NUREG/CR-5985
PNL-8919

Evaluation of Computer-Based Ultrasonic Inservice Inspection Systems

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Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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Manuscript Completed: December 1993
Date Published: March 1994

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Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC FIN L1100
Under Contract No. DE-AC06-76RLO1830

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Abstract

This report presents the principles, practices, terminology, and technology of computer-based ultrasonic testing for inservice inspection (UT/ISI) of nuclear power plants, with extensive use of drawings, diagrams, and UT images. The presentation is technical but assumes limited specific knowledge of ultrasonics or computers. The report is divided into 9 sections covering conventional UT, computer-based UT, and evaluation methodology. Conventional UT topics include coordinate axes, scanning, instrument operation, RF and video signals, and A-, B-, and C-scans. Computer-based topics include sampling, digitization, signal analysis, image presentation, SAFT, ultrasonic holography, transducer arrays, and data interpretation. An evaluation methodology for computer-based UT/ISI systems is presented, including questions, detailed procedures, and test block designs. Brief evaluations of several computer-based UT/ISI systems are given; supplementary volumes will provide detailed evaluations of selected systems.

Summary

This report provides a framework for reviewing and evaluating computer-based ultrasonic inservice inspection systems.

Computer-based ultrasonic inspection (UT) is based on the same technology as conventional (i.e., manual and automated) UT, with the capabilities of

- more sophisticated scanning control
- more sophisticated instrument control
- remote operation
- digitization of data
- magnetic storage of data
- signal analysis
- image analysis

Review and evaluation of computer-based ultrasonic inservice inspection (UT/ISI) systems require understanding the principles, practices, and terminology of both conventional ultrasonics and computer-based capabilities. The material is organized under the following topics:

Conventional UT comprises the methods and terminology in the field of ultrasonics that are not specialized to computer enhancements. This section describes instruments, transducers, scanners, and the conventional recording and interpretation of data.

Computer-based UT: General Description sets out the general facts and methods of computer-based UT that distinguish it from conventional UT, and introduces terminology and concepts of computerization.

Scanning Motions includes the linear and rotational modes used in conventional UT, with the addition of variable control over the angle of the transducer. With a computer in direct control of these motions, it is also possible to change sample spacing within a scan or index between scans, maintain normality over complex geometries, do multiple scans at different angles in order to look under obstructing surface features, and operate multiple transducers concurrently.

Transducer Arrays describes the use of multiple independent transducers and phased transducer arrays to enhance or speed up computer-based inspections.

Data Acquisition discusses the transformation of data from the domain of real-time ultrasonic and electrical signals into stored computer information. It is the most noticeable difference between conventional and computer-based UT. The terminology, the methods of data acquisition, and the methods of data validation are different from those used in conventional UT.

Image Processing and Display involves presenting and combining data from many points. It enables viewing UT indications from multiple space and time perspectives, enhancing the repeatability and sophistication of evaluation. Image analysis has no analogue in conventional UT.

Data Analysis and Interpretation discusses the requirements for manual analysis and interpretation of the data taken by the computer-based system. It also projects future requirements and directions in this area.

Evaluation contains analyses of a number of computer-based UT systems described in the technical literature.

Glossary contains definitions and explanations of UT and computer terminology relevant to computer-based UT/ISI systems.

Appendix A presents a method for characterization of computer-based UT/ISI systems.

Supplements to the report will provide detailed characterizations of selected UT/ISI systems, using the method described in Appendix A.

Acknowledgments

This work is supported by the U.S. Nuclear Regulatory Commission under Contract DE-AC06-76RL0 1830; NRC FIN L1100; Dr. Joseph Muscara, NRC program monitor; Richard Kurtz, PNL program manager.

M. S. Good, B. P. Hildebrand, and R. L. Hockey (as well as several of the authors of this document) contributed material to the 1991 seminar, "An Introduction to Computer-Based Inservice Inspection"; much of that material has been used here.

Laurence Poulter of AEA Technology, Risley, United Kingdom, and William Clayton of Southwest Research Institute, San Antonio, Texas, provided valuable suggestions for the characterization methodology.

Contents

Figures

1.0 Introduction

The U.S. Nuclear Regulatory Commission (NRC) requested the Pacific Northwest Laboratory (PNL)[1] to provide an introduction to computer-based inservice inspection technology and a description of selected computer-based systems. This report documents that information. A glossary of key terms is provided.

Computer-based ultrasonic inspection (computer-based UT) uses a combination of ultrasonics, mechanics, and computer technology to perform inspections, acquire and store data, and analyze and interpret the results. Computer-based UT provides faster and more repeatable inspections than conventional (i.e., manual or automated) UT, improves record-keeping, and introduces superior possibilities of data interpretation and review.

This report describes computer-based inspection technology under the following headings:

- conventional ultrasonics (Section 2)
- computer-based ultrasonics: general description (Section 3)
- scanning motions (Section 4)
- multiple transducers (Section 5)
- data acquisition (Section 6)
- image processing and display (Section 7)
- data analysis and interpretation (Section 8)

The major driving force in computerization of UT/ISI is to increase inspection reliability. Inspection setups are more nearly identical from component to component and from year to year, so that comparison of inspections is facilitated. Full coverage of accessible areas is dependent only on proper programming of the equipment, not on the field operator. Likewise, the interpretation of data is more reliable. In manual inspection, the examiner must watch an oscilloscope that displays A-scan information. As the examiner scans the test piece, transient information must be acquired by eye and be interpreted. The reliability of manual examination is thus highly dependent upon the examiner's ability to analyze this transient information.

Computer-based ultrasonic inspection technology provides two powerful features to overcome these human limitations. First, it provides the ability to integrate all data collected during an examination. The integration is generally accomplished by displaying the acquired data in an image. Using an image of all ultrasonic data collected during a scan, the analyst may look for patterns in the data that are not discernible during manual examination. The second feature of computer-based technology is that raw data are stored permanently. This feature allows analysis by more than one person or supplemental processing to provide additional information to the analyst. Discussion of the presentation and interpretation of images forms a large part of the text of this report.

Computerization also modifies the exposure of inspection personnel to radiation. Computerization enables the operator to be located remotely from the scanned component during the scanning process. It reduces the need for reinspection, by allowing more complete records to be taken during the initial scanning. It allows the scanning to be performed faster, since the mechanical scanner is more precise than manual movement, and electronic recording of data is faster than human perceptions. It allows easier access to restricted spaces, because the manipulator replaces the human arm and hand. Offsetting the advantages is the additional time spent setting up the scanner in a much more precise way than is necessary for manual inspections.

Another advantage to computerization is enhanced record-keeping. By the nature of computer systems, entries are restricted in scope and checked for correctness. The program never forgets, increased standardization is achieved, the entire bulk of records can be quickly searched for items of interest, and electronic storage consumes less space than paper records.

The concepts and technology described in Sections 2 through 8 are being applied by computer-based systems currently used for inservice inspection.

1. Operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

In Section 9, PNL's preliminary evaluations of the following selected computer-based ultrasonic inspection systems are presented:

- Intraspect I-98 (9.1)
- UDRPS (Ultrasonic Data Recording and Processing System, 9.2)
- Accusonex (9.3)
- GE-Smart UT (9.4)
- Phased Array (9.5)
- P-Scan (9.6)
- GERIS (9.7)
- SWRI/PAR EDAS (9.8)
- ARIS (9.9).

The system evaluations were performed to determine

- principles of operation
- potential limitations of operation
- reliability for flaw detection and sizing

The evaluations documented in Section 9 are based upon information obtained from system vendors, a literature search, a letter survey requesting information from vendors, and databases from such sources as PISC II, MRR, PVRC, and EPRI.

Appendix A details the methodology for evaluation of systems.

A Glossary is provided, giving definitions of ultrasonic and computer terminology used in the report or considered necessary for reviewing computer-based UT systems, and giving the meanings of acronyms used.

The detailed results of system evaluations will be found in supplements, published as the evaluations are carried out over a period of two to three years.

2.0 Conventional Ultrasonic Inspection Systems

This section describes conventional UT and explains the UT terminology used in later sections; the Glossary gives concise definitions of conventional as well as computer-related terms. The term "conventional UT" is used throughout this report to designate those aspects of UT that do not depend on the use of computers.

A system design for a conventional ultrasonic inspection system, along with the x, y, and z axes used to reference the scanner motion, is shown in Figure 2.1.

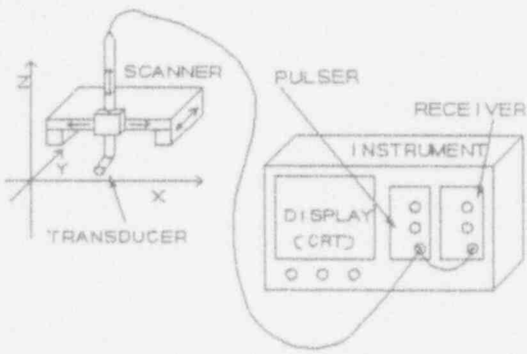

Figure 2.1 Conventional UT system

The modules of conventional UT are the instrument, the scanner, and the transducer (also called search unit or probe). The submodules of the instrument are the pulser, the receiver, and the display. The overall functioning of the system is as follows: the transducer is attached to the scanner and connected to the instrument. The pulser produces a pulse of electrical energy many times per second. The transducer converts (or transduces) this electrical pulse into sound, which travels through the part being inspected and returns to the transducer. This returning sound is converted by the transducer into electrical energy, which returns to the receiver. The receiver converts the returning electrical signal into a form suitable for presentation on the display. The receiver signal may also be used to produce, for reflections exceeding a predetermined threshold, a signal that activates an alarm, or is fed to a plotter to produce a visible record of the inspection. As the inspection proceeds, the scanner moves the transducer along the part. The details are explained in the following paragraphs.

2.1 Transducers

The ultrasonic transducer is a piezoelectric device that both translates electrical energy into sound energy and converts the sound energy into electrical energy. When electrical energy is supplied, the face of the transducer expands or contracts, producing sound energy that travels into the object to be inspected. Anywhere the sound encounters a change in velocity or material density, part of the energy is reflected. When this reflected energy returns to the transducer, it causes the face of the transducer to expand or contract. This produces electrical energy in the transducer. Processing and display of this energy enables the internal structure of the object to be examined.

One inspection technique, known as immersion, is to immerse the item to be inspected in a tank (Figure 2.2). The scanner (mechanical motion apparatus) then moves the transducer across the item being inspected.

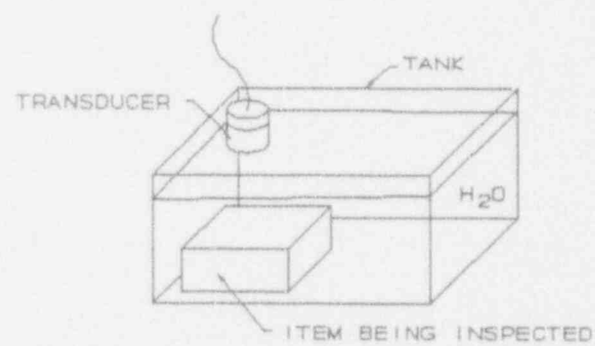

Figure 2.2 Example of immersion test

Another inspection technique, called contact, is to put the transducer in contact with the surface, as shown in Figure 2.3. In this case, a medium is needed also to couple the sound energy from the transducer into the item of interest. Usually, a light mineral oil, water, or acoustic gel is used to make this acoustic coupling.

In some contact inspections where the item has a rough surface that would damage the transducer, it is desirable to keep the transducer from touching the surface. In these situations, a liquid standoff can be used to

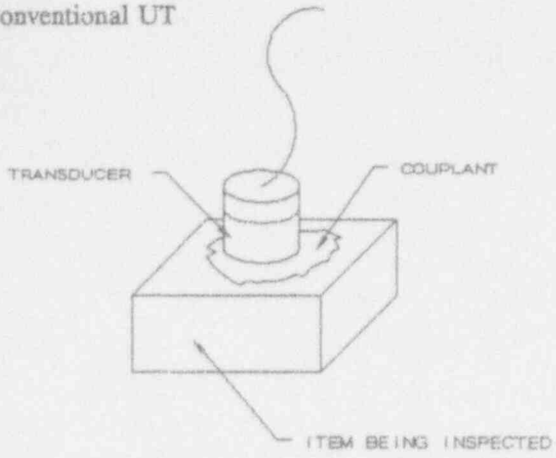

Figure 2.3 Example of contact test

couple the energy to the item being inspected, using a boot or a column of liquid that is held around the transducer, as Figure 2.4 illustrates. A film of coupling material (water, ultrasonic gel, oil) is then used to effect the coupling of the sound energy into the item. Another variant of this method dispenses with the membrane; a constant flow of couplant is provided, which runs off along the part surface and is discarded or recycled.

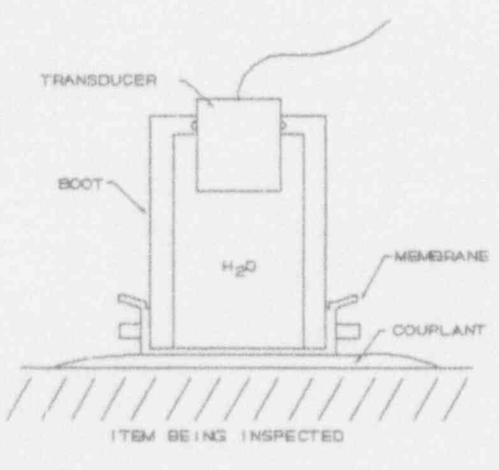

Figure 2.4 Coupling with a booted transducer

Another type of standoff is a solid material such as plastic. The transducer is mounted on this material, called a shoe, and the shoe makes contact with the surface, again using a material such as oil or ultrasonic gel to effect the coupling of sound into the item. The shoe, illustrated in Figure 2.5, is very useful in setting a preset angle of incidence for different angle beam inspections. In this case, it is often called a wedge.

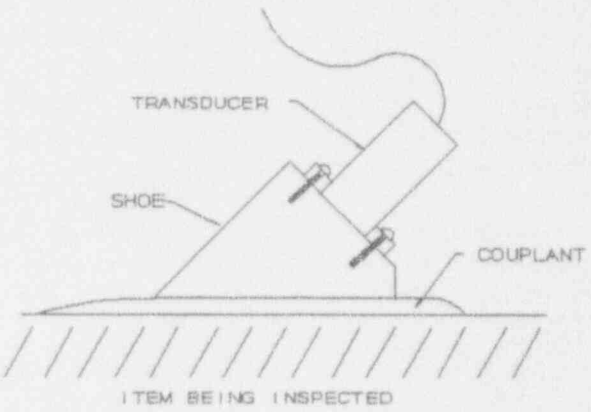

Figure 2.5 Coupling with a fixed angle wedge

2.2 Pulsers

The pulser is the instrument submodule that sends an electrical signal to the transducer. This signal is called the excitation pulse or the "main bang."

A spike pulser, as its name implies, produces a high-voltage (50 to 500 volts) negative spike. It is the oldest and simplest pulser, and is very efficient. It is often used for high-resolution flaw detection and thickness measurement.

A square wave pulser produces a rectangular pulse shape, usually negative, with controllable width, allowing more control over the shape and amplitude of the ultrasonic pulse, and more energy at a given voltage. The pulse is produced using vertical metal-oxide semiconductor field effect transistor (VMOS or vertical MOSFET) technology, which allows high voltages (typically 50 to 500 volts).

The burst pulser (also called gated continuous wave or gated CW pulser) provides a gated sinusoidal waveform of one or more cycles to drive the transducer. The number of cycles and the frequency are user-selected. A gated pulser is useful for very narrow banded systems (i.e., systems designed to use just one frequency). Figure 2.6 illustrates these typical waveforms.

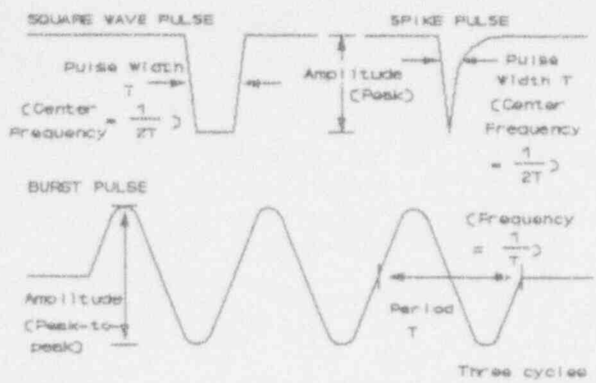

Figure 2.6 Types of pulses used in ultrasonic inspection

The operator selects the pulse amplitude, width or frequency, and the damping or load resistance. This selection is usually based on the transducer used and the type of inspection being performed.

All pulsers may be used in pulse-echo or pitch-catch applications, as well as more elaborate installations requiring the use of many ultrasonic pulse generators and transducers. Figure 2.7 depicts functions on a hypothetical square wave pulser.

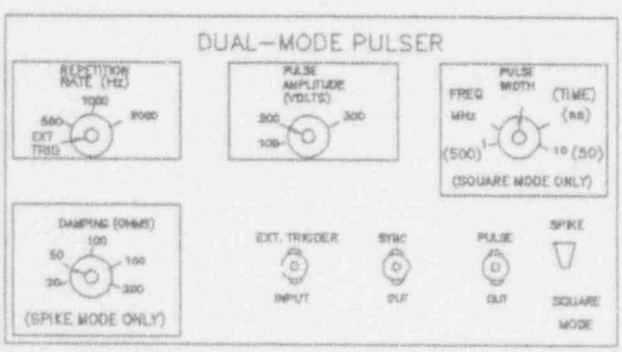

Figure 2.7 Pulser functions

2.3 Receivers

The receiver is the instrument submodule that receives and processes the electrical signal (called the RF waveform) produced by the transducer when returning sound waves strike the transducer. Other submodules that are associated with the receiver (and may be a part of the same physical module) are video detector, threshold detector, gates, filters, reject circuit.

The wideband ultrasonic receiver amplifier is designed for high-resolution applications. It is a low-noise receiver with a typical gain of 60-80 dB and a bandwidth of 50 MHz. The input may be connected directly to a pulser for pulse-echo applications. The receiver output is fed to a switch-selectable RF detector. The video filter frequency is continuously variable, and a variable reject control is also included for operation in the video (detected RF) mode. The reject control is designed to suppress baseline noise, and passes only signals that exceed the selected level.

When peak amplitude and time-of-flight (TOF) data are the only data being stored, the reject function can be useful in minimizing extraneous signals. The receiver is usually linear, with time-variable gain to increase the depth range. Some systems use a logarithmic amplifier to increase dynamic range.

A hypothetical front panel appears as depicted in Figure 2.8. Possible front panel controls and ranges are listed below.

Function	Normal Ranges
Filter (high-pass)	1, 2, 5, 10 MHz
Video (detector)	Off, On
Reject Level	0% to 100%
Detector Filter	Variable
Gain	-10 to +50 dB

Where the transducer is located at a long distance from the system, a remote preamplifier is advisable. This minimizes noise by providing 10 to 20 dB of wide-band gain as well as impedance matching to the cable.

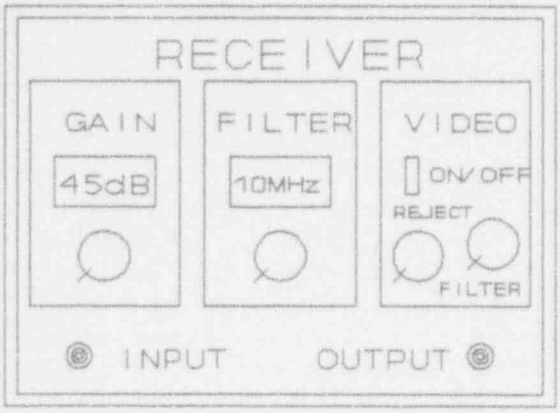

Figure 2.8 Typical receiver front panel

2.4 Peak detectors

The peak detector, or gated peak detector, also called the video module, is a signal processing circuit designed to isolate and enhance relevant signals. It uses a synchronized timing circuit ("gate") and an amplitude detection circuit ("threshold"), which are set by the operator to determine the time and level at which the peak detector should be activated. It detects the peak amplitude of an input signal that occurs during the gate interval, and it outputs a direct current (dc) voltage that corresponds to this peak signal. Either the positive- or negative-going peak (or the maximum of both) may be selected.

Figure 2.9 shows representations of displays from an A-scan monitor and an oscilloscope.

Trace A shows the RF data with no gates in use.

Trace B shows the same RF data, with two gates activated: a surface-following gate and a peak amplitude gate. The surface-following gate is designed to detect the front surface of the part, providing synchronization for the amplitude and TOF gates. The surface-following gate is indicated by a lowering of the baseline, and the peak amplitude gate, by a raised baseline (thus, during the time that both gates are active, the baseline is displayed at the same level as if there were no gates active).

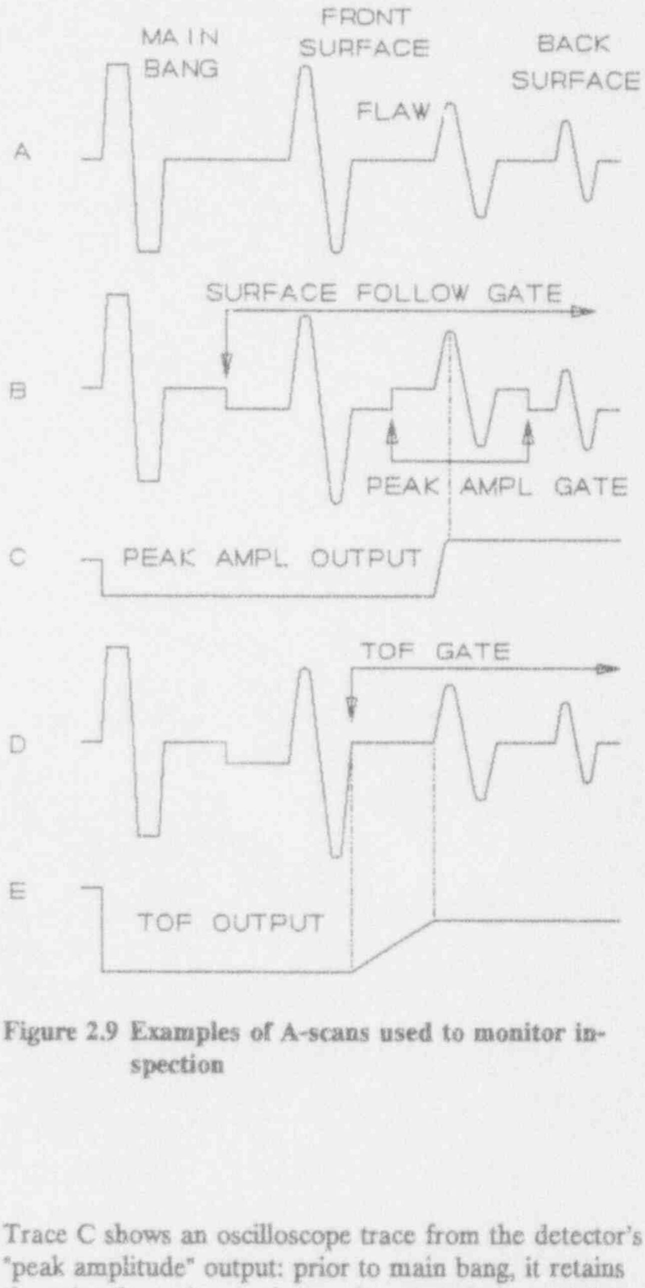

Figure 2.9 Examples of A-scans used to monitor inspection

Trace C shows an oscilloscope trace from the detector's "peak amplitude" output: prior to main bang, it retains the value from the previous pulse; at main bang, it is reset to zero; when a signal is received during the active time of the gate, the output value rises along with the signal, remaining at the highest value reached.

Trace D shows the same RF data as trace A, with two gates activated: a surface following gate, as in trace B, and a TOF gate, indicated by a raising of the baseline, that begins at the end of the front-surface signal.

Trace E shows the output from the detector's "time-of-flight" output: it is reset to zero at main bang, then increases linearly from the start of the gate, holding the value reached at the first signal, producing a voltage proportional to the time from the start of the gate to the first signal.

The baseline offset (sometimes called a "pedestal" enables the operator to visually position the gate to "capture" the signals of interest. A delayed trigger (surface follower) mode makes the peak detector very useful for normal-incidence immersion or delay-line tests. A special monitor sync output is provided, which allows a monitor oscilloscope to be triggered either at the main bang or at the beginning of the gate interval. These trigger signals are switch-selectable from the front panel and provide a means of obtaining a delayed sweep operation.

The peak detector may be set to respond after each main bang, or to count a set number of repetitions, to minimize the chance of a response to random noise. Possible front panel controls are as follows:

Function	Normal Ranges
Delay	0.2 to 800 μsec
Trigger Delay	1.0 to 400 μsec
Gate Width	0.1 to 800 μsec
Polarity	+, -, +/-
Out Mode	LIN, LOG
Gate Mode	Delayed Gate, Trig, TOF
Sync Source	Trig, Delay

Several gates can be used simultaneously, depending on how much information is needed. Each gate can be adjusted and calibrated by using the A-scan trace with the gate information either superimposed or multiplexed with the RF information. At the end of each gate, the peak voltage or other information is sampled and held for transmission to a storage and/or display medium. Detector functions are depicted in Figure 2.10.

2.5 Scanning Devices

A scanner is an electro-mechanical device that allows positioning and motion of a transducer relative to a part. The components of a scanning device include a set of axes and motors; a scanner controller; and a

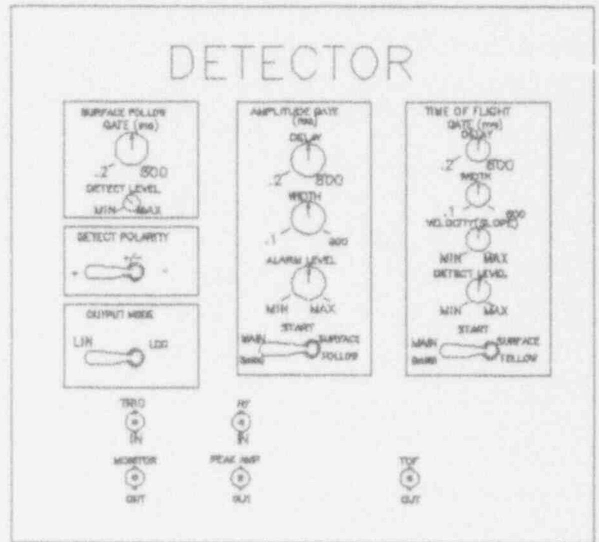

Figure 2.10 Combined peak amplitude and time-of-flight detector

transducer holder. In order to understand the scanner axis motions, a word is in order about coordinate systems.

2.5.1 Coordinate Systems

Many scanners are based on a three-axis rectangular coordinate system, as illustrated in Figure 2.11. The three axes are often designated x, y, and z, whence the common name "x-y-z coordinate system."

The axes are mutually perpendicular ("orthogonal"), and intersect in a point called the origin. Each axis has a positive and a negative direction, and coordinates of a point are positive or negative according to the established direction for each axis. Some points are illustrated in Figure 2.12.

It is important to note that the coordinate system of the scanner is not generally the same as the coordinate system used to describe an object under inspection. In the simplest case, the origin of the part is not at the origin of the scanner coordinate system, which means adding or subtracting constants to switch between scanner coordinates and part coordinates. In more compli-

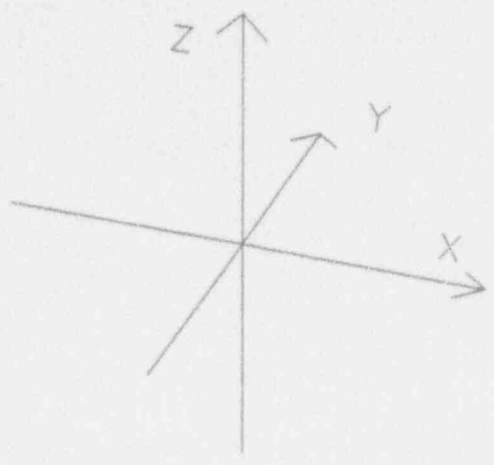

Figure 2.11 Rectangular coordinate system

cated cases, the part may be rotated, or the positive direction of some of the axes may be reversed. Such situations can lead to difficulty in relating scanner data to part features.

Often one or more rotational axes are used in addition to the three orthogonal axes. For example, the transducer may be twisted from side to side and angulated up and down; the part may be rotated on a turntable. In terms of scanner motion, these are independent

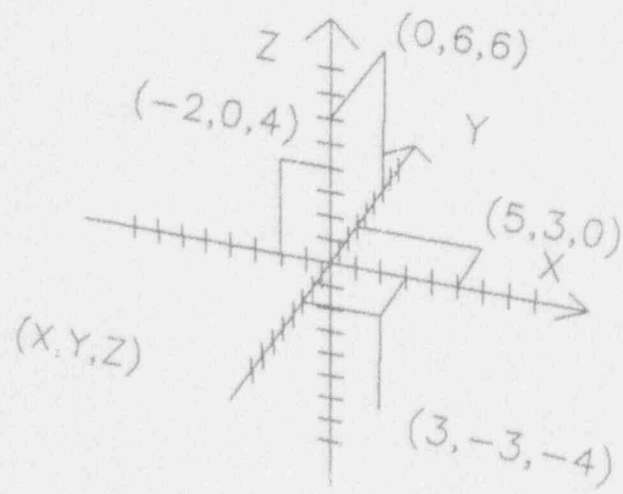

Figure 2.12 Coordinates of points

axes; but in terms of eventual interpretation of ultrasonic data, the positions of these axes must be combined mathematically with the x, y, and z axes to yield locations in terms of part coordinates.

Scanning a cylindrical object, such as a pipe or the exterior of a vessel, may be done in terms of a cylindrical coordinate system. Figure 2.13 shows a system in which the axis of the cylinder is x, the circumference is y, and the depth below the surface is z. In this case, z is not a scanner axis, but is used for reporting ultrasonic data.

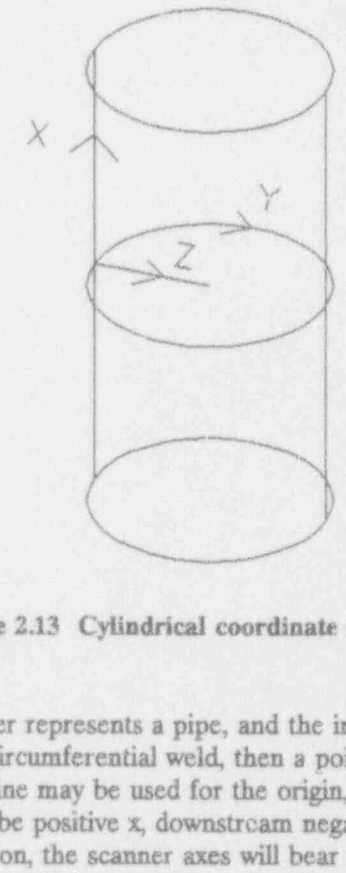

Figure 2.13 Cylindrical coordinate system

If the cylinder represents a pipe, and the inspection concerns a circumferential weld, then a point on the weld centerline may be used for the origin, and upstream may be positive x, downstream negative x. With this convention, the scanner axes will bear one relationship to the part if the scanner is placed on the upstream side, and a different relationship if the scanner is turned around and placed on the downstream side. The scanner controller may have features to account for this change in relationship without hardship to the user.

Robotics systems have a very complicated internal set of coordinates, related to the motions of the joints in the robotic arm, but the use of the robot will be in terms of a coordinate system suited to the object under inspection: for example an x-y-z system, a cylindrical coordinate system, or a spherical coordinate system.

Coordinate systems are further discussed in Section 7.3, in terms of ultrasonic image interpretation.

2.5.2 Rectilinear Scanner

A rectilinear scanner (Figure 2.14) will be used to discuss the different aspects, but these features are common to pipe scanners (Figure 2.15), vessel scanners, and many other scanners.

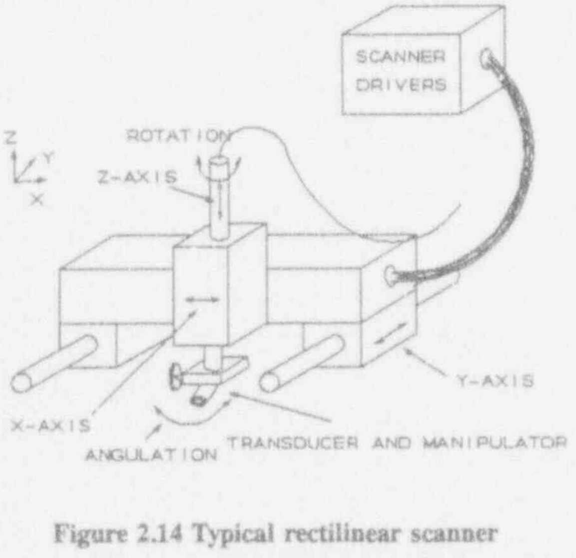

Figure 2.14 Typical rectilinear scanner

A rectilinear scanner, as the name implies, moves the transducer in a rectangular pattern, which is normally two-dimensional, but can involve the third dimension. There is normally an increment axis and a scan axis that can be defined in x, y, or z; for instance the scan axis might be x and the increment axis, y; or, both y and z might be increment axes. For example, letting the scan axis be x and the increment axis y, the transducer is moved one step in the y-direction and then moved the entire length of the inspection region in the x-direction. Then, the transducer is stepped again in the y-direction, then moved back along the x-direction axis to its original x-value. Data may be taken in both directions or, to increase mechanical accuracy, in one direction only.

2.5.3 Transducer Manipulator

The transducer manipulator has the function of orienting the transducer for the appropriate inspection taking place. It normally gives the operator the option of pointing the transducer at an angle and also rotating the transducer. This can be modified to be a surface-following, gimbal-mounted device: a shoe that rides the surface of the item being inspected.

2.5.4 Pipe Scanner

In the case of a pipe scanner (Figure 2.15) the increment axis is usually on a circle around the perimeter of the pipe, while the scan axis is in the longitudinal direction of the pipe.

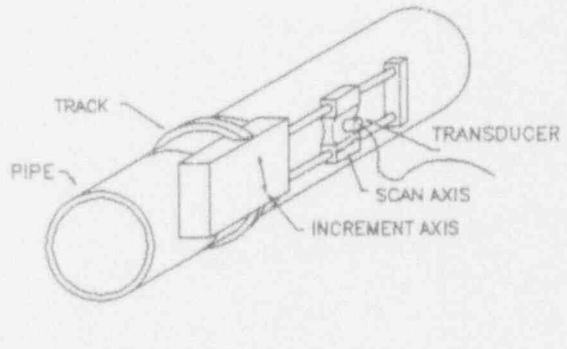

Figure 2.15 Typical pipe scanner

2.5.5 Scanning Speed

The speed at which the scan can be performed is determined by how quickly the system can produce ultrasonic pulses and record and store the data being collected. Scanning speeds normally range from 3 to 6 in./s, but speeds from 6 to 10 in./s are attainable.

2.5.6 Scanner Controller

The scanner controller (labeled "scanner drivers" in Figure 2.14) is an electronic device that contains switches, dials, and motor controllers to drive the mechanical parts of the scanner. It may also display data from position encoders attached to the scanner axes.

2.6 Conventional Scanning and Imaging

In order to lay the groundwork for the wide range of imaging techniques available in computer-based systems, a few words are in order about the conventional methods of imaging and the terminology attached to them.

2.6.1 A-scan: Time and Amplitude Information

In the conventional UT instrument, the basic display of data presents a line across the screen, representing echoes produced by reflectors in the piece, at one transducer location, i.e., one point in the scan. The depth from the transducer to an echo is represented by its horizontal distance across the screen, and the amplitude of the echo is represented by a vertical deflection of the line; where there is no echo, the line is horizontal. The general appearance of an A-scan presentation is shown in Figure 2.9 and (very schematically, in video form) in the lower left of Figure 2.16. The detail of each portion of the A-scan is dependent on the transducer and on various instrument settings.

2.6.2 B-scan: Cross-section showing depth

The next more sophisticated conventional presentation shows data from a linear scan across the piece (all scan positions from one increment position). In this case, horizontal distance along the scan is represented by horizontal distance across the screen, depth along the sound beam is represented by vertical distance down on the screen, and the amplitude of the echo is represented by the brightness or color of the presentation: a strong echo is a bright spot on the screen; where there is no echo, the screen is dark. A B-scan is shown in the upper right of Figure 2.16. The streaks are noise from the system or from grains in the part; if the gain is reduced, the streaks will disappear. The two distinct lines are the upper half of the two reflectors; and the lack of streaks below the lines is because all the sound is returned by the reflectors, leaving no noise below them. This is known as shadowing, and can be a problem if, for example, you want to inspect under a hole drilled laterally through the piece. Another method of B-scan presentation is to display all the A-scans at once, slightly offset to give a perspective effect, as shown later in Figure 7.11.

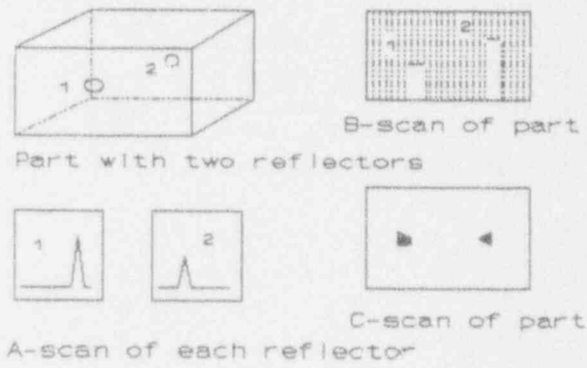

Figure 2.16 Conventional scanning presentations

2.6.3 C-scan: Plan View

The most sophisticated conventional presentation records the data from an entire planar scan (all scan positions from all increment positions), and displays a plan view of the position of reflectors in the part. In this presentation, normally recorded on a piece of paper, the length and width of the paper represent the length and width of the part, respectively; echo strength is indicated by darkness of the image; and data about the depth of the echo along the sound path is not indicated on the presentation. Echoes at different depths appear mingled together, and the part must be re-examined in that area to sort out the sources of the echoes. A C-scan is shown in the lower right of Figure 2.16. The shapes of the reflectors may be quite different when viewed from above than when viewed from the side.

3.0 Computerized Systems: General Description

Discussion of computer-based ultrasonic systems begins with a system design as illustrated in Figure 3.1. The scanner is the same as in a conventional UT system. The scanner controller is inside the computer. The instrument (labeled "flaw detector") is similar to a conventional one, but has computer connections. The computer serves as interface among the modules, and between the operator and the system. Records of the inspection (A-scans, B-scans, C-scans, and other printed records) are printed on the hard copy device, often a color printer.

A functional diagram of the system, which is the same for any computer-based system, is shown in Figure 3.2. A basic block diagram is shown in Figure 3.3.

The functions shown in Figure 3.2 are as follows:

- Controller -- computer and associated electronics. The system controller provides the interface between the operator and the inspection system, and synchronizes data acquisition with the mechanics of scanning. The controller provides motor control for automating the scanning process. The operator can specify the desired scan area by changing the settings of scan parameters. These settings are changed at the computer keyboard by making entries into the control parameter list. Besides basic data-entry capabilities, the user interface may provide graphical and tutorial assistance for the selection of control parameter settings, or may use graphics such as two- or three-dimensional computer-aided design (CAD) drawings to aid the selection of inspection parameters. The system control function is discussed in detail in Section 3.1.

- Data acquisition -- accomplished by a combination of software, executed by the computer, that control the mechanical scanner and ultrasonic data produced by the ultrasonic instrumentation. The operator enters the parameters used to control scanning motion, and the type of ultrasonic information used for data analysis, into the computer. The data acquisition function is discussed briefly in Section 3.2 and in detail in Section 6.

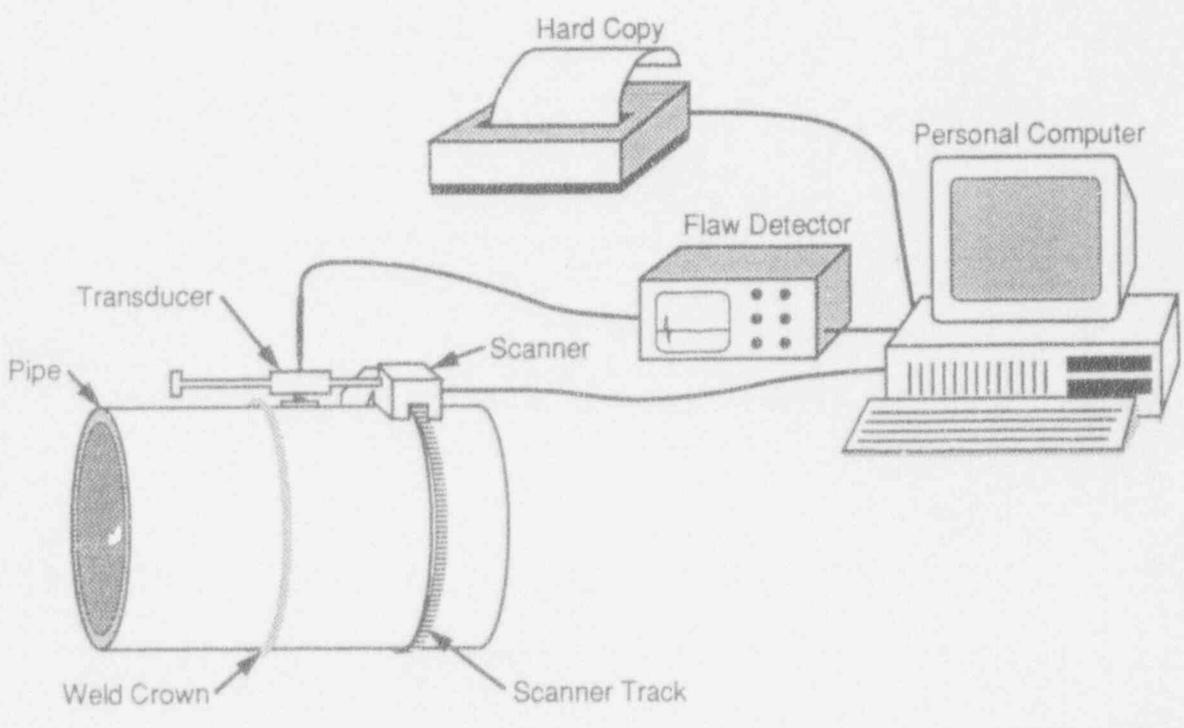

Figure 3.1 Computer-based pipe inspection system

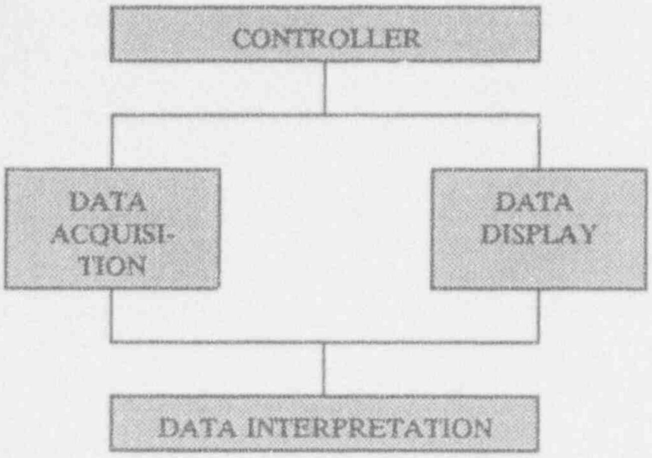

Figure 3.2 Functional diagram of computer-based ultrasonic system

- Data processing and display -- also controlled by software programs. Section 9 describes the methods of data display and basic concepts in data processing.

- Data interpretation -- performed by the operator. The interpretation of data is a vital but poorly understood process in ultrasonic inspection. Unfortunately this holds true for computer-based UT as for conventional UT. The ability of the data analyst to correctly interpret information is a major factor in defining the reliability of UT systems.

3.1 System Configurations

The block diagram shown in Figure 3.3 depicts a computer-based ultrasonic inspection system. The system consists of a computer, a scanner, and ultrasonic instrumentation. The computer (also called system controller) sends commands to the scanner controller, which gives detailed signals to the scanner drivers. The scanner drivers provide power to the scanner motors. The transducer, mounted on the scanner, is connected to the pulser and, through an optional preamplifier, to the receiver. The receiver, in turn, is connected to a detector, and the output of the detector is displayed on the optional monitor and returned to the computer for data reduction. The operator interacts with the computer

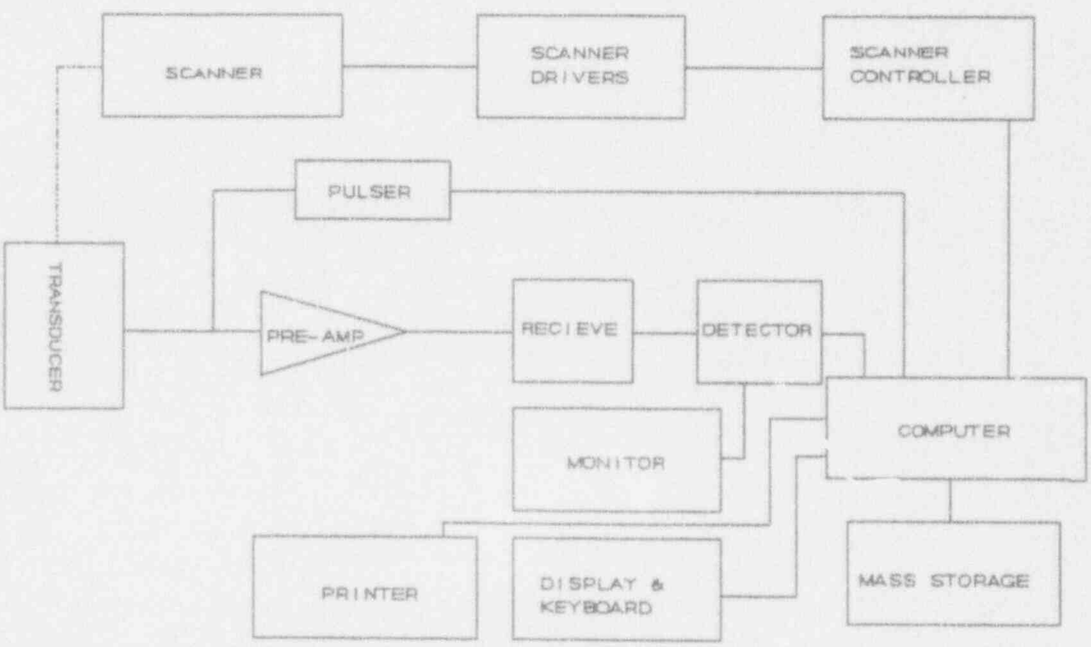

Figure 3.3 Basic System Block Diagram

through the display and keyboard. The printer is used for permanent visual records, and the mass storage provides both temporary and permanent electronic storage.

All modules except the scanner and the transducer may reside within the computer, so this system can be physically configured in many different ways.

Figure 3.4 illustrates a more complex inspection system. The basic elements (scanner, transducers, pulser, receiver, digitizer, and system controller) are functionally the same; however, this system is more versatile. The scanner here is a multi-axis scanner with four, five, or six axes. Therefore, the scanner requires a specialized microprocessor controller to receive program information from a main system processor. Instead of a single transducer there is an array of several transducers, necessitating a multiplexer to control activation of the transducers, and possibly multiple pulsers and preamplifiers. From the multiplexer, the raw RF signal is channeled to a receiver, which includes a time-variable-gain option and an amplifier that receives control from the computer system and provides the dynamic range for the digitizer. The digitizer replaces the detector of the conventional system and provides the capability to digitize full RF waveforms. Thus, the amount of data has increased, and the system can provide more sophisticated signal processing. A computer provides system control, arbitration between scanner and instrument, data manipulation, mass storage of data, user interface, hard copy, and permanent storage.

3.2 System Controller and Interface

The system controller provides the interface between the operator and the inspection system; synchronizes data acquisition and the mechanics of scanning; and performs data analysis and display.

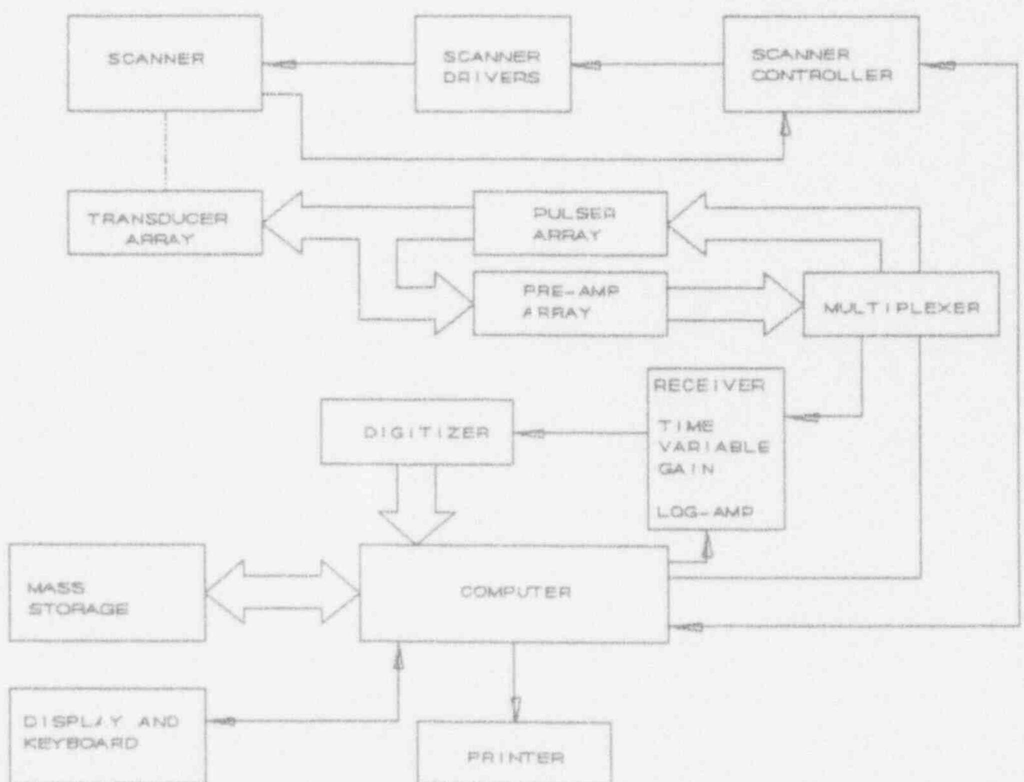

Figure 3.4 Complex System Block Diagram

The computer-based system provides motor control for automating the scanning process. The operator can specify the desired scan by changing the settings of scan parameters. These settings are changed at the computer keyboard by making entries into the control parameter list. The user interface may provide graphical and tutorial assistance for setting control parameters.

3.2.1 Controlling System Setup

The process of setting up the computer for an automated inspection may be accomplished in two ways. The first method employed by some systems involves drawing a cross section of the part geometry. As shown in Figure 3.5, the operator draws the upper and lower surfaces of the part. The drawing generally includes the position of the weld crown, the geometry of the weld root, and counter bores, when present. In addition, the operator can draw reference lines such as weld prep lines for added documentation. Some systems do not provide for upper surface correction from geometries such as weld crown and diametrical shrink. In these drawings of the two-dimensional part geometry, all of the lines are entered in a fixed scale so that they can be related to inspection data.

The second method for system setup involves use of a menu. The operator selects the system setup menu (for example by typing in the command "SETUP"). The operator is then required to fill in values that the system uses to perform an automated inspection. Table 3.1 shows an example of a setup menu.

Typical parameters that must be entered into the system are discussed in the following paragraphs.

3.2.1.1 Transducer Parameters and Sound Velocity

After the system has been properly set up, the operator must enter the transducer and metal parameters. Figure 3.6 shows a diagram for these entries. The computer interface routines draw the diagram that explains the parameters that must be entered.

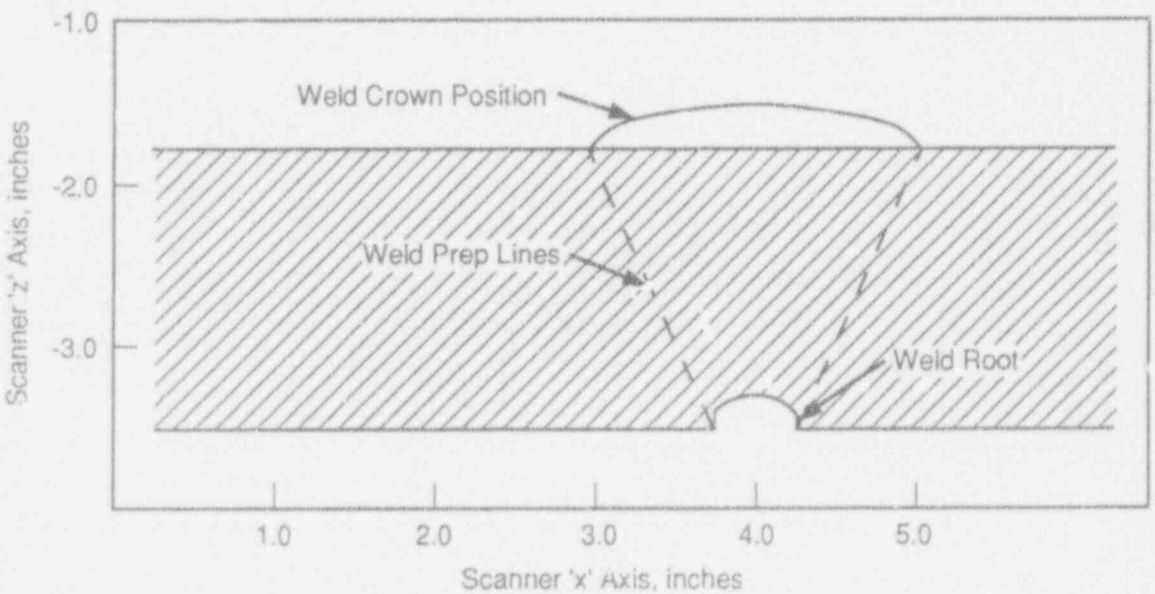

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Figure 3.5 Drawing the part cross-section

Table 3.1 Menu of control parameters

```
*** PARAMETERS MENU ***

TRANSDUCER PARAMETERS
   1 - ANGLE IN WEDGE
   2 - SOUND SPEED IN WEDGE
   3 - SOUND PATH IN WEDGE
   4 - SOUND TIME THROUGH WEDGE

METAL PARAMETERS
   1 - SOUND SPEED IN METAL
   2 - ANGLE IN METAL

SCANNER PARAMETERS
 X PARAMETERS
   1 - SCAN START POSITION
   2 - STEP SIZE IN SCAN
   3 - SAMPLES PER LINE
   4 - SCAN END POSITION
   5 - SCANNER SPEED
 Y PARAMETERS
   6 - STEP START POSITION
   7 - INCREMENT BETWEEN SCANS
   8 - NUMBER OF SCANS
   9 - STEP END POSITION

DETECTION PARAMETERS
   1 - GATE START
   2 - GATE END

RECEIVER PARAMETERS
   1 - GAIN
   2 - LOW FREQ CUTOFF
   3 - HI FREQ CUTOFF
```

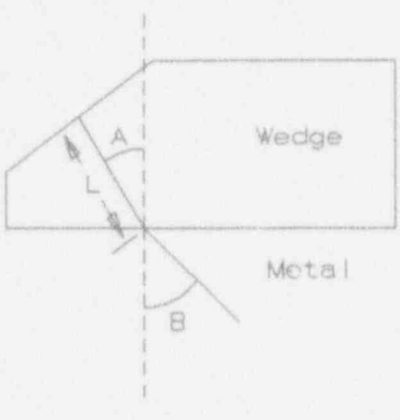

Figure 3.6 Specifying the transducer parameters

The operator enters the angle A that the sound makes in the wedge with respect to the normal to the surface, the speed of sound in the wedge, and the length L of the sound path in the wedge, measured from the center of the transducer face to the exit point on the bottom of the wedge. The computer calculates the delay time for the sound to propagate through the wedge. The operator enters the speed of sound in the metal, and the computer calculates the angle B of the sound in the metal.

3.2.1.2 Specifying the Scan Pattern

The user interface provides a help facility for specifying the features of the scanner motion. The software draws the part outline (Figure 3.7). The operator indicates the start and end positions for the scan on the part outline drawing. Then the operator enters the two parameters that control the scanner: the increment between scan lines and the step size in the scan line. At this point, the software calculates the scan speed, the number of samples per scan, the number of scans, and the number of data points required, and draws the inspection area on the part outline drawing.

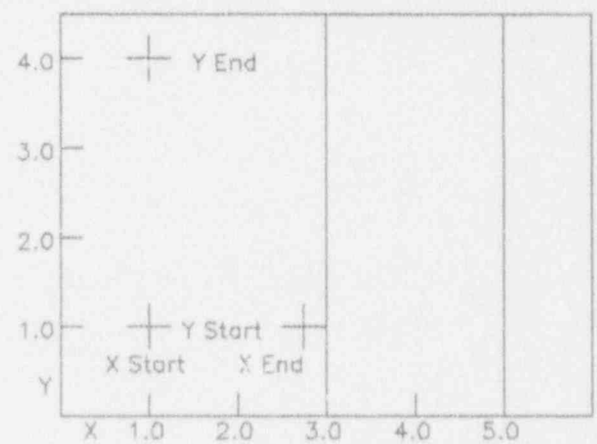

Figure 3.7 Specifying the scan pattern

3.2.1.3 Specifying Data Acquisition Parameters

The user interface provides a help facility for specifying the gate start and stop times. There are two major steps in this process. First, the operator sets the gate times for data acquisition (Figure 3.8). This gate set-

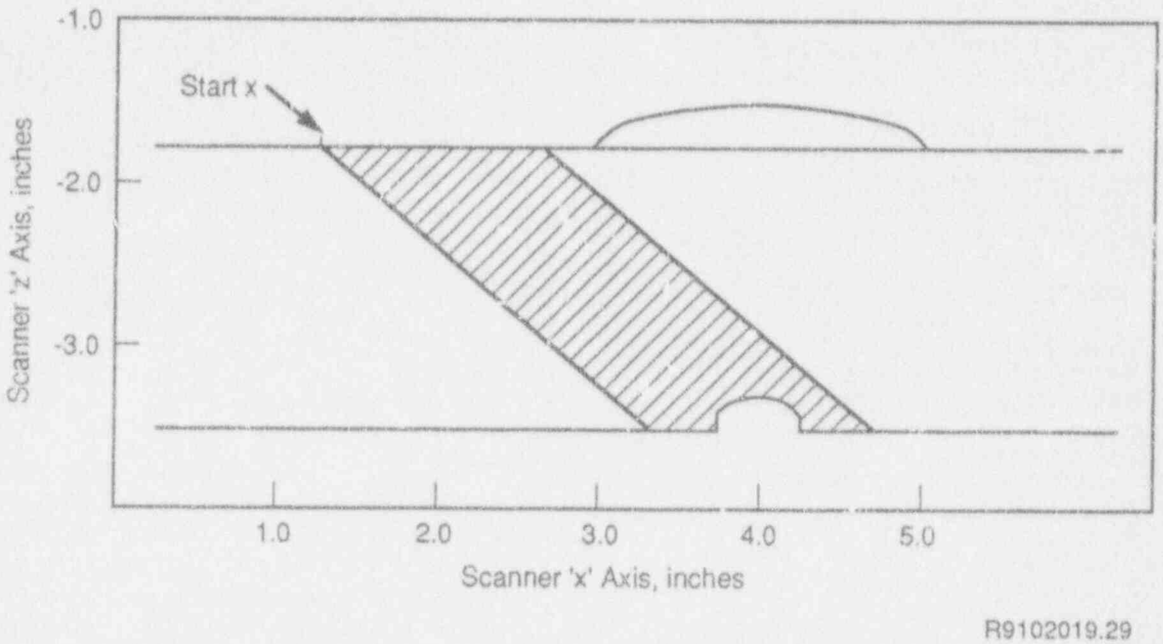

Figure 3.8 Specifying the gate times

ting is critical and must include the total inspection volume. Figure 3.9 shows how an artificial reflector can be drawn by the operator on the lower surface of the part outline drawing near the weld root position to aid in verifying the proper gate times.

If the system uses graphics, the operator can position the transducer on the upper surface of the part outline by moving the cursor. The software displays a tracing of the sound path. Figure 3.10 diagrams a computer-generated echo that shows the positions in time for the

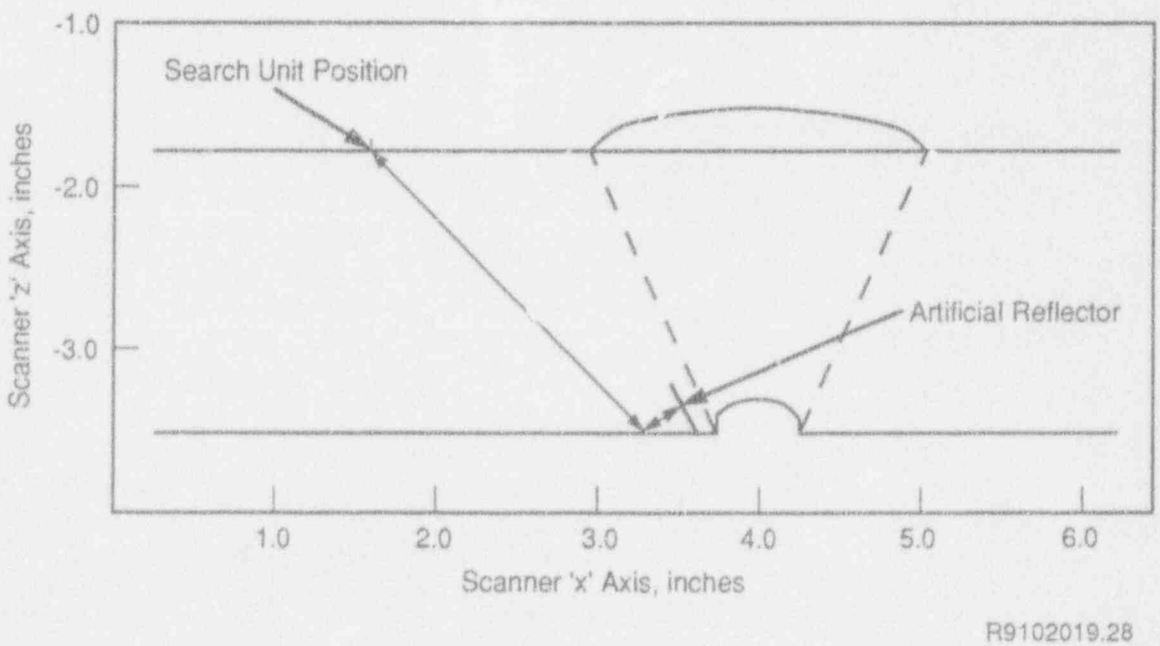

Figure 3.9 Drawing artificial reflectors

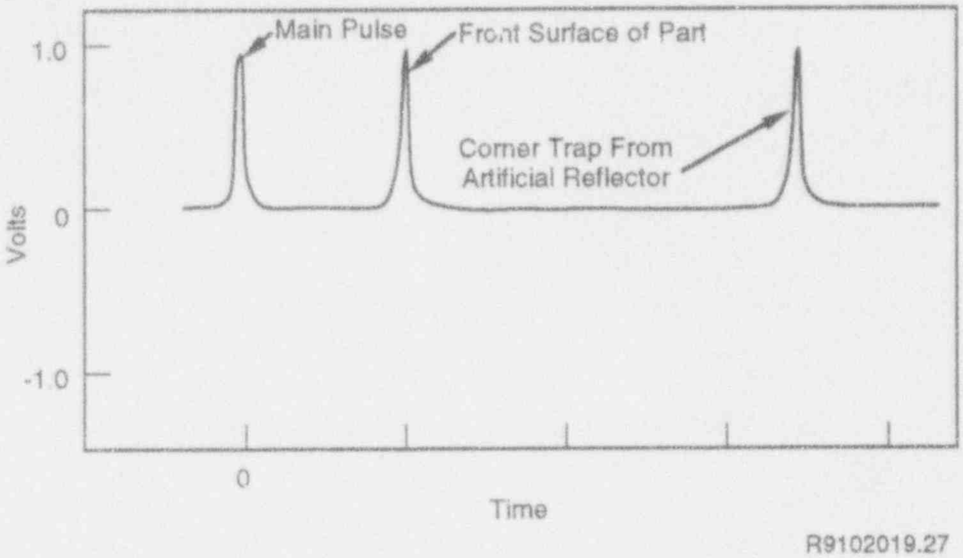

Figure 3.10 Computer-generated A-scan presentation

indication from the artificial reflector that was drawn in Figure 3.9. The operator can use this display to enter appropriate values for the gate start time and gate stop time control parameters.

3.3 Data Acquisition

The process of acquiring data requires a computer-based inspection system to:

- remotely activate a transducer and receive data from the component being examined
- remotely manipulate or scan a transducer
- automatically record and store (i.e., manage) data.

The specific designs of a computer-based inspection system to solve the problems associated with these three functions are as varied as the imagination of the design engineers. The concepts discussed in this report are general, and some systems may not employ every design discussed. As an example, some inspection systems may digitize only peak amplitudes, and not RF or video waveforms.

Section 6 (data acquisition) describes each of the preceding functions individually and in a generic sense.

3.4 Data Storage

Data storage means saving data on machine-readable media that retain data when power is shut off. The main storage media at present are fixed hard disk, floppy disk (including microdiskettes), tape (cassette, cartridge, or reel), removable hard disk, and optical storage. The fixed hard disk is a part of the computer; the other storage media are inserted then removed for archiving or transporting data.

4.0 Scanning Motions

4.1 Scanners

A scanning device, or scanner, is a mechanical arrangement to remotely manipulate and scan a transducer relative to a part. In conventional UT, the motion of the transducer relative to the part is generally linear or circular, but a computer-based system permits any desired motion, depending on the design of the scanner and the requirements of the inspection. Conventional scanners (rectilinear and pipe scanners) are discussed in the section on conventional UT.

In computer-based systems, the scanner may be more complex than in conventional UT. This is exemplified by the multi-axis rectilinear scanner diagrammed in Figure 4.1. The basic concepts of the rectilinear scanner are still used, giving x, y, and z axis manipulation. With the more versatile scanner, transducer movement is available in any of these directions. Agility is also added to the transducer so that it can swing both laterally and longitudinally, and the entire search tube can be rotated as well as moved up and down in the z axis. A mechanism can be added to rotate a part underneath the transducer while the transducer and the rest of the scanner perform scanning functions. This rotation can be provided by either a turntable or a horizontal rotator so that a variety of part configurations can be inspected. Figure 4.1 shows a multi-axis scanner with eight axes of movement.

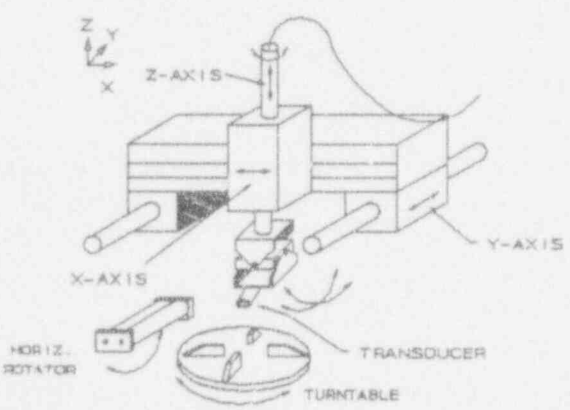

Figure 4.1 Multi-axis scanner

A highly sophisticated system may employ a robotic arm instead of the normal rectilinear scanner, as shown in Figure 4.2. A robotic arm provides the capability of being programmed to follow the contour of a wide variety of surfaces. In Figure 4.2, the robotic arm rotates about the base, the main arm rotates, the shorter extension rotates about its axis, and a wrist function rotates. The transducer itself is gimbal-mounted to provide movement in two directions.

Scanning functions are becoming more complex, and scanners are being developed to handle more complex structures. Specialized scanners can be fabricated that provide very high-speed coverage of large areas or very detailed scans of minute areas.

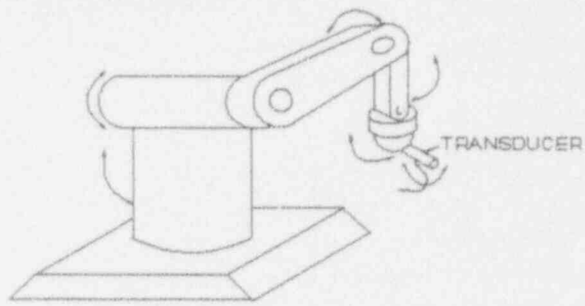

Figure 4.2 Robotic arm scanner

One very useful option that the inspection system may provide is the ability to operate the scanner remotely from the control system. To facilitate this capability, a joystick and sometimes a remote display are provided so that the operator can properly align the equipment to perform the inspection necessary. The joystick provides the capability of aligning the transducer, while a remote display allows the signals returning from the transducer or transducers to be adjusted to their optimum positions. A communication link between the operator at the console and the operator at the remote scanner may be necessary. Both audio and video are needed to ensure that instructions are executed properly and to ensure that the scanner is properly aligned relative to how the data are being stored and displayed.

4.2 Scanner Coordinates and Scan Patterns

Figure 4.3 shows a scanner coordinate system and scan patterns used in performing an inspection from the top surface of a test block.

The scanner coordinates in this example are shown in the diagram. The origin is at one corner of the area to be scanned. X and y are in the plane of the surface, with x perpendicular to the scanner track and y parallel to the scanner track. The z axis is normal to the surface of the test object.

The scan pattern is composed of scan lines and index increments. The scanner positions the transducer at the origin and scans in the positive x direction. At the end of the defined scan length, the transducer stops moving in the x direction and is indexed in the positive y direction. It is then scanned back in the negative x direction until the x coordinate is zero. The process is repeated until the y coordinate reaches its defined maximum. This type of scan is called a raster scan, and results in a grid of data, separated in the y direction by the index amount, and in the x direction by an amount determined by the pulser repetition rate; normally the rate is defined so that the x and y spacing of the grid are equal.

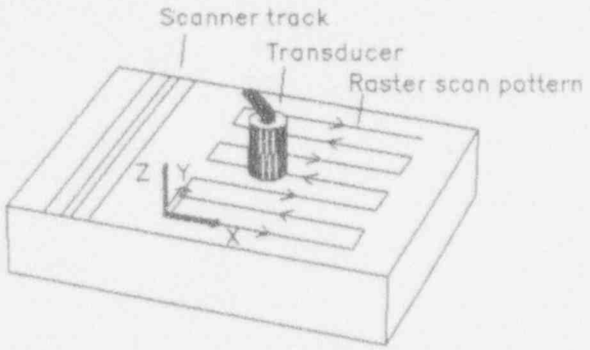

Figure 4.3 Axis definition from scanner coordinates (normal beam)

4.3 Scanner and part coordinates

Figure 4.4 shows an inspection similar to that of Figure 4.3, with two differences: there are two coordinate systems; and the transducer is mounted on a wedge.

In Figure 4.4, the origin of the object coordinate system is at one corner of the block, while the scanner origin is at the opposite corner; moreover, the positive directions for x and y in the object coordinate system are reversed from those of the scanner. Situations like this arise frequently, and are a potential source of confusion and error. It is vital that the operator note the origin and direction of the scan axes in relation to the part.

The use of an angle beam for this inspection adds another complexity: the relation between scanner and part coordinates varies with depth. For example, if the sound beam angle is 45°, then echoes at a depth of 1" are shifted by 1", and echoes at a depth of 2" are shifted by 2" (this holds true if "inch" is replaced by "centimeter" throughout). Ambiguity can result if an indication is reported at, for example, position x=5, y=4, z=-1.5: does this mean that the transducer was at x=5, y=4 when an indication was detected at depth 1.5, or that the position of the indication itself is x=5, y=4, at a depth of 1.5? These two points are separated by a distance of 1.5 (inches or centimeters), which is enough to make an important difference in the interpretation of the indication.

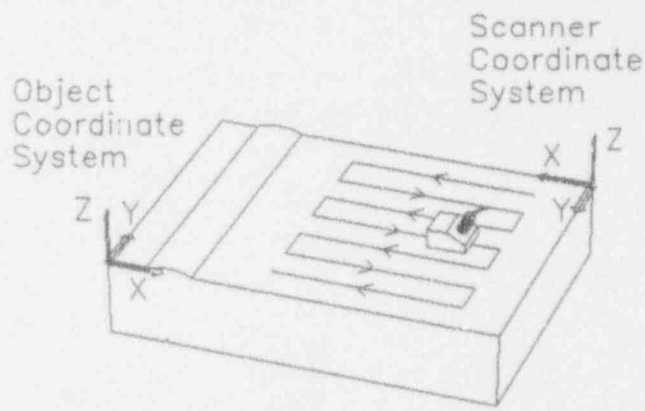

Figure 4.4 Axis definitions from object and scanner coordinates (angle beam)

5.0 Transducer Arrays

5.1 Array of Independent Transducers

In order to reduce the time spent in scanning, a system may employ a transducer array composed of independent transducers. An example of this configuration is shown in Figure 5.1, which shows schematically an array of three transducers. The transducer on the left provides an angle-beam inspection toward the right, the transducer in the center provides a normal-beam inspection, and the transducer on the right provides an angle-beam inspection toward the left.

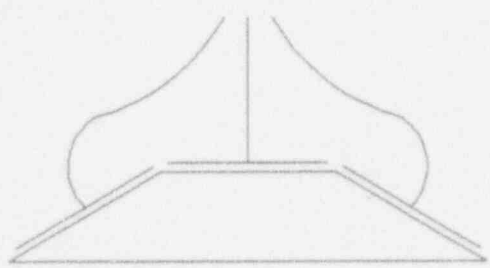

Figure 5.1 Array of three transducers

This array can be used, for example, to reduce the time and number of setups in scanning a circumferential pipe weld that is to be scanned from two sides. For a single-transducer inspection, the scanner is set up for the upstream side of the weld and an inspection is performed. Then the scanner is repositioned on the downstream side, and the inspection is performed on that side. With the array configuration, the scanner is set up to allow the transducer array to pass completely over the weld. The transducer on the right is activated when the array is to the right of the weld, and the transducer on the left is activated when the array is to the left of the weld. The normal-beam transducer is used to take data while the array passes over the crown. This combination inspection reduces setup time, and also ensures a known relationship between the positions of indications from the two angle-beam inspections. The indications from the normal-beam transducer give further positional information.

Another similar array configuration has several transducers of different angle and frequency in a single holder, which is positioned to bring the desired transducer into play. The purpose of this is to avoid having to change transducers, as for example in a hazardous environment.

There are systems using multiple independently positioned transducers that are not referred to as an array.

5.2 Transducer Phased Arrays

A different kind of transducer array is the phased array. The purpose of a phased array is to provide variable focus (dynamic focusing) or angle (beam steering) from a single transducer array. In the upper left of Figure 5.2 is a linear phased array transducer of 16 elements. All the elements have the same frequency. If all the elements are activated simultaneously, the array behaves like a single transducer of the same size as the array. If the elements near the end are activated slightly earlier than those in the center, a focus is created. If the elements are activated from left to right in sequence, the sound beam aims toward the right.

Phased arrays can also be configured as rectangular grids or as concentric rings, to provide other options for dynamic focusing and beam steering.

Phased array technology gives great flexibility to a system, including the ability to change transducer characteristics without changing transducers, and the possibility of scanning without physical motion. The latter capability is widely exploited in the medical field, and finds application in the inspection of thick parts such as reactor pressure vessels and nozzles.

5.3 Multiplexer

The multiplexer (Figure 5.2) is a key feature in a transducer array system. It enables the computer to control the activation of the elements of the array. In some cases, an array of pulsers as well as an array of preamplifiers is employed to match impedances and provide maximum signal-to-noise ratio. The multiplexer provides computer control of the array. The pulsers and preamplifiers can be integrated into the multiplexer, the transducer array, or in separate units. The multiplexer receives instructions from the computer as to which pulser or pulsers to trigger to provide the desired results. The return information from the preamplifiers is then multiplexed to a receiving unit.

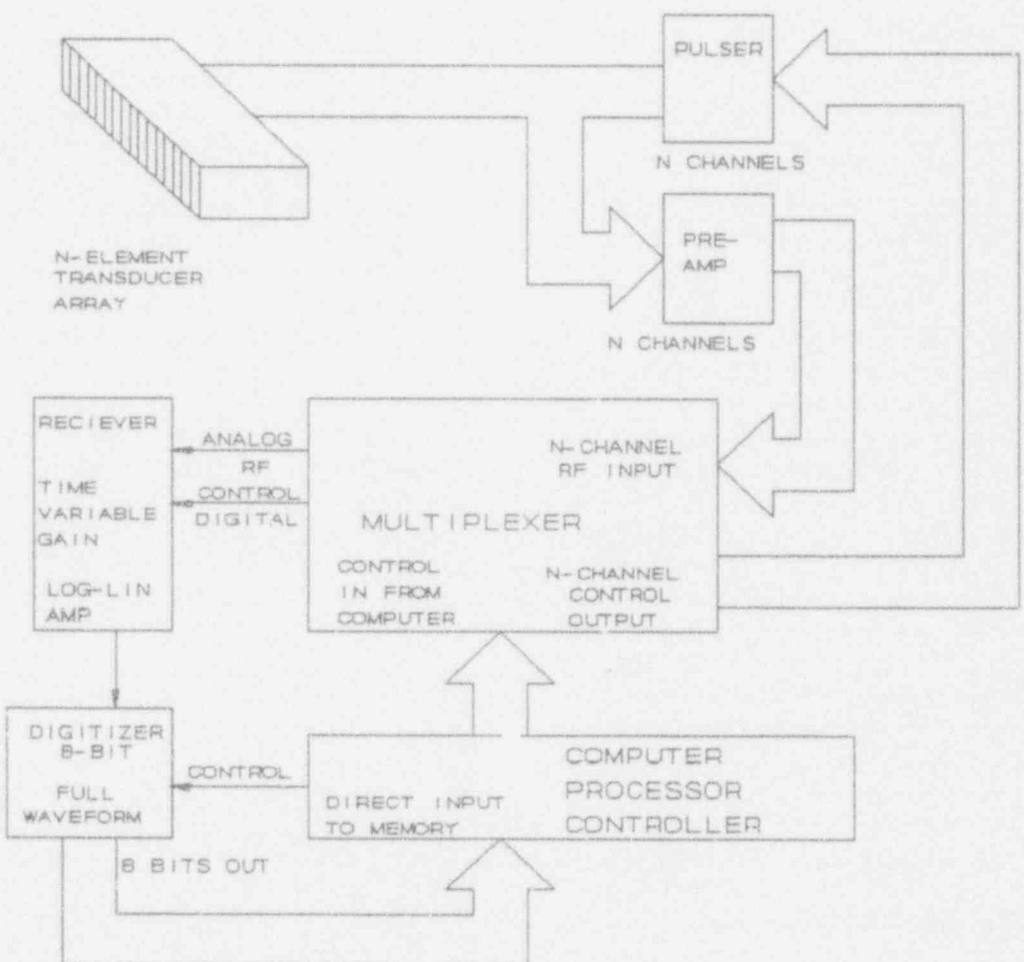

Figure 5.2 Linear phased array with multiplexer

6.0 Data Acquisition

Acquisition of data is of primary importance in computer-controlled ultrasonics. The level of detail and sophistication of data acquisition may vary greatly, however. At a minimum, the system will record the axis coordinates and instrument settings at which an indica tion was detected, and the time-of-flight and amplitude of the indication. At a maximum, the system also acquires and stores an RF waveform for every location inspected.

6.1 Video and Envelope Detection of RF A-Scans

Some computer-based systems are equipped with a digitizer that has a video detection circuit. This circuit is a rectifier and filter. By software selection, the input signal from the transducer can be routed through this circuit to transform an RF signal into a video signal. The filter can be programmed to optimize the smoothing output. Care must be exercised when using video detection; the output can be distorted by an incorrect filter setting, and some loss of signal strength occurs, even for a correct filter setting.

The system processor must be capable of transferring large quantities of information directly into memory; this is called direct memory access or DMA. The faster the information can be transferred into memory, the faster the scans can be performed.

The receiver may provide time-variable gain so that the signals at all depths are at levels where the digitizer preserve the maximum possible information. Some systems have logarithmic amplifiers to provide a greater dynamic range.

The digitizer in most systems is a high-speed digitizer capable of digitizing full waveforms. Once the data have been digitized and stored in memory, the operator must be given access to that information. It is also desirable to provide real-time information so the operator can monitor the scans for obvious problems such as loss of signal or extreme noise.

6.2 Detectors

An important feature of the detector in a computer-based system is that each RF waveform is a new sample. That is, a new reading is taken each time a pulse is generated (the sync pulse triggers both the pulser and the detector), and the output retains that reading until the next reading is obtained. Consequently, the response time of the detector to amplitude variations is limited principally by the repetition rate of the system. This is in contrast to conventional flaw detectors that can be adjusted to require several pulses to respond to a change in the input, as mentioned in Section 2.4. This also means that the system must use other means, such as averaging, to discriminate against transient noise. The information from the detector is digitized and made available to the system controller.

6.3 Digitizers

In many complex systems, the detector is replaced by a digitizer. Instead of having the computer digitize merely the peak amplitude and TOF, the entire RF waveform may be digitized. Depending on the system, it may be processed and stored for subsequent analysis, or it may be discarded.

Signal digitization is a very powerful and sophisticated means of improving system capabilities. To furnish useful data, certain requirements must be fulfilled.

First, the digitizer must sample and digitize data fast enough so that the recorded information adequately represents the signal. For all signals, it must satisfy the Nyquist criterion, which requires a sampling rate greater than twice the maximum signal frequency, to avoid the phenomenon of aliasing (appearance of spurious low-frequency signals). In most cases, the digitizer should take five to ten samples per cycle. For example, for a nominal ultrasonic frequency of 5 MHz, the digitizing rate should be 25 to 50 MHz.

Second, the digitizer must have enough bits to allow discrimination of features of interest in the waveform. Many systems use an 8-bit digitizer, which provides a precision of one part in 255, i.e. a dynamic range of 48 dB. A ten-bit digitizer gives four times greater precision (one part in 1023, or 60 dB).

The designer of the system must ensure that both frequency and amplitude requirements are properly satisfied. Otherwise, the process of digitization, storage, and later analysis and smoothing may result in the presentation of results that look convincing but are in fact meaningless.

7.0 Image Processing and Display

One of the principal features of computer-based systems is the imaging (or graphical display) of ultrasonic data. These displays permit the examination of the ultrasonic data in a number of powerful ways. Most important, inspection data can be used to form images of the reflectors in the test object. Displays of this kind enable us to recognize and identify patterns in the data.

All computer-based systems can display plan and elevated views of ultrasonic data (i.e., views from top, bottom, and sides). These views are called orthogonal views. Usually, the part geometry can be displayed also. In addition, color can be used to create special effects such as showing small amplitude changes. Displays can show the effects of angle beam inspection by projecting the data correctly with respect to the inspection coordinate system. Displays can aid in interpretation by showing the inspection coordinates and other information in a variety of forms such as axis labels, position markers, and header information displays.

Imaging requires specialized processing to convert raw numerical data into an image resembling the actual flaw. Ultrasonic data can be processed to correct for depth and anomalies, reduce noise, and improve the image. For example, the system can correct for the loss in signal strength with increasing depth by using a method called distance amplitude correction. The system can correct for variations in the scanning surface by making geometric corrections. These and other data processing methods are described in the following sections.

For simplicity, the discussion on data processing and display will refer to a hypothetical computer-based system provides basic echo-detection and position-recording capabilities, as well as additional data-taking and data-processing capabilities to improve the analytical powers of the system. It does not refer to any specific existing system.

7.1 Basic Concepts about Images

An image is a display of data in such a way as to present a true representation of the object from which the data was obtained. In the present context, it is an image produced on a CRT or a printer. Its size, shape, distance, intensity, and colors are perceived and interpreted to convey information about the original object. The shape and intensity are usually directly related to the ultrasonic or geometric characteristics of the original object; color may be used to represent various attributes.

7.2 Images in Ultrasonics

We now consider the data-taking capabilities of the ultrasonic equipment, with a view to relating these to production of realistic images. The A-scan is very basic for the machine, but is not a realistic image, since it presents a two-dimensional image of data taken along only a single line; it is as restrictive as a view through a long tube. It is the only view available in manual ultrasonics. The combination of A-scans into a B-scan or a C-scan is more realistic, as in both cases a two-dimensional image is presented, representing a two-dimensional slice through the object (B-scan) or projection of the object (C-scan). Both B- and C-scans can be constructed by conventional automated ultrasonics by recording images on paper or a storage oscilloscope during a scan.

With the possibility of storing and reproducing information digitally, other views are possible. A 3-D view can be produced by combining time-of-flight information with sensor position information and presenting it as a view of a transparent object with inclusions shown at the position of each echo. Images can be presented at various scales and image features can be highlighted by color. Information can be presented either for the whole volume at once (projected) or for individual planes, or as a cutaway view for some subvolume of interest. Some systems rely strictly on their own viewing formats, while others make use of the viewing and processing capabilities of Computer-Aided Design (CAD) programs.

The images normally used in ultrasonics are sometimes called "engineering views," as distinct from artistic renderings. Perspective views are not used (i.e., distant objects are not reduced in apparent size) but angle of view, coloring, and shading play important roles in presentation and interpretation.

7.3 Presentations of Ultrasonic Images

Figure 7.1 shows views of a solid object, as used in computer-aided drawing (CAD) systems and in ultrasonic presentations, including a general 3-D view (often loosely called an isometric), a true isometric view, and four orthogonal projections of the normal beam inspection volume. The top (or plan) view looks down on the inspection volume; that is, it shows the x-y plane, looking toward negative z (z being the axis perpendicular to the insonified surface). The other views (elevations) are variously called side view, end view, front view, and show the x-z and y-z planes of the inspection volume. The particular name attached to a view depends on the ultrasonic system in use.

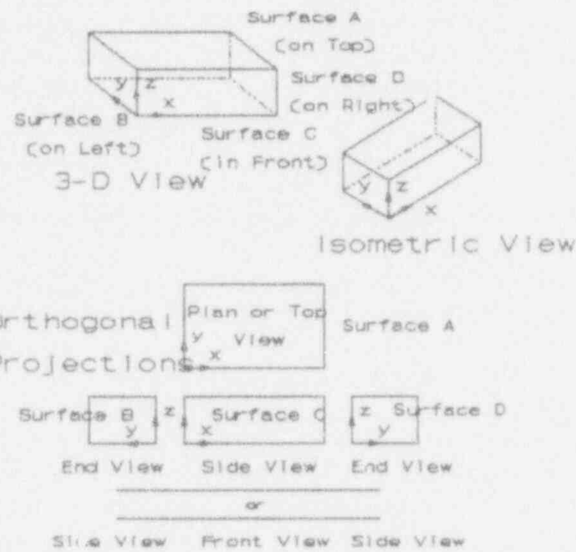

Figure 7.1 3-D and orthogonal views

Figure 7.2 shows a 3-D view and the corresponding projections of a test object with flat-bottom holes, and presentations of an ultrasonic inspection of the object. The top four drawings show how the holes map from the 3-D to the projected views. The origin of the coordinate system is at the upper left front, rather than lower left front as in Figure 7.1. The top view of the three holes shows the origin of the coordinate system in the lower left corner of the view. The side view is defined by looking in the positive y direction. The origin for this view is in the upper left corner of the view. The end view is defined by looking in the negative x direction. The origin for this view is in the upper left corner of the view. The shaded area of the side view indicates the position of the gate used for the inspection: only signals from reflectors that are within this shaded area are used in the display; any possible reflections from the upper portion of the block are ignored, and likewise reflections from the bottom surface (usually called the back surface) are ignored.

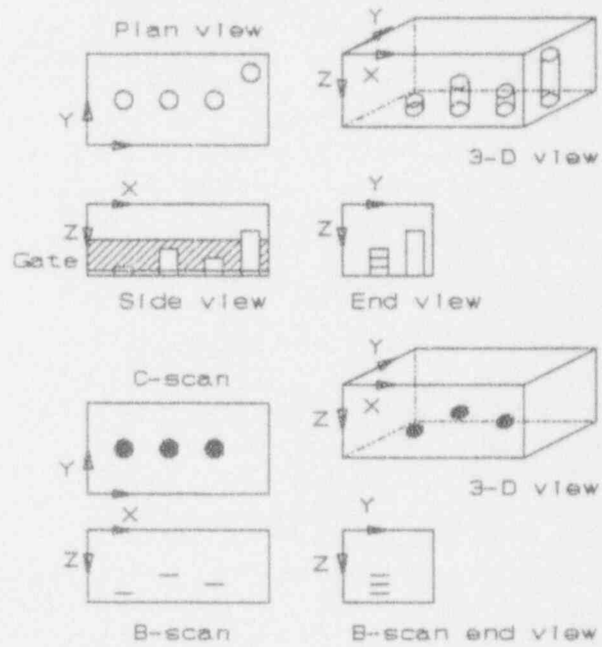

Figure 7.2 B- and C-scan views of normal beam UT data

The lower portion of Figure 7.2 shows a display of the data from a normal beam inspection of the test block shown in the upper portion. Since the gate covers only the lower half of the test block volume, excluding the back surface of the test block, the hole that is deeper than the others does not show up in the ultrasonic data, and the back surface is not shown ultrasonically. A presentation of the back surface only would show a dark bottom on the displayed box, with four – not three – light-colored holes in it. The 3-D and projected views of ultrasonic data are shown. Note that the top surfaces of the bottom-drilled holes are favorably oriented to the normal beam transducer and, for this reason, indications from them appear in the ultrasonic images while indications from the sides of the bottom-drilled holes do not. The axes in the lower portion are labeled with the scanner coordinates, which in this case are the same as the material coordinates.

Figure 7.2 also indicates the extension of conventional terminology to the context of computer-based systems. The top view of the ultrasonic data is called a C-scan view. The side view of the data is called a B-scan view. The B-scan end view is also sometimes called a B′-scan view (pronounced B-prime) or a D-scan view.

Figure 7.3 shows a 3-D view and the corresponding orthogonal projections of a section of welded pipe with saw cuts in the heat-affected zone. The significance of this figure is that it shows how the pipe features, e.g., weld root and saw cuts, map from the 3-D to the projection views. Note that the test object coordinate system is used in this illustration. All views have been chosen so as to place the origin at the upper right corner. The plan (top) view of the test object is the view looking in the z direction. The side view is defined by looking in the negative y direction. The end view is defined by looking in the negative x direction. Various systems orient the axes in different ways; in particular, the z axis may point either up or down.

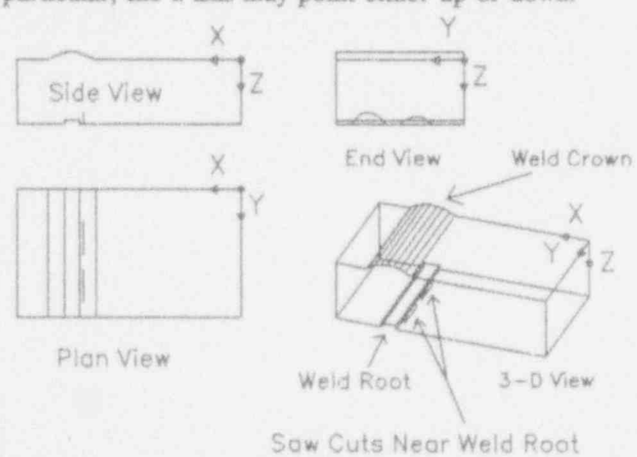

Figure 7.3 Views of test block with saw cuts

Figure 7.4 shows a display of an angle beam inspection of the test block of Figure 7.3. As in Figure 7.3, both the 3-D and orthogonal projection views of the test block are shown. The gate used for data acquisition is shown as the shaded area on these drawings. The gate

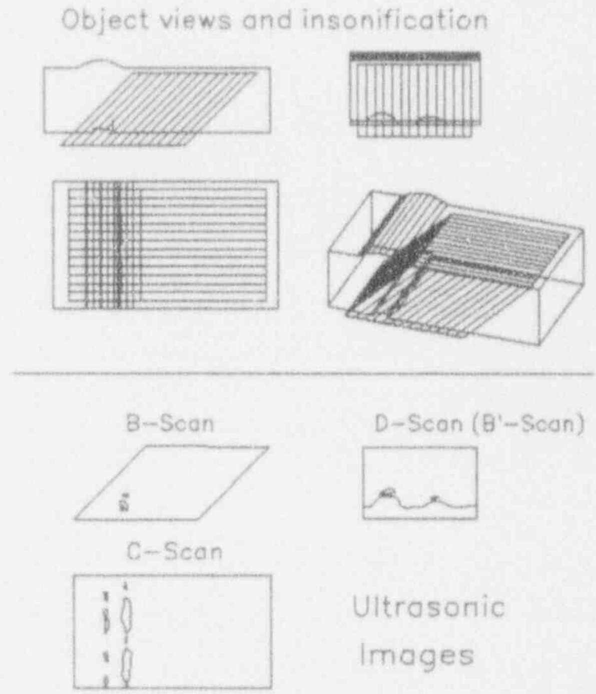

Figure 7.4 B-, C-, and D-scan views of angle beam UT data

covers most of the test block volume and extends beyond the back surface. Only signals from reflectors that are within this shaded area are used in the display. The ultrasonic views are also shown. Note that the side surfaces of the saw cuts and weld root are favorably oriented for angle beam inspection. For this reason, ultrasonic indications from them appear in the images of the data. Figures 7.9 and 7.10 show additional views of the same data.

7.4 Contour Plots of Ultrasonic Amplitude

The ultrasonic data shown in Figures 7.2 and 7.4 have been threshold-detected. That is, if an amplitude value from an indication was above a user-set level, then it was shown (as white); if not above the threshold level, the data did not appear at all. Displays of amplitude

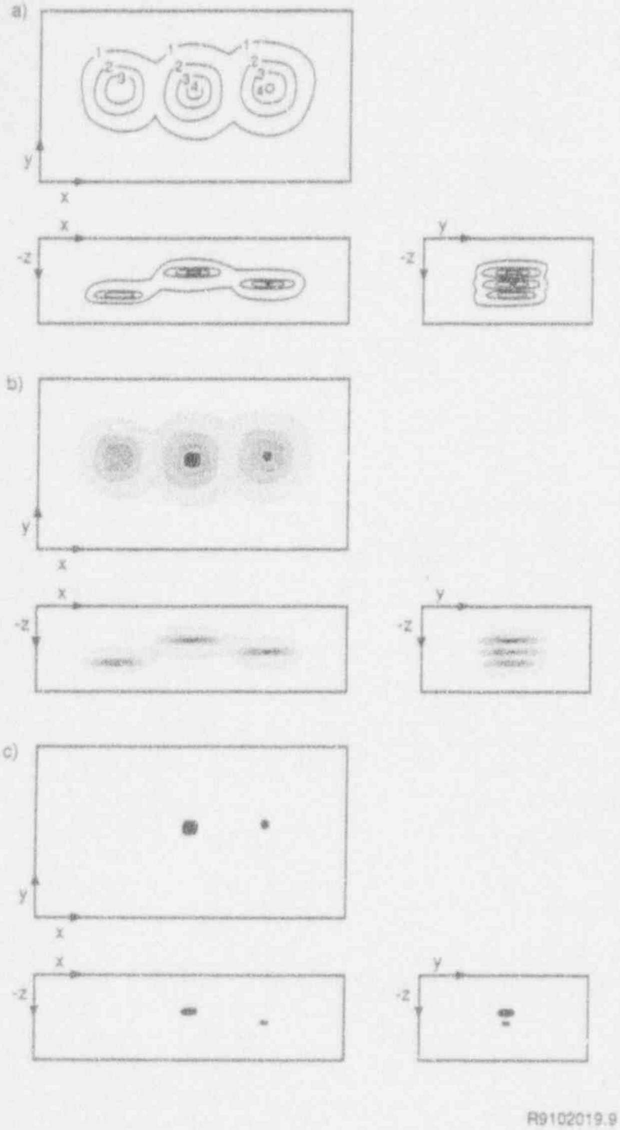

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Figure 7.5 Contour plots of amplitude

contours are often used instead of threshold detection, to show greater detail in the data.

Contour plots of the data from the normal beam inspection of the test block with bottom-drilled holes are shown in Figure 7.5. Figure 7.5a shows contour line plots in B- and C-scans. This graphic shows the diminished ultrasonic amplitude from the deeper holes.

Because the contour plot becomes cluttered very quickly, ultrasonic data are more commonly shown as color or gray-scale encoded amplitudes, as shown in Figure 7.5b. A scale bar is provided so that the colors in the figure can be interpreted as data of given amplitude. A number of different color bars are used in computer-based systems. The color selection can be chosen either to show gradation or to emphasize contrast between different amplitudes; special care must be used if the images are to later be reproduced in black and white. Figure 7.5c shows only the highest-amplitude data, giving in effect a threshold-detected presentation of the same data. Figures 7.6 and 7.7 show images of UT-RES-0000 (see Appendix A) as further examples of gray-scale and color imaging.

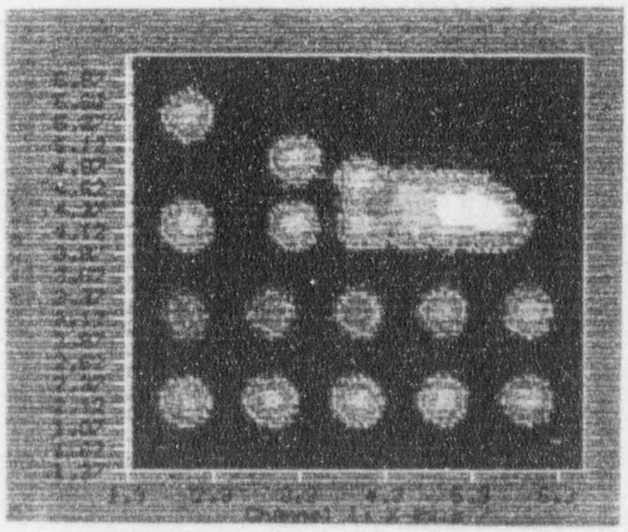


Figure 7.6 Gray scale contour images

7.5 Distance Amplitude Correction

The indications from the tops of the bottom-drilled holes have decreasing amplitude with depth, as shown in Figure 7.5b, because the ultrasonic beam spreads. Distance amplitude correction (available on both conventional and computerized systems) compensates electronically for this decreasing amplitude by using the depth (TOF) of the data to assign an adjustment factor that becomes progressively greater with depth (the exact progression being determined during setup by use of a reference block). Figure 7.5b, shows data without

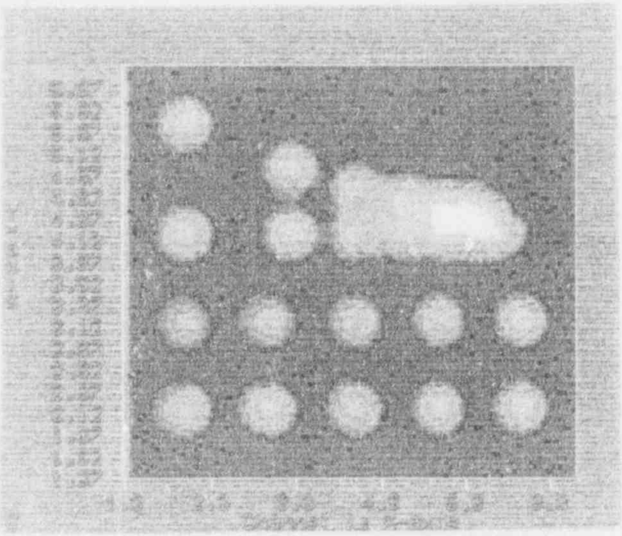


Figure 7.7 Color contour images

distance amplitude correction (in the C-scan view, the center hole appears noticeably larger and darker because it is closer to the transducer). Figure 7.9 (top) shows an inspection with distance amplitude correction (the indications from all three holes are quite similar).

7.6 Metal Path Projection and Position Labels

Figure 7.8 illustrates a display method called metal path projection, important for angle beam inspections; and position labels, useful for both normal beam and angle beam inspections. Figure 7.8a diagrams an angle beam inspection of a block with five targets. The direction of the sound beam is shown below the transducer. Figure 7.8b plots the ultrasonic data without metal path projection; the vertical dashed lines delimit the beginning and end of the inspection. Notice that the targets are incorrectly aligned, those at greater depth being farther to the left. This is because the data has been plotted according to transducer position, without compensating for the angle of the sound beam. In Figure 7.8c, the data has been corrected for the sound beam angle. Note that the dashed lines now follow the angle of the sound beam, and correctly delineate the inspection volume.

In Figure 7.8d, the axes are labeled with the test object coordinates, and the position of the indications (in two

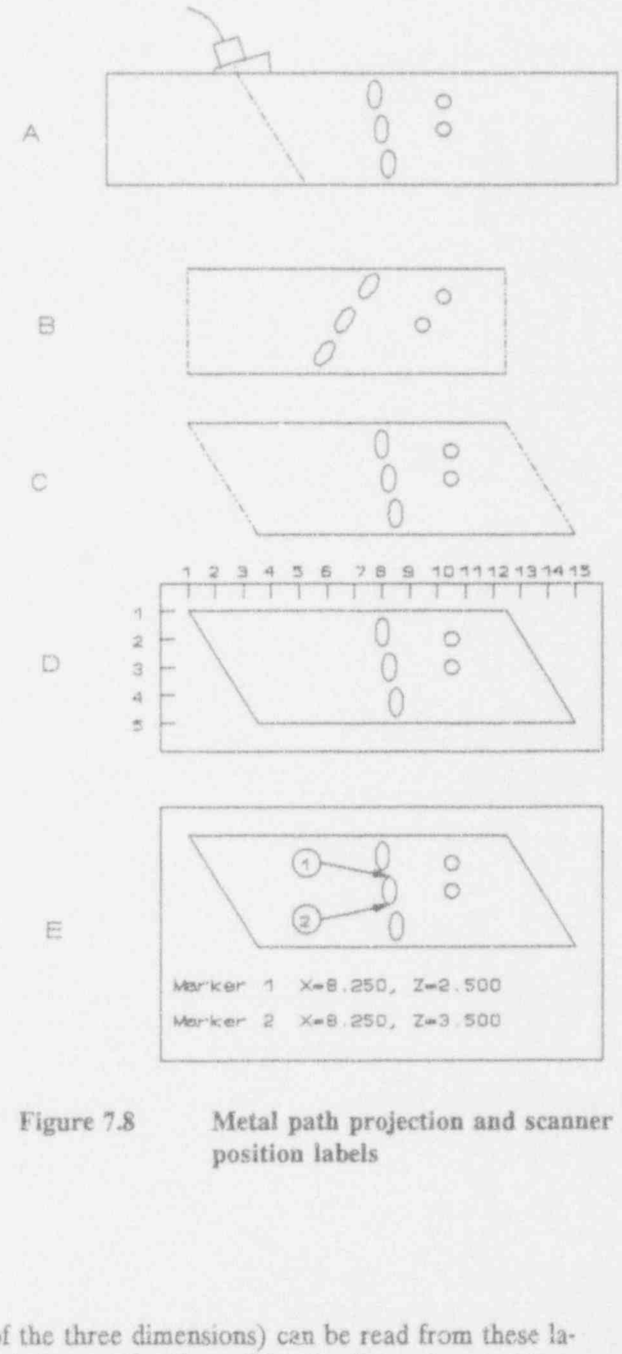


Figure 7.8 Metal path projection and scanner position labels

of the three dimensions) can be read from these labeled axes. In Figure 7.8e, the figure does not have scaled axes. Rather, the operator uses a feature called a position marker. To use the position marker, the user moves the display cursor to an indication, and the display shows the coordinates of the point. With two markers, sizes and distances can be determined by

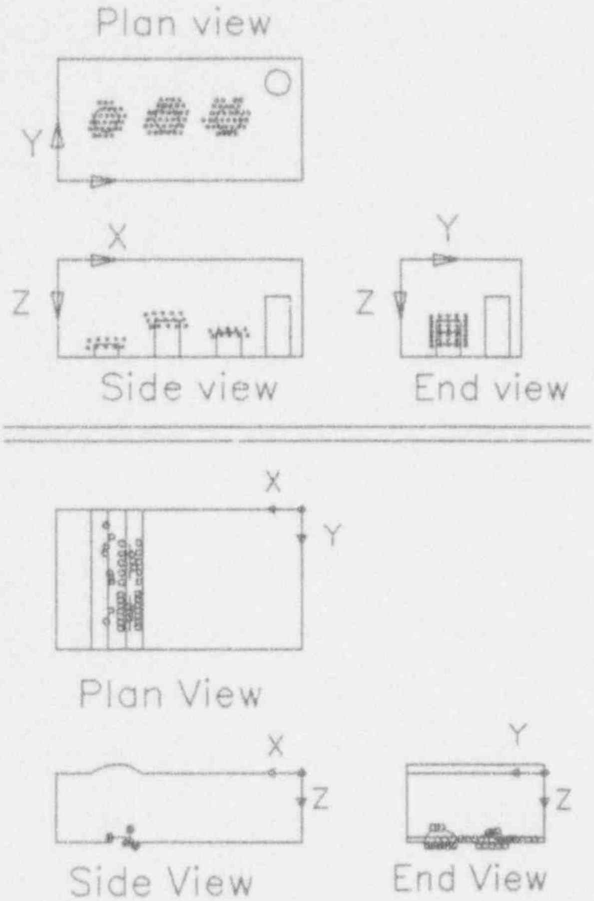


Figure 7.9 Part outlines on ultrasonic views

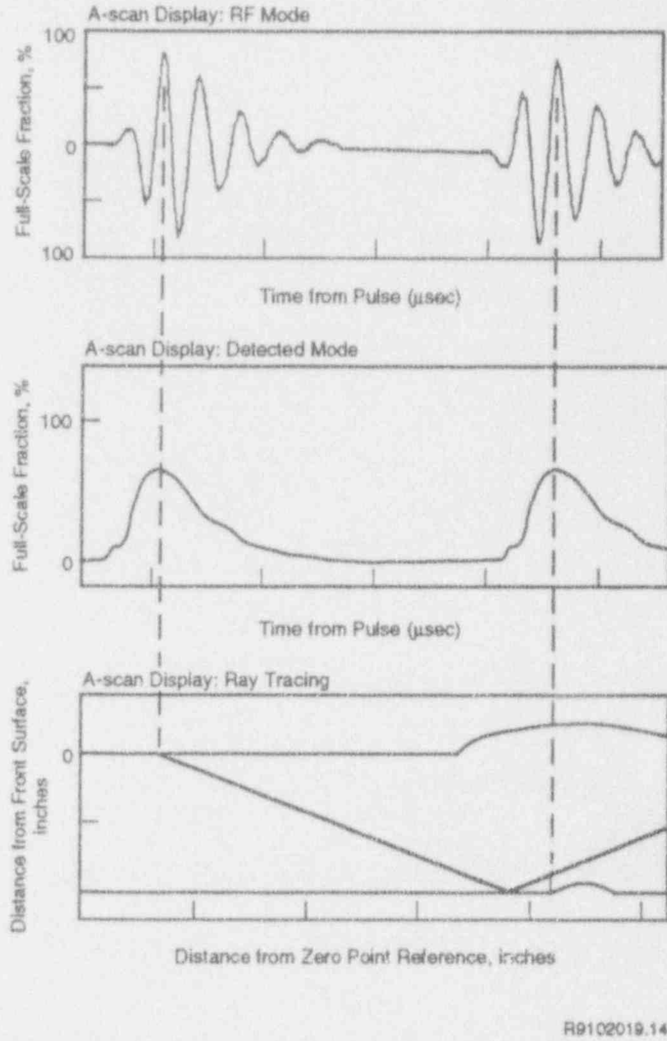


Figure 7.10 A-scan displays: RF, video, geometrical

subtraction; some systems perform the geometric calculations automatically.

7.7 Part Outline Overlays

A significant feature of many systems is the optional display of the orthogonal projections of the part, overlaid on the ultrasonic B-, C-, and D-scan views. The effect of this is shown in Figure 7.9 for two test blocks. This feature can aid in determining the origin of an ultrasonic indication; compare Figure 7.9 with Figure 7.5.

7.8 RF A-Scan Displays

Computer-based systems can display individual A-scans as a post-processing feature or in real time. Figure 7.10 (top) shows a typical RF ultrasonic waveform. This figure illustrates how the operator can view the details of the ultrasonic reflections. It also shows the effects of various types of processing that are done on the A-scan. During the inspection, it provides verification that the ultrasonic electronics are working (i.e. signals are present) and helps the operator view both the effects of adjustments in the control parameters, and the occurrence of significant events during the inspection, such as saturation of the digitizer or loss of couplant (complete loss of signal).

7.9 Video Waveform Presentation

Envelope detection methods are also provided. The digitizer records the RF A-scan and then extracts the low-frequency components of the waveform using a software algorithm. In general, these algorithms require central processing unit (CPU) time; some require much more than others.
Two algorithms are available or the system: the sliding window method and the Hilbert transform. In the sliding window method, the window is set to one half of one wavelength in width. After the data are rectified, each data point is set to the maximum value of the data in the window. In the Hilbert transform, the RF A-scan is first transformed to the frequency domain, then filtered, and transformed back to the time domain.

7.10 Relief Map Presentations

Figures 7.11 through 7.13 show ultrasonic data presented in a relief map format, in which amplitude is shown in the vertical dimension, and spatial information is shown in the horizontal dimensions.

Figure 7.11 shows the motion of a normal beam transducer along a single scan line over the top of three bottom-drilled holes, and three presentations of data from this single scan line. First, some representative A-scans along the scan line are shown at top right. Second, Figure 7.11b shows a typical rectified A-scan over one of the holes. Third, Figure 7.11c shows a B-scan relief map of rectified data from the scan across the three holes. The spatial axes (x, y, and z) are indicated, as well as the ultrasonic amplitude axis (A). Note that the amplitude axis is vertical, and the time or depth axis (z) is horizontal, even though physically the z axis is vertical.

In the format of Figure 7.11c, significantly more data can be shown than in a conventional B-scan. The data in this figure are artificial, show no noise, and have a large separation between the objects. Figure 7.12 shows an actual B-scan relief map of an object similar to the one shown, with the scan axis slanting upward to the right instead of downward top the right. The data here are not so clearly discernable as in the artificial presentation of Figure 7.11c.

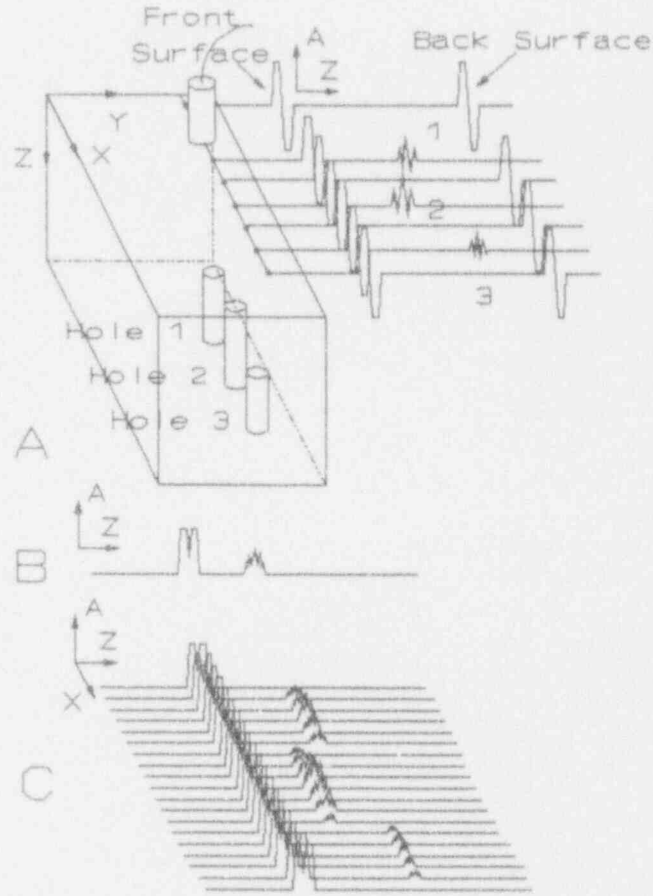


Figure 7.11 **A: Sequence of simulated RF A-scans from single scan line. B: Single rectified A-scan (Hole 2). C: B-scan relief map of rectified data, same scan line.**

Figure 7.11c should not be confused with the similar-looking C-scan relief map, Figure 7.13, in which the horizontal dimensions represent the analogous horizontal dimensions of the inspection volume, and the vertical dimension is the maximum of the A-scan at that point. In this latter case, as in any C-scan, information about all depths is collapsed into one plane. The data in Figure 7.11c, excluding the initial pulses, is collapsed into just one of the curves of Figure 7.13 (the seventh or eighth curve from the top). Each curve in Figure 7.11c represents one ultrasonic A-scan, whereas each curve (or line) in Figure 7.13 represents one scan across the part, each composed of data from many A-scans.

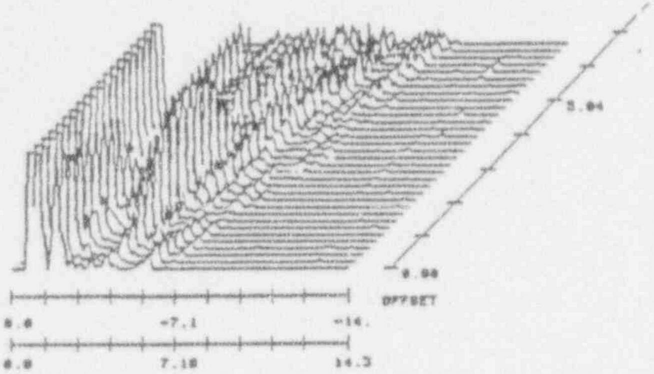


Figure 7.12 B-scan relief map of actual part

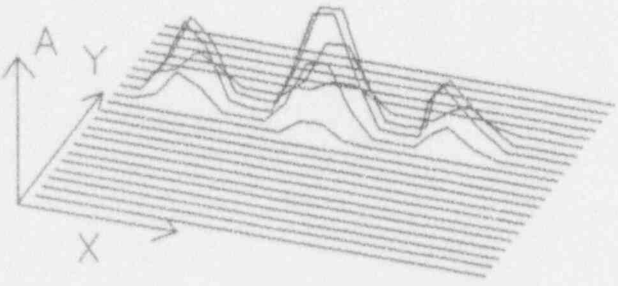


Figure 7.13 C-scan, relief map presentation

7.11 B-, C-, and D-Scan Views, Detected, Composite Planes, Angle Beam

The photographs in Figure 7.14a-i show various images from a shear-wave angle beam inspection of a pipe weld. A, b, and c show the basic inspection data; d, e, and f show data selection by position, and g, h, and i show data selection by amplitude.

Figure 7.14a shows a C-scan view, with the weld root visible as a bright vertical line.

Figure 7.14b is a B-scan view, in which the transducer motion and the beam angle are both in the plane of the paper, and the weld is perpendicular to the paper. A corner trap reflection from the weld root is visible as the red blob toward the right. Since it extends in and out of the paper, it appears as a single spot instead of as a line. Just to the left of the weld root is a corner trap reflection from an intergranular stress corrosion crack (IGSCC). At the top surface, irregularities of the weld crown appear as red splotches. The green and yellow horizontal line is due to mode-converted signals (some of the sound energy travels straight down and back as longitudinal waves, thus arriving much earlier than the angled shear waves). The horizontal dotted lines at the top represents the top surface of the part. The horizontal dotted line just below the weld root and crack signals should represent the bottom of the part. However, it has been incorrectly placed, as it should run through the weld root and crack indications; either the angle, the sound velocity, or the part thickness was incorrectly specified in the computer.

Figure 7.14c shows a B-scan end view, with the weld root in the plane of the paper. In this view, the crack signal is completely obscured by the weld root signal. This is because the display uses the signal from the crack or the signal from the root, depending upon which is the greater of the two. In fact, this type of display uses the value from whichever plane of data has the greatest value for that coordinate. This type of display may be contrasted with an object-oriented display such as that of Figure 7.15.

In Figure 7.14d, the B-scan view is shown again, with the crack signal surrounded by a selection box.

In Figure 7.14e, the selected box is shown enlarged at left, and the corresponding portion of the C-scan view is shown at right.

In Figure 7.14f, the selected box is shown enlarged at left, and the corresponding portion of the D-scan view is shown at right. Note that unlike Figure 7.14c, the crack image is isolated from the root signal (which is not visible at all).

Figure 7.14g, h, and i are the same views as a, b, and c, but with 6 dB of reject (noise suppression) applied: the color scale is changed so as to hide signals more than 14 dB below the maximum, as compared with the negative 20 dB threshold used for the other images (color scales are shown in the vertical bars at right, except where obscured by large images).

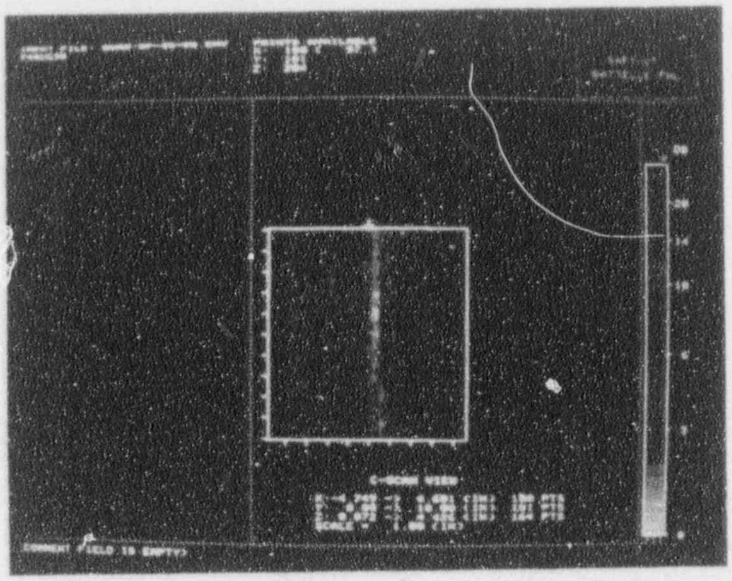


Figure 7.14a C-scan (plan) view of angle beam inspection

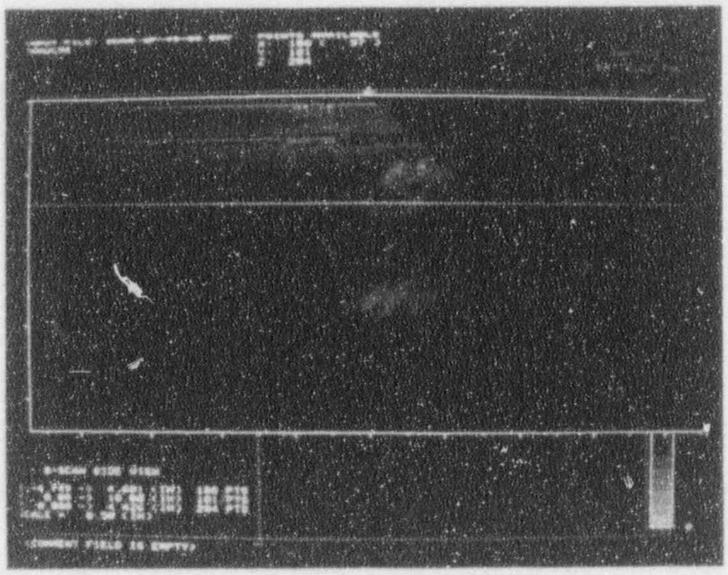


Figure 7.14b B-Scan View of Angle Beam Inspection, showing the inspection angle as a slope down toward the right

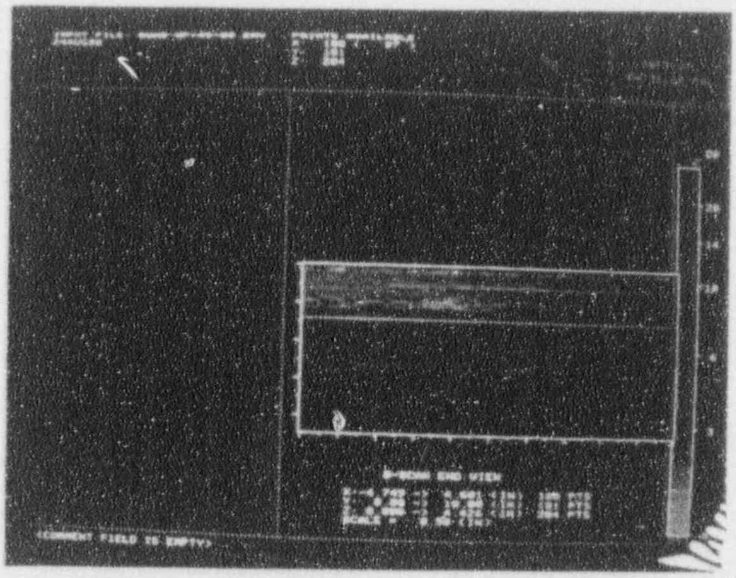


Figure 7.14c B-Scan End View of Angle Beam Inspection

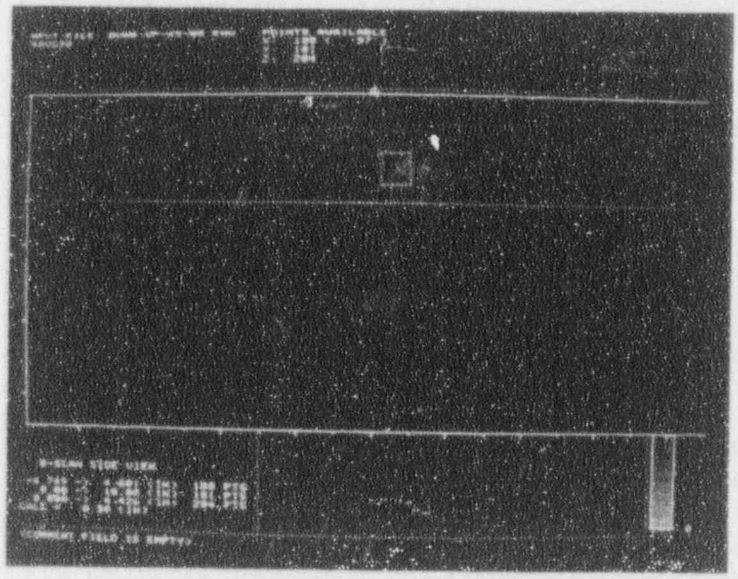


Figure 7.14d B-Scan view, in which a portion of the data has been selected for closer examination (square)

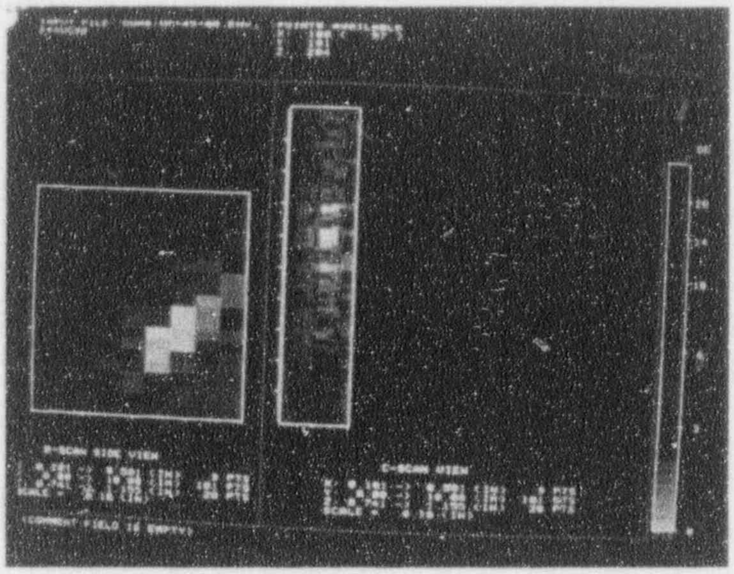


Figure 7.14e B-Scan and C-Scan views of the data selected in Figure 7.14d

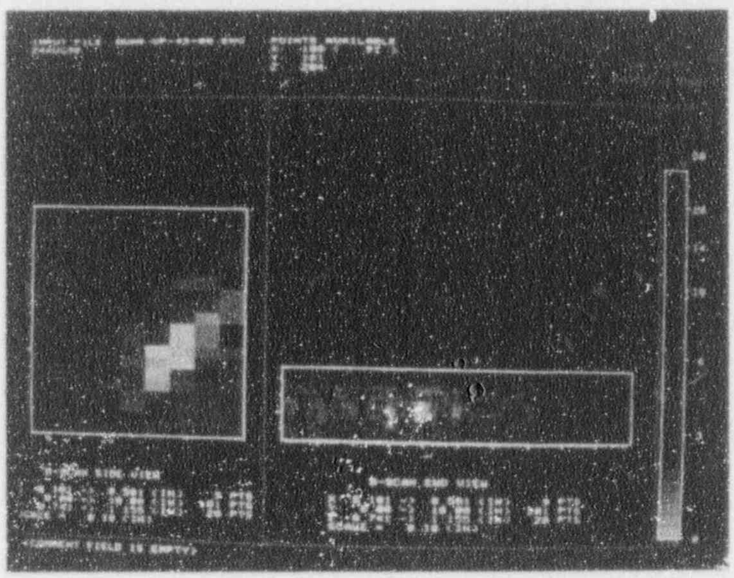


Figure 7.14f B-Scan Side and End Views of the same data as Figure 7.14e

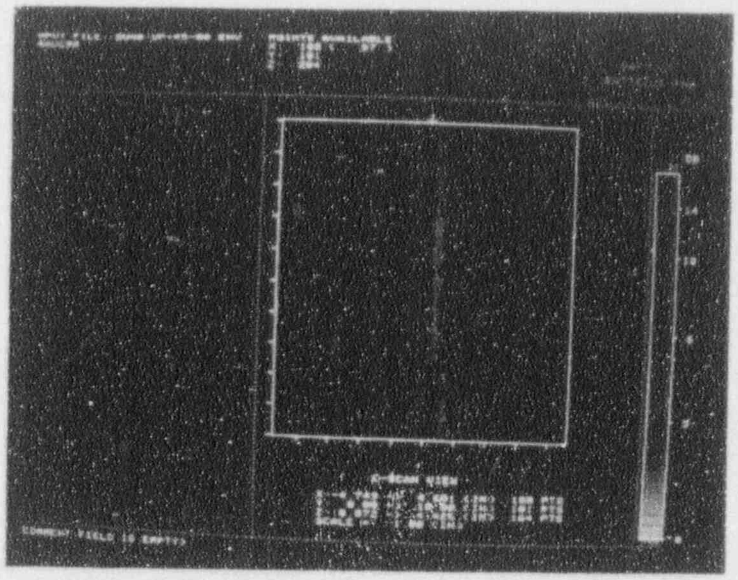


Figure 7.14g The same data as Figure 7.14a, but with reject applied to reduce extraneous data

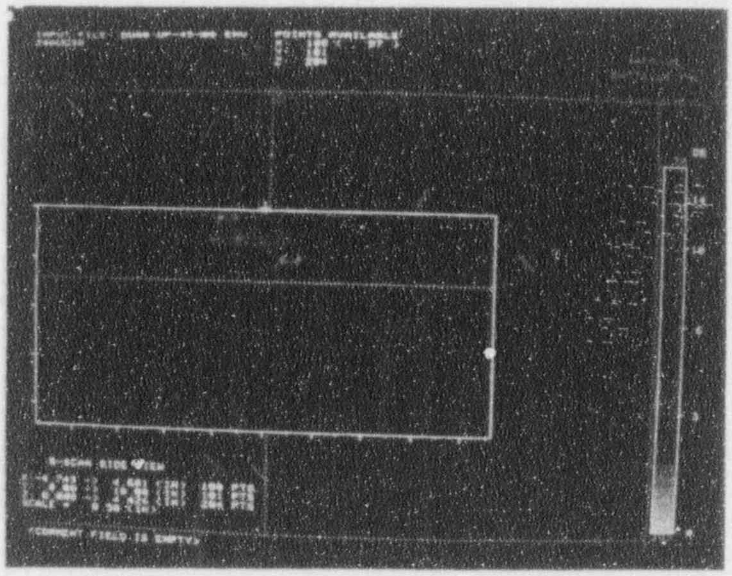


Figure 7.14h The same data as Figure 7.14b, but with reject applied

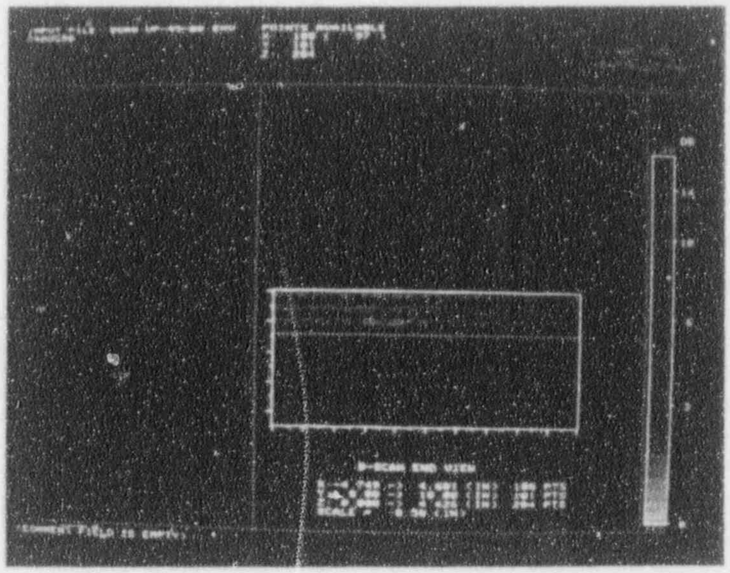


Figure 7.14i The same data as Figure 7.14c, but with reject applied

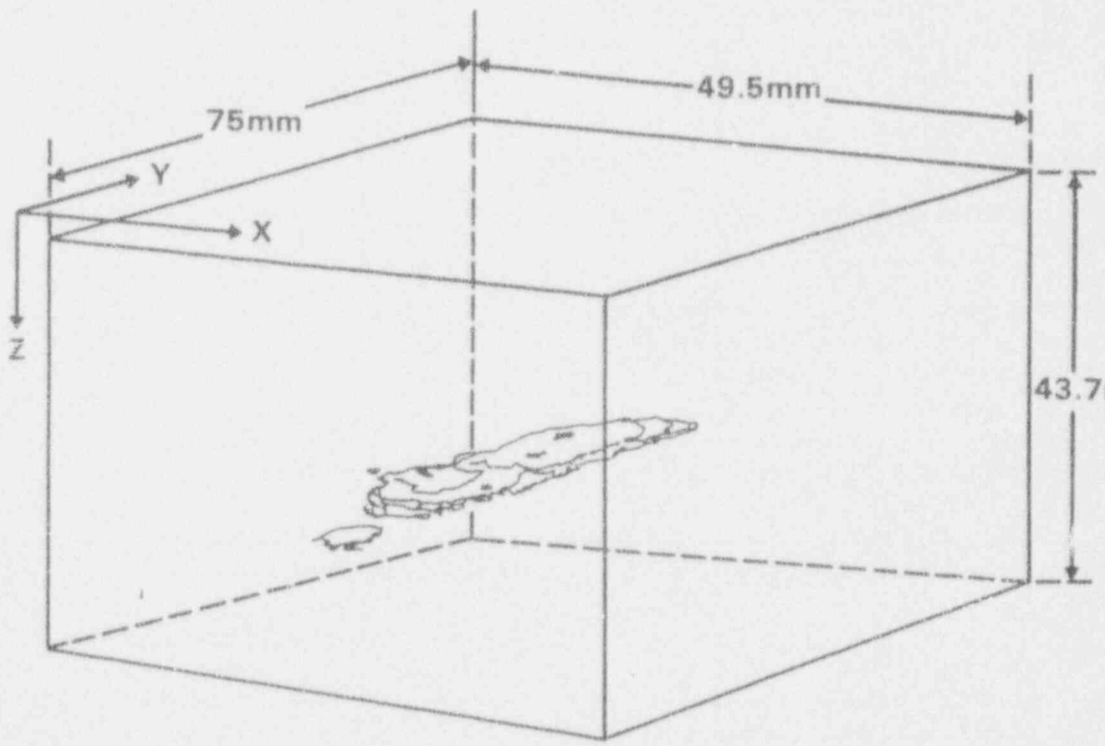


Figure 7.15 3-D view of internal object

Figure 7.15 shows a 3-D view of a slag inclusion in a piece of steel. This presentation is much easier to interpret than B- and C-scans. Unfortunately, defects of interest are frequently positioned near other discontinuities, whose interfering reflections make it difficult to separate the data cleanly and present a correct and unambiguous 3-D image.

7.12 Surface Geometry Correction

If the upper surface of the test object is not flat, then the image produced by the display software cannot correctly project the data along the true metal path unless the operator enters the surface geometry correction. Figure 7.16 diagrams the effects of surface geometry and corrections on ultrasonic inspections. Figure 7.16a shows a two-dimensional drawing of a section of welded pipe. The upper surface contains variations due to the weld crown. Figure 7.16b diagrams a normal beam image of the inside surface. Figure 7.16c shows the effects of surface geometry correction in a single plane side view. Figure 7.16d diagrams an angle beam inspection measuring the reflections from a saw cut and weld root. The effects of the surface geometry and angle beam corrections on the placement of the indications are shown in Figure 7.16e.

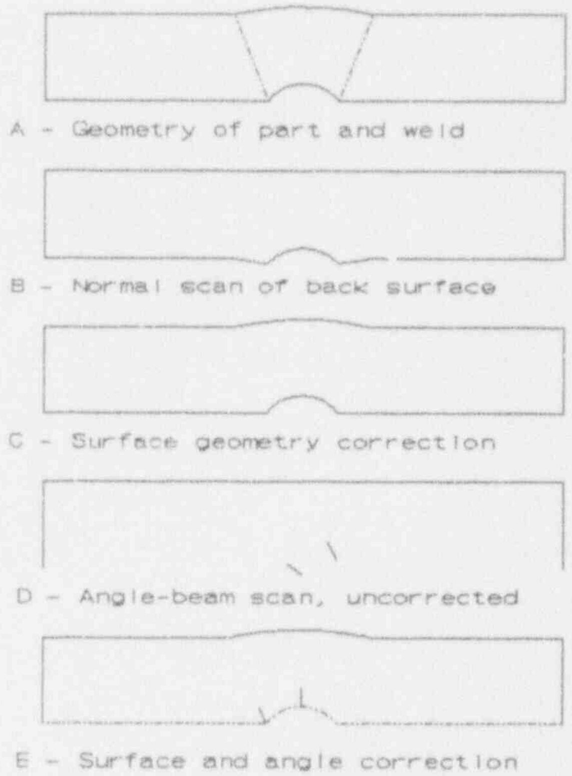


Figure 7.16 Surface geometry correction

7.13 Temporal and Spatial Averaging

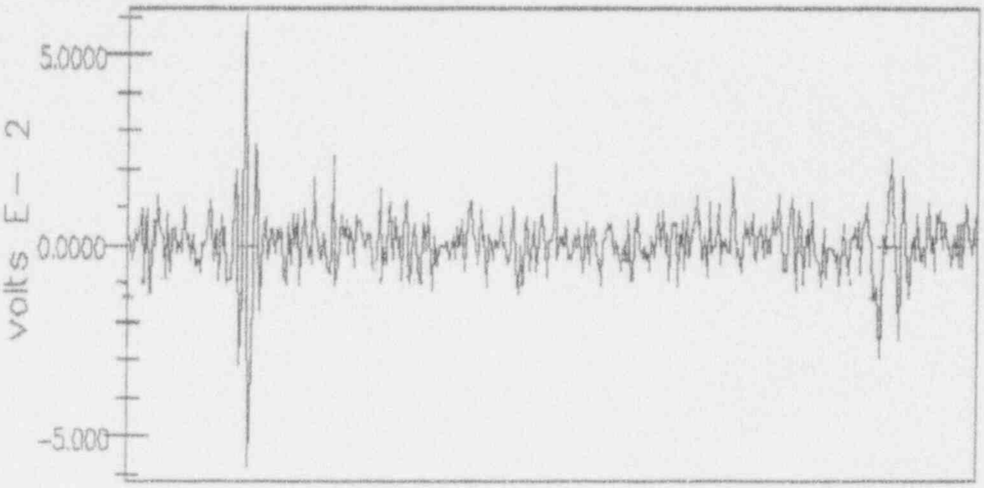
Some computer-based systems provide averaging as a way to reduce noise.

Random electrical noise, for example interference from drive motors or electronic noise from the preamplifier, can be reduced by acquiring N samples at each scanner position and then calculating the average A-scan from the individual samples. Noise is reduced by a factor of the square root of N. Figure 7.17 shows a single noisy A-scan and then an average of 16 A-scans from the same location. Note that the noise is reduced by about a factor of four, while the front surface and backface signals are unaffected.

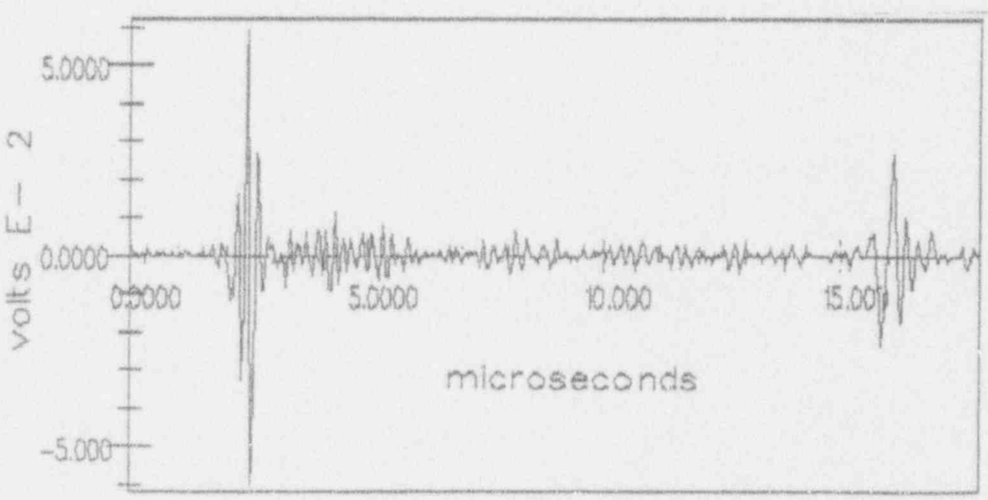
Spatial averaging is used to reduce ultrasonic noise, which consists of reflections from grain boundaries in the metal. The signals from adjacent points in the scan are averaged, which reduces the resolution of the scan but improves the signal-to-noise ratio. For example, in order to carry out a spatially averaged scan at a resolution of 0.1" (2 mm) in a noisy material, data may be taken at 0.01" (0.2 mm) intervals, and each set of ten consecutive A-scans averaged.

7.14 Synthetic Aperture Focusing Technique (SAFT)

The synthetic aperture focusing technique (SAFT) is a modified spatial averaging technique. It acts as a large lens focused on every point in the part, and has the combined effects of producing a highly desirable focusing of the image and reducing unwanted noise. It is, however, a very heavy computational task. Because of the volumetric nature of SAFT, the image presentation lags the scanning by an amount determined by the volume used for averaging.



Raw signal before averaging



Average of 16 signals

Figure 7.17 Single noisy signal and average of 16 signals

7.14.1 Theory of SAFT

As the transducer is scanned over the surface of the part, every reflector in the part produces a collection of echoes in the A-scan records. A point reflector produces a hyperbolic curve as shown in Figure 7.18. The apex and curvature of the hyperbola are determined by the depth of the reflector in the test object and the velocity of sound. This relationship between the hyperbolic echo pattern in the A-scans and the location of the reflector permits the calculation of the hyperbola that corresponds to each point in the test object. The hyperbola is used to shift the A-scans by the predicted amount. The time-compensated A-scans are averaged over a number of positions. If the point in the test object produced a hyperbola of echoes in the A-scan records, then the time-shifted A-scans will add in-phase during the averaging to produce a strong signal, as shown in Figure 7.19. If the point in the test object does not correlate with a locus of A-scan echoes, then destructive interference of the A-scans will cause the average to be nearly zero. Therefore, there is both an improvement in signal level due to coherent summation and a reduction in noise due to the averaging process. Figure 7.18 shows the mechanical setup and the hyperbolic data sets. Figure 7.19 shows the unshifted, shifted, and summed data.

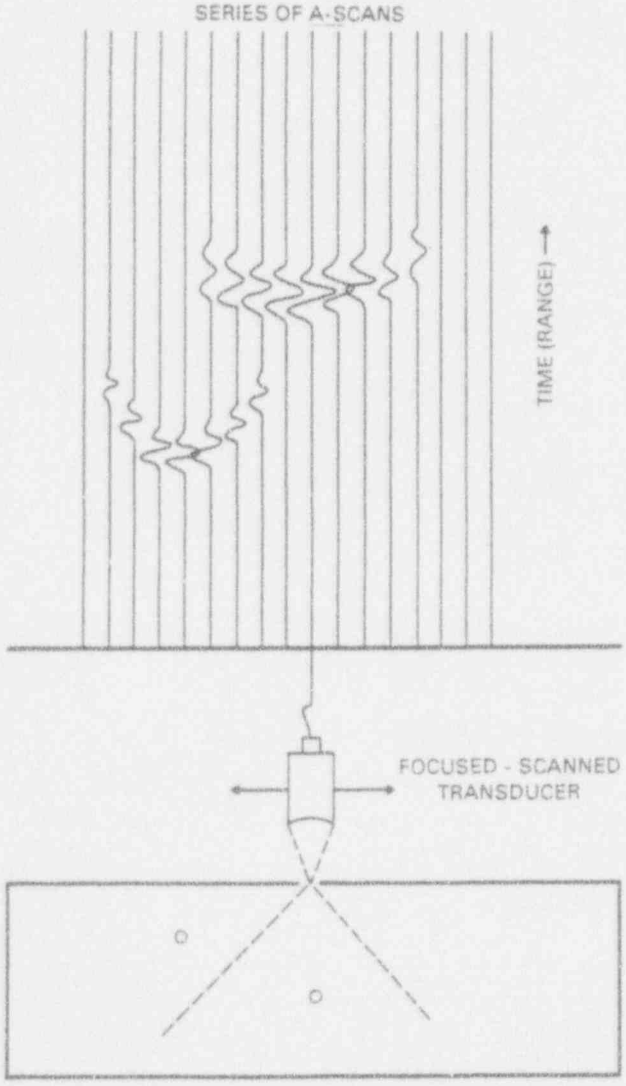


Figure 7.18 Schematic of SAFT scanning and data acquisition

Figure 7.20 shows (a) the unprocessed aperture elements from a data set with two reflectors, and (b) the synthetic-aperture processed aperture elements derived from the data in (a).

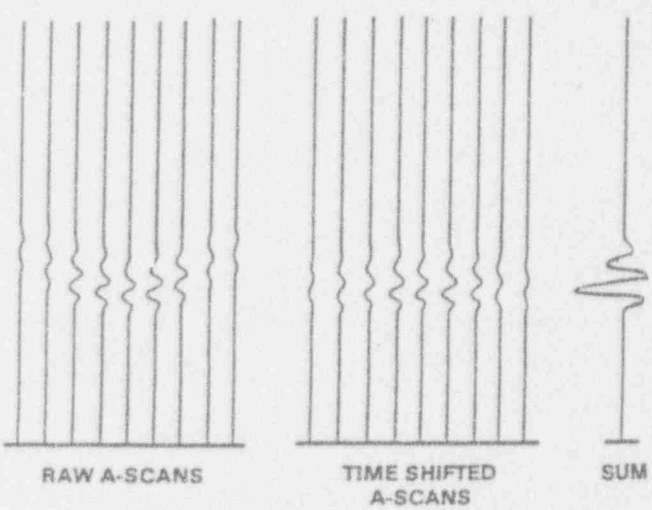


Figure 7.19 SAFT processing, single target

SAFT processing requires that scanning be done with a spread-beam transducer; this is achieved by using either a focused transducer, with the focal point at the surface of the part, or a small-diameter transducer, which has a naturally spreading beam.

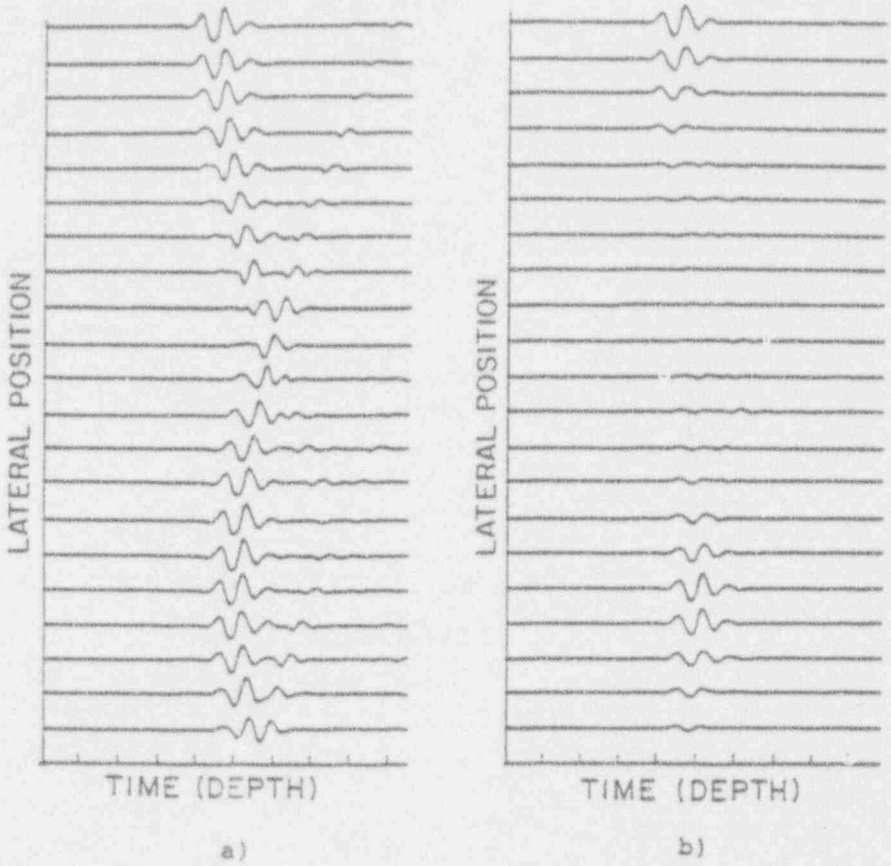


Figure 7.20 SAFT processing, two reflectors: (a) unprocessed; (b) processed aperture elements

7.14.2 Line SAFT and Full SAFT

The system offers two implementations for the SAFT processing: two-dimensional (line) SAFT and three-dimensional (full) SAFT. Line SAFT is used primarily to save processing time by only processing A-scans from the individual scan lines; the image quality is significantly poorer than full SAFT in most cases. The reason for this is that in line SAFT, each scan line is treated as an independent entity. There is thus an implicit assumption that sound is reflected only along the direction of the scan line. This assumption is correct in certain special cases: for instance, a hole drilled horizontally, at right angles to the scan line; or a crack at right angles to the scan line. For these cases, line SAFT gives quite good reconstruction. However, most objects reflect sound in more than one plane, so the calculations done with the false assumption that the object is directly beneath the scan line will produce a false location for the object. The proper summations and cancellations do not occur, and the image is distorted. In full SAFT, data from all the scans near a given point are combined to produce the image for that point, without any assumption as to the direction from which the sound came. It requires more calculation, but produces a correct image in all cases.

The benefits of performing full SAFT as compared with line SAFT can be seen in data from a test object such as the one shown in Figure 7.21. Seven flat-bottom holes are shown drilled in a Y pattern at a 45-degree angle from the normal. This test object is sufficiently complex to provide interference between adjacent objects. Figure 7.22a shows the unprocessed data from

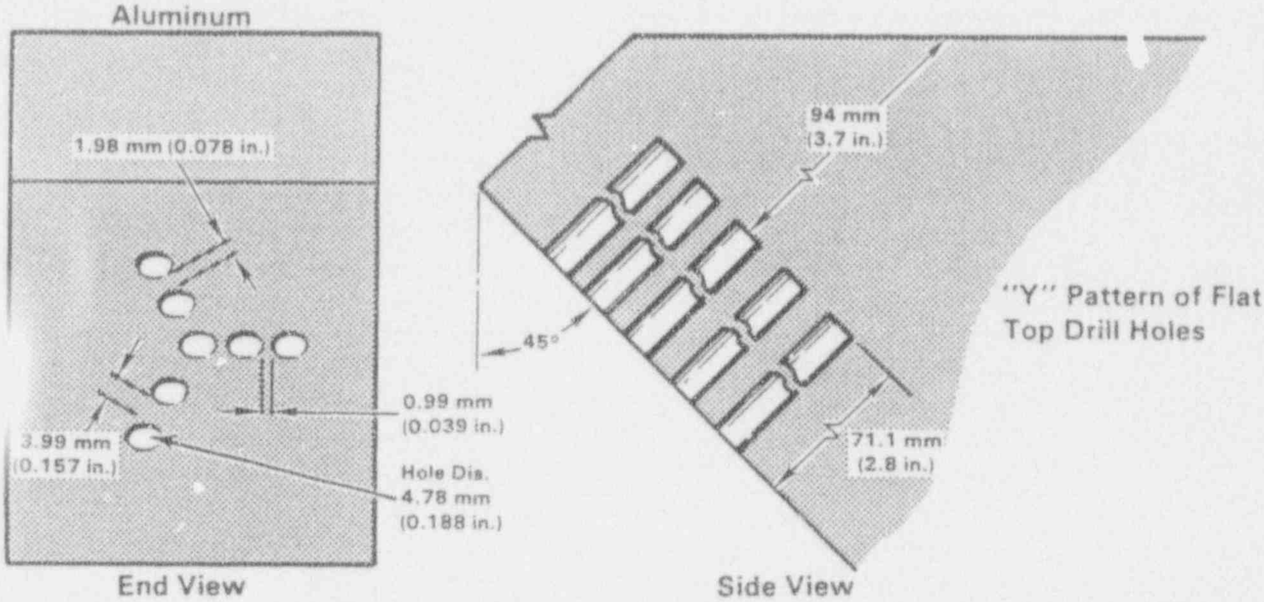


Figure 7.21 Resolution analysis block

the test object. The image of the holes is smeared by the interference arising from the fact that more than one hole is in the transducer's sound beam at the same time. Figure 7.22b shows a poorly focused image of the holes after two-dimensional (line) SAFT processing. Figure 7.22c shows a well-focused image of the holes after three-dimensional SAFT processing.

7.15 Acoustic Holography

Like SAFT, holography images a flaw by synthesizing a large lens from data taken over a wide field of view. It requires a small or focused transducer to spread the beam. Unlike SAFT, holography is normally used to produce an image in only one plane at a time. This means that to image a reflector at a given depth, much less processing is required; to image a whole volume, a time comparable to SAFT processing would be required. Another difference from SAFT is that holographic data consists of only two numbers per scan point, whereas SAFT requires many numbers.

7.15.1 Theory of Holography

At each point scanned, a burst of sinusoidal sound waves is sent out, and the phase and amplitude of the echo are digitized and stored as two numbers. These two numbers describe the shape of the wavefront reflected by the reflector(s). To produce an image, the computer "back propagates" this wavefront, according to the well-known theory of wave propagation, to a selected image plane. If the correct plane is chosen, a well-defined image will result. For a volumetric view, many such planes are reconstructed. Figure 7.23 shows the holographic phase variation that corresponds to the SAFT time-shifting shown in Figure 7.18. Figure 7.24 shows the circles of zero phase shift corresponding to the axis crossings of the upper curve in Figure 7.23.

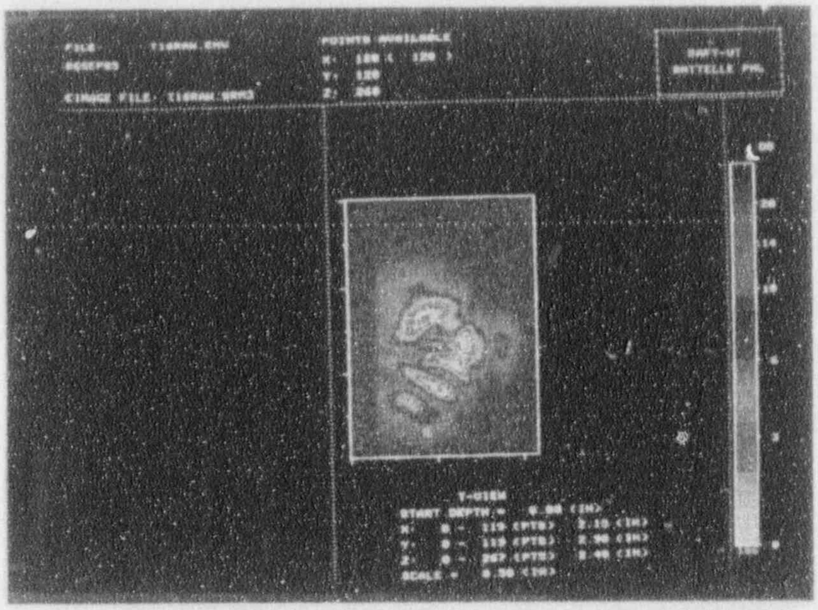


Figure 7.22a Unprocessed "Y" pattern

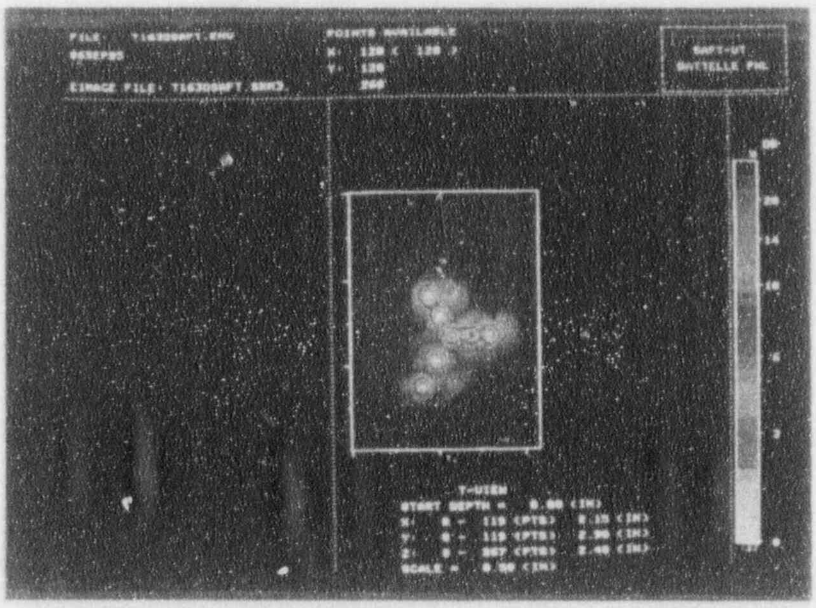


Figure 7.22b Line SAFT Reconstruction of the "Y" Pattern

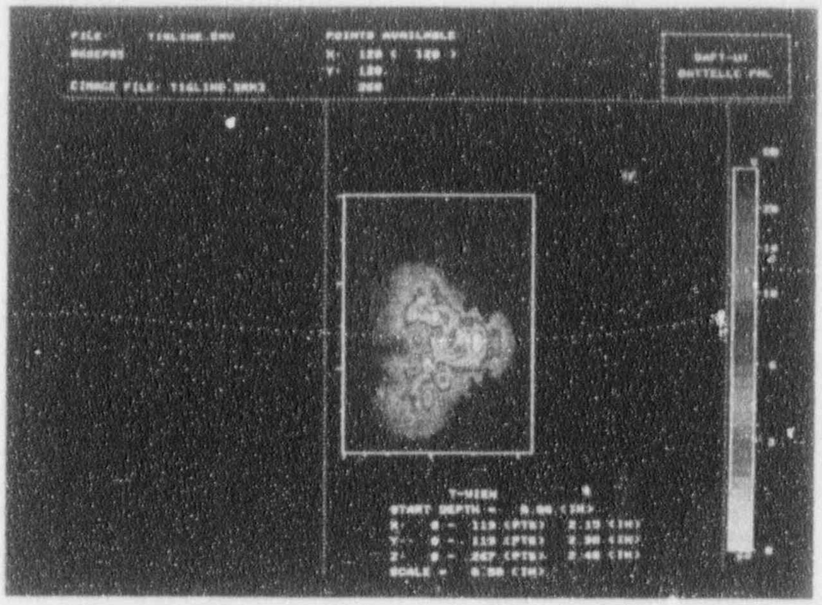


Figure 7.22c Full (3-D) SAFT Reconstruction of the "Y" Pattern

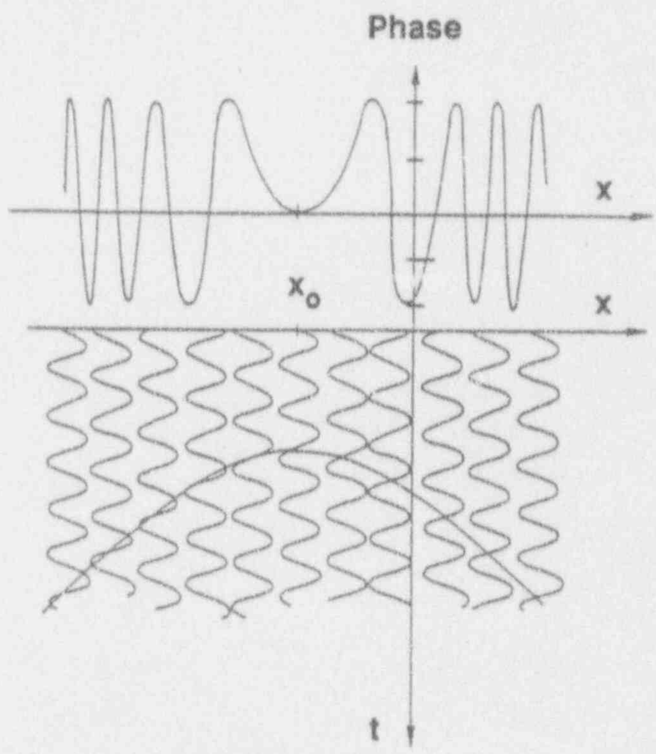


Figure 7.23 A-scans and phase plot in holographic method

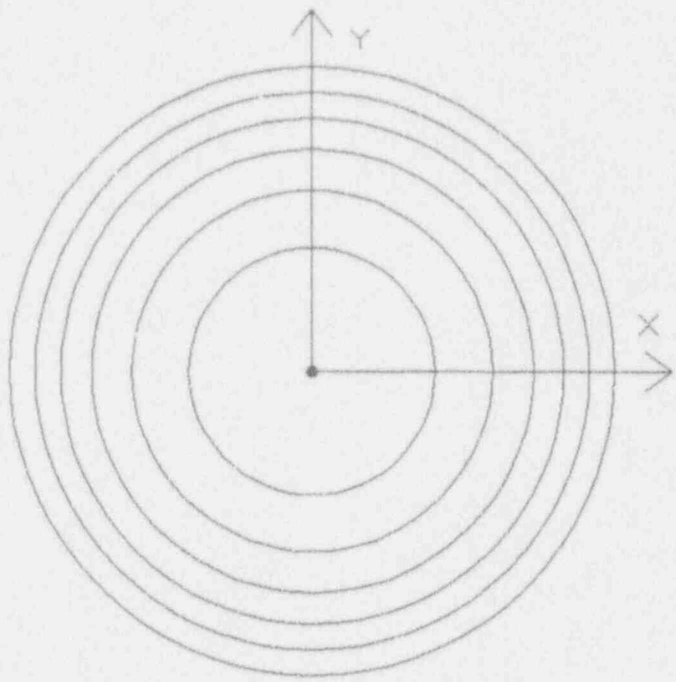


Figure 7.24 Phase plot in x-y plane

8.0 Data Analysis, Interpretation, and Storage

The most important but least understood process in inspection technology (conventional or computer-based) is interpretation of data. Once data have been acquired, processed, and displayed, the data analyst must make three decisions:

- Are the data acceptable and complete?
- Does the material being examined contain a defect?
- If the material has a defect, what are its location, size, shape, and orientation?

The integrity of the stored data is vital to the inspection process. Electronic data storage has special considerations in addition to those applicable to paper records storage. Electronically stored data is more fragile than paper records. Even minor damage to the data can make it unusable. It is subject to damage from contamination with moisture or dust, exposure to magnetic fields, or exposure to high-intensity electromagnetic radiation. It is also not readable without special equipment, so it is important to keep printed lists and descriptions of the contents with the records. Finally, its lifetime is much shorter than paper records.

8.1 Acceptability and Completeness

It is tempting to say "the computer did it, so it must be right." However, there are a few points worthy of attention, mainly to avoid "garbage in, garbage out." The system and its operators must be qualified to perform the inspection, just as for conventional systems. It requires special attention on the part of the operator to assure that the system did not encounter a situation that it was unsuited to cope with, such as excess of data beyond the storage capacity, inoperability of a system module, incorrect setting of manual adjustments, or some other special peculiarity of the system. Like any other complex system, computer-based UT can fail to perform as expected for a great variety of reasons, and it behooves the prudent investigator to try to anticipate them. The future use of the ASME Code Section XI Appendix VIII qualification process will aid in validating, for a given system, the adequacy of the data needed to pass performance demonstrations.

8.2 Image resolution

Image resolution is of central concern to the quality and efficiency of inspection. Too low a resolution reduces detection and analysis capabilities. Unnecessarily high resolution is costly in terms of inspection time, analysis time, and data storage requirements.

Image resolution has two components: lateral (x and y) and depth (time or z). Lateral resolution is a function of the transducer frequency and beam characteristics, the scanning speed, and the scan index. Depth resolution is a function of the transducer frequency bandwidth and the sampling speed of the digitizer. The required ultrasonic parameters (frequency and transducer type) are determined by a combination of theory and experimentation. The data acquisition parameters (scan size and speed and digitizer sampling rate) are then chosen to maintain the resolution of the ultrasonics.

The four images in Figure 8.1 illustrate the effects of image lateral resolution. All four images are of the normal-beam resolution block, UT-RES-0000, containing a set of 0.25" (6 mm) holes, as described in Appendix A. The first two are scans from the "back" of the block, through water, achieving a higher resolution than would be possible through the metal side with the available transducers. The second two are scans from the "front" of the block, passing through two inches of steel; the holes appear in mirror-image configuration compared to the first two scans, and the gray scale is reversed, since the target in the first pair is a non-reflector, and in the second pair, a reflector. The same transducer used for all four scans: 5 MHz, 0.5" (13 mm) diameter, 3" (8 cm) focus in water.

In scan 1, the block is scanned with the open ends of the holes facing up, and the transducer is positioned 3" (8 cm) above the surface. The scan spacing is .020" (.5 mm) in both the X and Y directions. Note that the circular shape of the holes is clearly distinguishable, and all holes are clearly separated.

In scan 2, the block and transducer positions are the same as in scan 1, but the scan spacing is .060" (1.5 mm) in each direction. Note that the holes have a squarish appearance, but are still well separated.

Scan 1:
High-resolution transducer, high-resolution scan

Scan 2:
High-resolution transducer, low-resolution scan

Scan 3:
Low-resolution transducer, high-resolution scan

Scan 4:
Low-resolution transducer, low-resolution scan

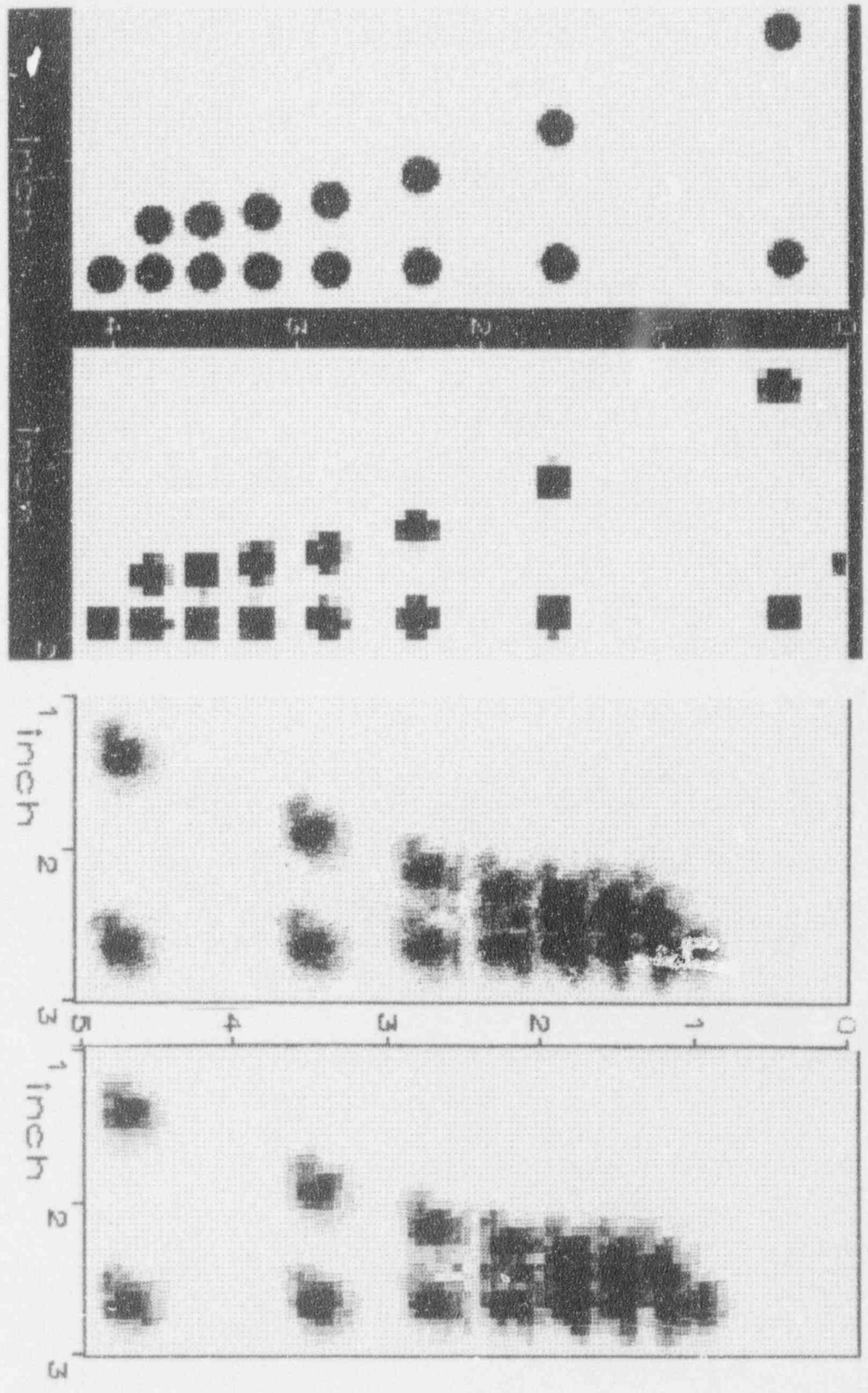


Figure 8.1 Lateral resolution illustrations

In scan 3, the block is scanned with the closed end of the holes facing up, so that there is 2" (5 cm) of steel between the transducer and the holes (turning the block over also causes the hole pattern to be reversed). Because sound travels about 4 times faster in steel than in water, the effective focal length of the transducer in steel is four times shorter than in water, or about 0.75" (2 cm). Thus the holes are badly out of focus, even with the transducer as close as practicable to the surface of the block. The scan spacing is the same as in scan 1, and the roundness of the holes is discernable, although distorted. The separation between some of the holes is virtually obliterated; in fact, on the basis of this image, one might posit a third row of holes between the more closely-spaced pairs.

In scan 4, the block and transducer are positioned as in scan 3, but the scan spacing is the same as in scan 2. Note that the additional squarishness of scan 4 compared to scan 3 is less pronounced than comparing scan 2 to scan 1, because the scan spacing is commensurate with the beam size of the transducer at the object depth.

In terms of inspection procedures, scan 2 is underscanned (some of the intrinsic ultrasonic resolution has been lost by using too large a scan spacing), and scan 3 is over-scanned (time has been wasted in scanning at a higher resolution than the ultrasonics permits). If the data is to be subjected to image reconstruction such as SAFT, then scan 3 is not over-scanned, as the image focus will be recovered; the resulting processed image would be comparable to scan 1.

Useful formulas for resolution limits are as follows, where Δx, Δy, and Δz are as shown in Figure 8.2. In the x and y directions:

$$\Delta X = \Delta Y = 1.22\ \lambda f/a \qquad \text{for lateral resolution}$$

and in the z direction:

$$\Delta Z = C/(2^*BW) \qquad \text{for depth resolution}$$

where

- λ is the wavelength in the material
- a is the effective transducer diameter
- f is the effective focal length
- C is the velocity of sound in the test material
- BW is the bandwidth of the transducer in MHz.

In practice, the transducer resolution dominates and limits the system resolution.

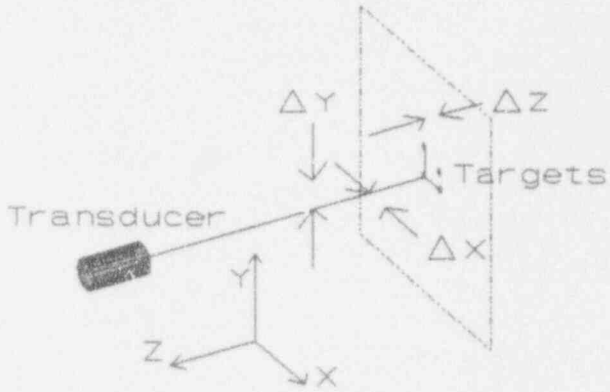


Figure 8.2 Diagram of lateral and depth resolution

Note that these formulas are relative to the degree of resolution desired. As given above, they refer to 6 dB resolution (a two-to-one difference between measurements). If a lower difference is acceptable, the constants 1.22 and 2 may be increased; the dependence on the various parameters remains the same, however. It is also important to note that the depth resolution formula refers to distinguishing two objects along the same sound-beam path, and not to measuring thickness profiles at varying x and y locations, which can be done to much higher resolution.

8.3 Defect Classification

Defect classification requires analysis of the image. The process of image analysis requires a systematic evaluation of the data. Most inspectors develop this process but in general have not documented it in writing and do not have it written into their procedure. This is one area that has always been weak for most nondestructive evaluation (NDE) procedures, regardless of whether the inspections are done manually or with computer-based systems. The new ASME Code Section XI Appendix VIII qualification requirements are designed to provide written procedures for this analysis methodology.

Several rules of thumb may be used to help classify one type of flaw or another. For example, volumetric or laminar flaws provide a response to a normal beam inspection. Vertically planar flaws do not provide a response from a normal beam examination, but rather from an angled beam inspection. Vertically planar flaws also may provide a top signal response and, if rough, will continue to provide a response upon skewing the transducer. The shape of an image may be used to distinguish between noise and planar flaws. Noise will tend to be non-directional, and response from reflectors will tend to have a smearing effect normal to the direction of the sound beam.

This is not a comprehensive review, but is meant only to provide a perspective for the kinds of steps that are typically found in the analysis methodology. Interpretation of data is a complex process, and many steps are required before deciding upon a final disposition for an indication.

8.4 Defect Sizing

The process of defect sizing is the key step in providing input to the fracture mechanics for determining structural integrity of a component. The sizing of defects is at least as complex as classification.

The sizing of defects requires, first of all, that the defect be detected and classified. For certain defects such as cracks, a tip diffraction signal may be found that has been shown in studies to give accurate dimensions of the through-wall extent of the crack. If the defect is oriented in a manner such that the sound field impinges at a normal angle, then the image that is generated for this defect will be more accurate to the actual dimensions of the defects, after correcting for the transducer beam size and the resolution limits of the data acquisition system. Many times, tips cannot be detected, and the defect is oriented at a skew or tilted angle such that limited information is available for sizing. In such cases, either additional inspections must be performed to improve the resolution performance of the system, or supplemental inspections at other frequencies, transducer sizes, inspection angles or modes (e.g., pulse-echo, tandem) must be conducted. With the new information, it is a matter of selecting the best data for the particular defect type for coming up with the estimate of the defect size. Some guidelines that should be followed include the following:

- For defects where tip-diffraction signals are found, use them for sizing the depth of the defect.
- For defects that are volumetric in nature, use sound fields that strike the defect in a normal fashion and use the best resolution that can be achieved for the system.
- For near-vertical planar defects, use a high-resolution tandem technique to determine the size of the defect.
- Determine the length of the defect by scanning parallel to the plane of the defect.
- If the defect is difficult to size, then try to use techniques that aid in determining whether the defect is shallow or deep. These techniques might include, for example, a full-V test or creeping wave probe test.

8.5 Requirements in Procedures and ASME Code

Little guidance except personal experience is available to the data analyst. Section XI of the ASME Boiler and Pressure Vessel Code does not address data analysis and interpretation. Instead, Section XI provides only requirements for data acquisition by imposing minimum data recording levels. Nuclear industry personnel (including regulatory authorities) have recognized the deficiencies regarding data analysis and have attempted to address the problem. Recently, the ASME code adopted a new appendix that requires that personnel, equipment, and procedures be qualified by a performance demonstration test. While performance demonstration testing does not provide rules for data analysis, it does help ensure that data analysts have assimilated (by whatever means) the ability to properly analyze data acquired by a specific inspection system.

Inservice inspection procedures written for computer-based inspection technology do not address data analysis either, except to declare that ultrasonic indications exceeding the recording threshold will be investigated. Sometimes the word evaluated or analyzed is substituted for investigated.

Because no formal requirements exist for analyzing data, the regulatory authority has no formal basis or guidance for determining the adequacy of data analysis, except in the cases where fundamental laws of physics are violated. Again, the new ASME Code qualification process will provide an impetus to writing the analysis methodology into the inspection procedures.

8.6 Data Storage

The electronic storage of data potentially permits great advantages in comparison of data between sites, between components at a site, and between inspections of the same component over time. This potential is only realized if the same system is used in both cases, or if the system provides some kind of data import/export possibilities.

Electronic records are much more fragile than paper records and minor damage can render them useless. If the site relies on electronic storage, it is vital that normal good practice be followed in the retention of records. The following are general guidelines to good practice.

Data stored in a computer in non-removable, rewritable storage (hard disks or non-volatile memory) should be backed up (copied) as soon as practicable to removable or non-rewritable media, to avoid loss of data due to machine malfunction or operator error.

All data should be stored redundantly, in locations far enough separated so that a catastrophic accident will not destroy both copies. Magnetic media (tapes, floppy disks, removable hard disks) should be protected from strong electromagnetic fields such as magnets, NMR, high-energy X-rays, and all ionizing radiation sources. Magnetic media can also degrade over time, due to the substrate becoming brittle, the coating flaking off, and especially, in the case of floppy diskettes, from repeated use. Magnetic media should periodically be recopied to fresh media, at intervals depending on the specific medium. Data stored on "WORM" (Write Once, Read Many) or other non-erasable optical media are probably as long-lived as paper data, and are not susceptible to damage from magnetic fields. All storage media are of course susceptible to problems from moisture and dirt.

Over the long periods of service of nuclear installations, computer technology will change; thus, some provision needs to be made for upgrading old data to make it accessible to new machines. This is in any case generally advantageous to the utility, since media are continually becoming smaller, cheaper, and more reliable.

9.0 Evaluation of Selected Computer-Based Ultrasonic Inspection Systems

Based upon input from NRC regional personnel, PNL selected nine computer-based ultrasonic (UT) inspection systems for evaluation:

- ACCUSONEX
- ARIS
- GE-Smart UT
- GERIS
- IntraSpect I-98
- P-Scan
- Phased Array
- SwRI/PAR EDAS
- UDRPS.

The system evaluations are of two kinds: preliminary and formal. In the preliminary evaluations, vendor information, literature review, and the results of databases from such sources as PISC II, MRR, PVRC, and EPRI are used. The results of the preliminary evaluations are presented in this section. In the formal evaluations, the equipment is rented and the procedure documented in Appendix A is followed. The results of the formal evaluations will be published as Supplements to this volume. To date, not all of the systems have been subjected to either kind of evaluation. Two systems (P-Scan and IntraSpect) have undergone formal evaluation, and the Supplements are in preparation. Formal evaluation of other systems will be performed as possible, but it appears unlikely that all systems will be formally evaluated. For some systems, a partial field evaluation may be possible.

For each system, the PNL evaluation seeks to determine

- the principles of operation
- potential limitations of operation
- the reliability for flaw detection and sizing.

The following preliminary evaluations were conducted using a literature search and responses to a letter survey requesting information from vendors. These evaluations are documented in Sections 9.1 through 9.9.

9.1 ACCUSONEX

ACCUSONEX™ is a multichannel ultrasonic data acquisition and imaging system manufactured by Babcock & Wilcox Nuclear Service Company (BWNS), Lynchburg, Virginia. This system is designed to provide inservice inspection for piping or pressure vessels. System features include:

- real-time images during inspection
- ability to use the following manipulators: AM-DATA pipe scanners, Puma 260 and 560 series six-axis robots, and the BWNS's ARIS II and III reactor vessel inspection manipulators.

9.1.1 Data Acquisition

Operating with the Hewlett-Packard 300 series computer systems, ACCUSONEX collects and processes either rectified or RF data. These data can originate from any or all of eight ultrasonic channels and be displayed in real time as A (amplitude), B (side view), rotated B (end view), and C (top view) scans.

The data are stored on either high-density magnetic tape or optical disk and are acquired through the use of the system functions SETUP and RUN.

The SETUP function offers these features:

- Twenty distinct setups
- Distance amplitude correction (DAC) curves for each UT channel
- Recording threshold for each channel
- Calibration values (gain, time, date, and others)
- UT instrument settings

In the RUN function,

- setup information is retrieved by the ACCUSONEX.
- data are displayed in real time and stored on hard media.

9.1.2 Data Processing and Display

The ACCUSONEX analysis system uses the data recorded during the acquisition mode to analyze both rectified and RF data. Data analysis can use multiple remote ACCUSONEX analysis stations interconnected through a local area network, allowing all stations to access the data simultaneously. The ACCUSONEX system analyzes data through use of the system functions TAPE SORT and ANALYZE.

The TAPE SORT function uses previously recorded data, geometry correction features, and calibration data to process the waveforms, which are then stored on an optical disk.

The ANALYZE function is used to view processed data stored on optical disk. Two different display formats are available.

The first format displays simultaneous views of C, B, and rotated B (end) scans. The example shown in Figure 9.1 is a thermal fatigue crack in a clad ferritic test block. The block dimensions are 14 inches in length, 8 inches in width, and 2-3/8 inches thick (35.6 x 20.3 x 6.0 cm). Both rectified and RF data can be viewed in this format. This format includes the following features:

- Full data set display
- Zoom
- Color manipulation
- Coordinate determination using the curser
- Determination of the distance between any two points using the Delta feature
- V-Cal: a plot of amplitude versus depth
- LBTMF (described in Section 9.1.3)
- Hardcopy color printouts.

The second format displays the image in the form of a B-scan with a simultaneous A-scan. This is used only for RF data and primarily for sizing. The same tools are available as for the first format except for V-Cal and LBTMF.

9.1.3 Data Interpretation

Data are interpreted by viewing the images and using a software program called Lower Bound Target Motion Filter (LBTMF) that looks for reflectors with a predetermined target motion (apparent motion of the target).

9.1.4 System Limitations

9.1.4.1 Mechanical

No limitations were noted.

9.1.4.2 Other

The system's primary limitation is physical accessibility to the area to be examined.

9.1.5 Other System Characteristics

The ACCUSONEX system is currently designed for examinations on piping, nozzles, reactor coolant pump cases, reactor vessels, or flat components. Other configurations can be incorporated. The system uses both pipe scanners and six-axis robotic manipulators. Therefore, any surface geometry may be examined.

9.1.6 System Reliability

The ACCUSONEX system has passed both the EPRI detection and sizing performance demonstrations. It has successfully completed the following tests:

1. Enhanced Ultrasonic Examination Technique Development for High Pressure Injection (HPI)/Makeup Nozzles on Reactor Coolant Systems, conducted during fall/winter 1989-90.

2. Balance of Volume Flaw Sizing performed at the Electric Power Research Institute (EPRI) NDE Center in June 1989.

3. EPRI/WOG/Wolf Creek Nuclear Generating Corporation-sponsored workshop on Ultrasonic Examination of Cast Stainless Steel conducted in June 1989.

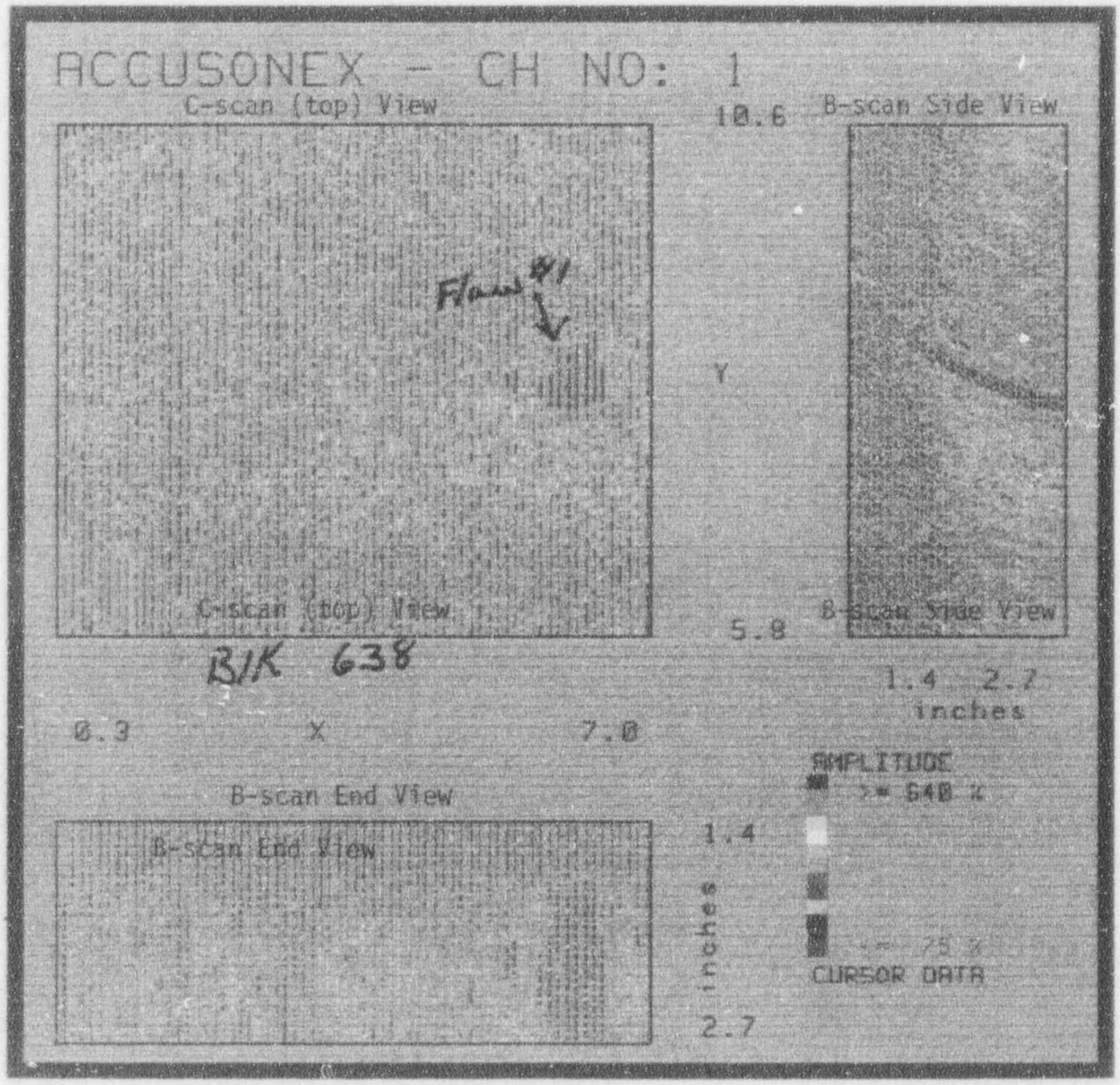


Figure 9.1 Typical ACCUSONEX display showing C- and B-scan views

9.2 ARIS

ARIS is manufactured by Babcock and Wilcox Nuclear Service Company, Lynchburg, Virginia. No evaluation has been performed.

9.3 GE-Smart UT

GE-Smart UT is manufactured by General Electric Nuclear Energy, San Jose, California and Norcross, Georgia. No evaluation has been performed.

9.4 GERIS

GERIS is manufactured by General Electric Nuclear Energy, San Jose, California and Norcross, Georgia. No evaluation has been performed.

9.5 IntraSpect I-98

The IntraSpect I/MC system (successor to the I-98), manufactured by ABB AMDATA, Inc., Windsor, Connecticut, has been formally evaluated. The Supplement will be published in early 1994.

9.6 P-Scan

The P-Scan, manufactured by FORCE Institutes, Brondby, Denmark, has been formally evaluated. The Supplement will be published in early 1994.

9.7 Phased Array Inspection System

The Phased Array system was designed by Siemens, Kraftwerk Union (KWU), Federal Republic of Germany (U.S. contact: Siemens Nuclear Systems, Chattanooga, Tennessee), and Universal Testing Laboratories (UTL), 15740 Shady Grove Road, Gaithersburg, Maryland, to perform ultrasonic examinations of nozzles. The system has two major components:

- a three-dimensional modeling software program that serves as a calculation tool for determining optimum parameters for designing the UT transducer and the scanning requirements

- a data acquisition package that includes:

    - remote scanner/manipulator

    - remote pulser used to beam steer the phased-array transducer

    - remote receiver and digitizer that digitizes the rectified A-scan data.

9.7.1 Data Acquisition

Acceptable data acquisition for the Phased Array system requires the inspector to have access to as-built drawings of the nozzle to be inspected. The Phased Array system then uses three-dimensional modeling software to derive ultrasonic beam parameters for the complex geometry of a nozzle inspection.

The computer software allows the user to define an angle of inspection for each potential defect location on the inside of a nozzle. The model then calculates the incident angle(s) and phased-array transducer location coordinates on the outside surface of the nozzle. Before a nozzle is inspected, the thickness dimensions obtained from drawings are checked. After drawing dimensions have been verified, the parameters that were calculated by modeling software are downloaded to the inspection system, which then calculates the correct time sequences for proper beam steering of the eight-element array and determines the proper scan pattern for the manipulator.

The data acquisition system records the entire rectified A-scan and probe location coordinates for every A-scan during an examination. The information recorded during the nozzle examination is used to reconstruct images for subsequent analysis.

9.7.2 Data Processing and Display

Tomographic images are processed from the A-scan and probe location information recorded during data acquisition. Color contours are used to describe the amplitude of recorded signals.

9.7.3 Data Interpretation

Defect locations are established using the intersection of points of the time-of-flight trajectories from the various scan radii. The time-of-flight intersections are also used to determine the circumferential and axial position of any defect. Once an indication is determined to be a flaw, the defect length is measured by the axial extent of the indication.

Flaw sizing using the Phased Array system is accomplished using an empirically developed table that uses a combination of amplitude and target motion data. The results from the blind test developed from notch data are provided in Section 9.7.5.

9.7.4 System Limitations

The Phased Array system as developed by KWU and deployed in the U.S. is designed only for nozzle inspection. However, the concept for phased arrays can be applied to plate or piping inspection.

9.7.5 System Reliability

The effectiveness of the techniques developed by KWU and UTL were demonstrated in a blind test. The blind test was performed on a nozzle mockup that contained geometric configurations similar to those in the feedwater nozzle to be examined (e.g., the mockup contained ground areas with and without notches).

The results of the blind test on the nozzle mockup used for the performance demonstration showed an impressive ability to detect and size notches. The Phased Array system detected 33 out of the 33 notches, and the sizing results, reported for three areas of the nozzle inspection, showed an error of better than ±20%. Because the sizing methodology is empirically derived, for notches only, one cannot predict how well the sizing methodology will work on actual cracks.

9.8 SwRI/PAR EDAS

SwRI/PAR EDAS is manufactured by Southwest Research Institute, San Antonio, Texas. No evaluation has been performed.

9.9 UDRPS

UDRPS is manufactured by WesDyne International, Concorde, California. No evaluation has been performed.

Glossary of Terms

A-scan -- a method of data presentation utilizing a horizontal baseline to indicate distance or time and a vertical deflection from the baseline to indicate amplitude.

acoustic impedance -- a mathematical quantity used in computation of reflection characteristics at boundaries; product of wave velocity and material density.

active area -- in an ultrasonic transducer, the portion of the transducer face that is capable of transmitting and/or receiving ultrasound. Some of the transducer face is taken up by the housing that holds the unit together, and some of the face of the transducer element itself may be inactive.

aliasing -- introduction of error into the computed amplitude of the lower frequencies in a Fourier analysis of a function carried out using discrete time sampling whose interval does not allow the proper analysis of the higher frequencies present in the analyzed function.

analog -- a physical variable that is proportional to another physical variable, such as voltage representing pressure, or height on a CRT representing voltage. Contrasted to "digital."

attenuation -- reduction in acoustic energy or signal strength

B-scan -- a method of data presentation that produces a two-dimensional view of a cross-section through the object.

back surface -- in terms of ultrasonics, same as far surface.

bandwidth -- the difference between the frequency limits of a band containing the useful frequency components of a signal; abbreviated BW. In UT, the lower limit is usually understood to be zero, if not otherwise indicated.

beam steering -- changing the direction of the major lobe of a radiation pattern, usually by switching transducer elements. In phased transducer arrays, the steering is accomplished by phasing or timing the response from individual adjacent elements.

boot -- a protective covering over a transducer fixture; a device to contain couplant between the transducer and the insonified surface.

C-scan -- a method of data presentation that produces a two-dimensional plan or top view of the test object.

couplant -- a substance used between the transducer and insonified surface to permit or improve transmission of ultrasonic energy.

conventional UT - ultrasonic inspection using manual or automated methods, but lacking digitization; those aspects of UT that do not depend on the use of computers.

CRT -- cathode ray tube. A display screen, either on an instrument or on a computer.

dB -- abbreviation for decibel; logarithmic expression of a ratio of two amplitudes or intensities: in ultrasonic usage, $dB = 20\log_{10}$ (amplitude ratio).

demodulate -- to recover the modulating wave from a modulated carrier; also known as decode, detect.

detect -- variously: to convert RF to video (video detector); to convert video to DC (peak detector); to convert time to voltage (TOF detector); to cause to be displayed or recorded (flaw detection). See discussion of receivers and detectors in the text, under conventional UT.

digital -- composed of discrete numbers; contrasted to "analog."

digitize -- to convert an analog measurement of a quantity into a digital value.

direct memory access (DMA) -- the use of special hardware for direct transfer of data to or from memory to minimize the interruptions caused by program controlled data transfers.

display -- CRT, or other display screen such as LCD.

DMA -- see "direct memory access."

dual transducer -- pitch-catch transducer (one containing two elements: one to transmit, one to receive).

electrical impedance -- a complex number characterizing an electrical circuit, or the electrical equivalent of an electro-mechanical circuit (one that includes a transducer).

element -- piezoelectric element, i.e., the active portion of a transducer. This word is used when necessary to avoid ambiguity between the element and its associated housing and electrical components internal to the housing.

elevation -- view parallel to the x or y axis (see "view").

far surface -- the surface of the part farthest from the transducer (e.g., for an O.D. pipe inspection, the I.D. is the far surface). Also called back surface.

flat bottom drilled hole -- a hole drilled from the "bottom" of a piece, with its end finished with a milled, approximately flat surface instead of the conical surface normally left by a drill. It is used as a calibration target; the piece is insonified from the surface opposite to the "bottom." Abbreviated "FBH."

frequency -- the rate of vibration or repetitive change. Measured in hertz.

front -- in terms of ultrasonic inspection, the front (or near) surface is the insonified face of the part, i.e., the face nearest the transducer (thus for an O.D. pipe inspection, the entire outside of the pipe is the front surface).

gain -- the increase in signal power that is produced by an amplifier; usually given as the ratio of output to input voltage, current, or power expressed in decibels, also known as transmission gain.

gate -- an electronic means of selecting a segment of the time range for monitoring or further processing.

gate interval -- the time domain during which an electronic gate is active.

gimbal -- a device on which a transducer or other object may be mounted. It has two mutually perpendicular and intersecting axes of rotation, thus giving free angular movement in two directions.

hardcopy -- human readable, typewritten or printed characters or images produced on paper from data encoded in computer format.

hertz -- cycle per second; the unit is 1/second (the word "cycle" does not refer to something physical, but to the repetition of the waveform).

holography (acoustic) -- an inspection system using the phase interface between the ultrasonic wave from an object in a reference signal to obtain an image of reflectors in the material under test.

Huygen's principle -- the principle that each point on a light or acoustic wavefront may be regarded as a source of secondary waves, the envelope of these secondary waves determining the position of the wavefront at a later time.

I.D. -- inside diameter: the inner surface of a pipe or tube.

impedance -- either acoustic impedance or electrical impedance, depending on the context.

in-phase -- waveforms that are of the same frequency and that pass through corresponding values at the same instant.

increment -- a small motion of the transducer between linear scans, in the direction perpendicular to the linear scans. Also "step."

indication -- the response from or the evidence of an anomaly or discontinuity in material condition or structure.

insonify -- to irradiate with ultrasonic energy. The "insonified surface" is the surface nearest the transducer.

instrument -- electronic instrument used to produce and receive electrical signals used and produced by an ultrasonic transducer.

interface -- the boundary between two materials, at which sound is reflected and refracted. Also, a connection between electronic and computer components, or between the user and a computer system.

isometric view -- a type of 3-D view in which the axes are at 60-degree angles; loosely, any 3-D view. See also "view."

joystick -- a two-axis displacement control operated by a lever, ball, or buttons for x-y positioning of a device.

LCD -- Liquid Crystal Display; a type of flat, low-power display screen.

linear amplifier -- an amplifier in which output voltage is directly proportional to the input voltage.

logarithmic amplifier -- an amplifier in which output voltage is a logarithmic function of the input voltage. It provides a much greater dynamic range than a linear amplifier.

main bang -- the electrical pulse produced by the pulser. Data-taking is synchronized to the main bang.

manipulator -- device for changing the angular orientation of the transducer.

mass storage -- computer data storage device with large capacity, especially one whose contents are directly accessible to a computer central processing unit (CPU).

megahertz (MHz) -- unit of frequency equal to 1,000,000 hertz; abbreviated MHz; formerly megacycle. The reciprocal of one microsecond.

monitor -- an instrument used to measure continuously, or at intervals, a condition that must be kept within prescribed limits, such as A-scan data acquisition during inservice inspection. Usually a CRT.

multiplexer -- a device for combining or switching between two or more signals, as for the elements of a phased-array transducer; also spelled multiplexor.

near surface -- the insonified surface: the surface nearest the transducer.

Nyquist criterion -- the requirement that sampling and digitizing must be done more than twice as fast as the highest frequency present in the signal. Nyquist's Theorem states that a signal that varies continuously with time is completely determined by its values at an infinite sequence of equally spaced times if (and only if) the frequency of these sampling times is greater than twice the highest frequency component in the Fourier transform of the signal. This theorem is often mistakenly quoted in reference to non-repetitive, pulse-like signals; the mistake arises because the Fourier transform of a pulse-like signal has infinitely high frequency components.

O.D. -- outside diameter: the outer surface of a pipe or tube.

orthogonal axes -- a set of two or three axes, each at right angles to the others, typically referred to as x and y for the first two, and z for the third.

orthogonal view -- a view parallel to any axis (see "view").

permanent storage -- a means of storing data for rapid retrieval by a computer; does not permit changing the stored data.

phased array -- a mosaic of transducer elements in which the timing of the excitation can be individually controlled.

piezoelectric -- having the ability to generate a voltage when mechanical force is applied, and conversely, to produce a mechanical force when a voltage is applied, as in piezoelectric crystal. It is the most common class of material used in making ultrasonic transducers.

pitch-catch -- the use of two transducers, one to transmit and one to receive, both moving together. Distinguished from pulse-echo and tandem.

plan view -- view parallel to the z (depth) axis (see "view"). Also called "top view."

pre-amp -- an amplifier whose primary function is boosting the output of a low-level signal to an intermediate level so that the signal may be further processed without appreciable degradation to the signal-to-noise ratio of the system; short for pre-amplifier.

pulse-echo -- the use of a single transducer to send out sound signals and receive the echoes. Distinguished from pitch-catch and tandem.

pulser -- the UT instrument module that produces electrical pulses sent to the transducer to produce ultrasound.

radio frequency (RF) -- in UT, unrectified (see RF). In general usage, a frequency at which coherent electromagnetic radiation of energy is useful for communication purposes, roughly the range from 10 kilohertz to 100 gigahertz. It is abbreviated RF.

receiver -- the UT instrument module that receives the electrical signal returned by the transducer.

rectangular coordinate system -- a coordinate system using orthogonal axes.

reject -- in UT, a control for minimizing or eliminating low-amplitude signals so that larger signals are emphasized.

RF -- abbreviation for Radio-Frequency. In UT, the unrectified (but possibly amplified) echo signal, i.e., a signal with a baseline across the center of the display screen and excursions both upwards and downwards from the centerline. This signal most nearly represents the actual sound wave from the reflector. Distinguished from "video."

SAFT -- synthetic aperture focusing technique. Described in detail in the text, Section 7.14.

scan -- a word of many meanings. A "scan" of a part means the process of moving a transducer back and forth over the part to acquire data. A single scan or linear scan is a single sweep of a transducer across a part, between increments. "Scan" is also used to refer to the motion of the dot that creates the presentation on a CRT.

scanner - mechanical device and associated electronics for moving a transducer and/or a part, to allow ultrasonic inspection of the part.

search unit -- an alternative word for transducer, used especially when distinguishing the active element of the transducer from the housing and other components of the transducer.

sync (synchronization) -- the maintenance of one operation in step with another as in keeping the display on the CRT (or the digitizing of data) in step with the main bang. See also "trigger."

tandem -- the use of two transducers moving in opposite directions; or one fixed and the other moving. Distinguished from pitch-catch and pulse-echo.

threshold -- the level above which an action should occur. In particular, a part of the peak or TOF detector circuitry that limits the detection to signals above the threshold amplitude.

TOF (time of flight) -- the elapsed time from the instant a particle or wave leaves a source to the instant it reaches a detector. Particularly in UT, referring to a waveform penetrating through an object: the time that it takes for the sound to leave the transmitting transducer, travel through the object, and reflect back to the receiving transducer. The reflection may be either from a discontinuity within the object, or from the far surface of the object.

top view -- plan view.

transducer -- a device that changes one form of energy into another. In UT, it changes electricity into sound and sound into electricity.

transducer array -- a group of transducer elements arranged to provide a desired variation of radiation transmission or reception with direction.

trigger -- 1) to initiate an action which then continues for a period of time as by applying a pulse to a trigger circuit; 2) the pulse used to initiate the action of a trigger circuit. See also "sync."

ultrasonic -- pertaining to ultrasound; having a frequency greater than the highest humanly audible frequency (approximately 20,000 hertz).

ultrasonics -- the use of ultrasound for inspection or other purposes.

ultrasonic gel -- a type of viscous couplant; see couplant.

ultrasound -- vibrations having a frequency greater than the highest humanly audible frequency (approximately 20,000 hertz).

UT -- ultrasonic testing; ultrasonic; ultrasonics; ultrasonic inspection.

UT-... -- designation used in the text for several test blocks developed at PNL for system characterization: UT-RES-0000 is a UT resolution block for 0° inspection; UT-RES-4560 is a UT resolution block for 45° and 60° inspection; UT-RPT-CIRC is a UT repeatability block containing holes with circular cross-section. They are described in detail in Appendix A, Section 7 (Ultrasonic Measurements).

video -- in UT, a rectified and filtered signal derived from the RF signal, i.e., the baseline is at the bottom of the screen and the signal excursion is always upward. It is often used to trigger an alarm (in conventional UT) or the taking of data (in computer-based UT), and may be used for evaluation in conventional UT. This term is derived from its meaning in general usage: pertaining to picture signals or to the sections of a television system that carry these signals in either unmodulated or modulated form; hence, a signal displayed on a CRT.

video filter -- filter applied to the RF signal as part of the process of obtaining the video signal.

views -- representations of a part from different directions. An orthogonal projection is a view from one of the axial directions. A view along the z-axis, i.e., showing true distances along the x and y axes, but collapsing all the z information, is called a plan view; a view along the x or y axis is called an elevation. A 3-D (or oblique) view is a view from an off-axis direction; and an isometric view is a 3-D view in which the axes are shown at 60 or 120 degree angles to each other. Loosely, "isometric" is used to mean any 3-D view.

VMOS -- vertical metal oxide semiconductor. A semiconductor technology used to produce arbitrary waveforms at high voltages in semiconductor-based ultrasonic pulser circuits.

waveform -- the pattern of rising and falling voltage associated with an ultrasonic phenomenon of interest.

Bibliography

American Society for Nondestructive Testing. 1991. *Ultrasonic Testing* (Volume Seven of *Nondestructive Testing Handbook*, Second Edition), Albert S. Birks and Robert E. Green, Jr., Technical Editors; Paul McIntire, Editor.

Appendix A

Methodology for UT/ISI System Evaluation

NUREG/CR-5985
Supplement n

Evaluation of XXX Computer-Based Ultrasonic Inservice Inspection System

Prepared by
[Name of person performing evaluation]

[Date of evaluation]

*[Preparing organization
City, State, USA]*

Preface

This Appendix presents the details of the procedure developed at PNL for the characterization of UT/ISI systems. It includes all the material in the Hypercard® stack used at PNL for note-taking during the characterization process, both the Question cards and the associated Explanation cards. All but two or three items are in the same order as in the Hypercard stack. In this Appendix, the Explanations are indicated by the notation, "Explanation of this item: ." Additional notes are *in italics and enclosed in [square] brackets.*

This Appendix can be used both as an aid to understanding the characterizations that have been done at PNL, and as a tool for characterizing other systems. The Hypercard stack is available from PNL for use on Macintosh® computers, and the text of this Appendix is available in Word Perfect® format for use on either PC or Macintosh® computers. The Hypercard stack does not have section numbers, and does not contain the peripheral sections such as Introduction and Bibliography. As used at PNL, the stack is strictly a data-gathering tool; the data is then exported into the Word Perfect document with modifications and amplification as needed.

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®Word Perfect - registered trademark of Word Perfect Corporation

Contents

Section **Page**

[All sections should be listed here, with page numbers.]
[For the purpose of this Appendix, only the major section headings are shown.]

Figures

[All figures should be listed here, with page numbers.]

Tables

[All tables should be listed here, with page numbers.]

Introduction

Explanation of these items: The unnumbered items at the start of the evaluation are free-form summaries to introduce the reader to the system. They are composed after all the other sections have been filled in.

General Description

Unusual Features

Positive Features

Negative Features

Aids to Evaluation

Hindrances to Evaluation

Potentially Significant Items

Peculiarities that may look like problems, but are not

The remainder of this report contains a detailed evaluation of the XXX system, a review checklist, a glossary of XXX terminology, and an index. The detailed evaluation contains numerous figures and images, and covers general system information, image interpretation, mechanical and ultrasonic operation, data acquisition, data processing, data storage, imaging capabilities, and special features or problems.

DETAILED EVALUATION

1.0 System Description

1.1 System name: *[XXX]*

1.2 Date: *[Evaluation beginning and ending dates]*

1.3 Manufacturer

Who manufactured the system?
[Name, address, phone, contacts]

1.4 Supplier

Who supplied the system used in this study?
[Name, address, phone, contacts]

1.5 Items Received

What items were received by the evaluation team?
[List the separate pieces in detail, with part and serial numbers.]

1.6 Components

Describe the components that make up the system.

1.6.1 XXX system

[Provide block diagrams and photographs, as well as prose descriptions of all modules and components.]

1.6.2 Identify which system components are fixed and which can be changed.

[ ] Software
[ ] Computer
[ ] Ultrasonic instrument
[ ] Mechanical scanner scanners
B = Built-in and fixed
O = Optional (possibly built-in, but can be changed)
[ ] Other (explain):

Explanation of this item: Some systems are entire, integrated ("turn-key") systems, supplied in a manufacturer-defined configuration; others are flexible and allow the user to configure the components. It is important to know which components are fixed and which can be changed, so that the auditor knows what baseline is used, i.e., whether the system in use at a given site is practically identical to that evaluated here, or perhaps could be quite different.

1.7 Operating Platform

What is the operating platform of the system?

1.7.1 Type of computer:

1.7.2 Operating system:

1.7.3 Multitasking:

Yes [ ] No [ ]

1.7.4 Windowing environment provided by system:

Yes [ ] No [ ]

1.7.5 Type, size, and resolution of display(s):

1.7.6 Type, size, and resolution of hard-copy device(s):

1.7.7 Pointing device(s):

[Mouse, joystick, etc.]

1.8 Describe the audible noise level of the system.

Explanation of this item: Are people able to carry on a conversation while the system is operating, or is it too loud?

2.0 Training

2.1 Describe the operator training required/provided.

3.0 Set-up

3.1 How does the operator set up the scanning parameters prior to scanning?

Explanation of this item: Is it easy? Does the operator scroll through the setup one item at a time? Or, does the operator have to select different items one at a time and enter values.

4.0 Documentation

4.1 User's Manual

Is an adequate manual explaining the overall operation of the system and indicating any other support documentation provided with the system?

Yes [ ] No [ ]

Explanation of this item: Is there a manual that explains to the user, with reference to any other support documentation, the overall operation of the system?

4.2 Support Documentation

What detailed descriptions are available to the sophisticated user who wishes to go beyond the straightforward applications of the system?

[ ] Software logic description
  [ ] Functional description
  [ ] Flow chart
  [ ] Layered logic presentation
  [ ] Other
[ ] Electronic block diagram
[ ] Cable configuration
[ ] Mechanical configuration
[ ] Other:

Explanation of this item: Is there documentation, in chart or diagram form, to help the user understand the interaction and sequencing of the software modules, such as data-taking, calibrating, analysis, plotting? Is there an overview chart that shows how the different components or modules of the system interact, in sufficient detail to help the user interpret the operation of the system?

5.0 Image Interpretation

Through examples, explain how to interpret the images produced by the system.

For example, show how the axes are displayed, what types of images are produced, how the A-scan can be viewed, where to find the color key, etc. This is a free-form section that will be different for each system. Its purpose is to help the reader understand images that are used in later sections.

6.0 Scanner/Mechanical Measurements

6.1 Mechanical Resolution

6.1.1 Does the operator have the ability to enter the step size?

Explanation of this item: Is it possible for the operator to request or demand a specific distance to be stepped between readings within a scan, or between scans? The system may simply define a grid size, i.e., both x and y steps are chosen simultaneously; or, it may allow specification of one or both axes independently. The x-axis is the axis which varies more slowly, i.e., one x-value for each scan. The y-axis is the axis that varies more rapidly, i.e., scanning axis, or "continuous" motion axis.

6.1.1.1 X- and Y-axis together:

Yes [ ] No [ ]

6.1.1.2 Y-axis independently:

Yes [ ] No [ ]

6.1.1.3 X-axis independently:

Yes [ ] No [ ]

6.1.1.4 Multi-axis: (describe)

Yes [ ] No [ ]

6.1.2 Is the step size set by software or hardware?

Are values entered from the keyboard or are values entered by moving jumpers or controls?

Explanation of this item: If the system sets the sizes without the operator moving a physical switch or jumper, the answer is "software."

6.1.2.1 X-axis:

Software [ ] Hardware [ ]

6.1.2.2 Y-axis:

Software [ ] Hardware [ ]

6.1.2.3 Multi-axis: (describe)

Software [ ] Hardware [ ]

6.1.3 What are the possible values for step sizes? (e.g. increments of 5, etc.)

Explanation of this item: Indicate the amount (metric, inch, or other) of the possible step sizes: for example, any number of thousandths of an inch would be entered as .001"; hundredths of a mm would be .01 mm; or if the spacing is irregular it might be .001", .002", .004", .008", .010", .020", etc.

6.1.3.1 X-axis:

6.1.3.2 Y-axis:

6.1.3.3 Multi-axis:

6.1.4 What are the system step size limits?

Explanation of this item: Indicate the smallest physical step size possible (may be the encoder resolution, if it is a dc feedback drive); and if there is a largest possible step size, indicate it.

6.1.4.1 X-axis:

	Operator Entry	Software	Scanner
Smallest:	x.xxxx	x.xxxx	x.xxx
Largest:	+/-xxx	+/-xxx	x.xxx

6.1.4.2 Y-axis:

	Operator Entry	Software	Scanner
Smallest:	x.xxxx	x.xxxx	x.xxx
Largest:	+/-xxx	+/-xxx	x.xxx

6.1.4.3 Multi-axis:

6.1.5 How many bits do the encoder counters have?

Explanation of this item: What is the maximum distance measured by the encoders? Answer will probably be 16 bits or 32 bits. This can be important in case of long scans, on which a 16-bit counter would reset halfway through the scan, necessitating software monitoring and giving rise to possible errors.

6.1.6 What scan distance is associated with each encoder count?

Explanation of this item: What distance is scanned for every increment of the encoder counter. For example, 0.001 inch, 0.1 mm, etc.

6.1.7 What determines the pulse time?

Explanation of this item: (e.g., on the fly or with the stepper motor - the vendor should provide this answer). When does the UT instrument pulse (fire the main bang)? Does it free run? Is it synchronized with a stepper motor? Is it triggered on a timing pulse that coordinates motion and pulsing?

6.1.8 Accuracy of Positional Information

Determine the accuracy of the ultrasonic path length over a 5" x 5" (12.7 cm x 12.7 cm) square by using accurate ultrasonic time-of-flight measurement.

Explanation of this item: One of the important analysis methods for UT/ISI systems is SAFT processing, which requires accuracy to about 0.1 wavelength. This test is intended to determine whether the system has such accuracy. Another approach would be to test the axis accuracies, but that would be indirect, and of more interest to the builder of the mechanical subsystem than to the analyst of the whole system. The method used is to scan a 5" x 5" square on a test standard with a round-bottom hole, using a phase or distance acquisition system (e.g., Holoview), and analyze the results. The expected phase (distance) pattern can be predicted well by theory, and variations indicate either local variations (e.g., wobbly lines) or systematic errors (e.g., 4-1/2" instead of 5").

6.1.9 Positional Repeatability

Test for positional repeatability by starting the transducer at a given distance from a reflector and recording the starting point on an oscilloscope display (a storage scope would be useful). Then, have the transducer travel a path that should take it back to the starting marker. Perform the repeatability test at the default speed and at the fastest speed. Do this using (simultaneously or separately) all degrees of freedom that can legitimately be used during an inspection scan. Include a scan of an inclined surface with the scan moving to and from the surface by at least 1 rotation of the encoder.

Record amplitude and time of ultrasonic signal before and after the excursion. Record amount of motion needed to restore original signal. Or, explain observations.

Explanation of this item: Repeatability is important in itself as a prerequisite to evaluation by re-scanning. It is also a good measure of the overall integrity of the mechanical subsystem and interface. It is important to know whether the repeatability degrades at high speed.

6.1.9.1 Repeatability

The variability in X was 0.008" (0.2 mm). The variability in Y was 0.003" (0.076 mm). These values were determined by using a 45° shear wave probe and the ball target of Test Block UT-RPT-CIRC-1. The probe was turned along the X and Y axes respectively for the two values.

6.1.9.2 Inclined surface scan

Include a scan of an inclined surface with the scan moving to and from the surface by at least 1 rotation of the encoder.

Explanation of this item: By scanning far enough to rotate the encoder completely, any anomalies in the processing of accumulated rotations will be uncovered.

6.2 Assurance of Positional Readings

6.2.1 What type of encoder is used?

[ ] Linear
[ ] Rotary (optical)
[ ] None

Explanation of this item: Are the position encoders relative or absolute? Absolute encoders assure that positions are accurate, trustworthy, and repeatable. If relative encoders are used, other system checks must be in place to guarantee valid position data.

6.2.2 Are the position encoders relative or absolute?

Relative [ ] Absolute [ ]

Explanation of this item: Absolute encoders assure that positions are accurate, trustworthy, and repeatable. If relative encoders are used, other system checks must be in place to guarantee valid position data.

6.2.3 Where are the encoders attached?

[ ] Motor
[ ] Motion Axis

6.2.4 What type of drive is used?

[ ] Stepper Motors
[ ] Servo Motors
[ ] Hydraulics
[ ] Other (describe)

6.2.5 What type of positioning is used?

[ ] Open Loop
[ ] Closed Loop

Explanation of this item: In an open loop system a move is made and no attempt is made to verify the move. In a closed loop system a move is made and the software uses encoder information to verify and, if necessary, rectify the move.

6.2.6 How is backlash taken care of?

If appropriate, record amount of backlash.

Explanation of this item: Some systems may take data in one direction only. Systems with encoders may have the encoder on the motor or the axis side of the gearbox, belt, etc. There may be a backlash compensation table. The point of the question is to know what limitations there are on multi-directional data taking.

6.3 Mechanical Limits

6.3.1 What is the amount of travel that can be done in one scan?

Determine this by operating the pipe and/or flat scanner through a series of test runs.

Explanation of this item: Indicate in inches or mm the maximum dimensions of the rectangle that can be scanned in one setup. Specify for x and y axis separately, and indicate any interaction between the two; for example, the maximum area may be less than the product of the two maximum values for x and y separately. This item is important for establishing the maximum size of image that can be formed in one setup; for verifying that there is no conflict between size of scan and resolution of image; for an estimate of length of time required to scan a certain area (because changing setups will take time).

6.3.2 What limits the travel? (e.g. scanner structure, etc.)

Explanation of this item: Indicate restrictions due to any hardware or software factors, such as mounting configuration, gravity, obstructions, data acquisition, analysis software, file size, etc.

6.4 Speed Limits of Scan

6.4.1 Does the operator have the ability to set the speed of the scans?

Yes [ ] No [ ]

Explanation of this item: Can the operator input a requested scan speed in inches per second, mm per second, square inches per second, etc.? (The answer can be Yes even if the software can override the request).

6.4.2 What are the slowest and fastest speeds that the operator can enter?

Explanation of this item: If the operator can input requested speeds, what are the lowest and highest speeds that can be requested, and in what units?

6.4.2.1 X-axis:

6.4.2.2 Y-axis:

6.4.2.3 Multi-axis:

6.4.3 What limits the speed of the scans? (e.g. software or hardware)?

Explanation of this item: Describe the limitations on the scan speed. It may be due simply to the maximum speed of the axis drive motors. It may be due to instrument rep rate limitations. It may be due to limitations of the data acquisition hardware or software. It may be due to deliberate limitation of the software based on the physics of the situation. Or...

6.4.4 Is the default speed too slow, or can the speed be set too fast, for proper sampling?

Explanation of this item: The intent of this question is to establish whether the system operates at maximum efficiency (maximum data points per time unit) without sacrificing reliability. "Too slow" means overkill, i.e., that the default scan speed is significantly slower than the speed required to achieve proper accuracy and 100% coverage. "Too fast" means that the scan can go so fast that 100% coverage is not achieved or position data is not accurate.

6.4.4.1 Too Slow:

Yes [ ] No [ ]

6.4.4.2 Too Fast:

Yes [ ] No [ ]

6.5 Mechanism for Repeating Scan

6.5.1 Does the possibility exist to repeat a scan for indication characterization?

Yes [ ] No [ ]

Explanation of this item: It is often of interest to re-scan a portion of the scanned area in order to verify the data taken or to get higher resolution or different amplitude thresholds. Does the system provide some means of doing so?

6.5.2 How is a scan repeated? (e.g. using an absolute home)

Explanation of this item: Indicate the mechanism by which a re-scan can be made: a simple menu choice; a new can using suitable parameters. Is it simple enough to be used routinely when required, or so complicated as to discourage the operator from doing a re-scan?

6.5.3 If a rescan is performed, can the new data be seamlessly integrated into the previous data?

Yes [ ] No [ ]

6.5.4 What is the level of rescan possible?

[ ] Any subset of previously inspected volume
[ ] Only previously defined subsections
[ ] Must rescan entire section

7.0 Ultrasonic Measurements

7.1 Dynamic Range

What is the dynamic range in dB?

Explanation of this item: Determine this by taking the ratio of the system RMS noise and the maximum signal that the system can display/store without saturation at constant gain. Perform this measurement at minimum gain and maximum gain and note both figures. Dynamic Range = 20*log (Max. Signal)/(RMS Noise). The ASTM definition for dynamic range is the ratio of the maximum to minimum reflective areas that can be distinguished on the cathode ray tube at a constant gain setting. Since this definition of dynamic range is both material and frequency dependent, this test plan shall measure dynamic range as stated above. Measure both the noise and the maximum signal at the same output point.

7.2 Resolution Blocks

Scanning of the resolution blocks is performed to show imaging of standard targets. It also measures resolu-

tion capabilities under less-than-ideal conditions. The standard probes used are not focused probes, so the lateral resolution is not the best that the system is capable of, unless the system has image processing capabilities such as SAFT or holography, in which case the images provide a test of the processing capabilities.

[Note: Figures A.1 through A.8, Tables A.1 through A.4, and the following text describe the geometry of the resolution blocks, which are also described in the American Society for Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section V, "Nondestructive Examination," Paragraph T-435, and Appendix E, Figures E-10 and E-20.

UT-RES-0000 (Tables A.1 and A.2, Figures A.1 and A.2) is a normal-incidence block containing a pattern of quarter-inch diameter holes at varying depths and spacings to permit analysis of the depth and lateral resolution capabilities of an ultrasonic imaging system. The set of holes used for depth resolution is at varying depths but on a regular lateral spacing. The set of holes used for lateral resolution is on varying lateral spacing but at a uniform depth. Figure A.1 shows the block as seen by the ultrasonics inspector when the block is insonified from the side opposite to the drilled surface. Figure A.2 is a machinist's view, for use in constructing the block.

The depth resolution holes are in two rows. One has a fixed, coarse depth change of 0.230" (5.8 mm) between adjacent holes, and the other has a fine depth change varying from 0.023" to 0.057" (0.6 mm to 1.4 mm) between adjacent holes.

The lateral resolution holes are arranged with a geometrically decreasing lateral spacing between adjacent edges from 1.0" to 0.016" (25.4 mm to 0.4 mm).

UT-RES-4560 (Tables A.3 and A.4, Figures A.3 through A.8) contains four sets of holes, two at 45 degrees and two at 60 degrees. One of the 45 degree faces and one of the 60 degree faces contains depth resolution holes, and the other two contain lateral resolution holes. The spacings and depths of the holes are similar to those of UT-RES-0000, with allowances for angle-beam inspection. The metal travel as shown in Tables A.3 and A.4 is measured along the centerline of each hole. The lateral-resolution holes are arranged so that all are at equal metal travel.]

7.2.1 Measure the lateral resolution by using the standard test blocks.

The lateral resolution is defined as the minimum separation between targets that results in a signal drop of at least 6 dB below the peak amplitude of the weaker target.

Explanation of this item: The lateral resolution of an ultrasonic system is defined as the ability of the system to distinguish between two objects in the XY plane (e.g., the plane which is perpendicular to the axis of the sound beam). The lateral resolution will be measured by determining which set of holes in the standard test block are separated. A set of holes is considered separated if the signal amplitude in the image decreases by at least 6 dB between the peak signals of two holes. Resolution will be measured for the most common inspection angles of 0, 45, and 60 degrees. 0° resolution is measured on block UT-RES-0000-2. 45° and 60° resolution is measured on block UT-RES-4560-2.

7.2.1.1 0 degree longitudinal:

7.2.1.2 45 degree shear:

7.2.1.3 60 degree shear:

7.2.2 Measure the depth resolution by using the standard test blocks.

Explanation of this item: Depth resolution of an ultrasonic system is defined as the ability of the system to resolve two objects in the XZ or YZ plane. The depth resolution will be measured by determining the actual difference in depth between holes in the test block. Resolution will be measured for the most common inspection angles of 0°, 45°, and 60°.

7.2.2.1 0 degrees:

7.2.2.2 45 degrees:

7.2.2.3 60 degrees:

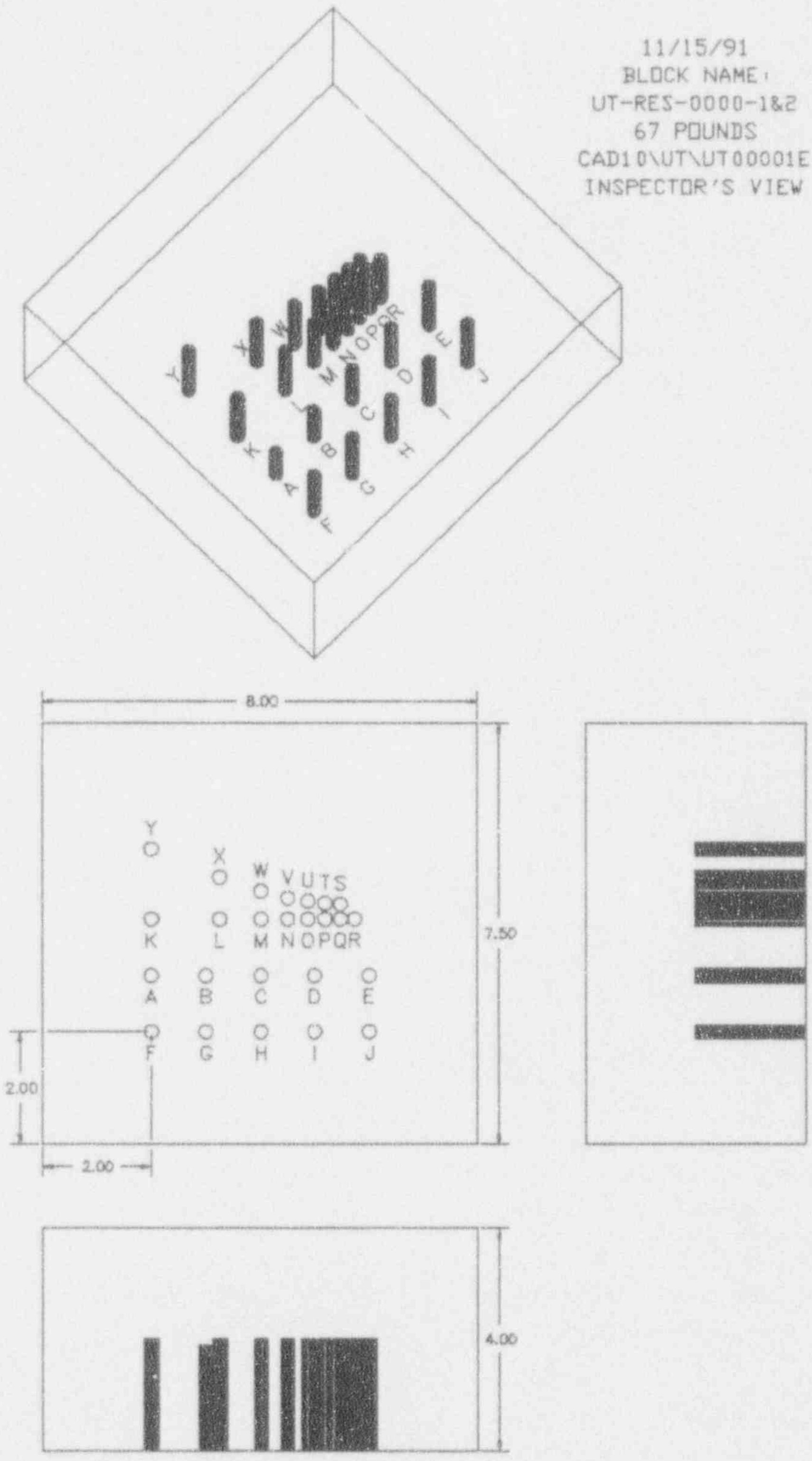


Figure A.1 UT-RES-0000: Inspector's view

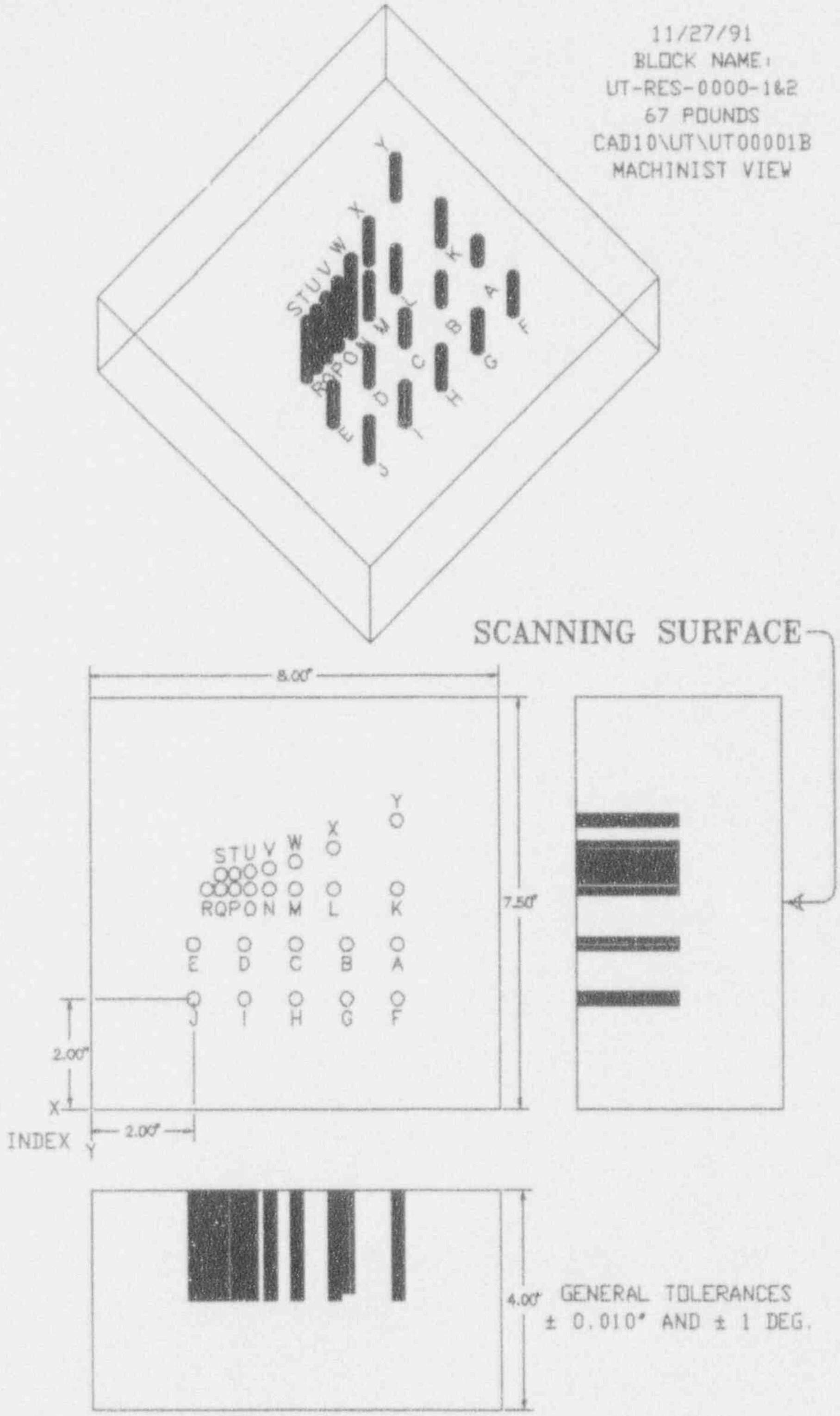


Figure A.2 UT-RES-0000: Machinist's view

TABLE A.1: HOLE PATTERN DIMENSIONS FOR CALIBRATION BLOCK UT-RES-0000

Dimensions in Inches

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.005	±0.005	±0.002	±0.002
A	6.000	3.000	1.080	2.920
B	5.000	3.000	1.310	2.690
C	4.000	3.000	1.540	2.460
D	3.000	3.000	1.770	2.230
E	2.000	3.000	2.000	2.000
F	6.000	2.000	1.828	2.172
G	5.000	2.000	1.885	2.115
H	4.000	2.000	1.943	2.057
I	3.000	2.000	1.977	2.023
J	2.000	2.000	2.000	2.000

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.002	±0.002	±0.005	±0.005
K	6.000	4.000	2.000	2.000
L	4.750	4.000	2.000	2.000
M	4.000	4.000	2.000	2.000
N	3.500	4.000	2.000	2.000
O	3.125	4.000	2.000	2.000
P	2.813	4.000	2.000	2.000
Q	2.532	4.000	2.000	2.000
R	2.266	4.000	2.000	2.000
S	2.532	4.266	2.000	2.000
T	2.813	4.281	2.000	2.000
U	3.125	4.322	2.000	2.000
V	3.500	4.375	2.000	2.000
W	4.000	4.500	2.000	2.000
X	4.750	4.750	2.000	2.000
Y	6.000	5.250	2.000	2.000

Drill all holes flat-bottomed and perpendicular to the scanning surface. Hole diameters shall be 0.250 ± 0.005 in Faces #1 and #2, and 0.250 ± 0.002 in Faces #3 and #4. Hole bottoms shall be parallel to the scanning surface to within 1°. Maximum radius of hole bottom corners shall be 0.010.

TABLE A.2: HOLE PATTERN DIMENSIONS FOR CALIBRATION BLOCK UT-RES-0000

Dimensions in Millimeters

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.13	±0.13	±0.05	±0.05
A	152.40	76.20	27.43	74.17
B	127.00	76.20	33.27	68.33
C	101.60	76.20	39.12	62.48
D	76.20	76.20	44.96	56.64
E	50.80	76.20	50.80	50.80
F	152.40	50.80	46.43	55.17
G	127.00	50.80	47.88	53.72
H	101.60	50.80	49.35	52.25
I	76.20	50.80	50.22	51.38
J	50.80	50.80	50.80	50.80

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.05	±0.05	±0.13	±0.13
K	152.40	101.60	50.80	50.80
L	120.65	101.60	50.80	50.80
M	101.60	101.60	50.80	50.80
N	88.90	101.60	50.80	50.80
O	79.38	101.60	50.80	50.80
P	71.45	101.60	50.80	50.80
Q	64.31	101.60	50.80	50.80
R	57.56	101.60	50.80	50.80
S	64.31	108.36	50.80	50.80
T	71.45	108.74	50.80	50.80
U	79.38	109.78	50.80	50.80
V	88.90	111.13	50.80	50.80
W	101.60	114.30	50.80	50.80
X	120.65	120.65	50.80	50.80
Y	152.40	133.35	50.80	50.80

Drill all holes flat-bottomed and perpendicular to the scanning surface. Hole diameters shall be 6.35 ± 0.13 in Faces #1 and #2, and 6.35 ± 0.05 in Faces #3 and #4. Hole bottoms shall be parallel to the scanning surface to within 1°. Maximum radius of hole bottom corners shall be 0.25. Metric equivalents to dimensions on drawing are as follows: 2.00" = 50.8 mm; 4.00" = 101.6 mm; 8.00" = 203.2 mm; 7.50" = 1[illegible] mm; 0.010" = 0.25 mm.

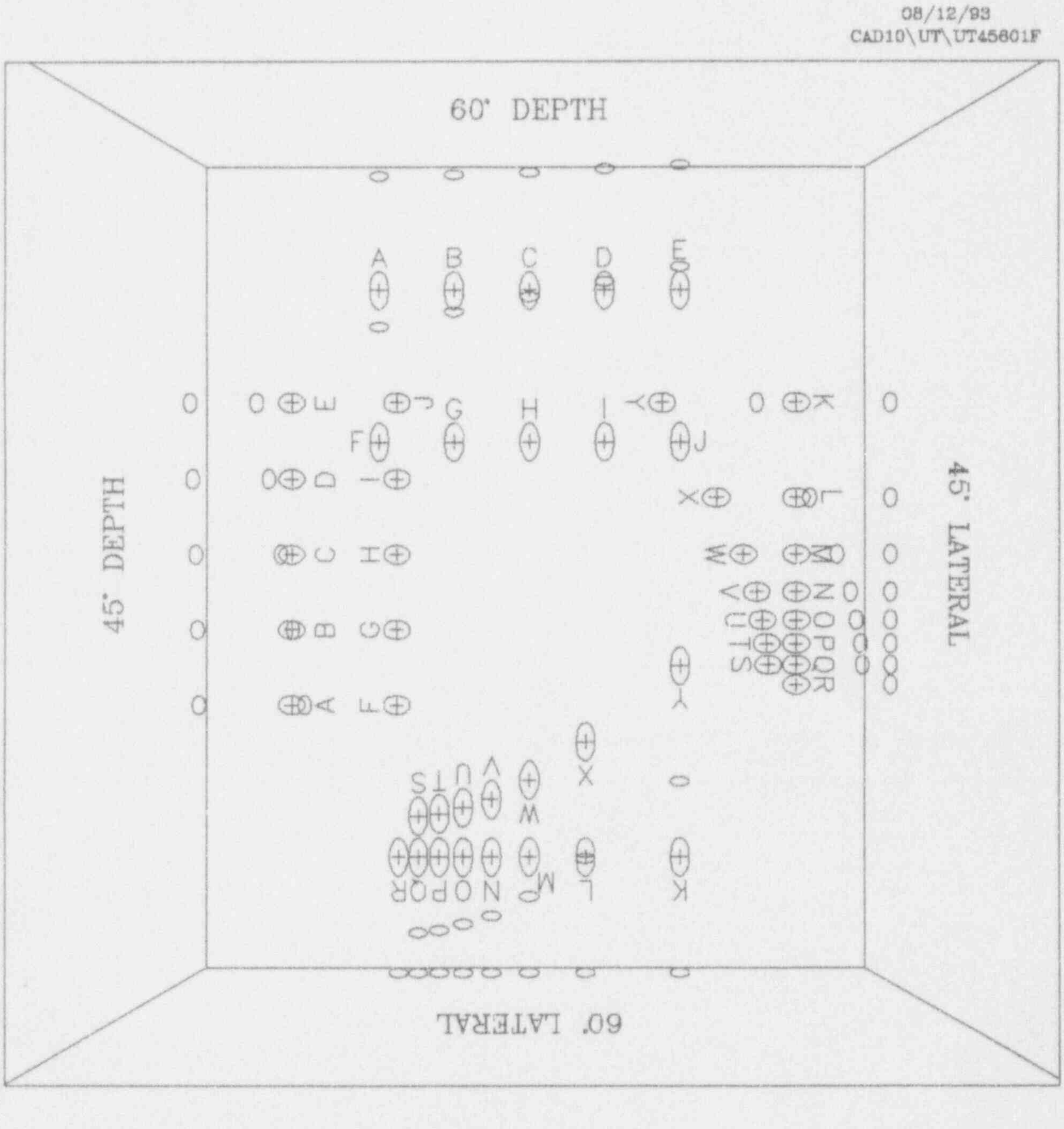


Figure A.3 UT-RES-4560, top view (transducer locations marked "⊕" and hole ends marked "O" only)

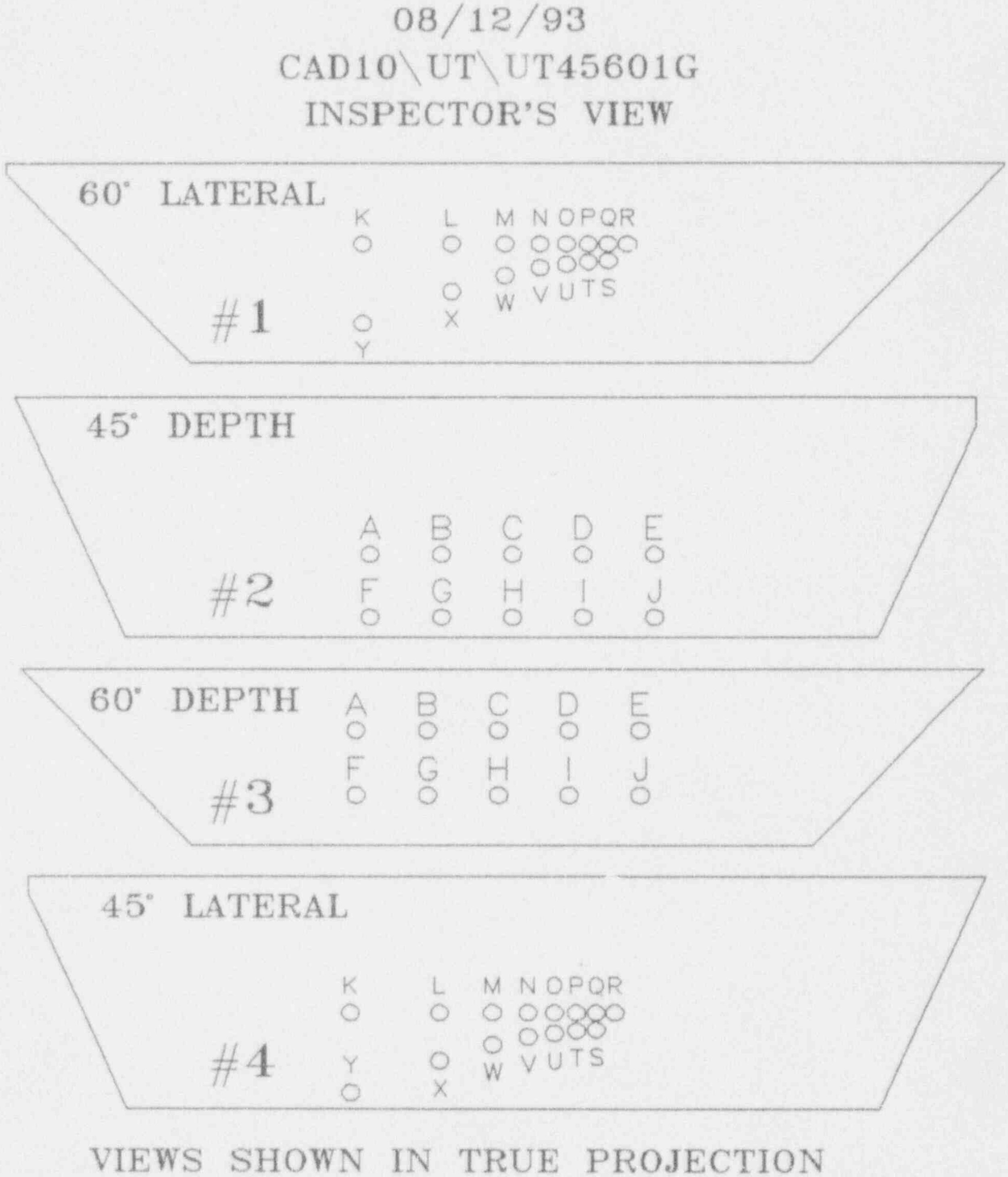
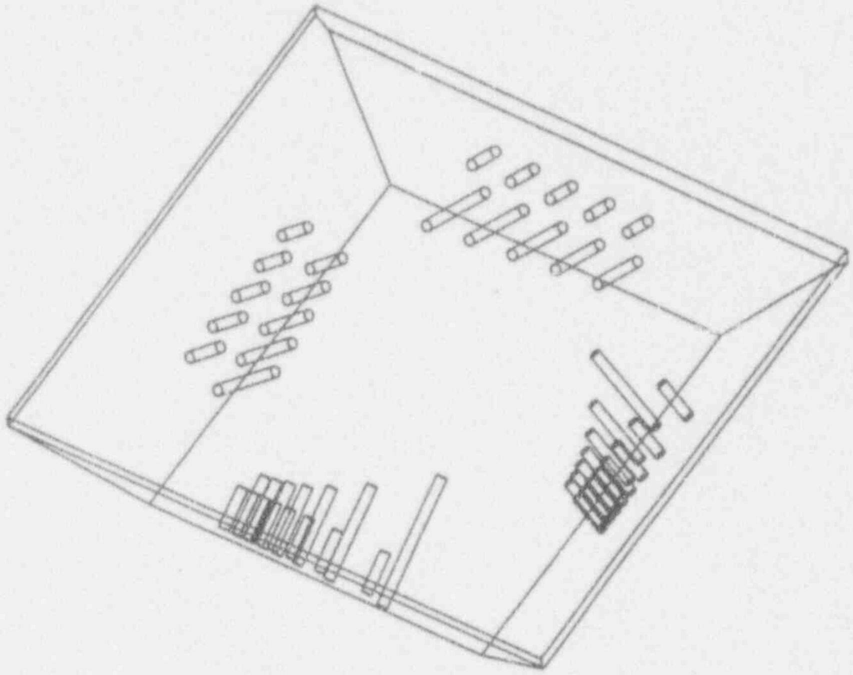


Figure A.4 Inspector's view of each face, parallel to plane of hole surfaces



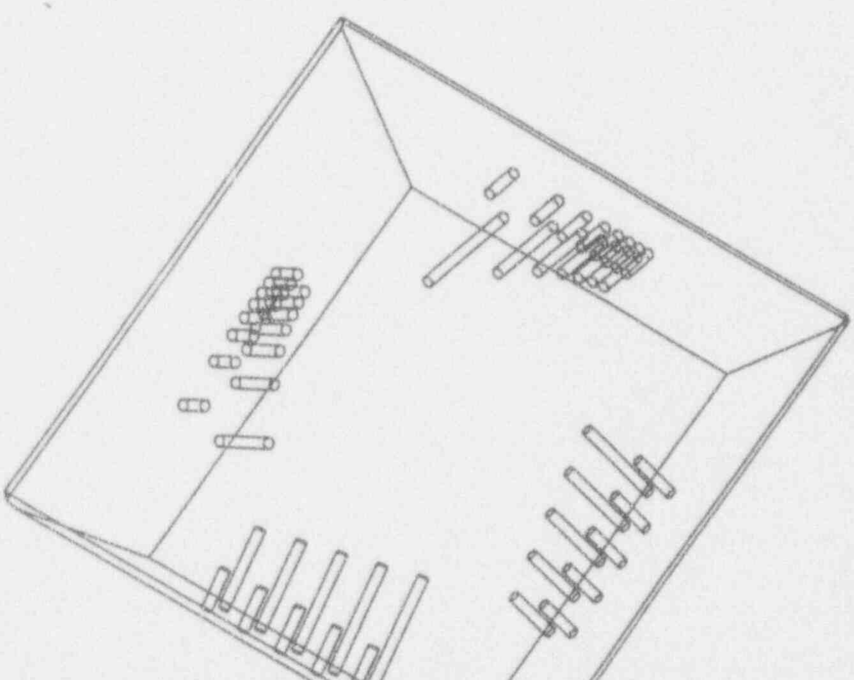


Figure A.5 UT-RES-4560 3-d views. Upper: lateral-resolution holes in foreground. Lower: depth-resolution holes in foreground.

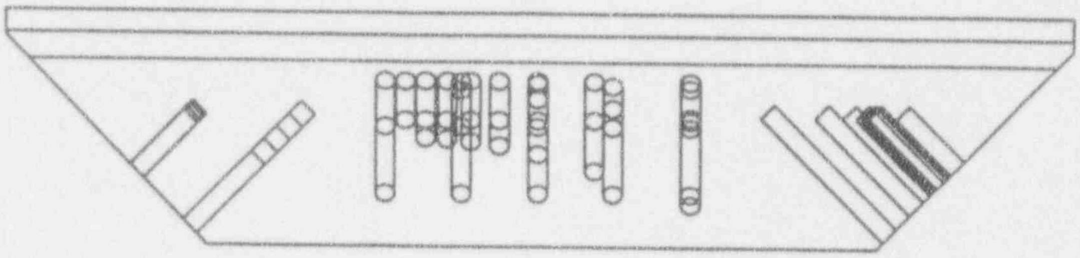


Figure A.6 UT-RES-4560, elevation view, profile of 45-degree faces (depth-resolution on left, lateral-resolution on right)

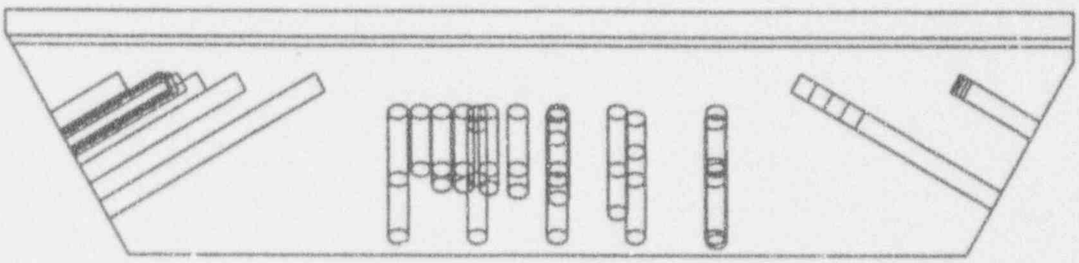


Figure A.7 UT-RES-4560, elevation view, profile of 60-degree faces (lateral-resolution on left, depth-resolution on right)

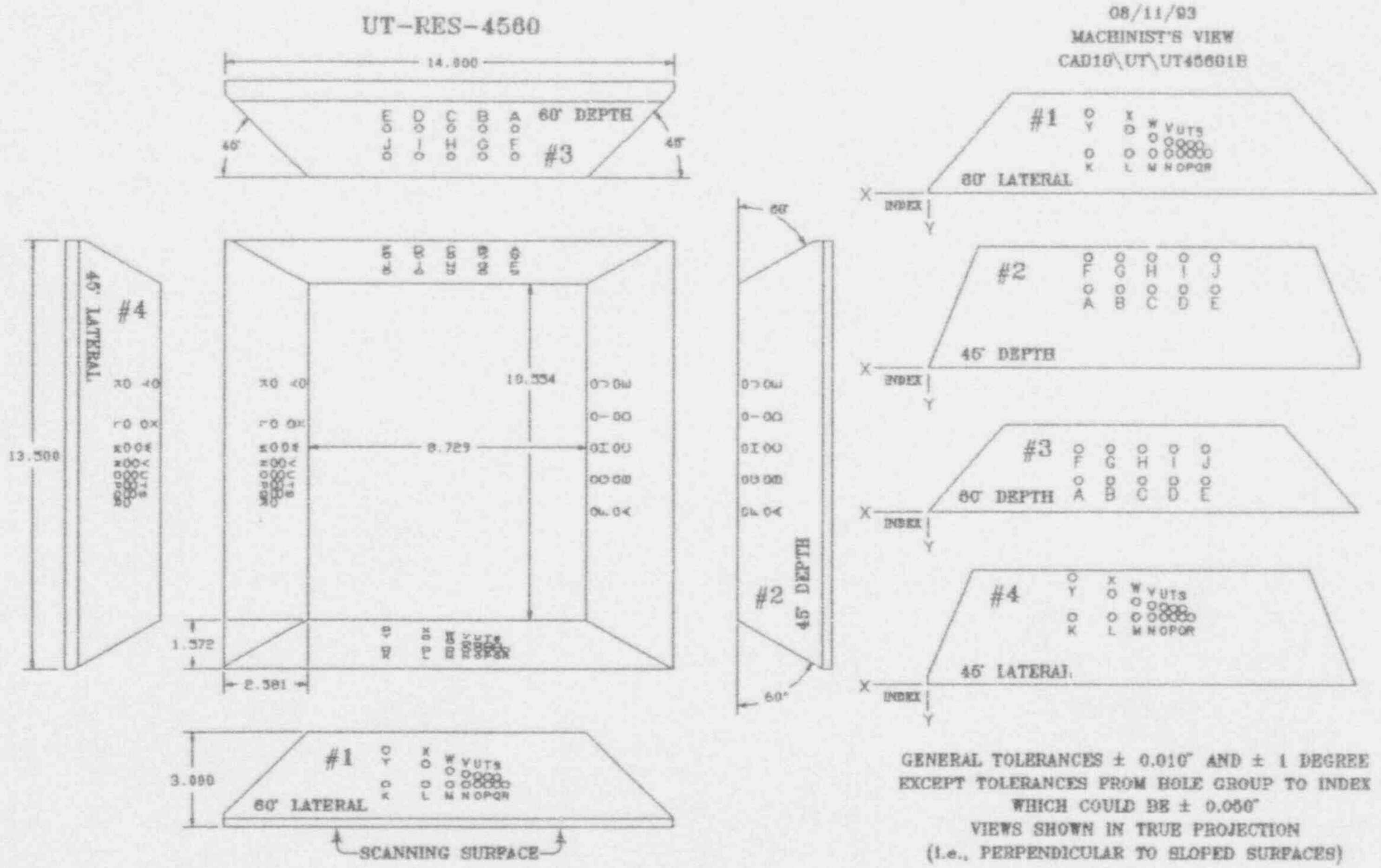


Figure A.8 UT-RES-4560: Machinist's views

TABLE A.3: HOLE PATTERN DIMENSIONS FOR CALIBRATION BLOCK UT-RES-4560

Dimensions in Inches

Face #1 60° Lateral

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.002	±0.002	±0.005	±0.008
K	5.000	1.268	1.000	1.750
L	6.250	1.268	1.000	1.750
M	7.000	1.268	1.000	1.750
N	7.500	1.268	1.000	1.750
O	7.875	1.268	1.000	1.750
P	8.188	1.268	1.000	1.750
Q	8.469	1.268	1.000	1.750
R	8.734	1.268	1.000	1.750
S	8.469	1.533	1.460	1.750
T	8.188	1.549	1.487	1.750
U	7.875	1.589	1.557	1.750
V	7.500	1.643	1.650	1.750
W	7.000	1.768	1.866	1.750
X	6.250	2.018	2.299	1.750
Y	5.000	2.518	3.165	1.750

Face #2 45° Depth

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.005	±0.005	±0.002	±0.007
A	4.981	2.485	1.172	1.750
B	5.981	2.485	1.149	1.773
C	6.981	2.485	1.115	1.807
D	7.981	2.485	1.057	1.865
E	8.981	2.485	1.000	1.922
F	4.981	3.485	2.172	1.750
G	5.981	3.485	1.942	1.980
H	6.981	3.485	1.712	2.210
I	7.981	3.485	1.482	2.440
J	8.981	3.485	1.252	2.670

Face #3 60° Depth

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.005	±0.005	±0.002	±0.011
A	4.688	0.970	1.172	1.750
B	5.688	0.970	1.149	1.773
C	6.688	0.970	1.115	1.807
D	7.688	0.970	1.057	1.865
E	8.688	0.970	1.000	1.922
F	4.688	1.970	2.904	1.750
G	5.688	1.970	2.674	1.980
H	6.688	1.970	2.444	2.210
I	7.688	1.970	2.214	2.440
J	8.688	1.970	1.984	2.670

Face #4 45° Lateral

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.002	±0.002	±0.005	±0.007
K	4.500	2.157	1.000	1.750
L	5.750	2.157	1.000	1.750
M	6.500	2.157	1.000	1.750
N	7.000	2.157	1.000	1.750
O	7.375	2.157	1.000	1.750
P	7.687	2.157	1.000	1.750
Q	7.968	2.157	1.000	1.750
R	8.234	2.157	1.000	1.750
S	7.968	2.422	1.266	1.750
T	7.687	2.438	1.281	1.750
U	7.375	2.478	1.322	1.750
V	7.000	2.532	1.375	1.750
W	6.500	2.657	1.500	1.750
X	5.750	2.907	1.750	1.750
Y	4.500	3.407	2.250	1.750

Drill all holes flat-bottomed and perpendicular to the sloped surfaces. Hole diameters shall be 0.250 ±0.005" in Faces #2 and #3, and 0.250 ±0.002" in Faces #1 and #4. Hole bottoms shall be parallel to sloped surface within 1°. Maximum radius of hole bottom corners shall be 0.010".

TABLE A.4: HOLE PATTERN DIMENSIONS FOR BLOCK UT-RES-4560

Dimensions in Millimeters

Face #1 60° Lateral

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.05	±0.05	±0.13	±0.21
K	127.00	32.21	25.40	44.45
L	158.75	32.21	25.40	44.45
M	177.80	32.21	25.40	44.45
N	190.50	32.21	25.40	44.45
O	200.03	32.21	25.40	44.45
P	207.98	32.21	25.40	44.45
Q	215.11	32.21	25.40	44.45
R	221.84	32.21	25.40	44.45
S	215.11	38.94	37.08	44.45
T	207.98	39.34	37.77	44.45
U	200.03	40.36	39.55	44.45
V	190.50	41.73	41.91	44.45
W	177.80	44.91	47.40	44.45
X	158.75	51.26	58.39	44.45
Y	127.00	63.96	80.39	44.45

Face #2 45° Depth

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.13	±0.13	±0.05	±0.18
A	126.52	63.12	29.77	44.45
B	151.92	63.12	29.18	45.03
C	177.32	63.12	28.32	45.90
D	202.72	63.12	26.85	47.37
E	228.12	63.12	25.40	48.82
F	126.52	88.52	55.17	44.45
G	151.92	88.52	49.33	50.29
H	177.32	88.52	43.48	56.13
I	202.72	88.52	37.64	61.98
J	228.12	88.52	31.80	67.82

Face #3 60° Depth

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.13	±0.13	±0.05	±0.27
A	119.08	24.64	29.77	44.45
B	144.48	24.64	29.18	45.03
C	169.88	24.64	28.32	45.90
D	195.28	24.64	26.85	47.37
E	220.68	24.64	25.40	48.82
F	119.08	50.04	73.76	44.45
G	144.48	50.04	67.92	50.29
H	169.88	50.04	62.08	56.13
I	195.28	50.04	56.24	61.98
J	220.68	50.04	50.39	67.82

Face #4 45° Lateral

	HOLE POSITION X	HOLE POSITION Y	HOLE DEPTH	METAL TRAVEL
	±0.05	±0.05	±0.13	±0.18
K	114.30	54.79	25.40	44.45
L	146.05	54.79	25.40	44.45
M	165.10	54.79	25.40	44.45
N	177.80	54.79	25.40	44.45
O	187.33	54.79	25.40	44.45
P	195.25	54.79	25.40	44.45
Q	202.39	54.79	25.40	44.45
R	209.14	54.79	25.40	44.45
S	202.39	61.52	32.16	44.45
T	195.25	61.93	32.54	44.45
U	187.33	62.94	33.58	44.45
V	177.80	64.31	34.93	44.45
W	165.10	67.49	38.10	44.45
X	146.05	73.84	44.45	44.45
Y	114.30	86.54	57.15	44.45

Drill all holes flat-bottomed and perpendicular to the sloped surfaces. Hole diameters shall be 6.35 ±0.13 in Faces #2 and #3, and 6.35 ±0.05 in Faces #1 and #4. Hole bottoms shall be parallel to sloped surface within 1°. Maximum radius of hole bottom corners shall be 0.25. Metric equivalents of dimensions on drawing: 14.000" = 355.60 mm; 13.500" = 342.90 mm; 10.554" = 268.07 mm; 8.729" = 221.72 mm; 1.572" = 39.93 mm; 2.581" = 65.56 mm; 3.000" = 76.20 mm.

7.3 Repeatability Block

Report the results from scanning repeatability test block UT-RPT-CIRC.

Explanation of this item: This block has blank faces normal to 45° and 60° beams, a round-bottom hole, and two cylindrical-bottom slots at right angles, in the bottom face. The scans should be done with both the native software and, if possible, an acoustic holography system.

The results concerning repeatability are presented elsewhere. The emphasis here is on the imaging of the block.

Note: Figure A.9 shows the construction of the repeatability block. It contains a large spherical target that gives an image containing concentric rings if imaged with depth-coded methods such as time-of-flight or acoustic holography. The uniformity of these rings is indicative of the mechanical and ultrasonic precision of the system. The block also contains two milled grooves with circular cross-section. Imaging these grooves measures the backlash of the system.

The metric equivalents of the dimensions on the drawing are as follows:

Inch	*Metric, mm*
0.001	*0.03*
0.005	*0.13*
0.010	*0.25*
0.125	*3.18*
0.132	*3.35*
0.250	*6.35*
0.300	*7.62*
0.500	*12.70*
1.000	*25.40*
1.250	*31.75*
2.000	*50.80*
2.500	*63.50*
2.550	*64.77*
2.750	*69.85*
3.125	*79.38*
4.000	*101.60*
4.625	*117.48*
5.000	*127.00*
7.000	*177.80*
7.750	*196.85*

7.4 How accurate is the field procedure for measuring depth or length?

Explanation of this item: If the system has a procedure for measuring the dimensions of a reflector, apply it to determine the accuracy of the procedure. It may be an automatic software measurement using a box or cursor, or a written procedure using a printed image, or some other method. If there is no procedure given, answer "n/a". Indicate any relevant factors in the accuracy of the method (how well it locates the boundaries of a reflection, whether it uses a specified dB drop in signal, etc.). This question is designed to test the procedure, rather than the image fidelity.

7.5 Procedure Review

Describe any procedural elements (calibration, examination, evaluation, etc.) that should be specifically addressed in field procedures for this equipment.

Note: This item is addressed in detail in a separate Appendix.

Explanation of this item: Review all field procedures (calibration, examination, evaluation, etc.) from a human factors viewpoint. If the system has a field calibration procedure, indicate how well it is written to assure that the operator will calibrate the equipment properly and repeatedly. Evaluate it for understandability, cogency, and logical presentation. Some questions to consider are the following: -- Is it clear and unambiguous? -- Is it easy to follow? -- Is it flexible enough to allow the operator to handle a variety of circumstances? Note: PNL evaluation of this is done by a separate team from the one performing the equipment evaluation.

7.6 Follow the calibration procedure to scan piping, flat plate, or other appropriate test specimens so that the data output for known specimens may be reported.

Explanation of this item: Describe the procedure followed and the data taken. Note any deviations from

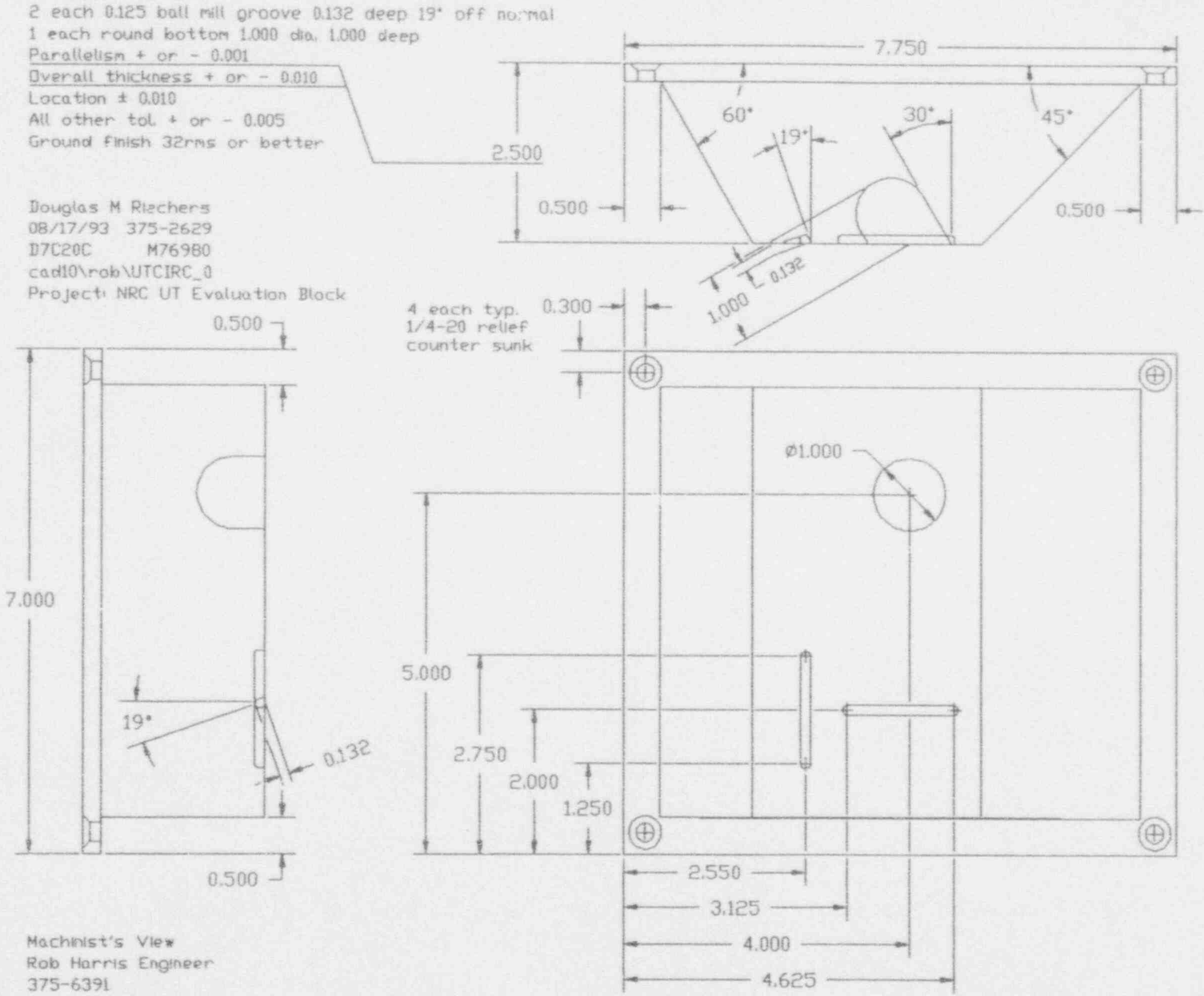


Figure A.9 UT-RPT-CIRC repeatability block what was expected.

The resolution block scans have been presented and described in other sections. Other specimens scanned were *[for example: a pipe with saw cuts, a pipe with artificially induced cracks, a Y-pattern test block, a smaller resolution block, a sample with shallow notches, ...]*.

7.7 Is there a mechanism for in-place calibration reference checks?

[ ] Yes
[ ] No

Explanation of this item: The question here is whether the calibration can be done under actual inspection conditions (remote wiring, etc.).

7.8 List and characterize, according to ASTM E-1065, the center frequency and bandwidth of all ultrasonic search units used in the evaluation, whether provided with the system or supplied by the evaluation team.

List the identification (manufacturer, frequency, model and serial numbers, etc.) of all transducers. Record all vendor markings, including serial numbers, so that data taken during the system evaluation can be correlated to the specific search units used. Note whether frequency and bandwidth determined agrees with that indicated by the vendor. Note: other search unit parameters are assumed to be as specified by the manufacturer. Beam profile is not controlled by relevant ASTM procedures, and is too time-consuming to measure here.

7.9 Number of Channels

7.9.1 What is the number of channels used by the system?

Explanation of this item: How many receivers, or how many multiple transducers, does the system have? Unless otherwise noted, it is assumed that the number of pulsers equals the number of receivers. Describe the nature of the system, if there is more than one channel, e.g., -- Does it do dynamic focusing or beam steering? -- Does it use multiple angle-beam transducers?

7.9.2 How does the system respond to non-functional channels?

Explanation of this item: Is there some check to make sure that a channel is not working? Is it the case that either the system will not inspect at all, or there is compensation for the missing channel, so that the system will not simply overlook the volume supposedly covered by the missing channel?

7.9.3 Are there software checks to ensure that all necessary data is taken?

Explanation of this item: Is it fail-safe?

7.9.4 What are the consequences of having non-functional channels?

Explanation of this item: Detail the response of the system, or the problems that may occur.

7.10 Error Recovery

Is there a mechanism to allow recalibration and continuation after an error?

[ ] Yes (describe)
[ ] No

Explanation of this item: If an error occurs after a large amount of scanning has been done, can you recover and continue, or must you start over from scratch? This is more an efficiency issue than capability. This is only an issue on a highly automated system; otherwise the operator can obviously continue the inspection from any place desired.

7.11 Frequency Ranges

7.11.1 What are the pulser frequency ranges used by the system? (e.g. 1 MHz, 5 MHz, 20 MHz, etc.)

Explanation of this item: Give the nominal pulser frequencies.

7.11.2 What are the receiver frequency ranges used by the system? (e.g. 1 MHz, 5 MHz, 20 MHz, etc., as determined by the preamp and receiver)

Explanation of this item: Give the nominal preamp and receiver frequencies. This indicates the bandwidth of the system.

7.11.3 What method is used to assure the pulser frequencies and the receiver frequencies coincide?

Explanation of this item: Normally the receiver frequency should be either broadband or equal to the pulser frequency. If the pulser and receiver frequencies are set separately, is there some means (software, procedure, other) to ensure this?

7.12 Repetition Rate for the System

7.12.1 What is the maximum repetition rate for the system?

Explanation of this item: Give the maximum pulser rep rate possible for the electronics of the system (without regard to deliberate software limitations based on geometry or scanning speed).

7.12.2 Describe the control of spatial sampling.

What is the minimum number of pulses per beamwidth, and how is it controlled (e.g., inspection rate versus pulse repetition rate, scanning speed, increment)?

Explanation of this item: If rep rate is set on the fly by software, in conjunction with axis speed and transducer beam size, what is the minimum number of pulse repetitions while the smallest cross section of the beam scans across a given point; or what is the minimum number of pulse repetitions per unit of length? Specify units used. What parameters does the software consider in limiting the rep rate (e.g., scanning speed, part thickness), and how are they used?

7.13 Pitch/Catch Ability

Does the system have pitch/catch ability?

Yes [ ] No [ ]

Explanation of this item: Is it possible to use two search units, or a split-element search unit, with one search unit or element transmitting and the other receiving?

7.14 Methods of Operation

What are the methods of operation?

[ ] Tone Bursts
[ ] Multiple Transducers
[ ] Lamb Waves
[ ] Creeping Waves
[ ] Square Wave Excitation
[ ] Tandem SAFT Mode
[ ] Phased Array
[ ] Spike Excitation
[ ] Other:

Explanation of this item: Check off or describe the special modes of operation of the system.

8.0 Data Acquisition/Processing

8.1 Acquisition Scheme

What type of data acquisition scheme is used by the system (raster scan, spiral, heuristic, etc.)? If not raster scan (which is detailed in separate questions), give details here.

8.2 Detection of Indications

Does the system automatically produce a list of indications?

Yes [ ] No [ ]

Explanation of this item: Does the system produce a list, in words and figures, or by special markings on a graphical presentation, identifying whether the volume scanned contains reflections that should be regarded as indications of potential defects? A graphical presentation of all reflectors is not a "yes." A "yes" means that some special additional marking is given to "indications."

8.2.1 If List Is Produced... What information is given about the indications?

[ ] Location
[ ] Amplitude
[ ] Other:

Explanation of this item: Check whether location and/or amplitude of the indication is given. If other information is given, describe.

8.2.2 If List Is Produced... Does the system display which transducer was used to find the indications?

Yes [ ] No [ ] N/A [ ]

Explanation of this item: If the system uses only one transducer, or pitch-catch, the answer is "n/a". If the system is capable of multiple transducer operation, the location and meaning of the echo is dependent on which transducer produced the echo. Does the system have some means for the analyst to determine this?

8.2.3 If List Is Produced... What methods are used to produce the list of indications?

[ ] Threshold
[ ] Target Motion
[ ] Other:

Explanation of this item: Check or describe the methods used by the software to designate certain reflections as indications. "Threshold" means the amplitude is used. "Target motion" means the relative time change of the reflector signal to a background signal is used. If some other method is used, name it or describe it.

8.2.4 If List Is Produced... What is the technical basis for the procedure (the physics)? Validate if possible.

Explanation of this item: What are the physical principles that form the basis of making the list of indications? If possible, present objects containing various reflectors and verify the classification. This question is only important if the method used is novel or unusual.

8.2.5 If List Is Produced... Does documentation exist to describe how the system determines the detection of indications (the algorithms)?

Yes [ ] No [ ]

Explanation of this item: Is the decision procedure documented in the available manuals? This question is only important if the method used is novel or unusual.

8.2.6 If List Is Produced... Is the system provided with a test data set that verifies the automatic detection methods?

Yes [ ] No [ ]

Explanation of this item: Is there a file or a set of files that exercises the software, i.e., demonstrates how the software analyzes the raw data to arrive at the processed data?

8.2.7 What procedures exist for the operator to determine indications?

Explanation of this item: Whether or not the system produces a list of indications, what methods does the operator have available to group sets of reflections?

8.3 Characterization of Indications

Does the system have any capability to automatically characterize indications?

Yes [ ] No [ ]

Explanation of this item: If there is a list produced, or the operator can indicate an area, can the system give further information about the indications, e.g., crack-like, volumetric, etc. (see following questions)?

8.3.1 If Indications Are Characterized... Can the system recognize and exclude geometric indications?

Yes [ ] No [ ]

8.3.2 If Indications Are Characterized... What parameters does the system characterize?

[ ] Location
[ ] Orientation
[ ] Size
[ ] Type: Volumetric/Planar (inclusion, void, crack, etc.)
[ ] Shape
[ ] Other:

Explanation of this item: Check or describe the parameters.

8.3.3 If Indications Are Characterized... What methods does the system use for characterization?

[ ] Multiple Transducers
[ ] Spectrum Analysis
[ ] Signal Smoothing
[ ] Spatial Signal Averaging
[ ] Automatic Image Analysis
[ ] Analyst-assisted Image Analysis
[ ] Other:

Explanation of this item: Check or list the methods.

8.3.4 If Indications Are Characterized... What is the technical basis for the procedure (the physics)? Validate if possible.

Explanation of this item: Describe the physical principles that form the basis for the characterization of indications. If possible, present test samples to the system to verify correct characterization.

8.3.5 If Indications Are Characterized... Does documentation exist to describe how the system determines the characterization of indications (the algorithms)?

Yes [ ] No [ ]

Explanation of this item: Is the characterization procedure documented in the available manuals? This question is only important if the method used is novel or unusual.

8.3.6 If Indications Are Characterized... Is the system provided with a test data set that verifies the automatic characterization methods?

Yes [ ] No [ ]

Explanation of this item: Is there a file or a set of files that exercises the software, i.e., demonstrates how the software analyzes the raw data to arrive at the processed data?

8.3.7 What procedures exist for the operator to characterize indications?

Explanation of this item: Whether or not the system characterizes indications, what methods does the operator have available to analyze sets of reflections?

8.4 Material Characterization

What types of material characterization are done, other than localized indications, e.g., noisiness, multiple cracking, attenuation?

9.0 Image Presentation

9.1 Is there a cursor readout? (used for aiding detection and characterization)

Yes [ ] No [ ]

Explanation of this item: Is there a cross hair or other pointer that allows the operator to refer to, and get information about, a specific point or area of the displayed volume?

9.2 Record the performance of the graphics tool for the following tests by using photographs of the display. Also, generate hard copies with a printer when appropriate.

9.3 How is data analyzed and presented for non-flat geometries?

[ ] Generic 3-d
[ ] Cylinder: unwrap
[ ] Slices
[ ] Other (describe)

Explanation of this item: Curved surfaces and complex shapes may require highly sophisticated techniques for beam correction on the one hand, and image presentation on the other. What is provided? For example, cylindrical, spherical, compound curve (nozzle insertion).

9.4 What is the fidelity of the imaged geometry (i.e. correct scaling)?

Explanation of this item: Scan a block containing reflectors of known geometry (at least 2" x 2" square scan; preferably 5" x 5" or more) and compare the imaged distances and shape to the true distances and shape. Use the most accurate tools possible and describe. For any distance measurement, subtract the actual distance from the (rescaled) imaged distance and divide by the actual distance. This gives the percentage error (if no scale is provided, choose a set of features from which to calculate a scale, indicate how the scale was calculated, and use it). Measure at least two x-axis distances, two y-axis distances, and two depths; also two opposite diagonal distances in the same plane; and compute the percentage error of each. To calculate the amount of skew, calculate the normalized amount of each diagonal measurement (the imaged distance divided by the actual distance) and divide the larger normalized amount of each pair by the smaller of the same pair. Subtract one from this number. This is the amount of skew.

9.5 Can the system perform geometrical corrections for scans done on complex geometries and curved surfaces?

Yes [ ] No [ ]

9.6 What views of the data are provided?

[ ] Top
[ ] End
[ ] Side
[ ] 3-D
[ ] Echo
[ ] Projection
[ ] Section

Explanation of this item: Does the system provide orthogonal views of the data, i.e., viewed parallel to the x, y, and z axes? Top = C-scan view, parallel to z-axis. Side and end refer to B-scan, B'-scan, or D-scan views, parallel to the x or y axes (no fixed definition whether "side" means "x" or "y"). Are any other views provided?

3-D = oblique = isometric, i.e., so you can see all 3 axes.

9.6.1 Are the views labelled?

Explanation of this item: Are labels such as side, top, and end provided with the views to allow the user to recognize what angle is being displayed?

9.6.2 What is the number of views that can be displayed at the same time?

Explanation of this item: Each rotation that can be viewed at the same time counts as one. For example, if you can view top, end, side, and a 3-d view all at once, the answer is 4. If you can present an indefinite number of views, the answer is "No limit."

9.6.3 Are the views maximum amplitude composites that are calculated from the individual planes of data?

(if not, or if other calculations are also provided, describe).

Yes [ ] No [ ]

Explanation of this item: A common way of calculating a view is to take the maximum amplitude of all data points that lie along the projection axis, and assign that value to the pixel shown. If some other method is used (e.g., slicing along a plane, or showing only the reflecting points closest to the viewer), describe.

9.6.4 Does the graphics tool calculate the composite views each time the user requests a display?

Yes [ ] No [ ]

Explanation of this item: Does the software have to start "from scratch" each time the view is changed? If so, the presentation might be very slow, discouraging the analyst from using many different views.

9.7 Do the views use a color scale to represent the data?

Yes [ ] No [ ]

Explanation of this item: Are varying amplitudes indicated by different colors?

9.7.1 Is the color scale adjustable?

Yes [ ] No [ ]

Explanation of this item: To get the most from a given set of data, you may want to choose a certain range of amplitudes and assign more or fewer colors to that range, or change the level at which one color grades into another. Is there a way to do this?

9.7.2 Is a scale other than color available?

Yes [ ] No [ ]
Type (gray, pattern, etc.):

Explanation of this item: If you want to print, photocopy, or fax data, you may need a pattern coding (dots, bars, gray scale) instead of color. Is one available?

9.7.3 If color or any other differentiating scales are possible, what are they used for?

9.8 Does the graphics tool project the ultrasonic data along the insonification angle?

Yes [ ] No [ ]

Explanation of this item: When an angle beam search unit is used, does the display show the reflected data in its true angular relation to the part?

9.9 Does the graphics tool permit the user to sequence through the individual planes of data for a given view?

Yes [ ] No [ ]

Explanation of this item: In order to visualize an indication, it is sometimes helpful to see a cross section of the data at a certain depth, then move the depth up or down and see how the trace of the indication moves on the screen as the depth is smoothly varied. Is this possible?

9.10 Can all or several of the individual planes of data be displayed (as separate tiles or windows) at the same time on the display?

Yes [ ] No [ ]

Explanation of this item: Can you see multiple cross sections at the same time, side-by-side vertically or horizontally, on the display? If so, how many (at the same time)?

9.11 Are the scales for the axes of the views equal? (i.e. does the display use the same number of screen inches per inch of material for both horizontal and vertical axes)

Yes [ ] No [ ]

Explanation of this item: There are various discrepancies possible between the axes, such as the different aspect ratios of screen and plotter, different motion sizes in x and y axes, correlating the time axis in z with the distance axes in x and y. Does the graphics software take this into account, so that squares look square and circles look round, both on the display and in print--outs? If the answer is "no", explain.

9.12 Is an option available to force all scales to be equal when more than one view is presented?

Yes [ ] No [ ]

Explanation of this item: When two or more views are presented, e.g., side and end, each view might be scaled to fit the screen space available. Is there a way to prevent this from happening, so that you are sure of having the same number of screen units per inch on all views that are present on the screen at any given time?

9.13 Are tick (fiducial) marks provided on all axes?

Yes [ ] No [ ]
If not, explain.

Explanation of this item: Does each axis have marks at regular intervals to indicate the axial measurement values?

9.14 Are all the axes of the views labeled in English and/or metric units?

Yes [ ] No [ ]

Explanation of this item: Does each axis have numbers beside the tick marks, indicating the distance of that tick mark (from some origin)? If only a legend is provided, answer "No" and explain.

9.15 Are the labels in scanner or material coordinates?

Scanner [ ] Material [ ]

Explanation of this item: Do the origin and direction of the axis labels correspond to scanner motion, or to part coordinates? If the system sets up a new set of coordinates with a new origin each time the scanner is moved to a different area of the part, the answer is "Scanner." If the system follows a consistent set of coordinates related to some feature on the part, the answer is "Material." If the system allows you to work in both coordinate systems interchangeably, check both "Scanner" and "Material."

9.16 What is the format of positional data?

List the data elements (X, Y, Z, tilt, rotation, etc.).

Explanation of this item: e.g., encoder data for each axis; a spatial tool-point readout from an integrated positioner; calculated measurements from a set of encoders.

9.17 Does the system record positional data that is tagged to each data point?

9.18 How are axis positions converted to transducer positions?

In the case of X-Y scanning systems, is the encoder step the same as (or an exact submultiple of) the position read-out step? For a multi-axis system, does positional accuracy depend on the collective positions of the axes, i.e., are there portions of inspection space that have better resolution than other portions?

Explanation of this item: For example software may convert encoder counts to positional numbers with some round-off error; or noise may cause random errors. In a robotic system, position may be guaranteed within an envelope, but the readout may be finer than the envelope, or the envelope may not be respected under all conditions.

9.19 In the case of a complex multi-axis vessel scanner, perform tests to verify the positioning of all relevant axes, including angular position, within a volume.

Note: This question involves many detailed measurements, but as the majority of systems do not have this capability, it is left to be done on a case-by-case basis.

9.20 Does the graphics tool permit the user to display a subset of the current image? (this is sometimes called zooming or boxing)

Yes [ ] No [ ]

Explanation of this item: The default presentation may not show as much detail as the analyst wishes to see. Can you select an area of the image and blow it up to see more detail? Describe: do you use a cursor to select, or enter desired coordinates, or some other method?

9.21 Does a reduction in the data of interest in one view carry over to any other views?

Yes [ ] No [ ]

Explanation of this item: Do all views zoom together? i.e., if you restrict the area to present in one view, do all other views (either on the screen or selected subsequently) reflect the same restriction?

9.22 Can you select the displayed size of a given image?

Yes [ ] No [ ]

Explanation of this item: Given an image that represents a certain portion of the data, can you retain the same portion of the data, but display the image larger (to see more detail) or smaller (to see more images at once)?

9.23 Does the graphics tool permit the user to move a cursor to individual pixels and obtain additional information on an individual datum?

[ ] Yes [ ] No
[ ] Amplitude
[ ] Position
[ ] Other:

Explanation of this item: For each kind of information provided, describe it. e.g., is amplitude given in dB or as a percent relative to some standard; is position given in part or scanner coordinates?

9.24 Does the graphics tool permit the user to display individual A-scans from the data volume?

Yes [ ] No [ ]

Explanation of this item: Can you select a given data point and ask for a presentation of the original A-scan data from which that point was generated?

9.25 Does the graphics tool permit the user to easily identify and display A-scans of interest from the various views?

Yes [ ] No [ ]

Explanation of this item: Given that it is possible to select and disp.ay A-scans, is a tool provided to select them easily from displayed images?

9.26 Does the graphics tool permit the user to display data from more than one file at a time on the display?

Yes [ ] No [ ]

Explanation of this item: This can come up in two ways: 1) you have to move the scanner setup position, and a given indication shows up in both setups, and therefore in two data sets, and 2) you want to see what the same area looked like last year or the year before, and compare it to the present scan on-screen.

9.26.1 Does this option include a single view that contains (color coded) data from more than one channel or file?

Yes [ ] No [ ]

Explanation of this item: Can the data from two or more files be superimposed to facilitate comparison?

9.27 Does the graphics tool permit the user to box across files?

Yes [ ] No [ ]

Explanation of this item: In this case the data files contain information on the material coordinates of the data and a selection of material of interest can be made to apply across any number of files.

9.28 How is the information (axis labels, etc.) used to determine where an indication is located in the material?

Explanation of this item: Does the inspector have to note where the origins are? Should you have photographs? How do you keep from mixing up different data files? Are part coordinates used in taking the data?

9.29 Is the image resolution at least as good as the ultrasonic data resolution?

Yes [ ] No [ ]

Explanation of this item: It should be possible to present images to mirror exactly the ultrasonic data taken; if not, evaluation will suffer needlessly because of inability to interpret the data.

9.30 Can the graphics tool map more than one datum to a given pixel?

Yes [ ] No [ ]

Explanation of this item: Is the image simply a one-to-one presentation of the data, or can many data points be presented as one pixel on the screen?

9.30.1 What is the method used to do this? (e.g. maximum value, last value, etc.)

Explanation of this item: In order to present many data points in one pixel, some transformation must be done on the data. The easiest but least representative is to take the value of the data point nearest to the center of the pixel. The most conservative is to take the largest nearby value. You could also do linear interpolation or averaging. Indicate what method (these or some other) is used.

9.31 Can the graphics tool map a given datum to more than one pixel?

Yes [ ] No [ ]

Explanation of this item: Is the image simply a one-to-one presentation of the data, or can one data point be presented as many pixels on the screen?

9.31.1 What is the method used to do this?

(e.g. data expanded to rectangle of pixels, smoothing, etc.)

Explanation of this item: In order to present one data point as many pixels, some transformation must be done on the data. The easiest but least representative is to use the value of the data point for all the pixels. You could also do smoothing (linear or other interpolation) between data points. Indicate what method (these or some other) is used.

10.0 Digitization

10.1 Does the system digitize the waveform?

Yes [ ] No [ ]

Explanation of this item: Does the system have a digitizer that captures the A-scan presentation (either RF or video) in digital form and saves it in a data set? This means that detailed post-analysis can be done without the need for re-scanning the part.

10.2 Is the RF signal digitized?

Yes [ ] No [ ]

Explanation of this item: Does the system have a digitizer that captures the RF (unrectified) A-scan presentation in digital form? If the RF signal is digitized, more information is available to the analytical software than if only the video (rectified) signal is digitized. For example, SAFT image processing and many other analyses require the RF waveform.

10.3 Is the video (detected) signal digitized?

Yes [ ] No [ ]

Explanation of this item: Does the system have a digitizer that captures the video (rectified) A-scan presentation in digital form? The video data can be used to do software thresholding as distinct from an electronic gated alarm realized in hardware.

10.4 What is the minimum digitizer sampling interval or maximum digitizer frequency?

Explanation of this item: Indicate the smallest time interval (in nanoseconds) between sampled points, or the highest frequency (in MHz) at which the digitizer is capable of operating. (Not the highest frequency that can be correctly digitized, which would be a lower number.) Indicate whether the sampling is real-time, or time-equivalent sampling.

10.5 How many bits resolution does the digitizer have?

Explanation of this item: Indicate the number of binary digits used by the digitizer (the sign, if used, is included as one of the bits).

11.0 Data Acquisition Limitations

11.1 What is the maximum length of the digitized A-scan?

Explanation of this item: Indicate the largest number of data points that can be digitized in one A-scan.

11.2 What is the maximum number of A-scans in a scan line?

Explanation of this item: Indicate the largest number of A-scans that can be stored during one pass across the scanned area, between two successive indexes (if the scanning scheme does not involve scans separated by indexes, explain the scanning scheme and data storage capacities).

11.3 What determines the maximum amount of data in a scan line?

Explanation of this item: Normally this would be the product of the amount of data per A-scan times the number of A-scans. However, there may be other software or storage limitations that cause the amount of data to be less than that product.

11.4 What is the maximum number of scan lines?

Explanation of this item: What is the greatest number of indexes that the system can achieve in one setup? If this depends only on the physical constraints of the system, the answer is "indefinite." If there are limitations due to storage or software constraints, note and explain.

11.5 Is the volume of material that can be inspected during a scan limited by the computer system?

Yes [ ]   No [ ]

Explanation of this item: Normally the system should be able to inspect all the volume that is physically accessible to it. If so, the answer is "No." If the computer system imposes some limit on the volume that can be scanned (due to data acquisition, storage, or processing constraints) the answer is "Yes."

11.5.1 If Limited... If the volume of material that can be inspected during a scan is limited by the computer system, what causes the limitation?

Is the inspection limit determined by limitation on the number of samples in each A-scan, on the number of A-scans in each scan line, or the number of scan lines in a scan?

[ ] Number of Samples
[ ] Number of A-scans
[ ] Number of Scan lines
[ ] A combination of the above (describe):

Explanation of this item: Check the appropriate limitation, and if necessary, describe how the limitation occurs.

11.5.2 If Limited... Are the limits set by the data storage medium or by the data processing software?

Storage Medium [ ]   Processing Software [ ]

Explanation of this item: If the system uses floppy diskettes or a small hard drive, the storage may be a limitation; or the software may have a limited buffer size (data processing limitation).

12.0 Data Types

12.1 What is the header format?

Explanation of this item: List, attach, or give document reference for the description of the header of the data sets.

12.2 What processed data storage options are available? (ASCII, binary, etc.)?

Explanation of this item: What kind of data formats can data be put in by the system? Particularly, is the data available only in a machine-specific binary format, or is it in (or is there an option to convert it to) a generic format such as ASCII or BCD?

12.3 Are the equipment settings attached to the data file itself or saved in a separate file?

Attached [ ]   Separate [ ]

Explanation of this item: This is of interest to make sure that if data is to be analyzed off-site, all the necessary identifying information is available.

12.4 Does the system record all or only some of the equipment settings that are needed to repeat a measurement?

If only some are recorded, list all those that are necessary but not recorded.

All [ ]   Some [ ]

Explanation of this item: Ideally, all relevant equipment settings are recorded with the inspection data in computer form. If not, it is vital for the values of the other settings to be manually recorded at the time of the examination. These other items are to be listed if "Some" is checked.

12.5 Does the system save the equipment settings in a portable format such as ASCII encoded strings or in machine specific (binary) format?

Portable [ ]   Specific [ ]
Format:

Explanation of this item: What kind of data formats can equipment setting values be put in by the system? Particularly, are the values available only in a machine-specific binary format, or in (or is there an option to convert them to) a generic format such as ASCII or BCD?

12.6 Is the format of the archived equipment settings given in the system documentation?

Yes [ ]   No [ ]

Explanation of this item: Does the documentation tell you how to interpret the equipment setting values recorded by the system?

12.7 Is the format used to archive the data given in the documentation?

Yes [ ]   No [ ]

Explanation of this item: Does the documentation tell you how to interpret the data values recorded by the system?

12.8 Is the data format strictly proprietary, fully public, or something in between?

If it is proprietary, what means are provided for translating or exporting it into a non-proprietary format?

Explanation of this item: The intent is to know what the vendor's stance is with regard to third-party use of the data, whether they consider their data format as proprietary and not available for outside review, or do they allow full access to the data?

12.9 Does the system store RF data?

If so, indicate the format.

Yes [ ]   No [ ]
Format:

Explanation of this item: It is possible that the system digitizes RF (unrectified) data and makes decisions, but does not store the RF data. If it does not store it, the answer is "No"; if it does store it, indicate what format is used. e.g., the format may be in character or binary format, 8-bit or 12-bit. If the RF signal is stored, more information is retained than if only the video (rectified) signal is kept. For example, SAFT image processing and many other analyses require the RF waveform.

12.10 Does the system store video detected data? **If so, indicate the format.**

Yes [ ]   No [ ]

Explanation of this item: It is possible that the system digitizes video data and makes decisions, but does not store the video data. If it does not store it, the answer is "No"; if it does store it, indicate what format is used. e.g., the format may be in character or binary format, 8-bit or 12-bit. Normally the RF rather than the video data is stored; however, if video data were used to do threshold detection in software, it would be appropriate to store the video data.

12.11 Is the RF or video data portable to other machines?

Yes [ ]   No [ ]

Explanation of this item: Are the values available only in a machine-specific binary format, or in (or is there an option to convert them to) a generic format such as ASCII or BCD?

13.0 Processing Options

13.1 Do data processing options exist for the system (e.g. SAFT)?

Yes [ ]   No [ ]

Explanation of this item: Are there any special processing options that go beyond linear functions such as shrinking, enlarging, or rotating an image?

13.2 Review and describe all data processing options by way of example from the data taken during the evaluation process or other available data.

Explanation of this item: For example, SAFT, FFT, software video detection. Attach examples of unprocessed and processed data.

14.0 Data Storage And Portability/Third Party Review

14.1 Storage Media/Durability

14.1.1 Does the system archive data files onto a removable data storage medium?

Record the type of media used; if none, explain.

Yes [ ]   No [ ]
Type:

Explanation of this item: The reason for the question is to know whether the data taken during part of an examination can be taken away and processed while further parts of the examination are being done. For example, 5-1/4 inch floppy, Bernoulli, 40 Mbyte tape cartridge, 9-track reel-to-reel tape, remote data link....

14.1.2 What are the size and media life limitations for the medium?

Size:
Life:

Explanation of this item: The size is of concern to know how many diskettes, tapes, etc. are needed to carry the data from an examination. The life is of concern to know how often the media need to be re-copied to ensure continuing archival integrity.

14.2 Data Availability for Third Party Review

14.2.1 Is there any type of data which requires physical rescanning?

Yes [ ]   No [ ]

Explanation of this item: Some systems may only record data that has been processed in some fashion (e.g., a system may only record maximum amplitude data). For such a system, physical rescanning will be required in order to obtain unprocessed data, such as A-scans. If this is the case, answer "Yes" and describe. The purpose of this question is to know whether there is any sort of information that you might like to have for evaluation that won't be available after the equipment has left the inspection site.

14.2.1.1 Describe:

14.2.2 Does the system produce data files that may be used by a second system?

Yes [ ] No [ ]

Explanation of this item: The purpose of the question is to know whether processing of the data files depends on having the exact same setup that the vendor supplies for the inspection, or whether it can be done on any generic computer of compatible type.

14.2.3 Describe the configuration of hardware and software needed to analyze data from the system.

Explanation of this item: What do you need in the way of hardware and software: indicate what constraints there are, if any, on the processor type, interface boards, co-processors, operating system, etc., for a system to analyze the data.

14.3 Make a list of recommended changes for the sake of increased portability of data files.

Recommendations:

Explanation of this item: Some items might be: other data that should be recorded (scanner placement, setup values, transducer/instrument data); different data format; more header information: better documentation.

15.0 Problems/Special Features

15.1 The review of computer-based systems will report any potential problems with systems that are reviewed.

15.2 Limitations of stored data:

Explanation of this item: List any additional limitations on data beyond those that have been noted in answers to other questions.

15.3 List any features or problems with the system that were not previously covered in this test plan.

Explanation of this item: This is a catch-all question in case the layout of the evaluation scheme was inappropriate or insufficient for certain features of the system being evaluated.

15.3.1 Features:

15.3.2 Problems:

15.3.3 Peculiarities:

16.0 Review Checklist

Explanation of this item: List the items that may require particular review when using this system.

Before and during inspection

After inspection

* * * * * * * * * * * * * * * * * *

Bibliography

Explanation of this item: List all books, manuals, etc. used for this evaluation.

* * * * * * * * * * * * * * * * * *

Glossary

This Glossary gives special or additional meanings of the indicated words, as used in the context of XXX operation. For basic or general meanings of many terms, see the Glossary to the Introductory Volume of NUREG/CR-5985.

* * * * * * * * * * * * * * * * * *

Index

<u>Explanation of this item</u>: Provide an index to the salient features of the evaluation.

Index

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NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-5985
PNL-8919

2. TITLE AND SUBTITLE

Evaluation of Computer-Based Ultrasonic Inservice Inspection Systems

3. DATE REPORT PUBLISHED

MONTH	YEAR
March	1994

4. FIN OR GRANT NUMBER

L1100

5. AUTHOR(S)

R. V. Harris, Jr., L. J. Angel, S. R. Doctor, W. R. Park, G. J. Schuster, T. T. Taylor

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

N/A

8. PERFORMING ORGANIZATION – NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

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9. SPONSORING ORGANIZATION – NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents the principles, practices, terminology, and technology of computer-based ultrasonic testing for inservice inspection (UT/ISI) of nuclear power plants, with extensive use of drawings, diagrams, and UT images. The presentation is technical but assumes limited specific knowledge of ultrasonics or computers. The report is divided into 9 sections covering conventional UT, computer-based UT, and evaluation methodology. Conventional UT topics include coordinate axes, scanning, instrument operation, RF and video signals, and A-, B-, and C-scans. Computer-based topics include sampling, digitization, signal analysis, image presentation, SAFT, ultrasonic holography, transducer arrays, and data interpretation. An evaluation methodology for computer-based UT/ISI systems is presented, including questions, detailed procedures, and test block designs. Brief evaluations of several computer-based UT/ISI systems are given; supplementary volumes will provide detailed evaluations of selected systems.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

automated ultrasonics, automated inspection, computer-based ultrasonics, computerization, computerized ultrasonics, inservice inspection, nondestructive evaluation, nuclear inspection, ultrasonic testing, ultrasonic equipment characterization, ultrasonic inspection, ultrasonic, ultrasonic imaging, ultrasonics

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)