µs (Allows compensation for acoustic sound path time in wedges and delay lines in order to calculate sound path and depth.)
Delay	Fixed delays of 0, 1, 2, 5, 10, 20, 50, 100, 200 in. or 0, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000mm or variable from 0 to 350 in. 0 to 8900mm at the velocity of longitudinal waves in steel.
Range	Fixed ranges of 0.1, 0.2, 0.5, 1.0, 2.0, 5.0 in./ div. or 2, 5, 10, 12.5, 20, 25, 50, 100 mm/div or variable from 0.06 to 7.4 in./div. or 1.5 to 190mm/div. at the velocity of longitudinal waves in steel; 0.3 to 4.0 in./div. or .76 to 102mm/div at the velocity of shear waves in steel. Optional extended range is available.
Expansion	Automatically expands gated portion of display to full graticule width.
Peak Memory	Produces stored display representing maximum signal at all locations. (Used for storing echodynamic.)
Ave Memory	Produces stored display representing the average amplitude at all locations for up to 1024 display updates.
Lock	Enables most system functions to be locked at preset value to avoid accidental readjustment.
Test Modes	Pulse-echo or through transmission (pitch and catch).
Display Update Rate	60Hz at test frequencies lower than 4MHz. 25Hz or greater at 4 - 6 MHz, and broadband filter positions.
Digitization Rate	20-40MHz at test frequencies lower than 4MHz. 65-80MHz at 4-6MHz, 10MHz, and broadband filter positions.)
Alarms	Visual on display showing maximum and current value of defect signal amplitude in gate. Audible horn or earphone.
Keyboard Annunciator	Rear panel switch controls audible tone when key-pads are depressed.
Outputs	Analog output 0 to 1 volt proportional to signal amplitude in gate. Composite video output, 75 ohms output impedance, 1 volt signal level into 75 ohms, black negative, sync negative. (Allows interface with a video printer, VCR or video monitor.)
Size	10.25 x 4.75 x 12 inches 260 x 121 x 305 mm

Table 1. Manufacturer's Specification sheet for EPOCH 2002 (continued)

Distance Readout	Provides sound path, surface, and depth to 0.001 in. or 0.04mm resolution
Refracted Angle	Can be entered at 0.0° or 10 to 85° refracted angle in 0.1° angle resolution.
Gate Start	Variable over complete display range with location readout in units of metal path.
Gate Width	Variable over displayed range with readout in units of metal path.
Gate Level	Off or on with level adjustable from 4 to 80% of full screen.
Time Varied Gain	Distance amplitude correction with resolution between correction points of 2µs min. and 30dB dynamic range. Gain curve can be of arbitrary shape. Linear interpolation is made between correction points.
Damping	Fixed settings of 60, 80, 150, and 400 ohms
Rectifier	Full wave, halfwave positive and negative
Frequency Range	Broadband (-6dB): 0.5 to 15 MHz Narrowband (1dB flatness): 0.4 - 0.6, 0.9 - 1.1, 2 - 4, 4 - 6, 9 - 11 MHz
Pulser	Shock excitation, -400V, open circuit, high and low energy
Status Readout	Displays list of all system functions with present value of each function. Ability to superimpose the status display over the A-scan for documentation.
Weight	12.5 lbs. (5.7 Kg) without battery 17 lbs. (7.7Kg) with battery pack
Operating Temperature	-20°C (+25°C typical) to 50°C
Storage Temperature	-40° to 60°C
Battery Pack	Quick disconnect battery pack allows battery pack to be charged without opening unit.
Battery Type	12 volt sealed lead-lead dioxide battery
Battery Life	12 hrs. @ 25°C
Battery Status	Full screen battery status indicator via front panel keypad shows state of charge.
Battery Charger	Short circuit proof battery charger capable of operating unit and charging battery simultaneously
AC Requirements	82 to 130 VAC/164 to 260 VAC, 47 to 66 Hz. 30 watt maximum.
Charging Time	16 hours max. depending on state of charge
Power Consumption	6 watts
Transducer Connector	BNC or Number 1 Lemo
Handle/Tilt Stand	Variable position, locking type
10 Stored Memory Set-up	Ability to store, recall and clear 10 distinct transducer calibrations

Components of the Epoch

The Epoch is a compact, field-portable unit which includes several subsystems. These subsystems are the digital oscilloscope and its attendant controls (gain and reject, distance and time base, peak and average memory), the pulser/receiver controls for the generation and detection of the ultrasonic signals (frequency filtering, pulse energy, signal damping), the internal microprocessor controls (gate controls, status and memory, recall and store setup functions, status and lock), and the transducers. The performance of the system, as a whole, depends on the optimization of the performance of the individual subsystems for the particular analytical task at hand. The settings which are recommended in this manual have proven to yield good results on fine-grained glacier ice. The settings recommended here may not yield the best possible results on other types of materials.

Keypad Layout

Figure 1 shows the layout of the softkey pad on the front of the Epoch. The keys are color coded into groups according to their function. The keys are grouped as follows:

Color	Key Nos.	Functions
Blue	1, 7, 3	gain and reject (vertical display axis)
Yellow	2,3,8,9,10,14,15	distance and time base (horizontal display axis)
Red	4,5,6	gate adjustment
Brown	11,12,17,18,23	pulser/receiver controls
Orange	16,20,21,22	status and memory

Additional special keys include the two large green **slewing keys** [19 and 24], the yellow **battery level key** [25], and the green **power key** [26].

OPERATION

Starting Up and Checking Initial Values

Before using the Epoch, an initial check of starting settings should be made. These include the following:

Rear Panel Settings:

audio alarm - off

units - mm

composite video - connected to printer or an auxiliary screen

The Epoch can be run either on battery power or AC-line power (115 or 230V). To run on battery power, seat the battery pack firmly on the two guide pins provided on the back panel of the Epoch, making sure that the 4-pin receptacle on the battery pack is aligned with the 4-pin plug on the Epoch. Tighten the thumbscrews on either side of the seating pins. The battery level may be examined any time the Epoch is running by pressing the **battery level key** [25]. If the battery power runs low during the course of operation, the Epoch can continue to operate while recharging the battery by connecting the charger/adapter into the battery back at the 4-pin connector on the side of the battery pack. To run on AC-line power, select the appropriate line voltage by means of the slide switch on the back of the charger/adapter, connect the charger/adapter to the Epoch by means of the 4-pin connector on the end of the DC output cable, connect the charger/adapter power cable to the line power source, and turn it on by means of the power switch on the front. To power up the Epoch, press the green **power key** [#26] on the front panel. If the Epoch is operating properly, it will beep as the power comes on, and the Panametrics logo will appear on the screen within five seconds. The unit will self-test for approximately ten seconds. When the self-test is competed the unit is ready for operation. Press the orange **status display key** [#16] until the full status screen is displayed (Figure 2). Values on the status display screen should appear as shown in Table 2.

Adjust the parameters on the screen to match those shown in Table 2 by one of two methods. The user may recall the correct stored setup from memory by entering the status only display mode (depressing key #16 twice), selecting memory position #1 with the **right slew key** [19], and pressing the **average memory key** [22]. Readjustment of the values for parameters shown on the status display screen may also be accomplished by resetting the values of the chosen parameter using the keys indicated at the left and right of each status line listed in Table 2. For example, if the **frequency key** [18] is pressed several times, the value shown under the parameter labeled "FILTER" on the status display screen will scroll through the values 0.5, 1.0, 2 to 4, 4 to 6, 10, and BROADBAND. If the **mode key** [23] is pressed, the value will toggle from thru mode to T/R mode (transmit and receive). The **reject** [1], **delay** [14], and **zero** [8] keys are designed to slew through a continuum of values rather than scroll through a table of preset values. To reset any of these values, first press the desired function key and then slew to higher or lower values, using one of the two **slew keys** [19 and 24].

Table 2. Information shown on the full status display only screen

KEY #			KEY #
1	REJ **0%**	xxxx* mm/DIV	15
13	xxxx dB		
14	DELAY xxxx **mm**	ZERO **2.43** μs	8
18	FILTER **broadband**	DAMPING **400 OHMS**	11
4	GATE START xxxx	ENERGY **HIGH**	17
5	GATE WIDTH xxxx	**HALF WAVE +**	12
6	GATE LEVEL **60%**	**THRU** MODE	23
2	VEL xxxx M/sec	**< 0.0° / 0.00 mm**	3

* values which are not critical at startup are indicated as xxxx

Calibrations

Delay or Zero Calibration

The first procedure necessary to acquire data is the determination of the travel time required for the ultrasonic signal to pass through everything exclusive of the sample itself. This includes the cables, backing plates, transducers, wearplates, and any buffer rods. This calibration should be made in two circumstances: (1) when the configuration of the system is changed, i.e. if a transducer or cable is changed, if a buffer rod is introduced, or if anything is done which changes the sound path length (exclusive of path length in the sample itself), or (2) when the operator chooses to change the portion of the signal over which the gate will be set for measurement, i.e. the operator wishes to redefine the first arrival in the wave train. An aluminum rod with a length-velocity-temperature calibration curve has been provided for this purpose. The factory calibrated delay (or "zero") for the system as it is configured for ice measurements is 2.43 μs. Due to the internal quartz crystal time-base compensation of the unit, the delay or system zero is temperature insensitive. Although the operator should periodically check the delay calibration, the value of the system zero should not change during the course of normal operation. The value of 2.43 μs assumes that the operator is using the two 6' HDAS cables, the 2.25Mhz transducers labeled 1 and 2, that glycerine bonding solution (Couplant B) is used to couple the transducers to the sample, that no buffer rods are used, and that the chosen first arrival is the leading edge of the second positive wave front (in the half-wave positive display) at a maximized peak signal of 80 percent and a gate level of 60 percent (see Figure 3). This is the standard configuration in which all measurements are made. If the operator chooses to change this configuration or to redefine the first arrival, the system zero must be recalibrated. The travel time in the

Epoch 2002 is calculated from the main bang to the first signal crossing into the gate minus the zero offset. Note that, using this algorithm, consistent setting of the signal peak and gate levels is crucial.

To check the calibration or redefine the system zero, ascertain that the ends of the aluminum rod are free from any buildup of ice or frost and then measure the length of the aluminum rod with a micrometer. This measurement should be precise to the nearest 0.1 mm. Measure the temperature of the rod and check these values against the calibration curve provided. Read the correct velocity off the curve or compute it from the equation provided. Ascertain that the Epoch is in thru-transmission mode, not transmit/receive mode using the **status key** [16], and that the **detector control key** [12] is in half-wave positive mode. Verify that the zero delay is set to 2.43 microseconds from the status display. Connect transducers #1 and #2 to the two HDAS cables and connect the cables to the Epoch. Apply three to four drops of warm glycerine to the center of the upturned face of one of the transducers, set it on a flat surface, and place the aluminum rod upright on the face of this transducer. Move the rod over the transducer with a circular motion until it wrings in slightly. Apply three to four more drops of glycerine to the center of the upright face of the aluminum rod and wring in the second transducer. At this point, a signal should be visible on the oscilloscope screen. If it is not, shrink the horizontal scale using the **range key** [15] until the signal is located, drag the gate over the signal using the **gate position key** [4], and then expand the screen using the **range expansion key** [9]. The gate and signal will now appear at the far left edge of the oscilloscope screen. To drag it to the center of the screen, press the **delay key** [14] once and use the **slew keys** [19 and 24] to reposition the signal and gate in the center of the screen. Adjust the position of the upper transducer on the face of the aluminum rod until the strongest signal possible is achieved. Leaving the transducers in the same position relative to each other, increase the signal to 80 percent by pressing the **dB key** [13] once and the **up slew key** [19]. Reposition the gate over the signal if necessary and drop the gate level to 60 percent using the **gate position** [4] , **gate level** [6], and **slewing keys** [19 and 24]. Press the **sound velocity key** [2], slew the displayed value to the correct sound velocity of the calibration rod from the calibration curve and then press the **distance to reflector key** [3]. The depth displayed on the lower left corner of the screen should match the measured half length of the aluminum rod. If you have changed the system configuration or wish to redefine the portion of the wave train you are measuring, use the **zero offset** [8] and **slew keys** [19 and 24] to adjust the system zero value until the correct path length is displayed for the calibrated velocity.

Attenuation Calibration

If the operator intends to measure relative acoustic attenuation as well as velocity, the system must be standardized to a stable reference material. Measurement of the signal attenuation in this standard provides a constant point of comparison for measurements of attenuation in ice samples. (Absolute acoustic attenuation cannot be measured with this system.) A small leucite block with two polished ends has been provided for this purpose. The loss characteristics of this block are such that a 10 cm truepath in ice will generally result in a positive signal loss relative to the standard (i.e. more signal is lost in the ice than in the standard). To perform this calibration, measure the signal as described in the delay calibration section, omitting the path-length measurement step. When coupling the transducers onto the block, visually inspect the bond through the leucite and confirm that the entire face of the transducer is bonded to the standard block. Position the transducers to maximize the signal and increase the gain until the signal reaches the 80 percent level. Drag the gate over the signal, set the gate level to 60 percent, and then depress the **reference level key** [7] twice. The new reference level should now appear in the upper left hand corner of the live screen. Do not press the **reference level key** again after the measurement has been made because this will cause the reference level to be reset to whatever level happens to be present in the gate at the time. After this calibration is completed, all other attenuation measurements will appear appended to this reference level as + or - values in decibels following the calibrated reference level. A positive value indicates that the measured sample has a larger acoustic loss than the reference standard and a negative value indicates that the sample has a smaller loss value.

Sample Preparation

Core samples should be trimmed with a band saw so that opposite pairs of faces are plane parallel to each other. Lack of plane-parallelism in these cuts is the major source of error in the velocity measurements. If no azimuth control is available on the core, two perpendicular sets of faces for the determination of longitudinal and transverse velocity are sufficient. If azimuth control is available, one set of faces for the longitudinal velocity and two perpendicular sets of faces for the transverse velocities should be cut. Cuts for the transverse velocity measurements should be made parallel and perpendicular to the direction of flow (see Figure 5). After the cuts are made, the cut faces should be sanded to smoothness on a wire mesh-covered, flat surface. Sanding should remove all traces of saw cuts and loose chips of ice . The distances between parallel faces can then be measured by calipers. These measurements should be repeated several times and averaged to obtain an estimate of the anticipated error arising from the uncertainty in the measurement of the path length.

Sample Measurement

Couple the transducers onto the ice sample with a small amount of warm couplant using a gentle wringing motion. Visually inspect the bond through the ice and confirm that the entire face of each transducer is bonded. If normal-incidence s-wave transducers are being used, apply several drops of cold water to the face of the transducer and freeze it onto the sample instead. Bring up the live waveform display on the Epoch using the **status key** [16]. If no signal appears on the screen, check the gain [13]. For a path length of approximately 10 cm of ice, the gain should be approximately +35dB relative to the standard. If the signal is not yet visible, either scroll along the screen using the **delay key** [14] or compress the horizontal axis using the **range key** [15] until the signal is located. When the signal is located, drag the gate [4] so that it is positioned over the second peak and adjust the gain again [13] to bring the signal above the gate level. Expand the range [9], if needed, so that the first arriving wave train fills the screen (Figure 4). Re-center the wave train on the screen if necessary. Position the transducers so that the amplitude of the signal is maximized. Investigate the sound paths through the sample by moving the transducers over the ice and watching the arrival time change. If large cracks are present in the sample or if the grain size is on the order of magnitude of the transducer diameter, large shifts in the velocity may be observed. Such samples may be unsuitable for analysis. Samples of deep ice that contain high concentrations of exsolved hydrate clathrates can also exhibit strong attenuation characteristics in directions normal to the exsolution plane. Anomalously low velocities will also be observed in these directions because the truepath length may be longer than the measured distance between the transducers.

When the position of the transducers yields a satisfactory signal, readjust the gain [13] so that the peak amplitude of the second wave (in half-wave positive mode) is 80 percent of the full vertical scale. Reposition the gate, if necessary, so that the leading edge of this portion of the wave train crosses into the gate at a level of 60 percent [6]. Press the **distance to reflector key** [3] to bring up the depth display in the lower left corner of the screen and press the **sound velocity key** [2] to bring up the velocity display in the upper right corner. Adjust the velocity until the correct value for the half-path length appears in the depth window. The velocity displayed in the upper right corner is now the correct velocity for the measured depth. To save the screen and status information for printing, press the **status key** [16] until the full status screen and the live data screen are superimposed. Press the **average memory key** [22] to freeze the screen and print the screen contents using the video printer chained to the Epoch. Repeat this process for the transverse measurements.

Record the temperature of the sample at the time of measurement. The measured velocities can be corrected back to the in-situ temperature using the data tabulated in Kohnen (1974) where it is shown that

$$dV_p / dT = -2.3 \text{ m/s per } ^\circ C$$

$$dV_s / dT = -1.2 \text{ m/s per } ^\circ C$$

Poisson's ratio and the pertinent elastic moduli can be calculated using the corrected data plus the temperature corrected densities.

TROUBLESHOOTING

No signal visible. Ascertain that the Epoch is functioning properly by decreasing the delay to 0.0 [Key 14] and increasing the gain [13] until the main bang is visible on the left edge of the screen. If no signal is visible, check the bnc connections between the cables and the Epoch and between the cables and the transducers. If the Epoch is functioning properly and the main bang is visible, slew the delay [14] to scroll across the screen without resetting the gain. If the signal is still not visible, check the filter [18] and damping controls [11] and the coupling at the transducers.

Noisy signal. Occasionally, samples with very high attenuation will yield very weak wave trains. If the sample cannot be cut thinner to allow more of the signal through, use the linear **reject key** [1] and **average memory key** [22] to improve the signal-to-noise ratio. Decoupling one of the transducers will help distinguish between what is signal and what is noise at very high gain settings. Very poor peak-to-background characteristics may be an indication that the sample is highly microcracked or is otherwise discontinuous (as in firn). Changing to a larger transducer may be helpful.

Inconsistent Signal. Remeasurement of a sample may yield inconsistent velocities if sound paths of varying lengths exist within the sample. It is advisable to investigate the propagation characteristics of the sample at the time of measurement by moving the transducers over the sample to insure that the measured velocity is the fastest the sample will yield. If possible, it is also advisable to make several measurements on an individual sample cut to successively shorter and shorter path lengths. If the velocity remains constant throughout this process, it may be assumed that the path length measured by calipers accurately reflects the truepath of the ultrasound waves through the ice.

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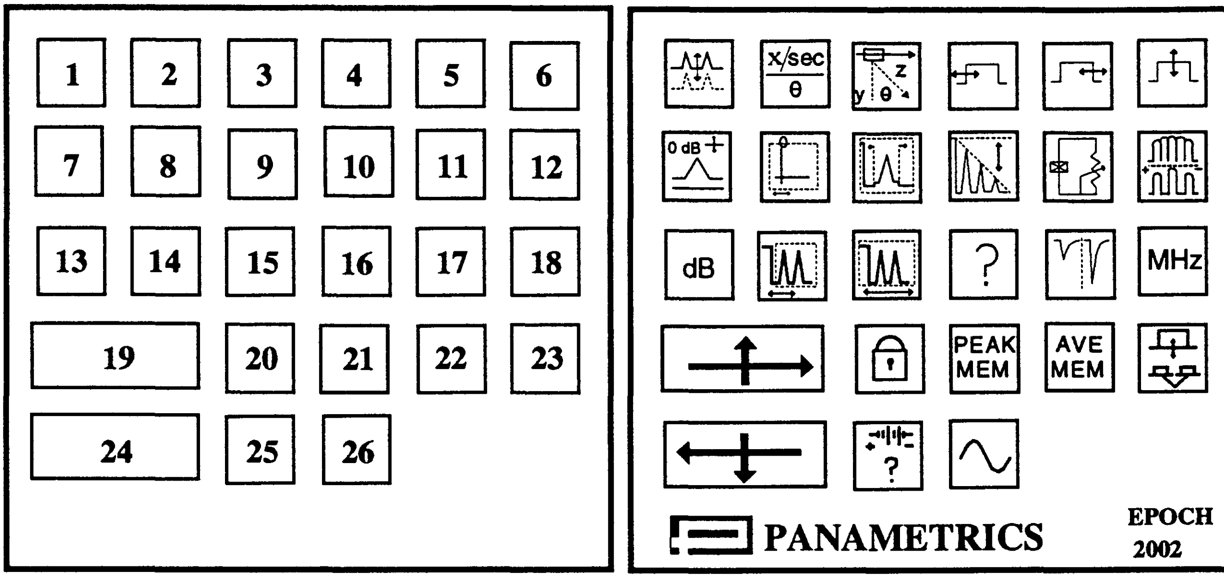
Pao, Y.H., ed., 1978, Elastic Waves and Non-Destructive Testing of Materials: American Society of Mechanical Engineers, Applied Mechanics Division Symposia Series, v. 29, 143 p.



1. REJECT (LINEAR)
2. SOUND VELOCITY / REFRACTED ANGLE
3. DISTANCE TO REFLECTOR
4. GATE POSITION
5. GATE WIDTH
6. GATE LEVEL
7. REFERENCE LEVEL
8. ZERO OFFSET
9. RANGE EXPANSION
10. TIME VARIED GAIN
11. DAMPING
12. DETECTOR CONTROL
13. SENSITIVITY (GAIN)
14. DELAY
15. RANGE
16. STATUS
17. ENERGY
18. FREQUENCY (FILTER)
19. SLEW (UP, RIGHT)
20. KEYBOARD LOCK
21. PEAK MEMORY
22. AVERAGE MEMORY
23. MODE
24. SLEW (DOWN, LEFT)
25. BATTERY STATUS
26. POWER (ON/OFF)

Figure 1. Keypad layout for the Epoch 20002

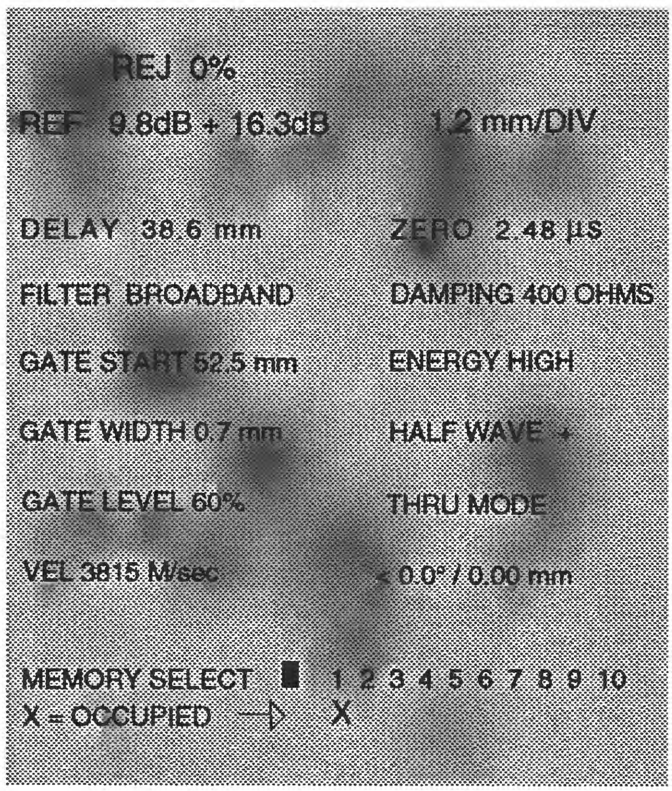


Figure 2. Full status display screen. After initial power up, press the status softkey twice to obtain this screen.

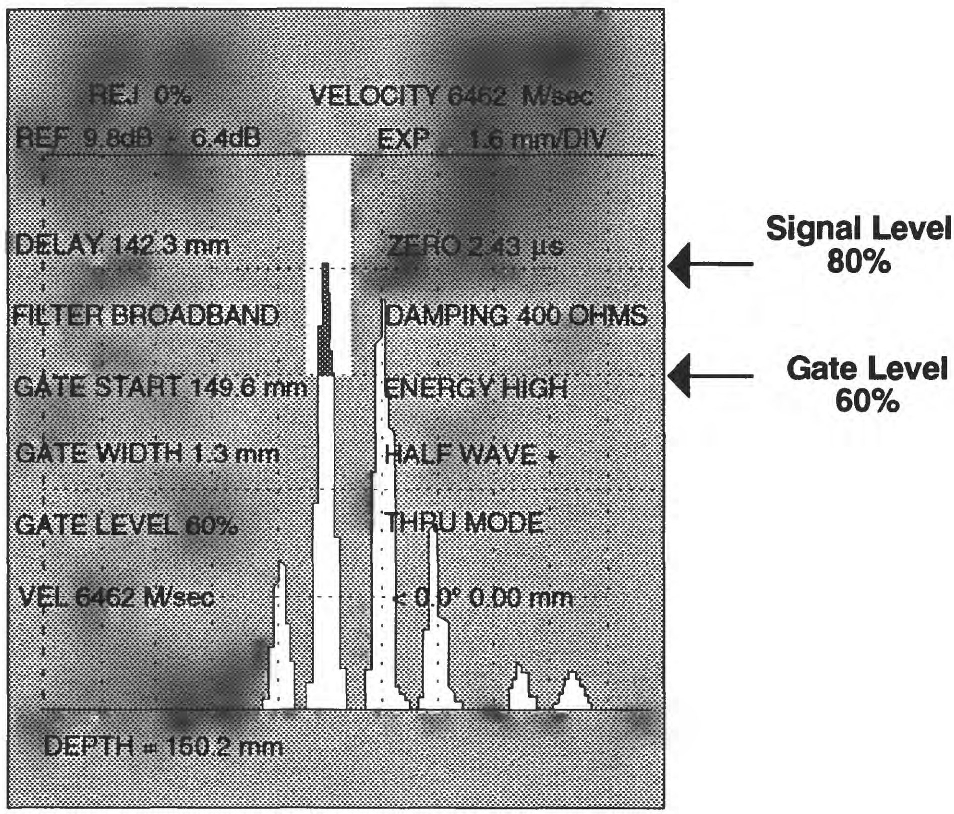


Figure 3. Example of full data screen for delay calibration. Note that the system zero is set to 2.34 µs. The detector control is set to display "HALF WAVE +", and the system has been calibrated to the leading edge of the second positive wave at a signal amplitude of 80% and a gate level of 60%. Under these conditions, a velocity of 6462 m/s yields the correct path length in the aluminum standard of 150.2 mm.

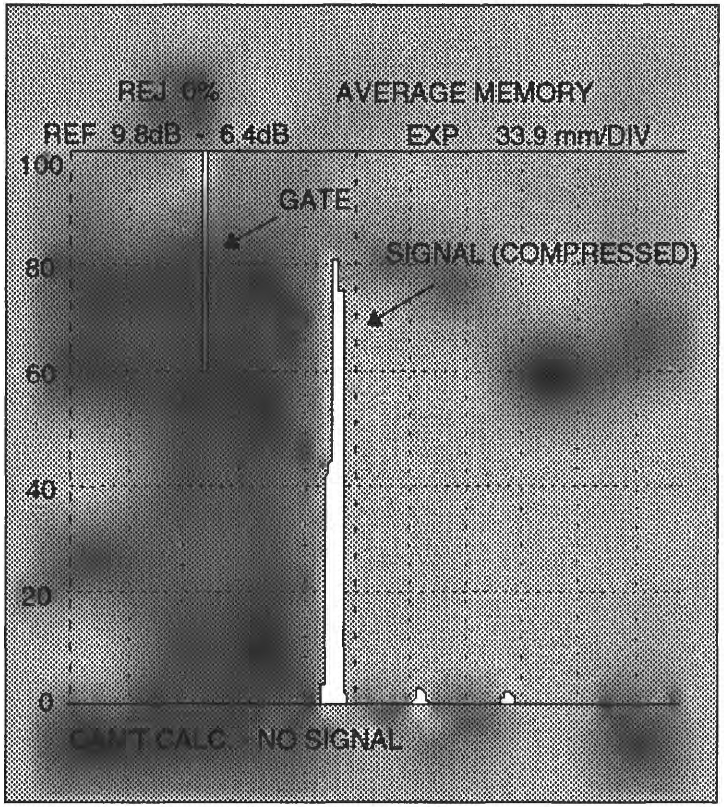


Fig. 4A

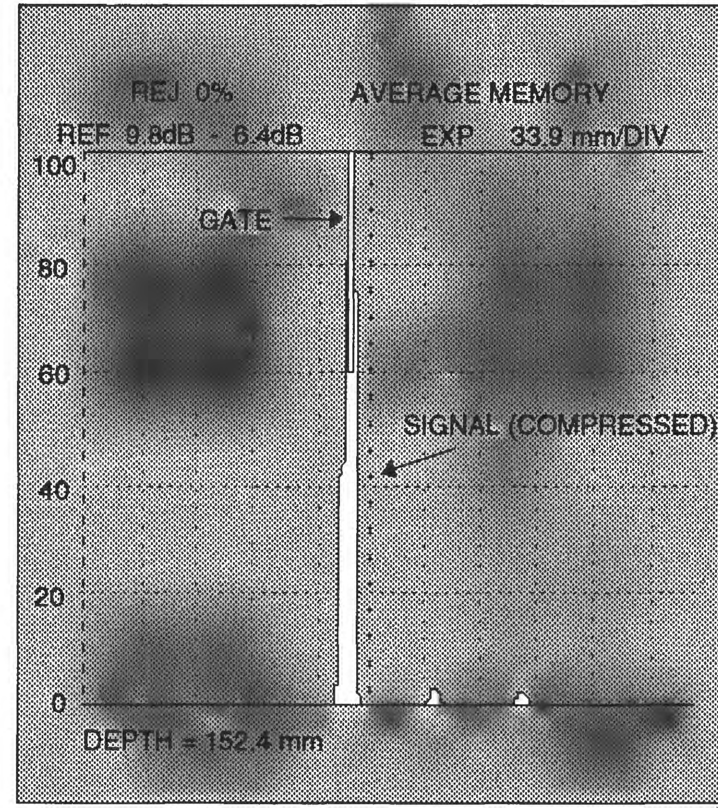


Fig. 4B

Figure 4. Typical screen sequence during a measurement.

A Signal as it appears in compressed display. Here the gate lies just to the left of the signal.

B. Same screen after the gate is repositioned over the peak.

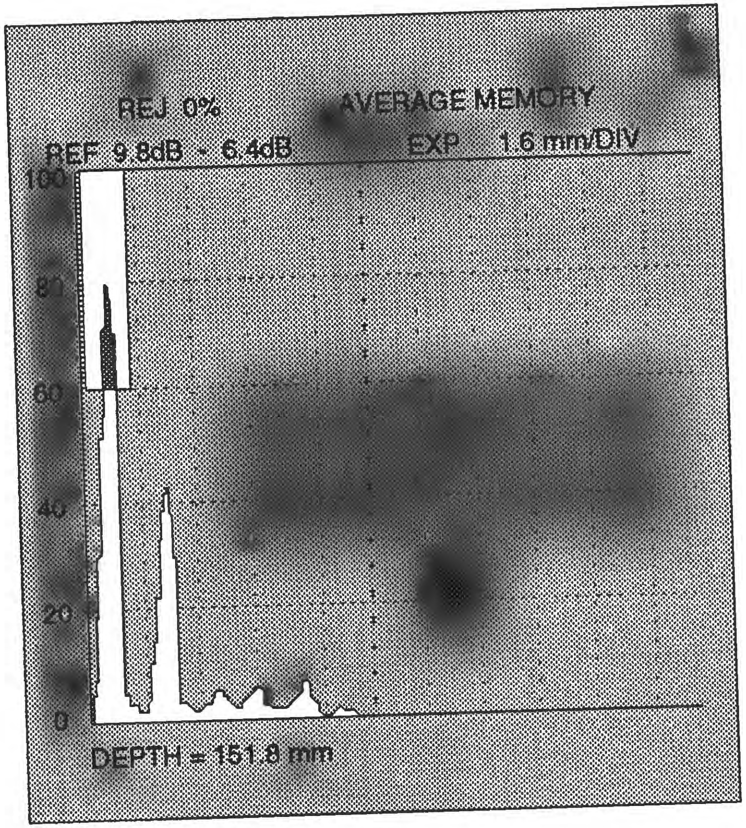


Figure 4C

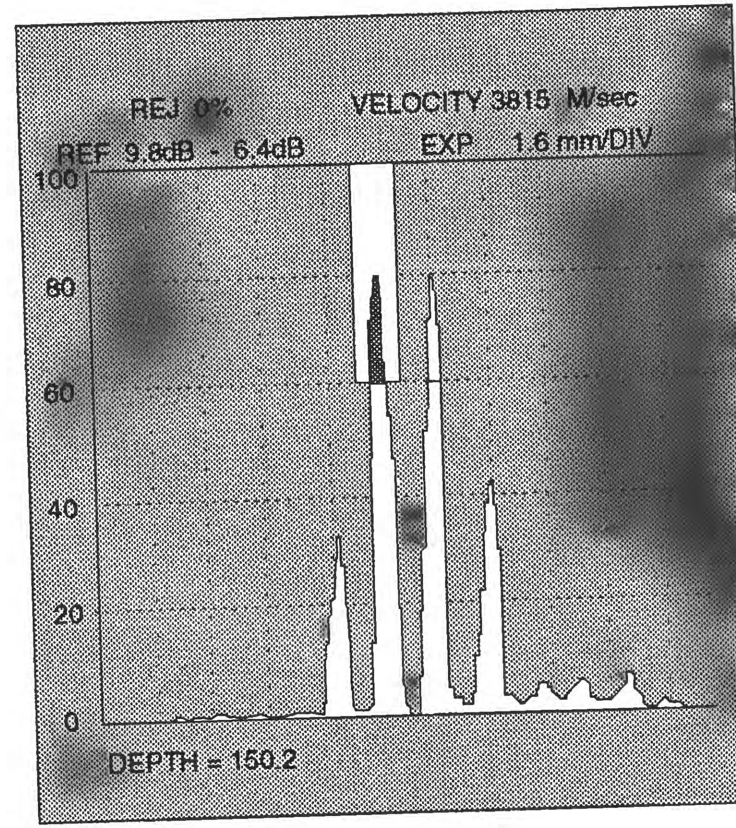
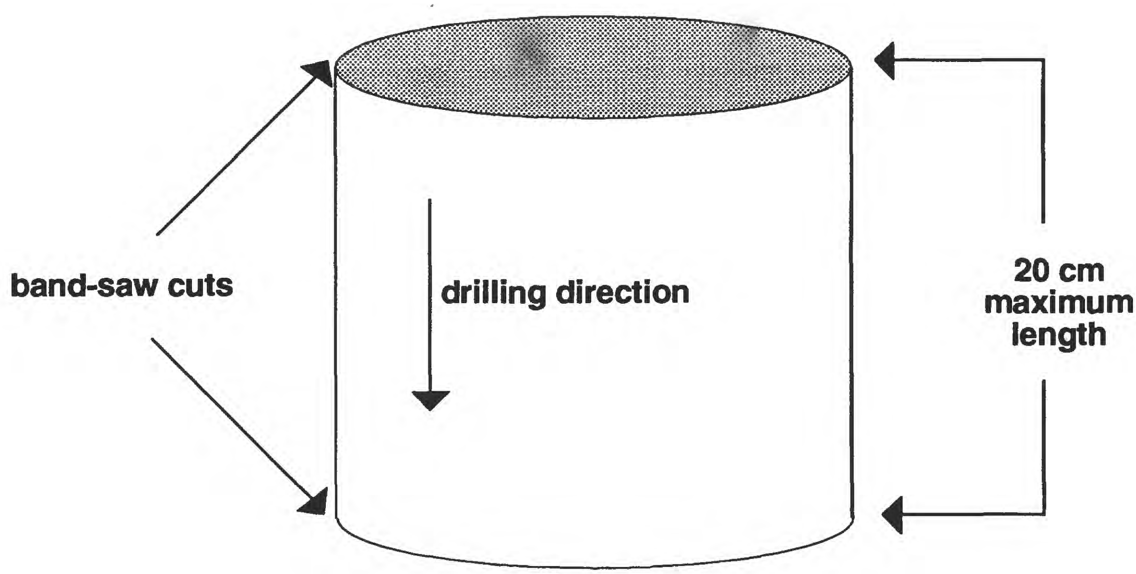


Figure 4D

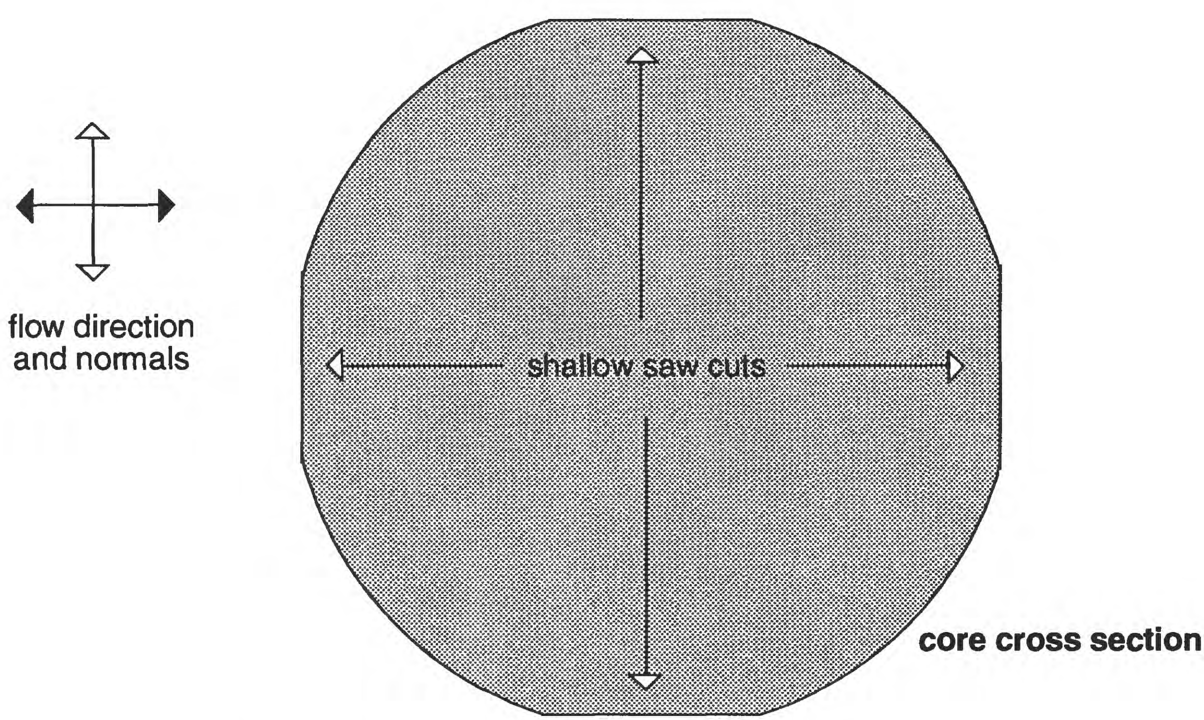
Figure 4. (cont.)

C. **Same screen after range expansion key (9) is activiated.**

D. **Signal correctly positioned in gate. Delay key (14) has been used to center the wave train and the gate on the screen. Signal is now ready for measurement.**



5b. Illustration of band saw cuts for vertical p-wave measurements.



5b. Illustration of band saw cuts for transverse p-wave measurements with azimuth control.

Figure 5. Illustration of band saw cuts for vertical and transverse p-wave velocity measurements.