

1992

## Development of an automated ultrasonic inspection cell for detecting subsurface discontinuities in cast iron

John Scott Burningham  
*University of Northern Iowa*

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**Burningham, John Scott, D.I.T.**

**University of Northern Iowa, 1992**

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DEVELOPMENT OF AN AUTOMATED ULTRASONIC INSPECTION CELL FOR  
DETECTING SUBSURFACE DISCONTINUITIES IN CAST IRON

A Dissertation  
Submitted  
in Partial Fulfillment  
of the Requirements for the Degree  
Doctor of Industrial Technology

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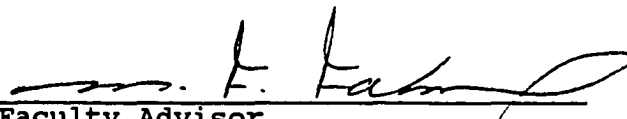
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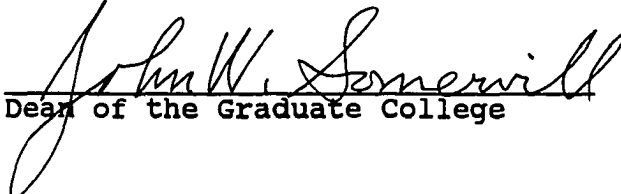
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DEVELOPMENT OF AN AUTOMATED ULTRASONIC INSPECTION CELL FOR  
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## ABSTRACT

Manufacturing of value added products by companies in today's global marketplace requires the vendors to meet certain minimum standards, SAE, ASTM, ISO, etc. In a global economy, as a manufacturer for the year 2000 and beyond, preferred vendors will become ISO 9000 certified to maintain a market share of produced goods.

An automated inspection cell was developed for the inspection of cast iron parts to detect subsurface discontinuities. The cell consists of an ultrasonic flaw detector (UFD), transducer, robot, immersion tank, computer, and software. Normal beam pulse-echo ultrasonic nondestructive testing is performed on each rough casting.

Using test blocks and castings supplied by an industrial partner and working with a skilled ultrasonic inspector; ultrasonic transducer selection, initial inspection criteria, and UFD setup parameters were developed for the gray iron castings used in this study. The skilled ultrasonic inspector's operation of the UFD was noted for development of the cell software.

The ultrasonic inspection cell control software (UICCS) was designed and developed to perform the necessary functions for control of the robot and UFD in real-time. The UICCS performed two main tasks; emulating the manual operation of the UFD through the communication link with

the unit, and evaluation of the ultrasonic signatures for detection of subsurface discontinuities.

The next phase of the cell development involved the testing of a lot of 105 castings. These casting were processed through the inspection cell. The castings which passed the inspection criteria were returned to the manufacturer for machining into finished parts where they were visibly inspected for defects after machining.

The castings that had ultrasonic signatures consistent with subsurface discontinues were manually inspected by the skilled ultrasonic inspector, with the manual inspection time recorded for comparison to the automated cycle time. The castings then were inspected using destructive testing techniques for detecting subsurface material voids.

The developed automated inspection cell correctly classified the inspection locations 99.8% of the time. Compared to manual inspection (as measured in the study), the automated cell's cycle time was 30 times more efficient.

## ACKNOWLEDGMENTS

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To my daughter, Jennifer, who amazes me with her enthusiasm for knowledge and joy of life--I hope you never change. To my parents, I thank you for giving me a good start down the path of life. And finally, to my wonderful wife, Anne, I give the heartfelt thanks of all for her patience, support, and love during this long haul.

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## CHAPTER I

### INTRODUCTION

#### Background of the Problem

Archeological research in Asia and Africa dates the manufacturing of cast bronze sculpture and statuary to 3100 B.C. The Chinese were casting iron in the first century B.C. Evidence supports that the Tanzania area of eastern Africa developed the casting of irons and steel around the ninth century A.D. In the 11th through 16th centuries A.D., metal casting evolved from what was an art form to the casting of engineering shapes for military hardware (Mikelonis, 1986).

Since the pouring of the first castings, discontinuities have been a problem. Discontinuities are irregularities, breaks, or gaps in the material structure. Most of the different types of casting discontinuities are visible to the naked eye, caused by variables in the casting process. Some casting discontinuities are not detectable by visual inspection because the defect is below the surface of the material. These subsurface discontinuities must be detected and identified before remedies to resolve the problems can be applied or value added work is performed on the casting that will later need to be rejected because of the defect.

Until the development and application of X-ray and ultrasonic inspection technology, subsurface discontinuities were not detectable until after value added processes were performed on the casting, or worst yet by the failure of a casting product in testing, or while in service. Today it is common practice, and many times required, for castings and other manufactured products to be 100% inspected, especially in the aerospace and nuclear industries. In castings for industries other than aerospace and nuclear, subsurface inspection is limited because of cost.

Every foundry would prefer to have a reputation of producing zero defects, but this reality is often far from ideal. The inspection process is but one step in the total quality assurance programs of most manufacturers. Manufacturers want to detect discontinuities early in the manufacturing process. If the defect is unrepairable or the rework costs are excessive, the part will be scrapped.

In foundries, the defective castings will be scrapped for remelt and recast, saving the investment in raw material. Scrapping defective parts costs money, not only for the material involved, but also for the value added processing that takes place prior to the detection of the defect. Early detection of flaws and defects in a

manufactured part reduces the value added processing cost lost because of discontinuities.

Inspection processes for detecting subsurface casting discontinuities are costly and labor intensive, adding to the cost of the final product. Quality assurance programs, as applied in many industries today, will often only statistically sample a production lot, passing or rejecting the lot on the result of inspecting only a few. As the cost of scrapping a casting goes up, there is a need for more thorough inspection to detect discontinuities before the value added operations have been performed via the manufacturing process.

After the foundry has delivered the casting to the customer and a defective casting is detected during the customer's manufacturing processes, foundries making the casting normally are required to replace the defective casting. Contractual agreements between the foundry and the customer also may involve a number of compliance parameters that cause financial burden to be placed on the vendor (the foundry). Manufacturing of raw materials and value added processes by companies usually requires the vendor to meet certain minimum standards, SAE, ASTM, ISO, etc. In a global economy, as a manufacturer for the year 2000 and beyond, preferred vendors will need to become ISO 9000 certified to maintain a market share of produced

goods. A foundry's business relationship with a customer can be influenced by the quality of the castings delivered in both a negative and positive manner.

When a company has a captive foundry, they absorb all the costs associated with the defective casting. When foundries bid on jobs, they add the cost of scrap into the bid. Foundries with lower scrap rates can bid lower prices while still maintaining the necessary margin of profit, thus underbidding competitors and becoming more competitive in the marketplace.

This proposal is designed to investigate existing technology and develop a prototype automated ultrasonic inspection cell for detecting subsurface discontinuities in a cast iron part. The cell needs to control the ultrasonic nondestructive evaluation (NDE) equipment, robot, analyze collected data, decide about the quality of the casting, and save inspection data for future analysis.

#### Significance of the Problem

The early detection of casting discontinuities is important to the foundry industry, allows reduction in scrap costs and to 100% quality of product in every delivery. A cost effective, advanced technology NDE system is needed to achieve quality assurance goals that will enable the American foundry industry to remain competitive in the national and international markets.

### Statement of the Problem

The problem of this study is to develop a prototype automated inspection cell for the detection of subsurface casting discontinuities while holding the investment of time and labor to a minimum. This involves interfacing existing technologies in ultrasonic inspection, robotics, and computers; developing inspection criteria and standards; producing software for emulating the necessary operator skills, decision making capacity, and cell supervisory control.

### The Research Question

Can a computer-controlled ultrasonic inspection cell increase the efficiency of the inspection process and accurately analyze the data in real-time for the quick detection of subsurface casting discontinuities in cast iron?

### Limitations

This research was funded in part by a grant from a major foundry. The iron casting to be used in this study was selected by the foundry, based on their identification of need to detect subsurface discontinuities. The casting to be analyzed in this study has 17 specific locations where subsurface discontinuities have a history of occurring. The study will be limited to gray iron

castings, one type of ultrasonic detector, one type of robot, and subsurface defects only.

#### Assumptions

For developing and calibrating the inspection system, simulated flaws are necessary. Flat bottom drilled holes at varying depths in sample castings will be used. These flat bottom holes have been shown to represent the type of echo condition that discontinuities of similar characteristics would present to ultrasonic inspection. The equipment in the ultrasonic cell identified for this study is representative in accuracy and capabilities to those commonly used in industry.

#### Definition of Terms

Adaptive Control. A control method in which control parameters are continuously and automatically adjusted in response to measured process variables to achieve better performance (Smith, et al., 1983, p. 1).

Artificial Intelligence. The ability of a device to perform functions that are normally associated with human intelligence, such as reasoning, planning, problem solving, pattern recognition, perception, cognition, understanding and learning (Smith, et al., 1983, p. 1).

ASTM. (American Society for Testing and Materials) Objectives--To develop and publish technical information designed to promote the understanding and advancement of technology and to ensure the quality of commodities and services and the safety of products. ASTM's primary mission is to develop voluntary full consensus standards for materials, products, systems, and services (Davis, 1989, p. 33).

Automation. The theory, art, or technique of making a process automatic, self-moving, or self-controlling (Smith, et al., 1983, p. 1).

Boss. Projection (usually of circular cross section) on a casting (Sylvia, 1990, p. 304).

Casting. A casting is a metal product that can be made by melting alloys and pouring them into molds (sand or ceramic). Generally, the mechanical properties of castings are worse than forged or machined products (Wright & Bourne, 1988, p. 316).

Cell. A manufacturing cell is a group of machines that work together as a team to carry out a step in the manufacturing process. In human terms, this would duplicate the effort of a group of blue-collar workers (Wright & Bourne, 1988, p. 316).

Expert System. An expert system is a program that is designed with the expressed purpose of making decisions that match the decisions made by a human expert(s) in the field (Wright & Bourne, 1988, p. 320).

Gray Cast Iron. Commonly known as cast iron--is more widely used than any other casting metal or alloy. It is defined as an alloy of iron, carbon, and silicon, in which the carbon content is greater than 2%. When the carbon content is less than this amount, the alloy is classified as steel. Cast iron contains free graphite or carbon, whereas steel does not (Sylvia, 1990, pp. 227, 230).

Inspection. The act of evaluating some characteristic of the casting as compared to a standard to determine if the part conforms to a specification (Mikelonis, 1986, p. 767).

ISO. (International Organization for Standardization) Objectives--The object of ISO is to promote the development of standardization and related activities in the world with a view to facilitating international cooperation in the sphere of intellectual, scientific, technological and economic activity (Davis, 1989, pp. 143-144).

Manufacturing Intelligence. This is the science of creating intelligent systems for manufacturing applications (Wright & Bourne, 1988, p. 327).

Robot. A mechanical device which can be programmed to perform some task of manipulation or locomotion under automatic control (Smith, et al., 1983, p. 10).

SAE. (Society of Automotive Engineers, Inc.)  
Objectives--The object of SAE is to promote the Arts,  
Sciences, Standards and Engineering Practices  
connected with the design, construction and  
utilization of self-propelled mechanisms, prime  
movers, components thereof, and related equipment to  
preserve and improve the quality of life (Davis, 1989,  
p. 202).



CHAPTER II  
REVIEW OF THE LITERATURE

Ultrasonic Testing

"For centuries man has practiced the art of testing by some form of sounding" (Banks, Oldfield, & Rawding, 1962, p. 1). Early methods of nondestructive evaluation (NDE) relied on the reality that a defect, such as a crack in a part, would alter the natural sound an object would make when struck.

The Russian investigator Sokolov in 1929 first suggested the use of ultrasonic vibrations for finding defects in materials (Banks et al., 1962). "The application of ultrasonics to flaw detection . . . was first mentioned in a German patent dated 1931 [O. Muhlhausen, D.R.P. 569598, 1931]" (Meadows, 1960, p. 103.) In 1943 the precursor of modern ultrasonic flaw detection equipment was demonstrated by Sproule, for Henry Hughes Limited (1960).

The coupling of the ultrasonic wave between the transducer and the material being inspected is one difficulty of automated ultrasonic inspection. In manual ultrasonic inspection, the transducer is typically placed in physical contact with the material being inspected, with a water-soluble or oil based liquid between the transducer

and material to ensure a good coupling so that the maximum ultrasonic energy enters the material (Banks et al., 1962).

In automated ultrasonic application, "The technique involving total immersion of the work under inspection has become universally accepted" (Banks et al., 1962, p. 167). This requires the use of an immersion tank where the part is placed under water and the transducer is immersed in the water over the inspection area. Ultrasonic immersion inspection involves one of the following four basic procedures: normal beam pulse-echo, normal beam through-transmission, angle beam pulse-echo, and angle beam through-transmission.

In a normal beam pulse-echo arrangement (see Figure 1), an ultrasonic sound beam is generated by the transducer that travels perpendicularly into a test piece. Upon encountering an anomaly or material discontinuity, the incident beam will split, resulting in a reflected beam off the interference returning in the direction of the source and a refracted beam passing through the interference. The reflected beam echo returning to the transducer is converted into electrical energy. The resulting analog electrical signal is converted into the digital data set that is interpreted as an indication of a subsurface discontinuity or anomaly. The refracted beam and the

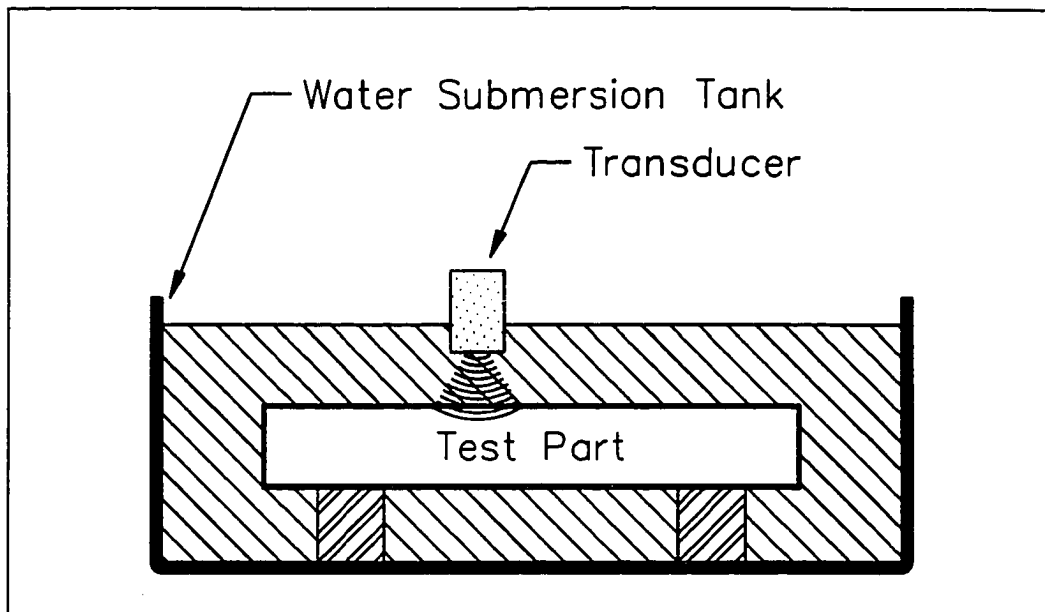


Figure 1. Normal beam pulse-echo arrangement.

uninterrupted initial sound beam will bounce off the rear of the test piece. The ultrasonic beam will then bounce around between parallel surfaces, losing some energy through the walls as attenuation from the material. These echoes can be detected by the energy that is lost through the walls and received by the transducer until the leakage level of the bouncing signal falls below the sensitivity of the transducer.

A normal beam through-transmission (see Figure 2) is similar to the pulse-echo, except a second transducer is placed on the opposite side of the test piece to detect the ultrasonic energy packets passing through the material. This technique is necessary when the reflections from the

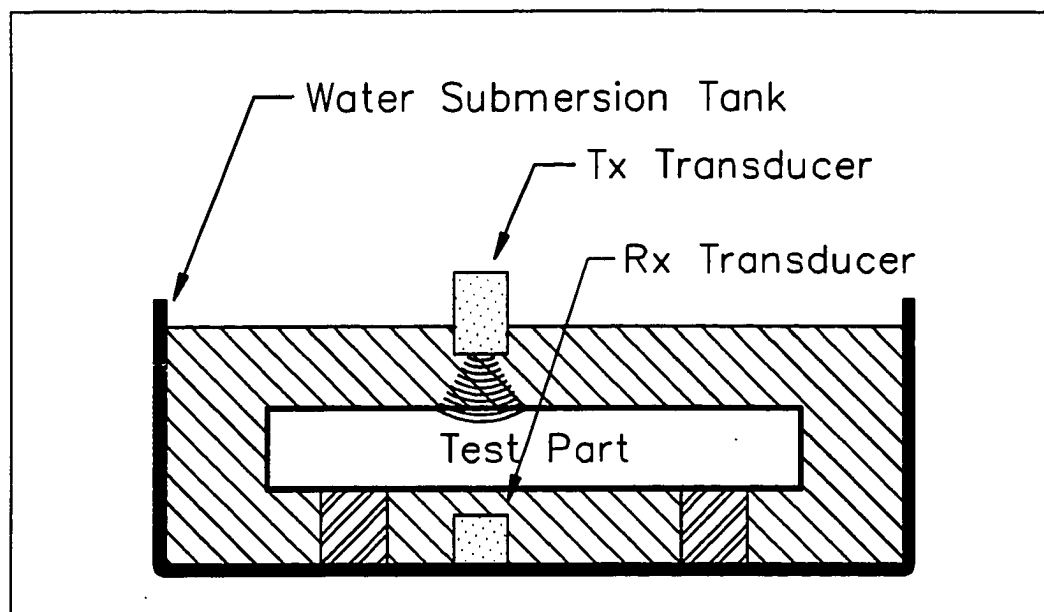


Figure 2. Normal beam through-transmission arrangement.

anomaly or material discontinuity are not adequate for detection by the initial transducer. It is not the reflection that is detected, but the increased loss of energy traveling through the piece caused by the interference.

The angle beam pulse-echo (see Figure 3) is similar to the normal beam pulse-echo arrangement, except the signal does not enter perpendicularly, but at an angle to the surface of the test piece, and a separate receiver transducer is used to detect the echo. Angle beam arrangements are normally used to inspect areas that are inaccessible to normal beam procedures (Bray & Stanley, 1989).

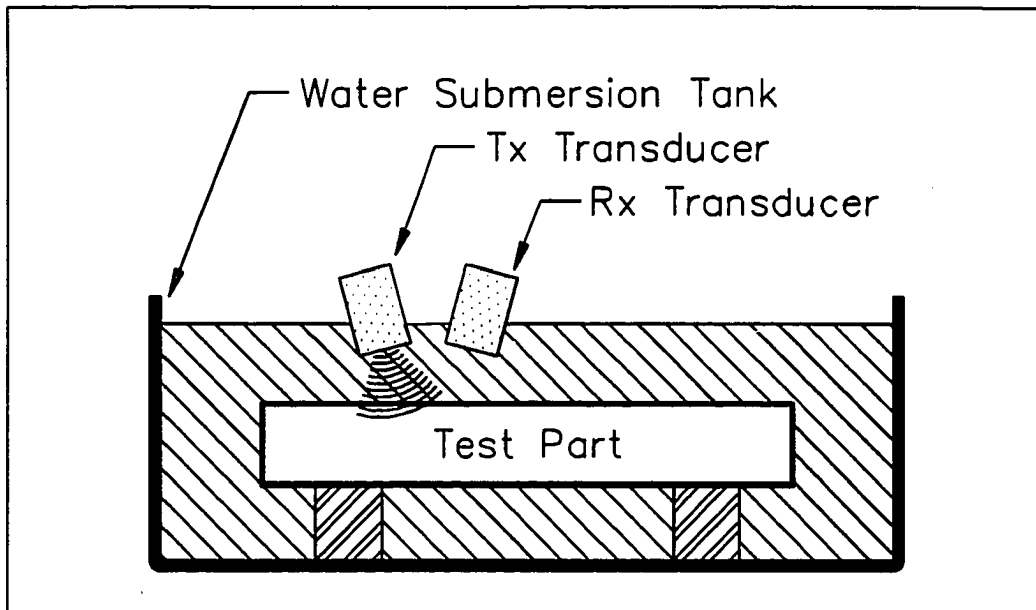


Figure 3. Angle beam pulse-echo arrangement.

The angle beam through-transmission (see Figure 4) is similar to the normal beam through-transmission arrangement, except the signal does not enter perpendicularly, but at an angle to the surface of the test piece. This arrangement can be modified by placement of the transmitter or receiver transducers to inspect difficult casting shapes.

Ultrasonic NDE is a labor intensive task, requiring highly skilled technicians for reliable results (Mikelonis, 1986). For cast iron, Mikelonis (1986) stated that "expert interpretation of readout is necessary" (p. 773).

Kochhar and Burns (1983) stated that manual inspection "is an expensive and time consuming process so statistical

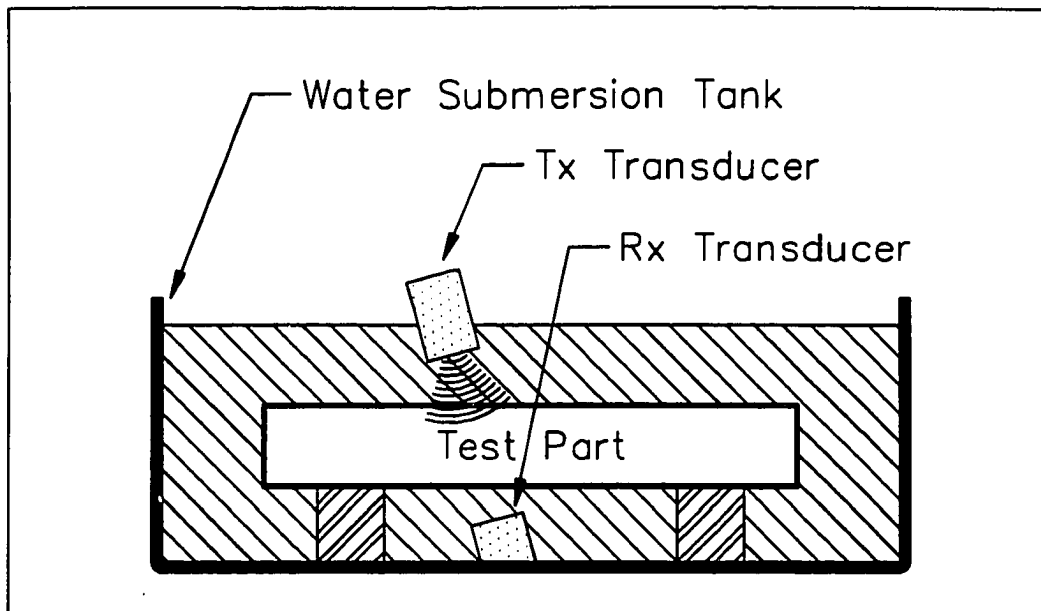


Figure 4. Angle beam through-transmission arrangement.

quality control techniques have been devised and implemented to reduce the need to test every single item" (p. 289). They however promote automated in-process quality control with 100% inspection.

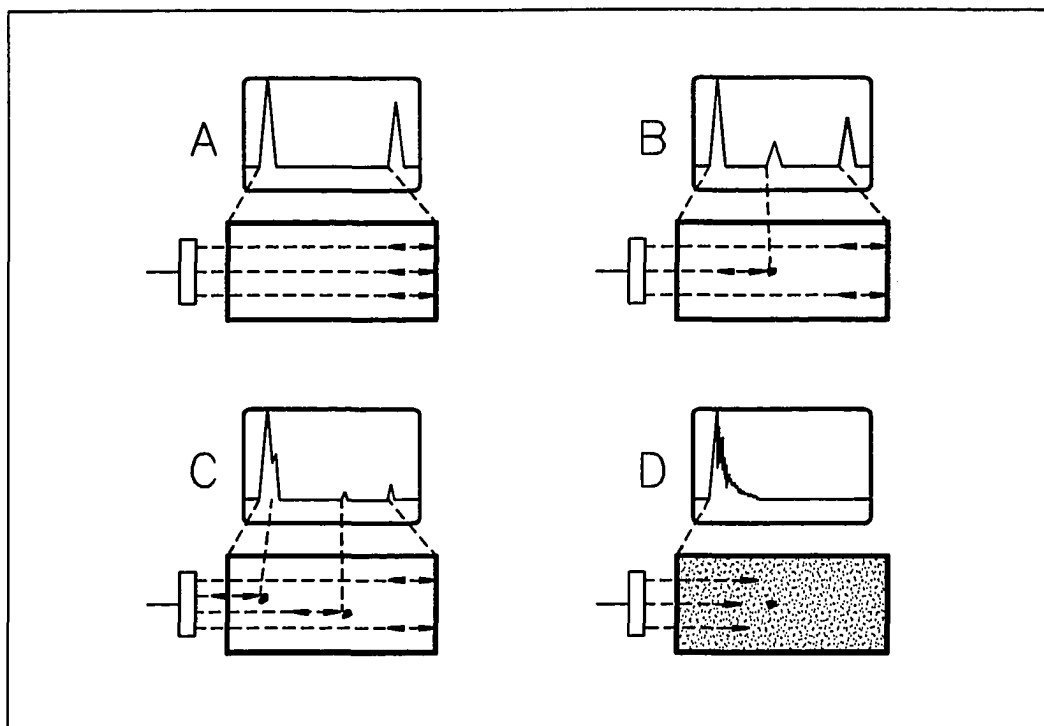
Traditional inspection techniques suffer from some disadvantages. Skilled inspectors are required to inspect products. Inspection costs are high and the inspection area frequently forms a bottleneck. Manual inspection is often inaccurate and the measurements made by inspectors are not always consistent. Once a manufacturing operation has been completed, it is difficult to relate the fault to the process operation. . . . Computer based automatic testing equipment makes it possible to overcome some of these difficulties. (p. 290)

Ensminger (1988) identifies some problems of inspecting cast iron parts, including "rough surfaces, large grain size, and unfavorable geometrics" (p. 312), and

the production of false ultrasonic echoes similar to voids caused by graphite in the casting. Filipczynski, Pawlowski, and Wehr (1963/1966) stated, "The chief difficulties and limitations in the use of ultrasonics [to detect discontinuities] are related to the roughness of the surface, irregularities in shape and the type of structure of the material" (p. 235).

Typical problems that may be encountered in ultrasonic inspection of the test part are illustrated in Figure 5. Figure 5-A represents a part void of defects, Figure 5-B shows a single defect located in about the center of the part. Figure 5-C shows a part with two defects, the first one located near the entrance surface, where the rough condition of the entrance masks the first defect, and the additional loss of signal strength caused by the first defect results in a reduced echo from the second defect and the rear wall. Figure 5-D is an example of attenuation of the signal due to scattering caused by graphite or grain size in the material, resulting in noise, which appears on the ultrasonic flaw detector (UFD) display as grass.

The use of ultrasonics for detecting subsurface casting discontinuities involves the transmission of ultrasonic sound waves into the area of the part to be inspected and listening to either reflected echoes or the transmission through the part. The sound echoes, or



**Figure 5.** Typical ultrasonic inspection conditions: (A) Void of flaws; (B) Single flaw; (C) Two flaws, one masked by front surface, reduced echo on second; (D) Strong attenuation due to scattering.

Note. Adapted from Krautkrämer and Krautkrämer, 1975/1977, p. 194.

transmissions through the part, are received by a transducer. The transducer converts the sound energy into an electrical signal that is transmitted to the UFD. The UFD displays the wave form on a screen using either an analog or analog-digital interface. The expert operator



interprets the displayed wave form pattern to detect subsurface discontinuities.

With the development of robots and small computers, it has become technically feasible to interface machines to perform the tasks previously requiring expert resident technicians. Papadakis (1991) advocates that in ultrasonics inspection, "The real growth, change, improvement, and advancement lies with the response of research, development, and technology transfer to certain basic issues. . . . output of work in each area must result in a 'new solution package'" (p. 1180).

#### Ultrasonic Transducers

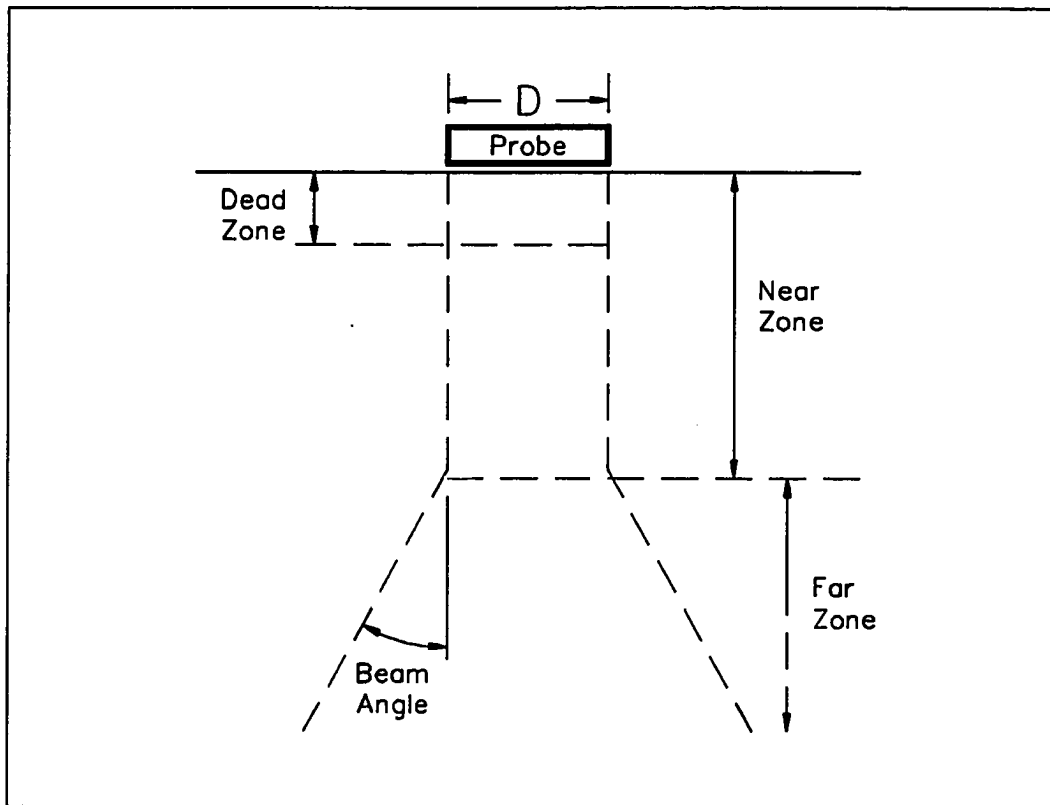
The transducer is one of the most important parts of any ultrasonic NDE system. The selection of the proper transducer is important to achieve the necessary sensitivity and resolution of the system (Panametrics, 1991). Transducers are available in a variety of frequency ranges, sizes, and application dependent housings.

Ultrasonic transducers were typically made of piezoelectric crystalline material, originally natural quartz. However, today ceramic materials such as barium titanate, lead metaniobate, or lead zirconate are replacing quartz (Hull & John, 1988). These transducer materials exhibit a piezoelectric effect when an alternating current is applied to the crystalline faces. The material will

contract and expand, generating a compression wave normal to the disc in the surrounding medium. The piezoelectric effect also works in reverse. An electric field will be created if the material is subjected to an incoming sound wave.

"The ultrasonic waves generated by a disc-shaped crystal will emerge initially as a parallel-sided beam which later diverges" (Hull & John, 1988, p. 60). The ultrasonic beam can be divided into three zones: the dead zone, the near zone, and the far zone. The dead zone is the area below the surface of the ultrasonic transducer where the detection of defects is severely restricted because the transducer is still vibrating from its generation of the ultrasonic signal when an echo would return from a discontinuity in this region. The near zone is the area where the beam is almost parallel sided; the sensitivity of detection of flaws is not constant in this area, being more sensitive toward the far end of the zone. The far zone is the region where the beam spread occurs, with the detection sensitivity decreasing with the square of the distance from the ultrasonic source (1988), see Figure 6.

The ultrasonic wave must be transmitted from the transducer to the test piece. This requires the use of a coupling medium. In manual ultrasonic applications, the



**Figure 6.** Ultrasonic beam shape.

**Note.** Hull and John, 1988, p. 61.

coupling medium can be applied to the transducer and the transducer placed in contact with the part with some pressure manually applied to ensure good acoustic contact with the test piece.

Automated inspection using a computer-controlled positioner is not conducive to emulating the manipulated skills of a human operator needed for applying a coupling medium. The principal method for achieving the necessary coupling is immersion, using water as a coupling medium.

The immersion method involved placing the part in a tank of water and manipulating the transducer into position, which is also immersed in the water with the part.

For the calibrating of the UFD, standard test block similar to those described in the ASTM E428-91 and ASTM E804-88 standards (American Society for Testing and Materials, 1991) are used. Testing and development of an automated system further requires the use of sample parts or sections of the areas to be inspected (see Figure 7).

Meadows (1960) states:

The designer of the component to be inspected should state the maximum size of defect that is tolerable. It is then assumed that this will be parallel to the scanning surface and it is related to one of the standard test blocks. The sensitivity of the flaw detector is set so that the indication from a flat-bottomed hole of the appropriate size is a convenient height on the screen. . . . Ideally, the block should be made of the same material as that being inspected. (p. 112)

#### Casting Defects

It is the goal of all manufacturers to emphasize profits and minimize costs. Defects add to increased costs, thus reducing profits. In the foundry industry, many types of defects are created in the casting by engineering and production problems. Subsurface casting defects include but are not limited to: carbon floatation (Kish), gas defects, hard spots, hard areas, chill spots, and shrinkage cavities (American Foundrymen's Society, 1966).

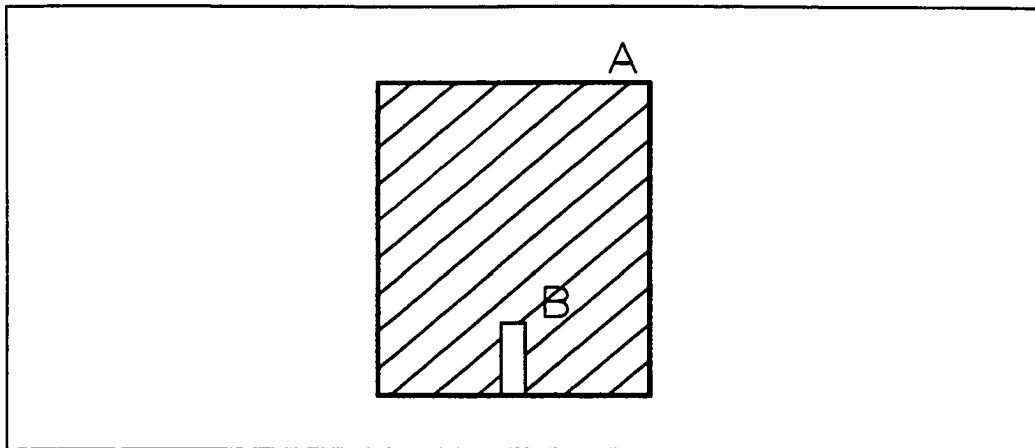


Figure 7. Typical test block, surfaces A and B must be parallel.

Before a problem can be rectified, it must be identified. Inspection is for the detection of problems. The resolution of the problem can include revisions to the product design, process revisions, remedial action, or just scrapping the part. Early detection of problems reduces costs by early corrective action.

Koo (1987) identified three separate stages in the evaluation of the ultrasonic wave which interacts with a defect in the material: flaw detection, flaw classification, and flaw characterization. Flaw detection, the identification of a problem without qualification of defect type, is an important first step. Other testing methods, destructive and nondestructive, can be used to qualify an identified problem area.

### Inspection

"Inspection involves evaluating the quality of some characteristic in relation to a standard" (Graham, 1988, p. 310). The inspection process is often divided into three distinct areas: incoming inspection, in-process inspection, and final inspection and testing.

The incoming inspection is for evaluating the quality of incoming materials, both raw and manufactured. The in-process inspection is performed as part of the manufacturing process, to detect nonconforming parts to allow remedial action to be taken or to terminate additional value added activities from being performed on the discrepant parts. Final inspection and testing are performed at the end of the manufacturing and production processes, before delivery to the customer; this can include adjustments and calibration on finished products. Statistical quality control concepts are applied in the manufacturing environment to assure "acceptable quality levels, average outgoing quality, and consumer-producer risk" (Melnyk & Narasimhan, 1992).

Harrington (1973), the father of CIM (Computer Integrated manufacturing), defines quality assurance as the "activities designed to assure that manufacturing methods, machines, and tools are used which have the greatest chance of producing acceptable parts" (p. 191). His definition of

quality control is the "detection of unacceptable parts" (p. 191) and corrective actions necessary. According to Harrington's definitions, the inspection process clearly fits into the quality control function.

Dau (1986, p. 2) emphasized that "a well-trained inspector conducting a manual inspection can obtain more information and make better decisions" is not supported by current evidence. He further presented an overview of automated inspection systems, listing five justifications for employing an automated approach to ultrasonic inspection:

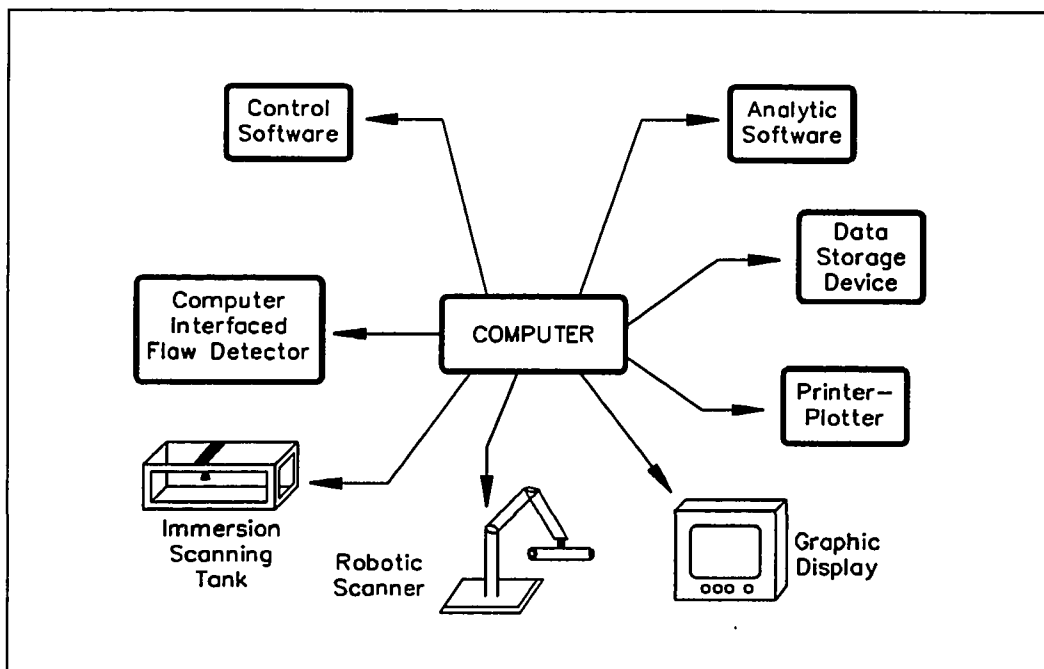
Full coverage of the item to be inspected is demonstrated, recorded, and repeatable. Automated data acquisition and analysis permit working at higher sensitivity because of the consequent increases in the volume of data that can be handled rapidly with modern computational hardware. Collecting and storing position annotated inspection signal information in a computer compatible format greatly increases signal interpretation options. Higher confidence that inspection results are repeatable. Reduces difficult task of training people in the art of manual inspection and decision making. (p. 2)

The automated ultrasonic inspection system needs to perform three basic functions: data acquisition, data analysis, and presentation of results. These three functions require the integration of five system elements:

Electronic hardware - provides the data acquisition control functions and data analysis for the system. Software - instructions that tell the system how to acquire data, how to analyze the data, and record and display the results. Transducer positioner - provides mechanical motion to place the sensor in positions necessary to conduct the inspection. Signal

transmitter and receiver - generates and receives a signal of sufficient fidelity and quality to permit detailed signal analysis. Transducer - the probe that injects the inspection energy into the component and receives the return signal containing information about component integrity. (Dau, 1986, p. 4)

Roller and Rose (1986) describe a computer-controlled UFD as "an ultrasonic instrument that can be connected to and operated by computer based devices and systems to carry out a specific inspection procedure" (p. 16). Their schematic diagram of a computer based ultrasonic inspection system is diagramed in Figure 8.



**Figure 8.** Schematic diagram of a computer based ultrasonic inspection system.

**Note.** Roller and Rose, 1986, p. 17.



Beller, Mikesell, and Holm (1986) stated that the "reproducibility [sic] of results is clearly an essential ingredient for reliable ultrasonic inspection system" (p. 29). Taszarek (1986) found that many companies are unwilling to implement fully-computerized inspection systems because of costs, but "it is possible to investigate computerization of specific test procedures at relatively low expense, so as to determine the benefits" (p. 145). Friedmann, Boring, and Cohee (1986) state "the most desirable goal totally automated inspection could produce [is] a good-or-bad decision based upon the ultrasonic information which has been collected" (p. 163).

#### ISO 9000

ISO 9000 "is a discipline for maintaining quality and uniformity in world trade" (Sprow, 1992, p. 73). French and Nicholas (1992) stated that "to remain competitive, companies must satisfy increasingly stringent requirements for quality processes and quality management systems" (p. 42). By the year 2000, "it will be the defacto minimum requirement for those wishing to compete globally" (Sprow, 1992, p. 77).

The ISO is a worldwide federation of national standards bodies based in Geneva, Switzerland. The organization is made up of over 90 members, including representation from the United States. The ISO 9000 series

of standards include ISO 9000 to ISO 9004. Specifically, ISO 9000, is a guideline for the selection and use of ISO 9001 to ISO 9004. ISO 9001 to ISO 9003 deal with external quality assurance programs, ISO 9004 involves internal programs.

ISO 9000 is an international standard for quality. The principle concepts of the series of standards as stated in ISO 9000 (International Organization for Standardization [ISO], 1987a) are:

- a) The organization should achieve and sustain the quality of the product or service produced so as to meet continually the purchaser's stated or implied needs.
- b) The organization should provide confidence to its own management that the intended quality is being achieved and sustained.
- c) The organization should provide to the purchaser that the intended quality is being, or will be, achieved in the delivered product or service provided. When contractually required, this provision of confidence may involve agreed demonstration requirements. (p. 2)

ISO 9004, deals with guidelines for internal quality management and quality system elements, section 10.1.5 (Quality in production) stated: "Efforts to develop new methods for improving production quality and process capability should be encouraged" (ISO, 1987b, p. 10). Section 12.2 (In-process inspection) (ISO, 1987b) stated:

Inspection or tests should be considered at appropriate points in the process to verify conformity. Location and frequency will depend on the

importance of the characteristics and ease of verification at the stage of production. In general, verification should be made as close as possible to the point of production of the feature or characteristics. (p. 12)

### Industrial Robots

In 250 B.C. the clepsydra, or water clock, was an improvement on the hourglass. The Middle Ages saw the development of pendulum clocks. These were the forerunners to the automated machines of industry (Stackpole, 1983).

"The early 1800's saw the development of one of the first industrial robots, a programmable loom used in the textile industry" (Goetsch, 1988, p. 154). The Jacquard loom was controlled by a paper punched tape to control the decorative patterns weaved into the textile. The later part of the 19th century through the first half of the 20th century saw the development of a variety of automated machines. Seward Babbitt developed a motorized crane with special grippers for removing white-hot ingots from a furnace in 1892. The DeVilbiss Company in 1938 developed a programmable spray painting machine. The Atomic Energy Commission was using articulated arms for handling radioactive material in 1951 (Goetsch, 1988).

Modern industrial robots can trace their heritage to George Devol Jr., who in 1954 filed a patent on a programmable transfer device. The first commercially available robots entered the marketplace in 1962 (Zeldman, 1984); the company was Unimation, an adaptation of Devol's

universal automation buzzword of the late 1950's and operating under a 1958 license from Devol. The first industrial application of the robot was to unload hot metal castings at a General Motors foundry (Garrison, 1991).

The industrial robot is typically comprised of four basic units: mechanical arm, end-of-arm tooling, power source, and control unit. The mechanical arm, or manipulator, is what gives the robot a humanoid appearance, allowing combinations of waist, shoulder, elbow and wrist motion. The end-of-arm tooling, or end effector, is the hand of the robot; it is designed to perform standard or specialized tasks such as welding, painting, grinding, or holding, sometimes being automatically interchangeable. The power source is the energy conveyance to the axes and end effector. Different power sources include electrical, pneumatic, and hydraulic; many industrial robots will use a combination of power sources. The control unit is a reprogrammable computer for controlling the actions of the industrial robot.

#### Early Automation in Manufacturing

The first attempts at automation in manufacturing "was based primarily on sophisticated mechanical machinery controlled by cams and levers or electrical switching gear" (Rembold, Blume, & Dillmann, 1985, p. 7). The early automated equipment was designed to perform fixed

manufacturing tasks; changing the task usually required redesigning the machine.

Custom designed automated machines today are called hard automation or fixed automation, to distinguish this single task automation from soft automation or programmable automation that allows the hardware to be programmed to perform a broad range of manufacturing tasks. Where the volume is large enough to justify the expense of hard automation, often it is the least expensive approach (Graham, 1988).

The development of the electronic computer was realized as having immense potential for manufacturing automation (Rembold et al., 1985). Numerical Control (NC) machine technology was developed at the Massachusetts Institute of Technology under contract from the U.S Air Force, first demonstrated in early 1952. This was the first application of computers to manufacturing automation.

These early computer-controlled machine tools were driven through series of preprogrammed motion steps, varying spindle speeds, feedrates, and later changing cutting tools. An open-loop control system was used to send computer-processed instructions from the computer control to the stepping motors, causing motion in either the cutting tool or the work table. The computer had no

feedback input from the motion to verify that the hardware executed the commands as required.

The NC machine tool operator's job was to "setup the part, start the control, carry out any manual interventions, such as tool changes, and resolve problems as they occur" (Boyle, 1986, p. 230). The operator was capable, depending on the cycle time and length of production runs, to operate more than one NC machine. One early advancement in NC machine tools was the incorporation of a closed-loop system for the machine to monitor error in motion. This allowed the machine controllers to counteract axes' motion errors. As the cost and size of more sophisticated computers were reduced, more complex tasks were incorporated into Computer Numerical Control (CNC) controllers. This included accurately measuring machined surfaces and adaptive control for automatically compensating for tool wear and material conditions.

#### Manufacturing Intelligence

With advancements in computer technology, both hardware and software, manufacturing systems are employing artificial intelligence, mainly through the application of expert systems to perform useful functions in the automation of specific manufacturing tasks. The intent in developing manufacturing expert systems "is to provide some level of nonhuman decision making, without having to

completely utilize the on-line interaction of humans"  
(Graham, 1988, p. 220).

Considine and Considine (1986) identify four goals of manufacturing automation: improved productivity, enhanced product quality, upward shift of worker's role, and the reduction of personnel accidents. Improved productivity is directly related to a firm's profitability and return on investment, realized through increased production capacity and better inventory control. Enhanced product quality improves the firm's position with the customer and gives them a competitive advantage. The upward shift of the labor force is caused by reducing low-skilled positions and an associated increase in higher-skilled needs of automated manufacturing. The reduction of personnel accidents is through the appropriation of accident-prone tasks by automated processes.

## CHAPTER III

### METHODOLOGY

#### Introduction

The purpose of this work was to test the feasibility of automated testing of cast iron to enhance the efficiency and, perhaps, the effectiveness of manual methods of quality control in a production setting. The work was done in conjunction with an industrial partner (who wishes to remain unidentified), at the University of Northern Iowa's Department of Industrial Technology Metal Casting Center. An overview of the work is provided below and details of the methodology follows.

#### Overview

This feasibility test consisted of four steps-- inspection cell design, software development and integration with the inspection cell, testing of actual castings, and follow-up of the tested castings. A general discussion of each of these steps follows.

The first step involved the design of the apparatus (inspection cell) necessary for the automated testing which was to be carried out using ultrasonic inspection of actual castings. The specific make-up of the inspection cell had to be determined and components selected to: perform the ultrasonic A-Scan and collect the echo signatures,



automatically position the transducer at the various points to be inspected, and integrate all the testing activities.

Once general decisions about the inspection cell were made it was possible to begin design of the software which would analyze the echo signatures and indicate whether the signature suggested the existence of subsurface discontinuities in the regions of the castings that were to be tested. Development of the software involved working with a skilled ultrasonic inspector from the industrial partner to understand the methods and procedures for inspecting the specific casting using ultrasonic equipment, this knowledge was emulated in the control software. This process had several steps: initial design of the software, an interactive process of scanning test blocks (of known quality) supplied by the industrial partner and revising the software until satisfactory assessments of the test blocks were achieved, and integration of the testing software with the automatic positioning equipment of the inspection cell.

The next phase of the cell development involved the testing of a lot of 105 castings. These casting were processed through the inspection cell. The castings passing the developed inspection criteria were returned to the manufacturer for machining into finished parts where they were visibly inspected after machining for defects.

The castings found to have ultrasonic signatures consistent with subsurface discontinuities were manually inspected by the skilled ultrasonic inspector, with the manual inspection time recorded for comparison to the automated cycle time. The castings then were inspected using destructive testing techniques for detecting subsurface material voids.

#### The Problem

The foundry funding this research had identified a problem of defects, subsurface shrinkage cavities (one type of subsurface discontinuity), near the top of 17 bosses in a specific iron casting. "A shrinkage cavity is a jagged hole or spongy area lined with fernlike crystals called dendrites" (American Foundrymen's Society, 1966, p. 111). The causes of shrinkage cavities include abrupt changes in section size (American Foundrymen's Society, 1972), typical of the 17 identified problem locations. Hénon, Mascré, and Blanc (1971/1974) identify net expansion in cast iron as one of the most frequent causes:

The expansion which takes place within the solidified surface areas of the casting causes displacement of the liquid from the central region, creating a void. This void is not filled when the residual liquid solidifies because feeding is impaired by a dense network of dendritic crystals. (p. 107)

Because of the resources necessary to perform 100% manual ultrasonic inspection of the problem areas, a less expensive approach is necessary to detect the defects to reduce scrap costs associated with the additional work that

is performed on the castings before finding the defects in later manufacturing processes. The foundry funding this research has specified that the inspection process is to take place prior to any machining of the casting. The castings used in this study to develop and test the inspection cell were supplied by the foundry in the typical condition that exists on the production line at the required specified stage in the manufacturing process.

#### Inspection Cell Description

The automated ultrasonic inspection cell consisted of an immersion tank, Panametrics EPOCH 2002 digital ultrasonic flaw detector (UFD), Panametrics 5.0 Mhz V309-SU ultrasonic transducer in a normal beam pulse-echo arrangement, Hitachi M5030 robot, and a 80386 CPU based microcomputer. The immersion tank was fitted with a part holding fixture, supplied by the foundry, for locating the part while under inspection. The parts were manually loaded and unloaded for testing and evaluation purposes.

The Panametrics EPOCH 2002 digital UFD was used to transmit and receive the ultrasonic signals, perform the analog-to-digital conversion of the signal echo of the A-Scan from the transducer, and average multiple A-Scan signatures together. The UFD has an optional RS-232 communication port, running at 19.2 kilobaud for full command and communication capability with the cell

computer. This is the same type of UFD typically used for manual inspection, only with the addition of a communication interface.

The development of the computer program to perform the necessary zeroing procedures on the UFD were developed in conjunction with the skilled ultrasonic inspector. This involved the observation of UFD setup and zeroing by the inspector, as well as emulating the process and decision logic with the developed software.

The Ultrasonic Inspection Cell Control Software (UICCS) performs the zeroing routine to adjust the UFD for variations in casting height, which required taking an initial reading to determine the transducer distance to the part surface, adjusting the signal peaking the echo signature of the part surface, and adjusting the zero offset of the UFD to place the part surface at the zero reference of the flaw detector display. In manual operation, the inspector adjusted the UFD by viewing the echo signature on the display and adjusting front panel controls.

#### Test Blocks

A set of nine test blocks, supplied by the foundry and machined from a sample casting, was used for evaluation and development of the system. Seven test blocks had 0.089 in. flat bottom holes drilled from the back side at varying

distances from the part entrance surface, one hole in each block, representative of the location and minimum size of defects to be detected.

#### Ultrasonic Transducer Selection

Working with a skilled ultrasonic inspector, a series of tests were run using 2.25 Mhz, 3.5 Mhz, and 5.0 Mhz transducers. The inspector calibrated the UFD according to standard calibration procedures. All three transducers produced acceptable results for the inspector to locate and identify the simulated defects in the test blocks. For computer analysis of the ultrasonic echo signature, the 5.0 Mhz transducer was selected because it produced the signature with the maximum differentiation between the relative echo signal amplitude of the simulated defects and the echo noise in the surrounding part.

The Panametrics V309-SU (SN:124007) unfocused 5.0 Mhz immersion transducer that was selected for use in the cell has a nominal element size of 0.50 in. The transducer specifications and technical notes (Panametrics, 1991) calculate the near field far limit at 5.287 in. using a water coupler. "The minimum and maximum practical focal lengths have been determined by considering the acoustic and mechanical limitations" (p. 32). For the 5.0 Mhz transducer using a water coupler, the minimum practical focal length is specified at 0.75 in., and the maximum at

4.20 in. A transducer to part distance of one inch was used for programming the transducer placement. This allowed for minor part height variations in the holding fixture without violating the minimum practical focal length.

#### Ultrasonic Signature

The ultrasonic inspection data collected from each inspection location consisted of 200 digitized data points, representing the ultrasonic signature of the location under inspection, for a depth of 1.0 in. Each digitized data point represents 0.005 in. of material thickness. This signature is called an A-Scan. "The A-Scan plots reflection amplitude versus time" (Wolters, 1980, p. 35).

#### Ultrasonic Signature Evaluation Criteria

The development of the ultrasonic signature evaluation criteria was based upon the problem areas in the casting identified by the foundry. They specified that shrinkage cavities were known to occur near the surface of the 17 bosses on the part. The part bosses were designed so the top 0.150 in. are machined off in the manufacturing process. The foundry identified that the defects can fall in the top 0.750 in. of the boss area after machining and have a larger concentration near the surface. The ultrasonic signature evaluation criteria were developed

from test blocks having simulated defects of varying depths.

The parameters for evaluating the ultrasonic signature were developed using the echo signatures from the test blocks. Working with a skilled ultrasonic inspector, UFD inspection settings were developed for inspecting the bosses (see Appendix A). This involved taking a series of A-Scans of the test blocks, interpreting the data, and constructing the acceptance/rejection criteria. Sample signatures were collected from test blocks A-G (Figures 9 and 10 typify the set collected).

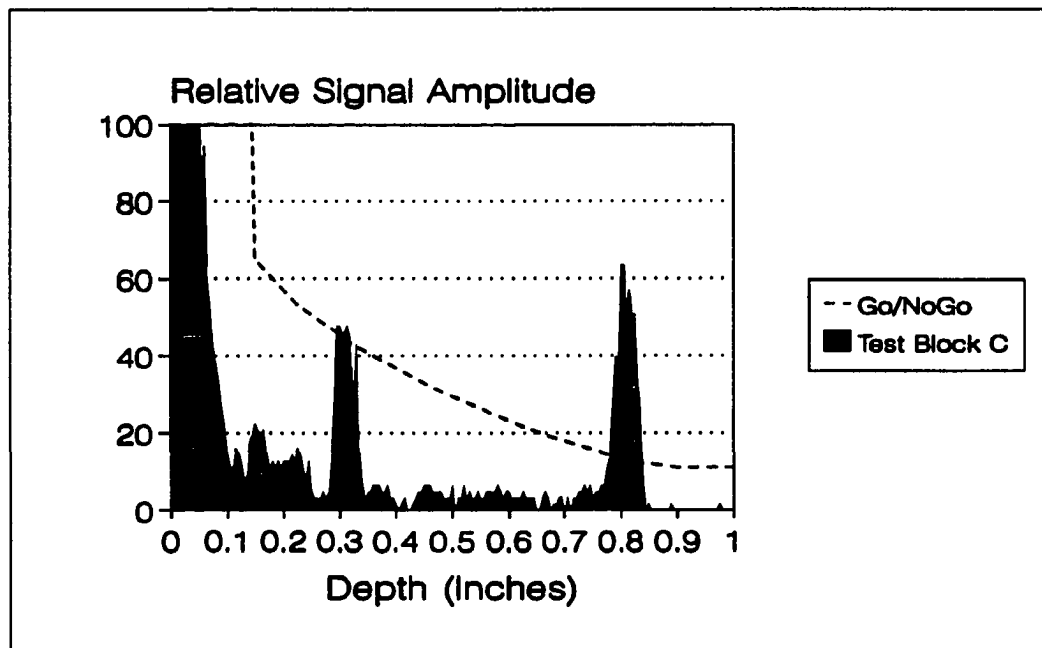


Figure 9. Ultrasonic A-Scan, test block C.

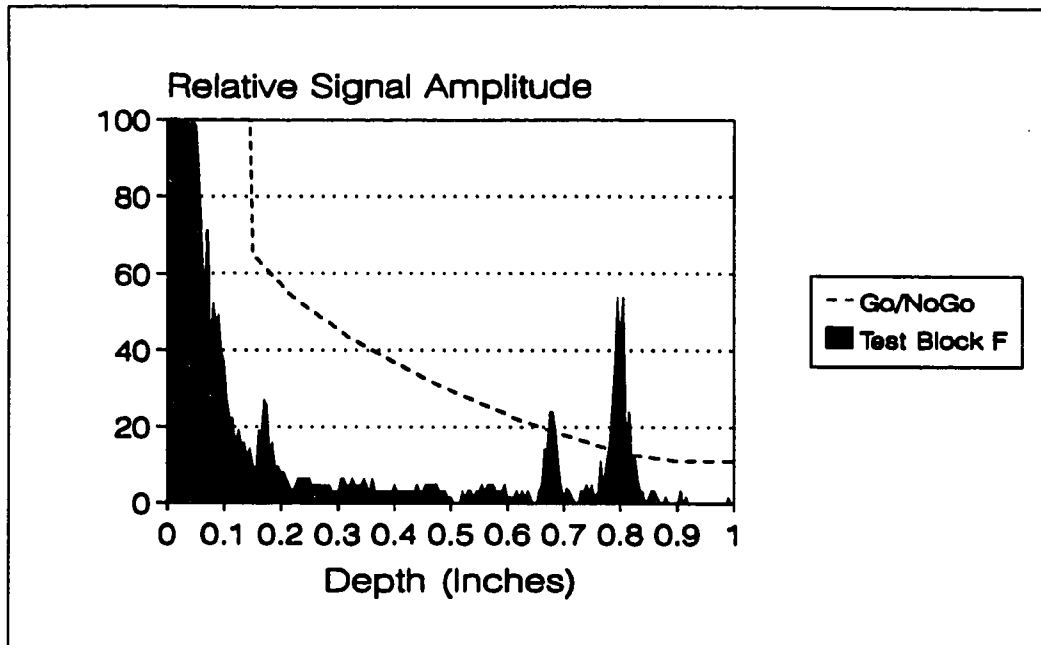


Figure 10. Ultrasonic A-Scan, test block F.

The developed criteria were a series of data point values, representing the minimum peak relative signal levels for part rejection. The developed parameters were used to evaluate each inspection signature for a Pass/Fail or Go/NoGo decision. Echo signatures that pass the inspection criteria were defined not to have a defect; echo signatures that fail the criteria were classified as having suspected defects.

Initial testing and development was performed in a static setup where the transducer was fixed above the test block under inspection. The test block runs for verifying the software and finding the error rates were performed in



a dynamic setup where the robot was programmed to move the transducer into position for each A-Scan. It was found that the robot induced a vibration into the dynamic setup that resulted in very high levels of signal noise and unstable images. This problem was very apparent in that A-Scans of the test blocks void of defects had noise levels sufficient to violate the Go/NoGo parameters in 48% of the cases in the initial dynamic test run. The total error rate for the test blocks with simulated defects in the initial dynamic test run was 1.14% (see Table 1).

The solution to the problem involved four basic modifications to the cell operation and software. First, the robot's approach speed to the inspection point was decreased. This reduced the vibrations injected into the system by the robot. Second, a programmed delay between the robot arriving at the inspection point and the start of the A-Scan was added. This delay dampened the robotic induced vibrations. Third, the number of A-Scans averaged together for each signature was increased to four from an initial value of three. This digital signal processing further helped in filtering out noise, both internal to the system and externally induced. Finally, the test procedure was changed to repeat any A-Scan that did not pass the inspection criteria. This test procedure modification helped in two ways--it allowed a minimum programmed delay

Table 1

Software Development VerificationDynamic Test Block Run 1

Block	Flaw Depth (in inches)	Go	NoGo	Error
A	.20	0	100	0%
B	.25	0	100	0%
C	.30	1	99	1%
D	.40	3	97	3%
E	.50	1	99	1%
F	.60	1	99	1%
G	.70	2	98	2%
X	---	48	52	52%
Y	---	56	44	44%

Note. Blocks X and Y do not have any flaws.

before the start of the A-Scan, in keeping with the need for a minimum cycle time, and reduced random noise interference. After these modifications, the fifth dynamic test block run produced no errors in properly classifying the nine test blocks (see Table 2).

After the dynamic test block runs and revisions to the software, two castings, later serialized as AA and AB, were tested in the integrated ultrasonic inspection cell. This testing involved verifying cell operation, both hardware

Table 2

Software Development VerificationDynamic Test Block Run 5

Block	Flaw Depth (in inches)	Go	NoGo	Error
A	.20	0	100	0%
B	.25	0	100	0%
C	.30	0	100	0%
D	.40	0	100	0%
E	.50	0	100	0%
F	.60	0	100	0%
G	.70	0	100	0%
X	---	100	0	0%
Y	---	100	0	0%

Note. Blocks X and Y do not have any flaws.

and software, determining cell cycle time, and verifying classification error rates on 34 additional bosses. Both castings were inspected 25 times, with each repetition inspecting 17 bosses, for a total of 850 inspection points. Both castings were found to be void of subsurface discontinuities. There were no classification errors during the test repetitions, but communication problems with the UFD were encountered that caused the system to halt the inspection cycle. The cause of the communication problem

was isolated to the internal software of the UFD. The only method of reestablishing the communication link was to manually power the UFD off and back on. The UICCS was modified to detect the problem and notify the operators of the situation, which required human intervention to correct. This communication problem occurred three times during later cell testing, requiring aborting an inspection cycle and starting the part inspection over.

#### Signal Processing

Wolters (1980) showed that the signal processing technique of averaging A-Scans resulted in reduced echo noise in the resultant signature. As noise is an anticipated problem in cast iron from a review of the literature and preliminary testing, this signal processing technique was applied to all A-Scans internally within the UFD under software command. Initially, three A-Scans were averaged together to process out noise; later, in dynamic testing of the system, the number was increased to four.

#### Robot Programming and Interfacing

The Hitachi M5030 is a light duty electric 5-axis articulated-arm robot. The robot was programmed by way of a teach pendant to move along a programmed path, stopping at the 17 inspection points with the transducer positioned 1.0 in. above the inspection point and perpendicular to the

surface of the part (see Appendix B for robot program description and interface wiring diagram).

The robot was interfaced to the cell computer via digital I/O lines. The cell computer used an Industrial Computer Source DIO8-P optically isolated digital I/O interface for communicating with the robot. The interface was selected for the optical isolation provided between the cell computer and the robot; this allowed for safe and easy interfacing of the different signal levels used by the hardware.

The UICCS instructs the robot to select and execute a preprogrammed set of instructions. The robot sends a digital output signal to the cell computer indicating that the robot is at a predefined location (inspection point) awaiting a digital input signal from the cell computer before continuing execution of its program.

The robot was fitted with end-of-arm tooling for holding the ultrasonic transducer below the water line of the immersion tank. The end-of-arm tooling was designed to break away from the robot arm if a collision occurred.

#### The Software

The UICCS was written and compiled in Microsoft's QuickBasic V4.5, operating under Microsoft's MS-DOS V5.0 operating system. An action diagram, a program diagramming technique described by Martin and McClure (1985), of the

program is in Appendix C. The UICCS handles the communications with the UFD and robot, analyzes ultrasonic echo signatures, interfaces with the cell operator, displays A-Scan data, and produces printed inspection reports.

The software for analyzing the ultrasonic signature was developed using nine test blocks, seven of which had flat bottom holes at varying depths, and two which were void of defects were used in the development and calibration of the cell hardware and software.

The software development goal, as specified by the industrial partner, was to have less than a 5% error in correctly classifying test blocks with simulated defects, and 1% error in properly classifying test blocks void of defects. For calculating classification error rates, each test block was inspected 100 times. The software development cycle involved analyzing the signatures of erroneously classified test blocks and developing solutions to achieve development goals.

#### Manual Inspection of Suspected Castings

The evaluation phase involved the testing of 105 production castings. The castings were serialized and identified as AA through EA. Production castings evaluated as passing were machined into finished products with any discovered defects in the inspected locations reported.

Production castings failing the developed inspection criteria were manually inspected using contact ultrasonic inspection by a skilled inspector, and then inspected using destructive technique.

#### Understanding Cell Operation

Understanding how the automated ultrasonic inspection cell operates is best achieved by following an example part through the system. (A flow chart of the cell operation can be found in Appendix D.) When the part is loaded onto the holding fixture, the cell is ready to inspect the part.

The UICCS requires the operator to input the part serial number. This information is used to match the collected data with the individual part. The UICCS first instructs the robot to select a stored set of instructions that were previously programmed into the robot via a teach pendent. The UICCS then instructs the robot to start execution of the selected instruction set, causing the robot to move the transducer that is mounted on the robot arm to the first preprogrammed inspection location. While the robot is moving to the inspection location, the UICCS commands the UFD to recall a set of initial parameters that are stored in the unit's memory. These parameters control the operation of the interface between the UFD and the transducer. The UICCS then waits for a signal from the robot indicating arrival at an inspection point. Upon the

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robot's signal of arrival, the cell computer delays for one second to dampen the robot's vibrations that could interfere with obtaining a reliable A-Scan.

The UFD requires the operator, when using the UFD for manual ultrasonic inspection in an immersion tank, to make a series of adjustments to the unit using the UFD display to view the ultrasonic signature and UFD keypad for entering parameter adjustments. The UICCS must duplicate these operator's skills and decision making ability to perform the same setup tasks through the communication interface. The setup tasks are adaptive in nature, the software must make adjustments to external equipment based upon sensorial input.

The first adaptive control task of the UICCS is to peak the part surface echo's relative signal level. This task is required because of casting material variations in material thickness and surface condition causing the distance between the ultrasonic transducer and part surface to vary.

The task starts with the UICCS commanding the UFD to take an A-Scan; all A-Scans are programmed to be the results of four time-sequential A-Scans averaged together, digitally processing out most of the signal noise. The analog A-Scan signature is converted to a digital representation comprised of 200 data points within the UFD,



with each data point containing a relative signal amplitude between 0 and 63 along a time interval calibrated to represent a distance of 0.005 in., making the data set represent a depth of 0.995 in. The UFD acknowledges successful completion of the A-Scan averaging to the UICCS. The UICCS then commands the UFD to upload the A-Scan signature data set.

The UICCS needs to identify the part surface of the casting in order to adjust the zero offset. The part surface is the peak echo signal in the A-Scan signature data set, but at low relative amplitude signal levels, resolution of the part surface from the data set is not possible, so the relative amplitude signal level must be increased to determine the relative part surface location within the data set.

If the peak echo signal, representing the part surface, is below the maximum relative amplitude of the data set the UICCS calculates the needed signal level increase necessary for the peak echo signal to approach the maximum relative amplitude. This signal level change is downloaded to the UFD, along with another request for an A-Scan. The new A-Scan is then uploaded to the UICCS. This process is repeated until the peak echo signal from the part surface is at the maximum relative amplitude.

The second adaptive control task of the UICCS is to adjust the UFD's zero offset to place the part surface echo at a depth of zero in the A-Scan signature data set. The UICCS calculates the needed zero offset for the UFD so that the part surface approaches the zero depth position in the A-Scan signature data set. Due to signal impedance variations within the casting and between different casting, the ranging capability of ultrasonics is not exact, but only an approximation; these impedance variations cause the speed of the signal to vary. The ranging error is reduced as the distance measured decreases, this necessitates the adaptive control to make adjustments that approach the desired results, repeating until the solution is achieved. The UICCS downloads to the UFD the new zero offset value, requests an A-Scan, and uploads the A-Scan signature data set. This process is repeated until the part surface is at the zero depth position in the A-Scan signature data set.

Upon successful completion of the two adaptive control tasks, the UFD is ready to inspect the boss. The UICCS sets the inspection signal level (67 dB) in the UFD for the inspection A-Scan, then commanding an A-Scan and the uploading of the A-Scan signature data set. The uploaded A-Scan signature data set is compared to the Go/NoGo criteria. The A-Scan passes the Go/NoGo criteria if all

the data points relative amplitudes fall below the rejection criteria. If the A-Scan fails the Go/NoGo criteria, the A-Scan is discarded and the inspection point is reinspected; this reinspection is to reduce misclassifications caused by internal and external noise. The second A-Scan is used to determine if the inspection point passes or fails. The last A-Scan of an inspection point is saved to a data file.

The UICCS then instructs the robot to continue executing its instruction set, causing motion to the next inspection location or after the last location returning to a home position. The UICCS repeats the sequence of events for each inspection location. A part passing all inspection criteria for each inspection point is classified as a good casting; failure of any inspection criteria will classify the part as having a possible defect. If a part is found having a possible defect, the whole part is reinspected two additional times.

CHAPTER IV  
PRESENTATION OF RESULTS

Overall Results

The testing of 105 castings involved the ultrasonic inspection of 1785 bosses. Five bosses failed the inspection criteria, one each on five different castings. The remaining 1780 bosses had no ultrasonic signatures consistent with subsurface discontinuities. The 100 castings that had all 17 bosses passing the inspection criteria were returned to the manufacturer for machining into finished products. The manufacturer reported they found no shrinkage cavities in the inspected areas during the manufacturing or final inspection process.

Of the five castings, each with a boss failing the inspection criteria, AZ, BJ, and BS failed each of the three test repetitions. Castings DK and DX both failed only two of the three test repetitions. All five bosses were manually inspected by the foundry's ultrasonic NDE inspector using contact transducer procedures. This required that the rough casting surfaces be machined flat for good contact transducer coupling. After machining of the rough cast surface, the inspector could not identify any subsurface discontinuities in castings BJ, DK, or DX. Ultrasonic echo signatures consistent with the depth location from the automated ultrasonic A-Scans were

Table 3

Inspection Results of Castings FailingUICCS Inspection Criteria

Serial Number	Inspection Points																Summary	
	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	UICCS
AZ(1)	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	P	F	F
AZ(2)	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	P	F	
AZ(3)	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	P	F	
BJ(1)	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	F	P
BJ(2)	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	F	
BJ(3)	P	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	F	
BS(1)	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	F	F
BS(2)	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	F	
BS(3)	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	P	F	
DK(1)	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	F	P
DK(2)	P	P	P	P	P	P	P	P	P	P	P	P	P	F	P	P	F	
DK(3)	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	
DX(1)	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	F	P
DX(2)	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	F	F	
DX(3)	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	

Note: P = Pass, F = Fail

identified by the inspector in castings AZ and BS. The automated inspection erroneously classified 3 of the 1785 bosses inspected. The UFD used by the inspector was not capable of producing either hardcopy or data file output. Table 3 summarizes the test results of the five castings failing the UICCS inspection criteria for both the UICCS analysis of the signature and the manual inspection of castings.

Destructive testing for subsurface shrinkage cavities in the five suspect castings was performed by the foundry. No subsurface shrinkage cavities (one type of subsurface discontinuity) were reported in the five suspected bosses. The destructive testing involved the machining of successive layers of material, visually inspecting each layer for shrinkage cavities breaking through the machined surface. This destructive testing was only capable of finding subsurface shrinkage cavities and not qualifying other subsurface discontinuities that can produce echoes.

#### Results of Good Castings

The 100 castings determined to be void of subsurface discontinuities in the inspected regions all produced A-Scans that fell within the acceptance criteria for a good part. Figure 11 shows the peak relative signal amplitude of all A-Scans that met the acceptance criteria shown by the Go/NoGo line. The Go/NoGo is displayed on all A-Scans of

reference. The A-Scan of AA-01, the first boss of casting serial number AA and typical of the A-Scans passing the inspection criteria, is shown in Figure 12. Additional typical A-Scans of bosses passing the inspection criteria are shown in Figures 13-14.

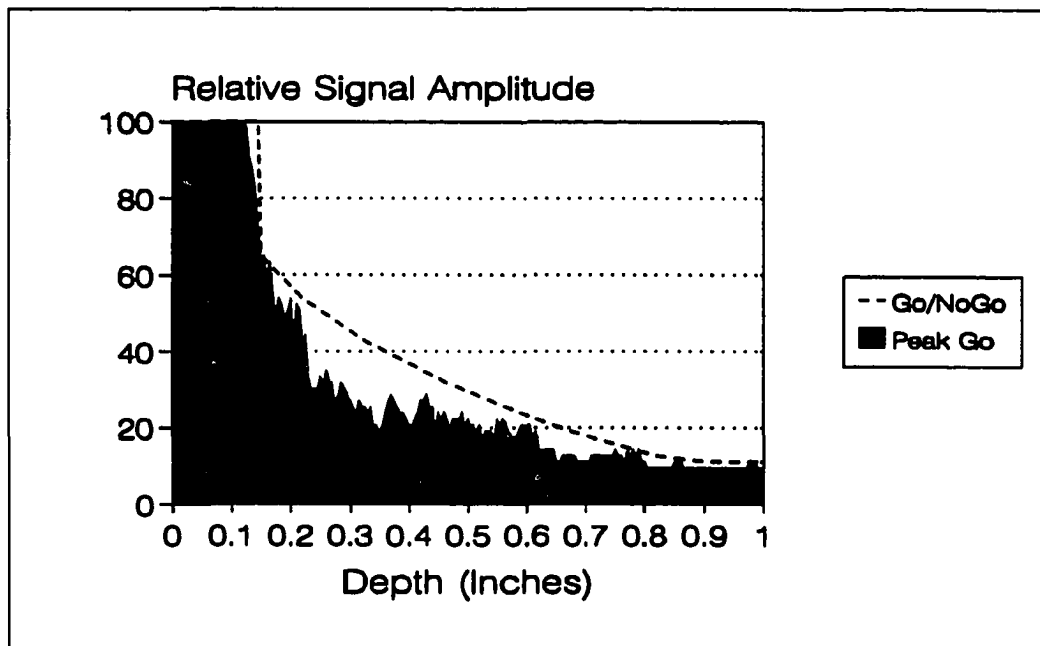


Figure 11. Ultrasonic A-Scan, peak go signals.

#### Results of Suspected Defective Castings

For each casting having suspected defects, there are three A-Scans of the suspected bosses. Bosses AZ-12, BJ-04, and BS-14 were identified as failing the Go/NoGo demarcation in each of the three data sets. It should be noted that the UICCS required two sequential failures to

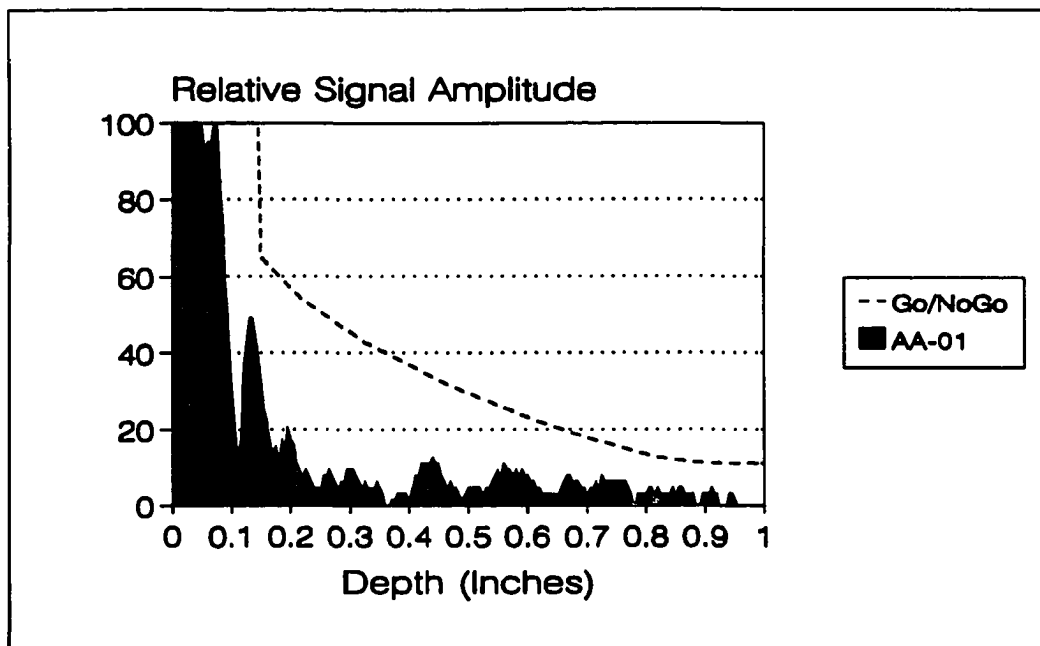


Figure 12. Ultrasonic A-Scan, AA-01.

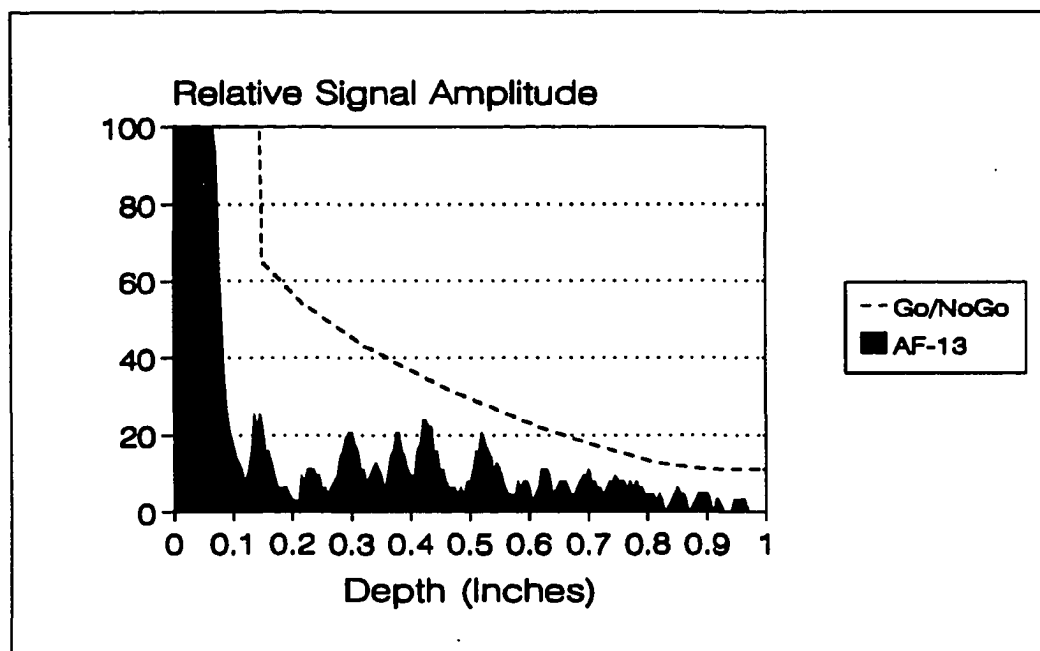


Figure 13. Ultrasonic A-Scan, AF-13.



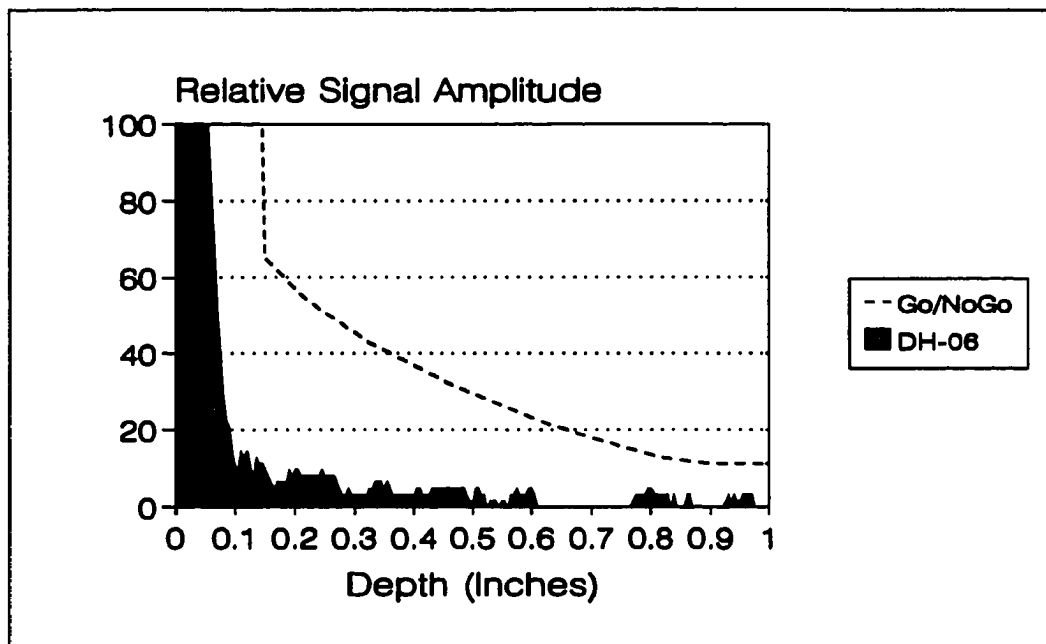


Figure 14. Ultrasonic A-Scan, DH-06.

flag the boss as failing. This repeat failing was without the repositioning of the robot. Upon failing in the first set, the operator reinspected the complete part two additional times.

Part number AZ, boss 12 (AZ-12) shows an echo at about the 0.175 in. depth in all three A-Scans failing the acceptance criteria. This was verified by manual inspection (see Figures 15-17). Boss BJ-04 shows an echo violating the acceptance criteria at about the 0.150 in. depth. This was not verified by manual inspection (see Figures 18-20). Boss BS-14 shows in all three A-Scans an acceptance criteria violation at the 0.50 in. depth. This

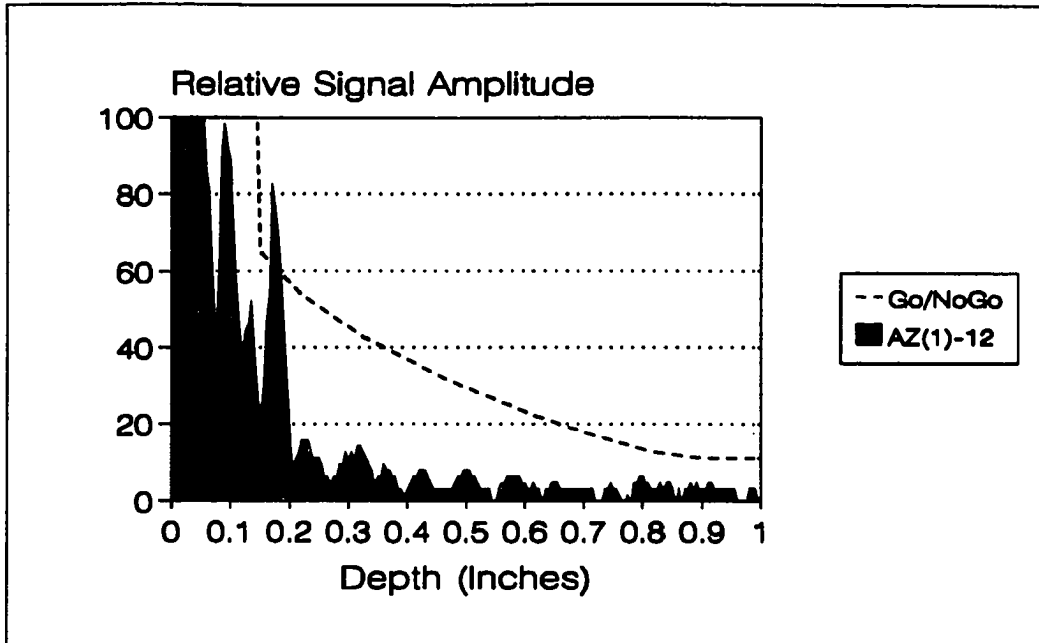


Figure 15. Ultrasonic A-Scan, AZ(1)-12.

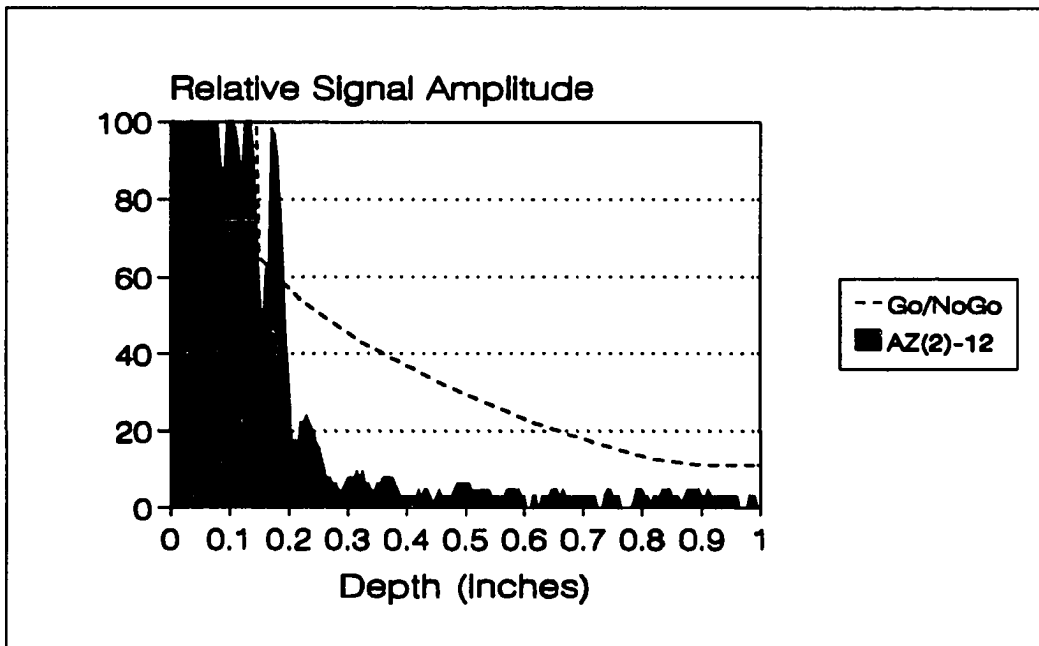


Figure 16. Ultrasonic A-Scan, AZ(2)-12.

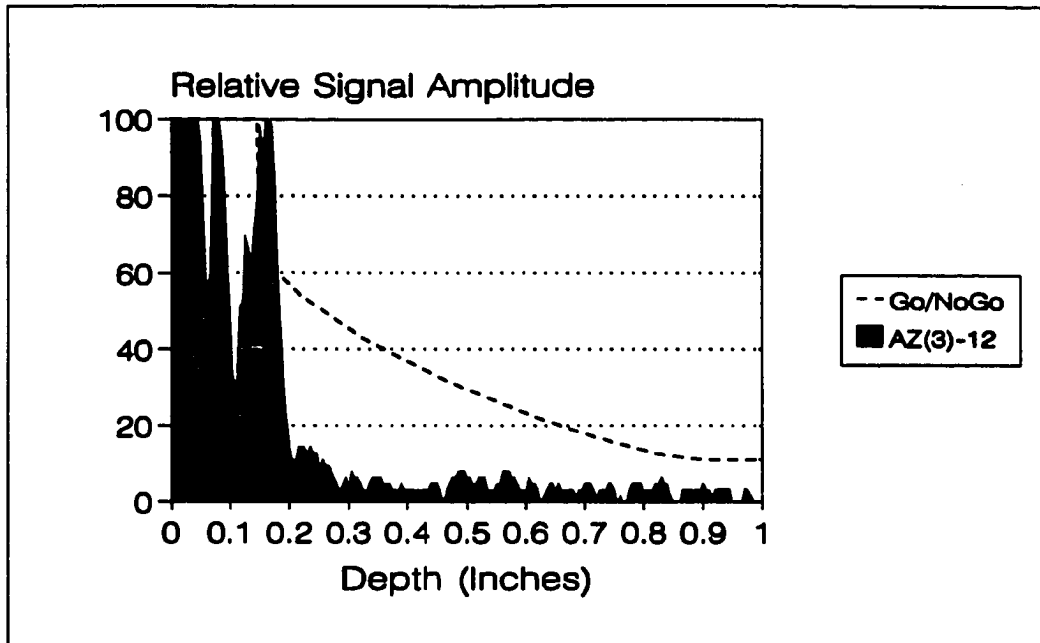


Figure 17. Ultrasonic A-Scan, AZ(3)-12.

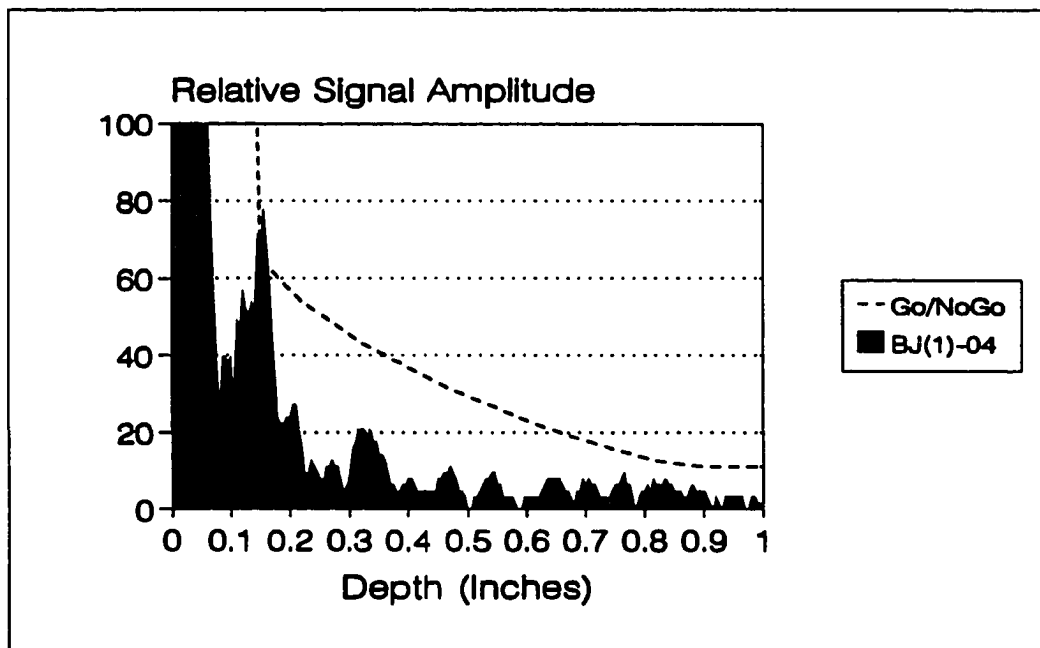


Figure 18. Ultrasonic A-Scan, BJ(1)-04.

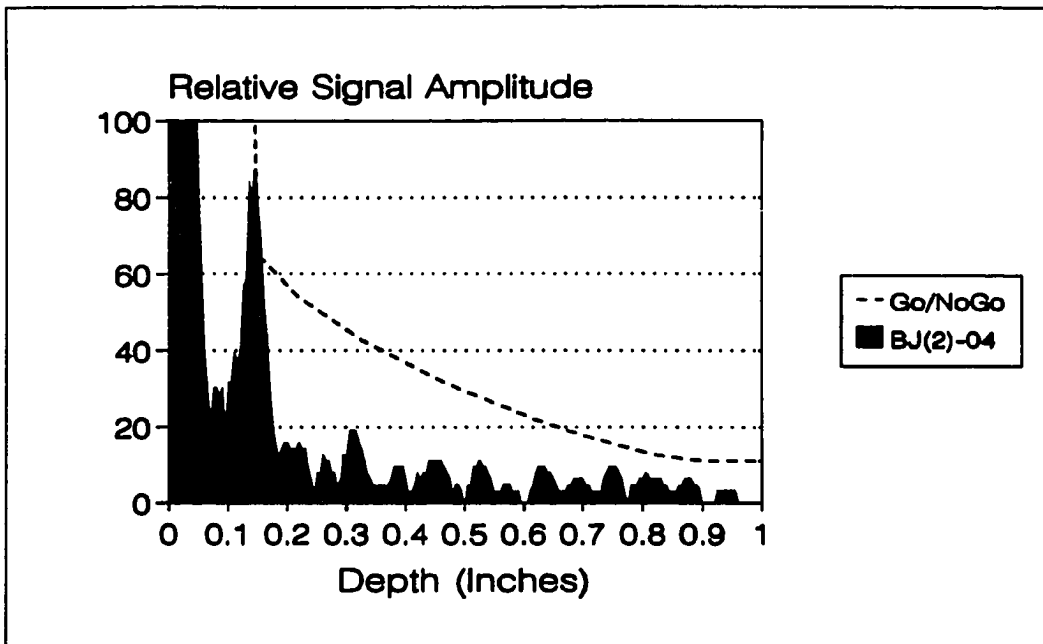


Figure 19. Ultrasonic A-Scan, BJ(2)-04.

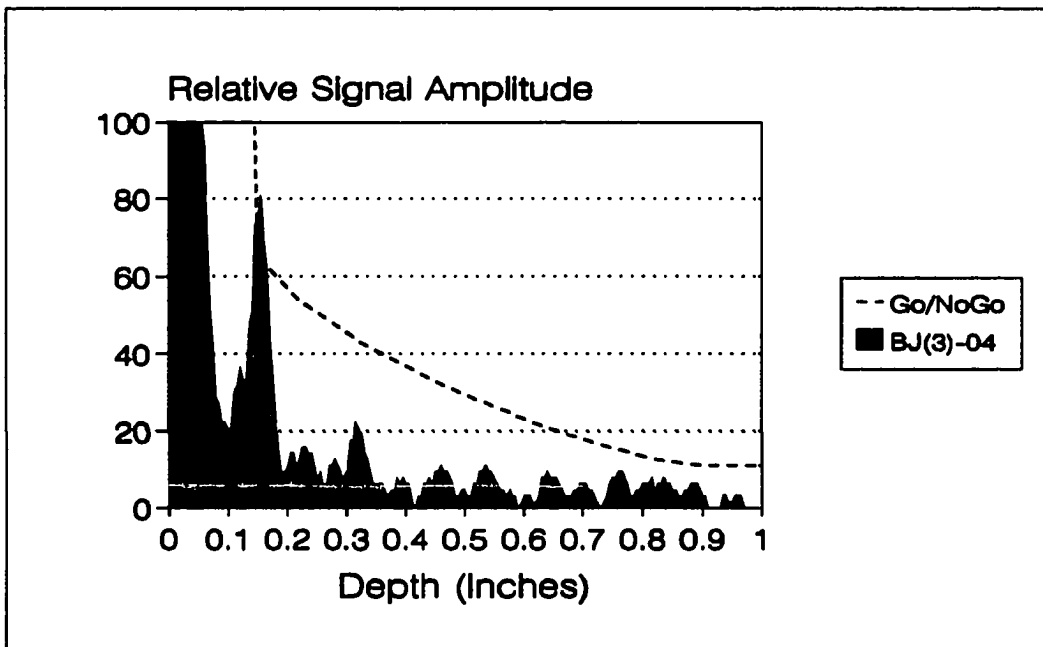


Figure 20. Ultrasonic A-Scan, BJ(3)-04.

was also verified by manual inspection (see Figures 21-23). Boss DK-15 shows a strong echo at the 0.20 in. depth, but only violating the inspection criteria in two of the three scans (see Figures 24-26). Boss DX-17 shows a strong echo near the 0.15 in. depth, violating the inspection criteria in only two of the three scans (see Figures 27-29).

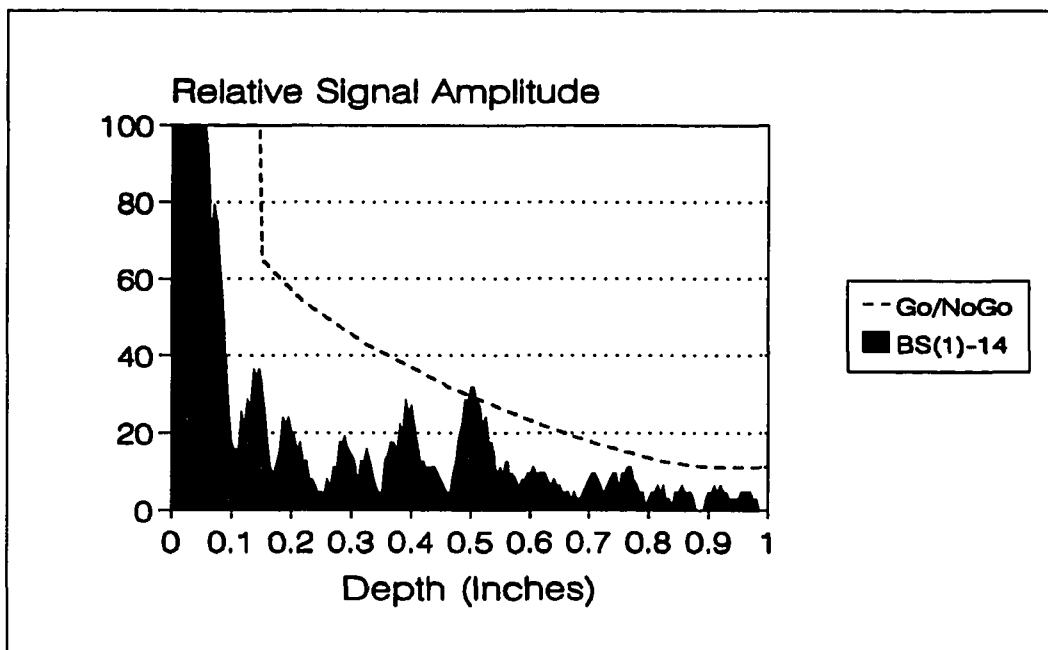


Figure 21. Ultrasonic A-Scan, BS(1)-14.

#### Inspection Cycle Time

Inspection cycle time was an important UICCS design consideration. The cycle time data was processed using SPSS/PC+ 4.0 (1990). The mean cycle time for automatic inspection of a casting (17 bosses) was 3.242 min ( $N = 50$ )

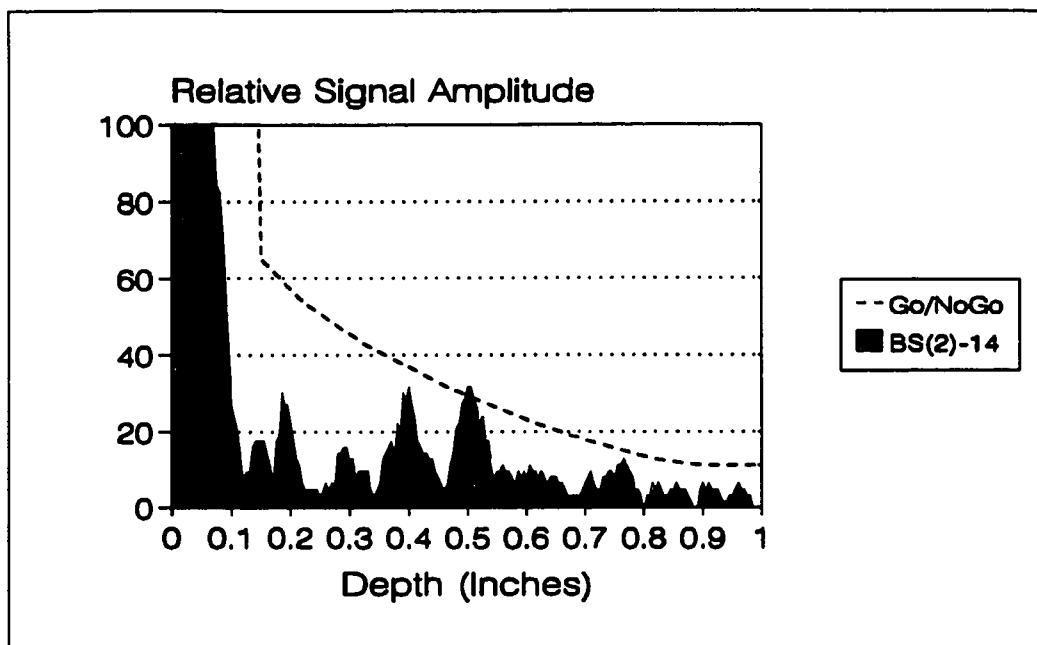


Figure 22. Ultrasonic A-Scan, BS(2)-14.

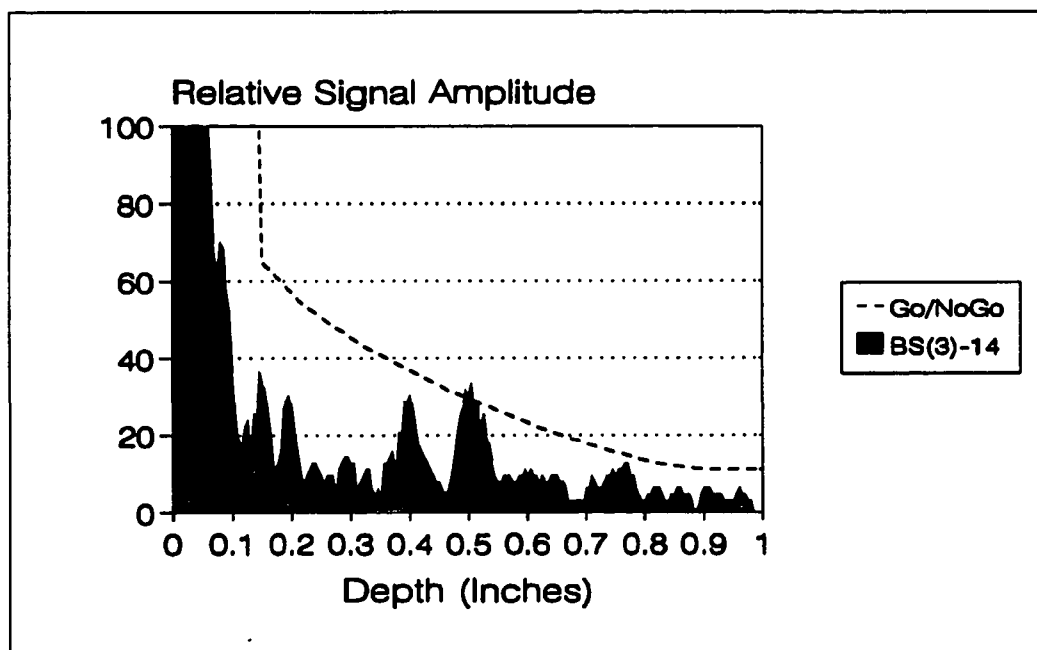


Figure 23. Ultrasonic A-Scan, BS(3)-14.

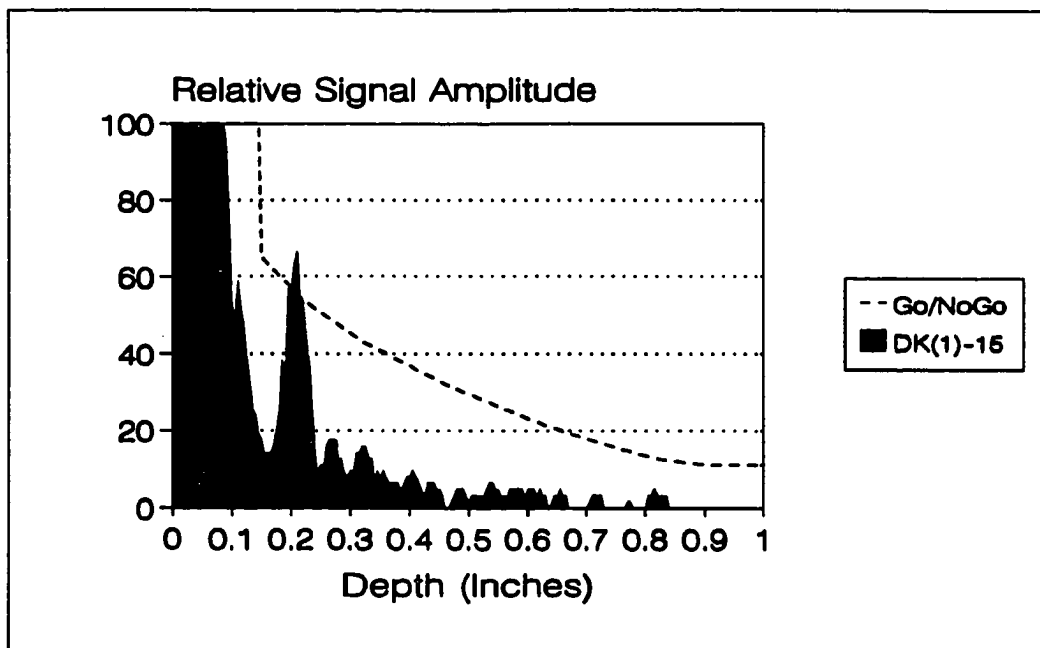


Figure 24. Ultrasonic A-Scan, DK(1)-15.

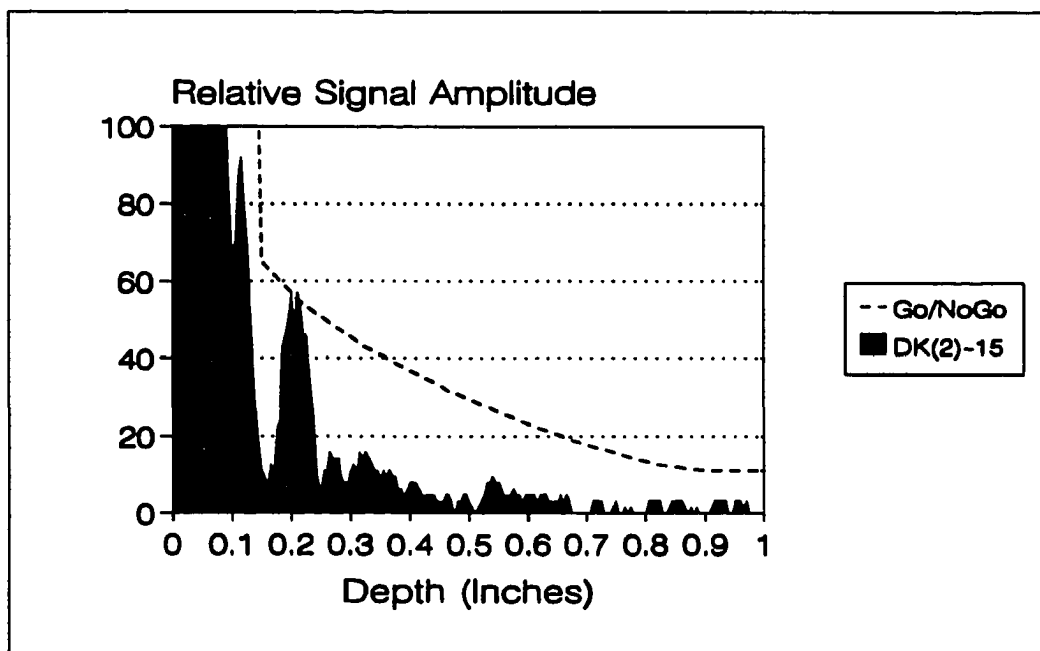


Figure 25. Ultrasonic A-Scan, DK(2)-15.

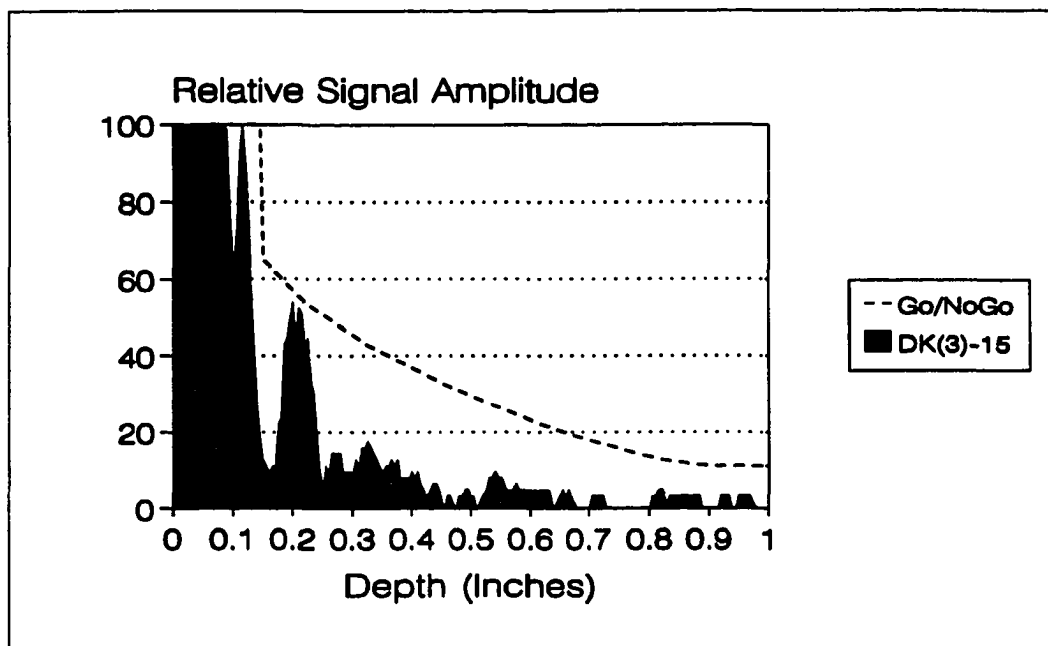


Figure 26. Ultrasonic A-Scan, DK(3)-15.

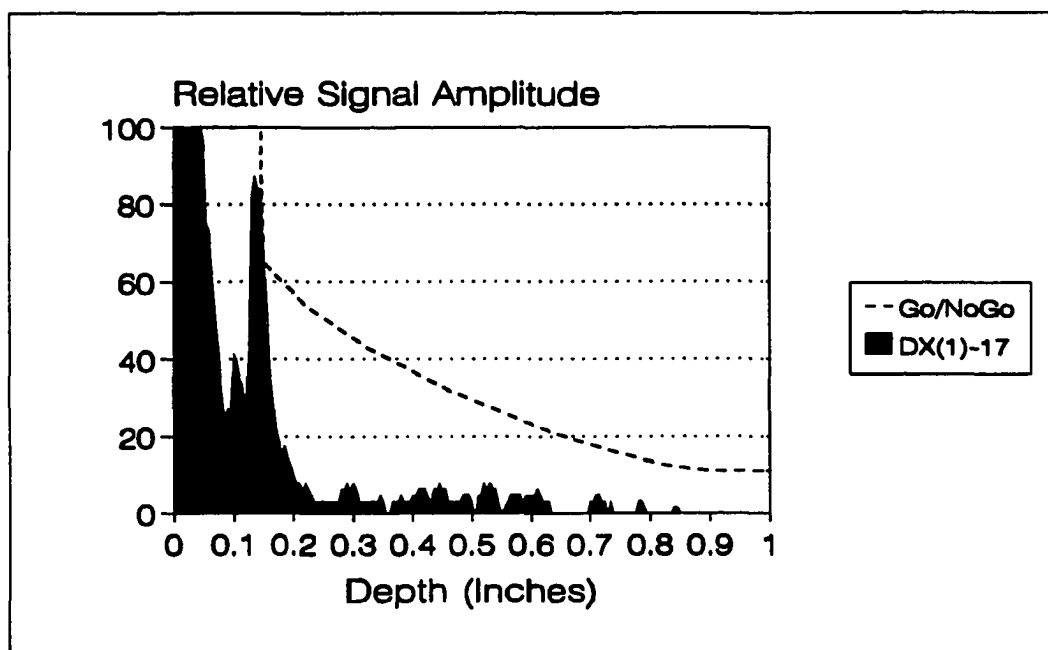


Figure 27. Ultrasonic A-Scan, DX(1)-17.



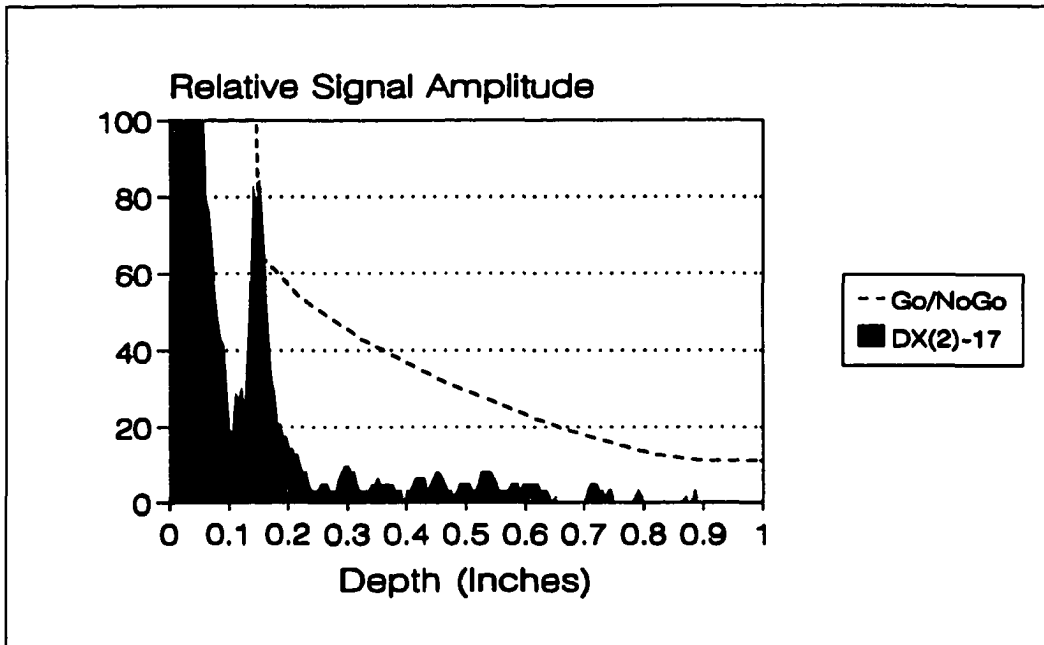


Figure 28. Ultrasonic A-Scan, DX(2)-17.

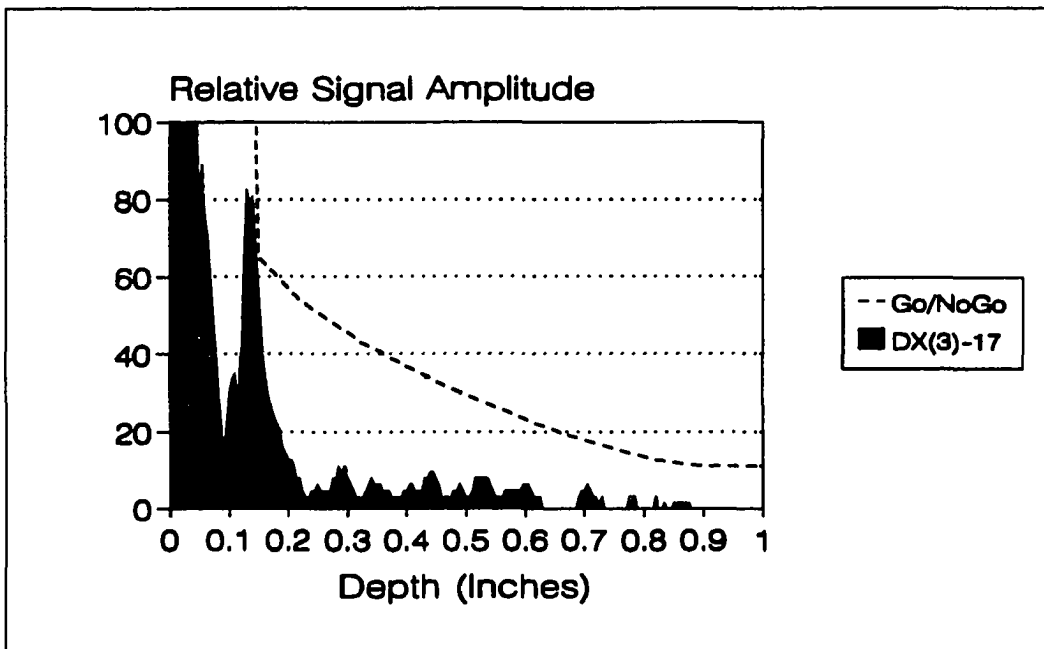


Figure 29. Ultrasonic A-Scan, DX(3)-17.

with a standard deviation of 0.254 measured during the test run repetitions on casting AA and AB. The cycle time data was positively skewed (Skewness = 1.404). Figure 30 is a histogram of the inspection cycle time. The histograms were produced by the Graphic routine in SPSS/PC+ 4.0 (1990).

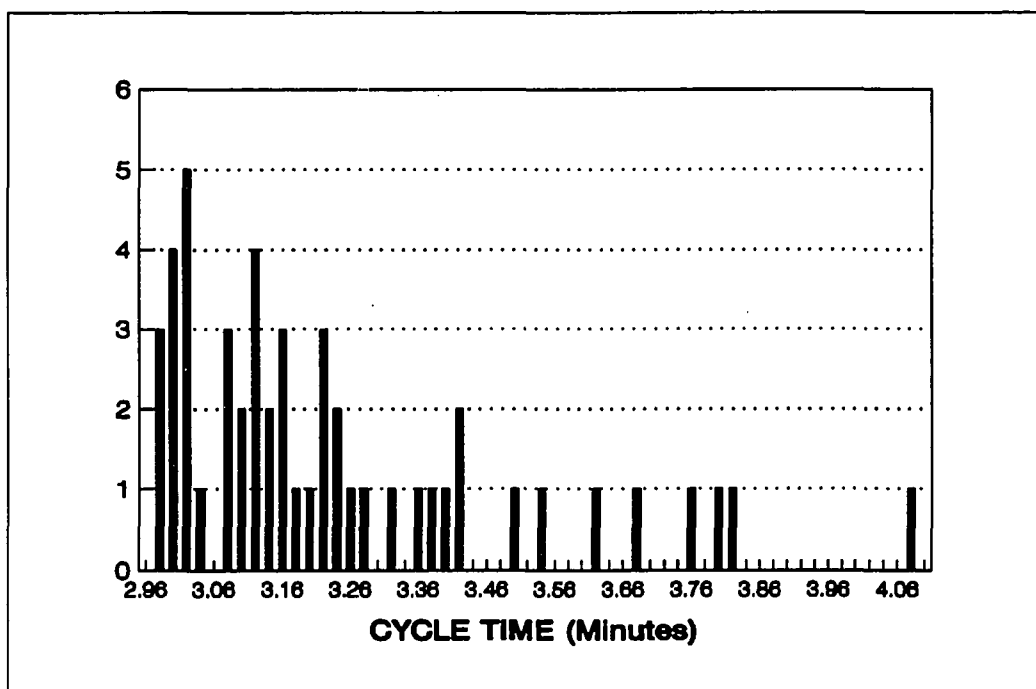


Figure 30. Automated inspection cycle time for one part.

A large segment of the measured cycle time was comprised of communications with the UFD and waiting for the UFD to complete the A-Scan task. A minimum of five A-Scan data sets were required for instrumentation zeroing

and inspection for each boss. It took 1.2 s for the UFD to receive an A-Scan request, take four A-Scans, average them together, and notify the UICCS it was ready to upload the resultant data set. The A-Scan data set consisted of a string of 613 bytes, at 19.2 kilobaud. This required 0.32 s per A-Scan upload. A minimum of 85 A-Scan data sets needed to be uploaded from the UFD for each part. This calculates to a minimum inspection time of 129.14 s for each casting not including robotic motion. The cycle time did not include casting loading nor unloading time. In a production environment this would typically be performed by automated material equipment.

The skilled ultrasonic NDE inspector's mean cycle time for inspecting each boss was 5.760 min ( $N = 5$ ) with a standard deviation of 1.118 and negatively skewed (Skewness = -0.635) (see Figure 31). This cycle time included surface preparation, but not instrumentation setup time. This calculates to 97.92 min for manual inspection for 17 bosses (one casting).

#### Projected Direct Labor Cost Savings

Compared to the automatic inspection, manual inspection is 30 times more time consuming. Using the industrial partner's direct labor rate of \$27.37 (\$22.25 per hour labor plus 23% benefits) and the mean cycle times, the direct labor costs for manual ultrasonic inspection of

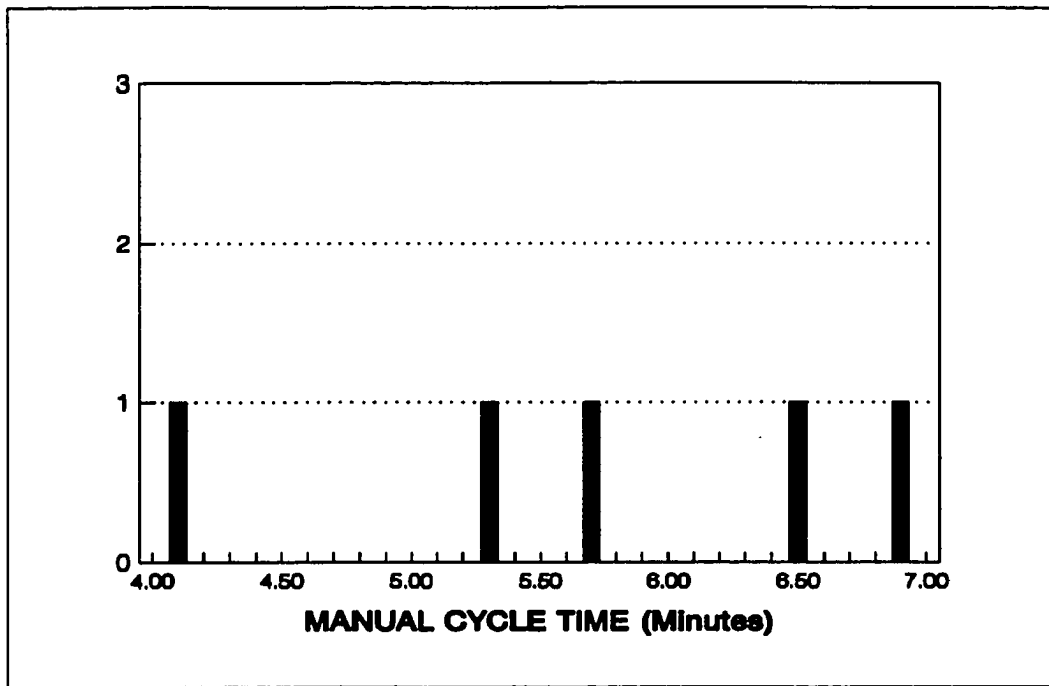


Figure 31. Manual inspection cycle time for one boss.

one casting is \$44.67. The direct labor costs for the automated ultrasonic inspection cell to inspect one casting is \$1.48. Based upon the foundry's production of 100 castings per day, the projected direct labor cost savings is \$4,319 per day. The manpower requirements are also a consideration, the automated inspection cell would require 5.4 man-hours per day to process 100 castings, the manual inspection method would require 163.2 man-hours per day.

## CHAPTER V

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The thrust of this research was to learn if a computer-controlled ultrasonic inspection cell could accurately detect subsurface casting discontinuities in cast iron and increase the efficiency of the inspection process. The developed cell used a normal beam pulse-echo transducer arrangement in an immersion tank, generating an ultrasonic energy beam which entered the boss perpendicularly to the part surface. Upon encountering a material discontinuity, part of the ultrasonic energy packet was reflected back in the direction of the ultrasonic source. Only that portion of the ultrasonic energy packet received by the transducer and converted into electrical energy was converted into an ultrasonic signature data set by the UFD and transmitted to the cell control computer for analysis by the UICCS.

The UICCS quantitatively analyzes the signature data set to decide if any data byte violated developed Go/NoGo criteria. A violation of the Go/NoGo criteria identifies a condition with the casting that reflects ultrasonic energy in excess of predetermined acceptance criteria.

The automated ultrasonic inspection cell was successful in quantifying the ultrasonic echo signatures

for the existence of signature characteristics consistent with Go/NoGo criteria developed from simulated defects. The manual inspection showed that no defects in the areas inspected by the automated cell avoided detection in the 100 castings machined into finished parts. Of the five bosses found to have subsurface discontinuities, two were verified by manual inspection after the rough casting surface was machined for the use of ultrasonic contact transducer inspection. The three remaining bosses showed no subsurface discontinuities after surface preparation for manual inspection. The developed automated ultrasonic inspection cell correctly classified 1782 of the 1785 bosses (99.832%) inspected; this was a success.

The automated inspection cycle time was an average of 30 times faster than the manual inspection of the suspected bosses. In a production situation where 100% manual inspection was required, the manual inspection cycle time could be reduced by the use of semi-automated or automated equipment for the surface preparation necessary for manual ultrasonic inspection.

#### Conclusions

The developed computer-controlled ultrasonic inspection cell is the interfacing of existing hardware technology, coupled with an expert system control program that emulates the necessary skills of a human inspector to

perform an inspection of a specific cast iron part in an expeditious manner with the minimum of operator interaction. The system is a tool, identifying areas for further investigation by a skilled inspector. It is an inspection tool that can perform 100% inspection in a timely and cost efficient manner, passing parts found void of possible defects, and identifying those castings that have an ultrasonic signature consistent with the type of flaws that a foundry wants to detect. The developed system is quantitative in design and ability. The UICCS makes a simple Go/NoGo decision based upon the relative signal amplitude of ultrasonic echoes caused by subsurface discontinuities and acceptance criteria.

The casting surface condition caused false echoes in three of the five suspected bosses, evident by the fact that the automatically detected subsurface echoes disappeared after the part surface was machined for manual inspection. The false echoes were near the top of the boss inspection area.

The destructive testing of the suspected bosses did not locate any subsurface shrinkage cavities, this was a qualitative test for detecting material voids, as opposed to the quantitative inspection for subsurface discontinuities by both the automated and manual ultrasonic inspection.

Artificial intelligence, manufacturing intelligence, adaptive control, and soft automation are all part of the technological advances that are in the process of migrating from varying development stages to industrial utilization through technology transfer initiatives. The industrial partner was satisfied with the results, their technology transfer of the developed automated inspection cell is currently in the planning and design phase.

#### Recommendations

Some recommendations ultimately are derived from research conclusions and the enlightenment the researcher encounters during the research. These recommendations hopefully influence others to look in the same direction the researcher was at the terminal point of the research.

Investigation into ultrasonic inspection methodologies to filter out surface condition interference is necessary to reduce false echoes. The qualification of ultrasonic signatures is necessary for an expert system to increase the reliability and accuracy of defect detection. This may require scanning techniques other than the A-Scan used in this research. Scanning from multiple axes and using three dimensional imaging may be necessary to qualify the discontinuities. Other issues that need to be addressed are: probability of detection, new transducer coupling methods, focused versus unfocused transducers, signal



processing, artificial intelligence, manufacturing intelligence, feedback process control, and managerial and worker resistance to new technology.

This research is knowledge; it is intended to be digested and dissected. It is a small step toward building a better and more profitable tomorrow for the American foundry industry.

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**APPENDIX A**  
**PANAMETRICS EPOCH 2002**  
**SETUP PARAMETERS**

## Panametrics EPOCH 2002

## Setup Parameters

Software: V06B.63E

Transducer: V309-SU (SN:124007)

Delay: 0.000 in

Filter: 4-6 Mhz

Zero: 69.93  $\mu$ s

Damping: 80 Ohms

Energy: High

Rectification: Full

Mode: T/R

Velocity: 0.1893 in/ $\mu$ s

Scale: .1 in/dev

APPENDIX B  
HITACHI M5030 ROBOT PROGRAM  
AND  
INTERFACE WIRING DIAGRAM



Hitachi M5030 Programming Sheet  
Page 1 of 3

Step	Description	I/O
1	Rapid above Boss #1, clearing tank	
2	Rapid 4" above Boss #1	
3	Slow 1" above Boss #1	
4	Signal arrival	OUT1 High
5	Wait for Signal to move	IN1 High
6	Signal departure	OUT1 Low
7	Rapid 4" above Boss #1	
8	Rapid 4" above Boss #2	
9	Slow 1" above Boss #2	
10	Signal arrival	OUT1 High
11	Wait for Signal to move	IN1 High
12	Signal departure	OUT1 Low
13	Rapid 4" above Boss #2	
14	Rapid 4" above Boss #3	
15	Slow 1" above Boss #3	
16	Signal arrival	OUT1 High
17	Wait for Signal to move	IN1 High
18	Signal departure	OUT1 Low
19	Rapid 4" above Boss #3	
20	Rapid 4" above Boss #4	
21	Slow 1" above Boss #4	
22	Signal arrival	OUT1 High
23	Wait for Signal to move	IN1 High
24	Signal departure	OUT1 Low
25	Rapid 4" above Boss #4	
26	Rapid 4" above Boss #5	
27	Slow 1" above Boss #5	
28	Signal arrival	OUT1 High
29	Wait for Signal to move	IN1 High
30	Signal departure	OUT1 Low
31	Rapid 4" above Boss #5	
32	Rapid 4" above Boss #6	
33	Slow 1" above Boss #6	
34	Signal arrival	OUT1 High
35	Wait for Signal to move	IN1 High
36	Signal departure	OUT1 Low
37	Rapid 4" above Boss #6	
38	Rapid 4" above Boss #7	
39	Slow 1" above Boss #7	
40	Signal arrival	OUT1 High
41	Wait for Signal to move	IN1 High
42	Signal departure	OUT1 Low
43	Rapid 4" above Boss #7	

Hitachi M5030 Programming Sheet  
Page 2 of 3

Step	Description	I/O
44	Rapid 4" above Boss #8	
45	Slow 1" above Boss #8	
46	Signal arrival	OUT1 High
47	Wait for Signal to move	IN1 High
48	Signal departure	OUT1 Low
49	Rapid 4" above Boss #8	
50	Rapid 4" above Boss #9	
51	Slow 1" above Boss #9	
52	Signal arrival	OUT1 High
53	Wait for Signal to move	IN1 High
54	Signal departure	OUT1 Low
55	Rapid 4" above Boss #9	
56	Rapid 4" above Boss #10	
57	Slow 1" above Boss #10	
58	Signal arrival	OUT1 High
59	Wait for Signal to move	IN1 High
60	Signal departure	OUT1 Low
61	Rapid 4" above Boss #10	
62	Rapid 4" above Boss #11	
63	Slow 1" above Boss #11	
64	Signal arrival	OUT1 High
65	Wait for Signal to move	IN1 High
66	Signal departure	OUT1 Low
67	Rapid 4" above Boss #11	
68	Rapid 4" above Boss #12	
69	Slow 1" above Boss #12	
70	Signal arrival	OUT1 High
71	Wait for Signal to move	IN1 High
72	Signal departure	OUT1 Low
73	Rapid 4" above Boss #12	
74	Rapid 4" above Boss #13	
75	Slow 1" above Boss #13	
76	Signal arrival	OUT1 High
77	Wait for Signal to move	IN1 High
78	Signal departure	OUT1 Low
79	Rapid 4" above Boss #13	
80	Rapid 4" above Boss #14	
81	Slow 1" above Boss #14	
82	Signal arrival	OUT1 High
83	Wait for Signal to move	IN1 High
84	Signal departure	OUT1 Low
85	Rapid 4" above Boss #14	

Hitachi M5030 Programming Sheet  
Page 3 of 3

Step	Description	I/O
86	Rapid 4" above Boss #15	
87	Slow 1" above Boss #15	
88	Signal arrival	OUT1 High
89	Wait for Signal to move	IN1 High
90	Signal departure	OUT1 Low
91	Rapid 4" above Boss #15	
92	Rapid 4" above Boss #16	
93	Slow 1" above Boss #16	
94	Signal arrival	OUT1 High
95	Wait for Signal to move	IN1 High
96	Signal departure	OUT1 Low
97	Rapid 4" above Boss #16	
98	Rapid 4" above Boss #17	
99	Slow 1" above Boss #17	
100	Signal arrival	OUT1 High
101	Wait for Signal to move	IN1 High
102	Signal departure	OUT1 Low
103	Rapid 4" above Boss #17	
104	Rapid up to clear tank	
105	Rapid to home position, clearing tank	
106	END	

Robot/DIO8-P  
Interface Wiring Diagram

Hitachi M5030	DIO8-P
Output 1 (TMOA) .....	IP0-P08
Output 1 (TMOB) (12v) .....	IP0-P27
Input 1 .....	OP1 (NO) -P19
P Select 2(0) .....	OP2 (NO) -P16
P Select 2(1) .....	OP3 (NO) -P33
Remote Start .....	OP4 (NO) -P13
PGR (12v) .....	OP1 (C) -P37
PGR (12v) .....	OP2 (C) -P34
PGR (12v) .....	OP3 (C) -P14
PGR (12v) .....	OP4 (C) -P31

**APPENDIX C**  
**UICCS PROGRAM ACTION DIAGRAM**

```

*****
*   Ultrasonic Inspection Computer Control Software (UICCS) Project   *
*****
*   University of Northern Iowa                                     *
*   Dept of Industrial Technology                                 *
*   Metal Casting Center (MCC)                                  *
*   Cedar Falls, Iowa 50614-0178                               *
*****
*   Copyright 1992, John S. Burningham                           *
*   All rights reserved.                                         *
*****

```

```

Written by: John S. Burningham
            Synchronous Solutions
            PO Box 616
            Mahopac, NY 10541-0616
            (914)621-1794

```

```

Hardware Requirements: 80286/80386/80486 IBM compatible
                      One Serial (RS-232) Port
                      One Parallel Printer Port
                      VGA Graphics
                      1 MB Ram Memory min.
                      Hard Drive

```

```

(Digital Isolated I/O Board)
Model DIO8-P
bus address: &H300
Industrial Computer Source
4837 Mercury St.
San Diego CA 92111
(619)279-0084

```

```

(Digital Ultrasonic Flaw Detector)
EPOCH 2002 w/RS-232 Interface (19200 baud)
Panametrics, Inc.
221 Crescent Street
Waltham MA 02254
(617)899-2719

```

```

Software Development System: MS-DOS V5.00
                             QuickBasic V4.5

```

```

*****
*   Documentation Section           Revised 10/21/92   jsb   *
*****

```

```

Inspection Data Output File -- [serialnumber.INS] (3643 bytes)

```

POSITION	DESCRIPTION
0001-0008	Part Serial Number
0009-0022	Date-Time stamp [yyyymmddhhmmss]
0023-0026	Decibel Level (Single percission variable)
0027-0043	Pass/Fail summary [P/F] for points 1-17
0044-0243	Inspection Reject Table
0244-0443	A-Scan Data Set -- Inspection Point 01
0444-0643	A-Scan Data Set -- Inspection Point 02
0644-0843	A-Scan Data Set -- Inspection Point 03
0844-1043	A-Scan Data Set -- Inspection Point 04
1044-1243	A-Scan Data Set -- Inspection Point 05
1244-1443	A-Scan Data Set -- Inspection Point 06
1444-1643	A-Scan Data Set -- Inspection Point 07
1644-1843	A-Scan Data Set -- Inspection Point 08
1844-2043	A-Scan Data Set -- Inspection Point 09
2044-2243	A-Scan Data Set -- Inspection Point 10
2244-2443	A-Scan Data Set -- Inspection Point 11
2444-2643	A-Scan Data Set -- Inspection Point 12
2644-2843	A-Scan Data Set -- Inspection Point 13
2844-3043	A-Scan Data Set -- Inspection Point 14
3044-3243	A-Scan Data Set -- Inspection Point 15
3244-3443	A-Scan Data Set -- Inspection Point 16
3444-3643	A-Scan Data Set -- Inspection Point 17

```

DEFINT A-Z      ' Default Variable type
CONST true = -1
CONST false = 0
CONST nul = ""
CONST Star = "*"
DIM AdumpValue(200) AS INTEGER
DIM RejectString AS STRING * 200
DIM DateTimeString AS STRING * 14
DIM FrontZeroOffset AS SINGLE
DIM PartSerialNumber AS STRING
DIM PutPSN AS STRING * 8
DIM Realtmp AS SINGLE
DIM RejectTable(200) AS INTEGER
DIM RobotDelayTimer AS SINGLE
DIM Decibel AS SINGLE
DIM Sort1 AS STRING * 8
DIM Sort2 AS STRING * 8
DIM Sort(5000) AS STRING * 8
Decibel = 67!
EOB$ = CHR$(23)
ESC$ = CHR$(27)
CR$ = CHR$(13)
OK$ = "OK"
'
' Define Inspection Record
'
TYPE Type1
  PSN AS STRING * 8      ' Part Serial Number
  DTS AS STRING * 14    ' Date/Time
  DB AS SINGLE          ' Signal Level
  PF AS STRING * 17     ' Pass/Fail
  RT AS STRING * 200    ' Reject Table
  DAT AS STRING * 3400 ' Inspection Date (200 bytes * 17 points)
END TYPE
DIM InspRecord AS Type1
'
' Read COMMAND Line for runtime options
'
IF INSTR(COMMAND$, "/D") > 0 THEN
  DebugFlag = true
ELSE
  DebugFlag = false
END IF
IF INSTR(COMMAND$, "/Q") > 0 THEN
  SoundFlag = false
ELSE
  SoundFlag = true
END IF
IF INSTR(COMMAND$, "/M") > 0 THEN
  colorf = 7
ELSE
  colorf = 14
END IF
'
' User Instructions for command line "?"
'
IF INSTR(COMMAND$, "?") THEN
  PRINT
  PRINT "Command Line Options:"
  PRINT " /D  Debug"
  PRINT " /Q  Quite (No sound)"
  PRINT " /M  Monochrome (No Color)"
  GOTO byebyeend
END IF
'
' Check for DIO8 Board at &H300 address
'
OUT &H300, 0 ' Force DIO8 to zero
IF INP(&H300) = 255 THEN ' If no board, value will be 255
  CLS
  PRINT "Robot Digital I/O Board not detected at address &H300"
  IF NOT DebugFlag THEN
    PRINT "Disabling Inspection Module"
    PRINT "(You can restart the program with a /D option to enable)"
  END IF
  INPUT "Press <enter> to continue: ", s$
  DIO8Flag = false
ELSE
  DIO8Flag = true
END IF

```

```

FOR loopcount = 1 TO 8
  RobotBit(loopcount) = false
NEXT

:
: Allow Fn keys to toggle Output bits on D108 board for debugging
:
IF DebugFlag THEN
  ON KEY(1) GOSUB F1key
  KEY(1) ON
  ON KEY(2) GOSUB F2key
  KEY(2) ON
  ON KEY(3) GOSUB F3key
  KEY(3) ON
  ON KEY(4) GOSUB F4key
  KEY(4) ON
  ON KEY(5) GOSUB F5key
  KEY(5) ON
  ON KEY(6) GOSUB F6key
  KEY(6) ON
  ON KEY(7) GOSUB F7key
  KEY(7) ON
  ON KEY(8) GOSUB F8key
  KEY(8) ON
  DisplayBoxTop$ = CHR$(201) + STRING$(8, CHR$(205)) + CHR$(187)
  DisplayBoxMiddle$ = CHR$(186) + " " + CHR$(186)
  DisplayBoxBottom$ = CHR$(200) + STRING$(8, CHR$(205)) + CHR$(188)
END IF

:
: Reject Table (Go/NoGO) Table
:
DATA 00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00
DATA 00,00,00,00,00,00,00,00,00,00,41,41,40,40,39,39,38,38,37,37
DATA 36,36,35,35,34,34,34,33,33,33,32,32,32,31,31,31,30,30,30,29
DATA 29,29,28,28,28,27,27,27,27,26,26,26,26,25,25,25,25,24,24,24
DATA 24,23,23,23,23,22,22,22,22,21,21,21,21,20,20,20,20,20,19,19
DATA 19,19,18,18,18,18,18,17,17,17,17,17,16,16,16,16,16,15,15
DATA 15,15,15,14,14,14,14,14,14,13,13,13,13,13,13,12,12,12,12,12
DATA 12,12,11,11,11,11,11,11,11,10,10,10,10,10,10,10,09,09,09,09
DATA 09,09,09,09,08,08,08,08,08,08,08,08,08,08,08,08,08,08,08,08
DATA 07,07,07,07,07,07,07,07,07,07,07,07,07,07,07,07,07,07,07,07
:
: This routine reads the reject table and creates RejectString
:
tmp$ = nul
FOR SubScript = 1 TO 200
  READ RejectTable(SubScript)
  tmp$ = tmp$ + CHR$(RejectTable(SubScript))
NEXT
RejectString = tmp$

```

```
|
| Screen Mode 12 (VGA) with blue background for color
|
ON ERROR GOTO NoVGA
SCREEN 12
IF colorf = 14 THEN
  PALETTE 0, 65536 * 25
END IF
|
| Setup Error trapping
|
ON ERROR GOTO ErrorTrap
|
| Clear Robot activity flag
|
RobotActiveFlag = false
|
| Initialize screen width and foreground color
|
WIDTH 80, 30
CLS
COLOR colorf
|
| Initialize Clock Display
|
ON TIMER(1) GOSUB ClockDisplay
|
| Display Intro Screen
|
GOSUB IntroScreen
```



```

:
: Main Menu Loop
DO WHILE MainMenuSelection <> 4
:
: Display Main Menu
GOSUB ClearViewPort
s$ = "M A I N M E N U"
LOCATE 10, 40 - LEN(s$) / 2
PRINT s$;
column = 26
LOCATE 13, column
IF DIO8Flag OR DebugFlag THEN
PRINT "1. INSPECT PART";
ELSE
PRINT "1. <<disabled>>";
END IF
LOCATE 15, column
PRINT "2. Report Menu";
LOCATE 17, column
PRINT "3. Display Inspection Record";
LOCATE 19, column
PRINT "4. Quit (Exit to DOS)";
LOCATE 21, column
COLOR 15
PRINT "Enter Selection: ";
COLOR colorf
PRINT CHR$(178);
LOCATE 21, column + 17
:
: Get menu selection
DO
MainMenuItemSelection$ = INKEY$
LOOP WHILE MainMenuItemSelection$ = nul
PRINT MainMenuItemSelection$;
selection = VAL(MainMenuItemSelection$)
IF (selection > 1 AND selection < 5) OR (selection = 1 AND (DIO8Flag OR DebugFlag)) THEN
IF SoundFlag THEN SOUND 1000, .5
SELECT CASE selection
CASE 1
GOSUB InspectPart
CASE 2
GOSUB ReportMenu
CASE 3
GOSUB DisplayInspectionRecord
CASE 4
EXIT DO
END SELECT
selection = false ' force continued looping
ELSE
GOSUB InvalidEntry
END IF
LOOP
IF SoundFlag THEN SOUND 2000, .5
GOTO byebye

byebye:
TIMER OFF
:
: Force DIO8 board to zero
:
OUT &H300, 0
:
: Reset screen and terminate execution
:
SCREEN 0
COLOR 7, 0 ' reset screen colors
CLS
byebyeend:
END

```

```

ClearViewPort:
  TIMER STOP
  VIEW PRINT 9 TO 30
  CLS 2
  VIEW PRINT
  TIMER ON
  RETURN

ClockDisplay:
  ClockDisplayRow = CSRLIN
  ClockDisplayColumn = POS(0)
  LOCATE 5, 31
  PRINT DATES; " ": TIMES;
  LOCATE ClockDisplayRow, ClockDisplayColumn
  GOSUB DebugDisplayIO
  IF TimeOutTimer < 32767 THEN TimeOutTimer = TimeOutTimer + 1 ' Increment timer
  ' Force error on lack of Robot motion
  '
  IF RobotActiveFlag AND TimeOutTimer > 30 THEN
    ERROR 254
  END IF
  IF IntroScreenFlag THEN
    DO
      IntroScreenColor = RND * 11 + 1
    LOOP WHILE IntroScreenColor = LastIntroScreenColor
  END IF
  RETURN

ComOpen:
  ErrorFlag = false
  OPEN "COM2:19200,N,8,1,BIN,CS0,DS0,CDO,RB1024" FOR RANDOM AS #6
  GOSUB SendStar
  PRINT #6, "DISP=G"
  GOSUB ReadResponse
  RETURN

ComClose:
  CLOSE #6
  RETURN

```

```

dBcalculate:
  dBreal! = 0
  AdumpPeakLoop = AdumpPeak
  DO WHILE AdumpPeakLoop < 5
    dBreal! = dBreal! + 2.2
    AdumpPeakLoop = AdumpPeakLoop + 1
  LOOP
  DO WHILE AdumpPeakLoop < 16
    dBreal! = dBreal! + .6
    AdumpPeakLoop = AdumpPeakLoop + 1
  LOOP
  DO WHILE AdumpPeakLoop < 27
    dBreal! = dBreal! + .3
    AdumpPeakLoop = AdumpPeakLoop + 1
  LOOP
  DO WHILE AdumpPeakLoop < 40
    dBreal! = dBreal! + .2
    AdumpPeakLoop = AdumpPeakLoop + 1
  LOOP
  DO WHILE AdumpPeakLoop < 62
    dBreal! = dBreal! + .15
    AdumpPeakLoop = AdumpPeakLoop + 1
  LOOP
  IF AdumpPeakLoop = 62 THEN
    dBreal! = dBreal! + .19
    IF DB > 3 AND dBreal! = .19 THEN dBreal! = .2
  ELSE
    dBreal! = 0      Done
  END IF
  DB = INT(dBreal! * 10)
  Force Error if excessive dB
  IF ReaddB + DB > 1000 THEN
    ERROR 253
  END IF
  RETURN

dBchange:
  IF DB <> 0 THEN
    IF ReaddB = 0 THEN
      GOSUB SendStar
      PRINT #6, "DB=?"
      GOSUB ReadResponse
      ReaddB = CINT(VAL(MID$(ResponseString$, INSTR(ResponseString$, CHR$(10) + "DB=") +
        4)) * 10)
    END IF
    SET SYSTEM SENSITIVITY
    GOSUB SendStar
    PRINT #6, USING "DB=###.##"; (ReaddB + DB) / 10
    GOSUB ReadResponse
    ReaddB = ReaddB + DB
  END IF
  RETURN

```

```

DebugDisplayIO:
IF DebugFlag THEN
: Force DebugFlag to prevent recurrsvie call
:
DebugFlag = false
TIMER OFF
: Save current cursor position
:
DebugDisplayIOrow = CSRLIN
DebugDisplayIOcolumn = POS(0)
FOR DebugDisplayIOloop1 = 1 TO 3
LOCATE DebugDisplayIOloop1 + 1, 71
SELECT CASE DebugDisplayIOloop1
CASE 1
CmdValue1 = CmdValue
CASE 2
IF DIO8Flag THEN
CmdValue1 = INP(&H300)
ELSE ' DIO8 Board not installed, Allow FunKeys to force condition
CmdValue1 = CmdValue
END IF
IF CmdValue1 <> InHex300 THEN
SOUND 750, 1
END IF
InHex300 = CmdValue1
CASE 3
GOSUB Hex301Get
END SELECT
D$$ = nul
FOR DebugDisplayIOloop2 = 7 TO 0 STEP -1
IF CmdValue1 >= 2 ^ DebugDisplayIOloop2 THEN
D$$ = D$$ + "1"
CmdValue1 = CmdValue1 - 2 ^ DebugDisplayIOloop2
ELSE
D$$ = D$$ + "0"
END IF
NEXT
PRINT D$$;
NEXT
LOCATE 2, 1
PRINT USING "FRE(-1):#####"; FRE(-1)
PRINT USING "FRE(-2):#####"; FRE(-2)
PRINT USING "FRE(-3):#####"; FRE(-3)
PRINT USING "Timeout:#####"; TimeOutTimer
LOCATE DebugDisplayIOrow, DebugDisplayIOcolumn
: Restore DebugFlag
:
DebugFlag = true ' Reset flag
TIMER ON
END IF
RETURN

```

```

DisplayInspectionRecord:
GOSUB ClearViewPort
LOCATE 13, 27
PRINT "DISPLAY INSPECTION RECORD";
GOSUB GetPartSerialNumber
IF PartSerialNumber <> nul AND tmpASC <> 27 THEN
    :
    :   Open Data File
    :
    DataFile$ = RTRIM$(PartSerialNumber) + ".INS"
    OPEN DataFile$ FOR BINARY AS #1
    IF LOF(1) = 0 THEN
        :
        :   File is empty (DID NOT EXIST)
        :
        CLOSE #1
        KILL DataFile$
        LOCATE 17, 28
        PRINT "Data File does not exist";
        IF SoundFlag THEN
            FOR Scan = 1 TO 20
                SOUND 1300, .4
                SOUND 1000, .4
                SOUND 700, .4
            NEXT
        END IF
    ELSE
        :
        :   Get Data from file
        :
        GET #1, 1, InspRecord
        :
        :   Close Data File
        :
        CLOSE #1
        :
        :   Display Part Serial Number
        :
        LOCATE 30, 1
        PRINT "Serial #: "; PartSerialNumber;
        :
        :   Display Date/Time of Inspection
        :
        LOCATE 30, 24
        PRINT "Date/Time: "; MID$(InspRecord.DTS, 5, 2); "/";
        PRINT MID$(InspRecord.DTS, 7, 2); " /"; LEFT$(InspRecord.DTS, 4); " ";
        PRINT MID$(InspRecord.DTS, 9, 2); " :";
        PRINT MID$(InspRecord.DTS, 11, 2); " :";
        PRINT MID$(InspRecord.DTS, 13, 2);
        :
        :   Display Signal Level
        :
        LOCATE 30, 60
        PRINT USING "Signal Level:###.##dB"; InspRecord.DB;
        :
        :   Display Inspection Point Status
        :
        FOR Scan = 1 TO 17
            LOCATE 8 + Scan, 75
            IF MID$(InspRecord.PF, Scan, 1) = "P" THEN
                COLOR 2
            ELSE
                COLOR 4
            END IF
            PRINT USING "##"; Scan;
            COLOR colorf
        NEXT
    END IF
END IF

```

```

FOR Scan = 1 TO 17
  LOCATE 8 + Scan - 1, 72
  PRINT SPACES(2);
  LOCATE 8 + Scan + 1, 72
  PRINT SPACES(2);
  LOCATE 8 + Scan, 72
  COLOR 15
  PRINT ">>";
  COLOR colorf
  GOSUB DisplayScan
  DO
    key$ = INKEY$
    LOOP WHILE key$ = nul
    IF LEN(key$) = 2 THEN
      IF RIGHTS(key$, 1) = CHR$(72) THEN
        IF Scan > 1 THEN
          Scan = Scan - 2
          key$ = CR$
        ELSE
          key$ = nul
        END IF
      ELSEIF RIGHTS(key$, 1) = CHR$(80) THEN
        IF Scan < 17 THEN
          key$ = CR$
        ELSE
          key$ = nul
        END IF
      ELSEIF key$ = CHR$(27) THEN
        Scan = 17
        key$ = CR$
      END IF
    LOOP WHILE key$ <> CR$
  NEXT
END IF
RETURN

```

```

DisplayScan:
  RejectString = InspRecord.RT
  GOSUB DrawGraphicScreen
  :
  :   Display Scan
  :
  FOR SubScript = 1 TO 200
    temp1 = ASC(MID$(InspRecord.DAT, (Scan - 1) * 200 + SubScript))
    temp2 = ASC(MID$(RejectString, SubScript, 1))
    LINE (SubScript * 2 - 1, 254) - (SubScript * 2, 254 - temp1 * 4), 2, B
    IF temp2 > 0 AND temp1 > temp2 THEN
      LINE (SubScript * 2 - 1, 254 - temp2 * 4) - (SubScript * 2, 254 - temp1 * 4), 4, B
    END IF
  NEXT
  GOSUB DrawRejectLine
  RETURN

DrawGraphicScreen:
  :
  :   Setup Graphic View Port
  :
  VIEW (120, 136) - (520, 390), 8, 1
  :
  :   Draw division lines
  :
  FOR i = 40 TO 360 STEP 40
    LINE (i, 0) - (i, 254), 14, , &HF0F0
  NEXT
  GOSUB DrawRejectLine
  :
  :   Lable Graphic Screen
  :
  LOCATE 26, 16
  PRINT "0      .2      .4      .6      .8      1.0"
  RETURN

DrawRejectLine:
  :
  :   Draw Reject line on screen
  :
  FOR SubScript = 1 TO 200
    temp = ASC(MID$(RejectString, SubScript, 1))
    IF temp > 0 THEN
      PSET (SubScript * 2 - 1, 254 - temp * 4), 3
      PSET (SubScript * 2, 254 - temp * 4), 3
    END IF
  NEXT
  RETURN

```

```

ErrorTrap:
  GOSUB ClearViewPort
  ecode = ERR
  IF ecode = 57 OR ecode = 255 OR ecode = 253 THEN
    : Error code 57 is Device I/O error
    : Error code 255 is program generated for a device timeout.
    LOCATE 10, 7
    IF ecode = 253 THEN
      PRINT "The Panametrics EPOCH 2002 is not reading a signal (+100dB gain)"
    ELSE
      PRINT "There is a communication problem with the Panametrics EPOCH 2002"
    END IF
    LOCATE 12, 7
    PRINT "Press any key to reset the Robot to Home. You will need to cycle"
    LOCATE 14, 7
    PRINT "the EPOCH 2002 off and back on again, and then restart the program."
    LOCATE 18, 30
    IF ecode = 57 THEN
      PRINT "Device I/O Error"
    ELSE
      PRINT "Device Timeout Error"
    END IF
    DO
      key$ = INKEY$
    LOOP WHILE key$ = nul
    GOSUB ResetTOT
    RobotActiveFlag = true
    FOR ErrorLoop = InspPoint TO 17
      : Move Robot to next InspPoint
      :
      RobotBitSubScript = 1
      GOSUB RobotBitSetTrue
      GOSUB RobotControl
      :
      : Clear Robot Control Bit
      GOSUB RobotBitSetFalse
      GOSUB RobotControl
      :
      : Wait until Robot Clears [sets False] position ready bit
      DO
        GOSUB Hex301Read
      LOOP WHILE Hex301(0)
      IF ErrorLoop < 17 THEN
        : Wait until Robot is in position
        DO
          GOSUB Hex301Read
        LOOP WHILE NOT Hex301(0)
      END IF
    NEXT
    GOTO bybybye
  ELSEIF ecode = 254 THEN
    : Error code 254 is program generated for a device timeout on Robot
    LOCATE 10, 7
    PRINT "There is a communication problem with the Hitachi M5030 Robot"
    LOCATE 12, 7
    PRINT "Press any key to terminate program. You will need to reset"
    LOCATE 14, 7
    PRINT "the Robot, if this problem continues, the interface or the Robot"
    LOCATE 16, 7
    PRINT "program may be the error or the Robot is not in REMOTE MODE."
    DO
      key$ = INKEY$
    LOOP WHILE key$ = nul
    GOTO bybybye
  ELSE
    SELECT CASE ecode
    CASE 2: Error.Msg$ = "Syntax Error"
    CASE 3: Error.Msg$ = "RETURN without GOSUB"
    CASE 4: Error.Msg$ = "Out of DATA"
    CASE 5: Error.Msg$ = "Illegal function Call"
    CASE 6: Error.Msg$ = "Overflow"
    CASE 7: Error.Msg$ = "Out of Memory"
  
```



```

CASE 9: Error.Msg$ = "Subscript out of Range"
CASE 10: Error.Msg$ = "Duplicate Defination"
CASE 11: Error.Msg$ = "Division by Zero"
CASE 13: Error.Msg$ = "Type Mismatch"
CASE 14: Error.Msg$ = "Out of String Space"
CASE 16: Error.Msg$ = "String Formula too complex"
CASE 19: Error.Msg$ = "No RESUME"
CASE 20: Error.Msg$ = "RESUME without error"
CASE 24: Error.Msg$ = "Device timeout"
CASE 25: Error.Msg$ = "Device fault"
CASE 52: Error.Msg$ = "Bad filename or number"
CASE 53: Error.Msg$ = "File not found"
CASE 54: Error.Msg$ = "Bad file mode"
CASE 55: Error.Msg$ = "File already open"
CASE 57: Error.Msg$ = "Device I/O error"
CASE 58: Error.Msg$ = "File already exists"
CASE 61: Error.Msg$ = "Disk full"
CASE 64: Error.Msg$ = "Bad file name"
CASE 67: Error.Msg$ = "Too many files"
CASE 68: Error.Msg$ = "Device unavailable"
CASE 70: Error.Msg$ = "Write protected disk"
CASE 71: Error.Msg$ = "Disk-drive door is open or no disk in drive"
CASE 72: Error.Msg$ = "Disk media error - disk is defective"
CASE 75: Error.Msg$ = "Path file access error"
CASE 76: Error.Msg$ = "Path not found"
CASE ELSE: Error.Msg$ = "Error code" + STR$(ecode)
END SELECT
LOCATE 15, (72 - LEN(Error.Msg$)) / 2
PRINT "ERROR - "; Error.Msg$
DO
PRINT "Press <RETURN> to continue or <ESC> to exit"
BEEP
DO
key$ = INKEY$
LOOP WHILE key$ = nul
LOOP WHILE key$ <> CR$ AND key$ <> ESC$
IF key$ = ESC$ THEN GOTO byebye
RESUME
END IF
STOP ' ***This line should never be executed***

```

```

:
: The Fn keys are only used for debugging
: Define Fn keys for toggling DIO8 output bits
:
F1key:
RobotBitSubScript = 1
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F2key:
RobotBitSubScript = 2
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F3key:
RobotBitSubScript = 3
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F4key:
RobotBitSubScript = 4
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F5key:
RobotBitSubScript = 5
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F6key:
RobotBitSubScript = 6
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F7key:
RobotBitSubScript = 7
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN

F8key:
RobotBitSubScript = 8
GOSUB RobotBitToggle
GOSUB RobotControl
RETURN
```

```

GetAdump:
  ErrorFlag = false
  ' Average 4 A-Scans together in EPOCH 2002
  '
  GOSUB SendStar
  PRINT #6, "AVE=4"
  GOSUB ReadResponse
  IF NOT ErrorFlag THEN
    ' Get ADUMP from EPOCH 2002
    '
    GOSUB SendStar
    PRINT #6, "ADUMP=?"
    ResponseLength = 613
    GOSUB ReadResponse
    IF LEN(ResponseString$) < ResponseLength THEN
      ERROR 255
    ELSE
      ' Convert Adump data (hex) to Base10
      '
      Response$ = RIGHT$(ResponseString$, ResponseLength)
      SubScript = 1
      Position = 1
      DO
        tmp$ = MID$(Response$, Position, 1)
        Position = Position + 1
        HexToBase10 = -1
        IF (ASC(tmp$) >= 48 AND ASC(tmp$) <= 57) THEN
          HexToBase10 = (ASC(tmp$) - 48) * 16
        END IF
        IF (ASC(tmp$) >= 65 AND ASC(tmp$) <= 70) THEN
          HexToBase10 = (ASC(tmp$) - 55) * 16
        END IF
        IF HexToBase10 > -1 THEN
          tmp$ = MID$(Response$, Position, 1)
          Position = Position + 1
          IF (ASC(tmp$) >= 48 AND ASC(tmp$) <= 57) THEN
            HexToBase10 = HexToBase10 + (ASC(tmp$) - 48)
          END IF
          IF (ASC(tmp$) >= 65 AND ASC(tmp$) <= 70) THEN
            HexToBase10 = HexToBase10 + (ASC(tmp$) - 55)
          END IF
          AdumpValue(SubScript) = HexToBase10
          SubScript = SubScript + 1
        END IF
      LOOP WHILE SubScript < 200
    END IF
  ELSE ' Com error
    ERROR 255
    STOP
  END IF
  RETURN

GetAdumpPeak:
  GOSUB GetAdump
  AdumpPeak = 0
  AdumpPeakPosition = 0
  FOR Position = SubscriptStart TO SubscriptEnd
    IF AdumpValue(Position) > AdumpPeak THEN
      AdumpPeak = AdumpValue(Position)
      AdumpPeakPosition = Position
    END IF
  NEXT
  RETURN

```

```

GetDateTime:
DTSS = DATES
DTSS = MID$(DTSS, 7, 4) + LEFT$(DTSS, 2) + MID$(DTSS, 4, 2) + TIMES
DTSS = LEFT$(DTSS, 10) + MID$(DTSS, 12, 2) + RIGHT$(DTSS, 2)
DateTimeString = DTSS
RETURN

GetPartSerialNumber:
|
| Get Part Serial Number
|
PartSerialNumber = nul
LOCATE 15, 20
COLOR 15
PRINT "Enter Part Serial Number: [      ]";
COLOR colorf
LOCATE 15, 46
DO
  tmp$ = UCASE$(INKEY$)
  IF tmp$ = nul THEN
    tmpASC = 0
  ELSE
    tmpASC = ASC(tmp$)
  END IF
  LenPSN = LEN(PartSerialNumber)
  IF (tmpASC >= 48 AND tmpASC <= 57) OR (tmpASC >= 65 AND tmpASC <= 90) THEN
    IF LenPSN < 8 THEN
      | Letter or Number Character
      |
      PartSerialNumber = PartSerialNumber + tmp$
      LOCATE 15, 47
      PRINT PartSerialNumber; SPACES(7 - LenPSN);
    ELSE
      |
      | Already 8 Characters (Max)
      |
      BEEP
    END IF
  ELSEIF tmpASC = 8 THEN
    | Backspace Character
    |
    IF LenPSN > 1 THEN
      PartSerialNumber = LEFT$(PartSerialNumber, LenPSN - 1)
    ELSE
      PartSerialNumber = nul
    END IF
    LOCATE 15, 47
    PRINT PartSerialNumber; SPACES(9 - LenPSN);
  ELSEIF tmpASC <> 13 AND tmpASC <> 0 AND tmpASC <> 27 THEN
    | Invalid character
    |
    BEEP
  END IF
LOOP WHILE tmpASC <> 13 AND tmpASC <> 27
RETURN

```

```
Hex301Get:
  IF DIO8Flag THEN
    CmdValue1 = INP(&H301)
  ELSE
    CmdValue1 = DebugInHex301
  END IF
  InHex301 = CmdValue1
  RETURN

Hex301Read:
  GOSUB Hex301Get
  InHex301Temp = InHex301
  FOR Hex301ReadLoop = 7 TO 0 STEP -1
    IF InHex301Temp >= 2 ^ Hex301ReadLoop THEN
      Hex301(Hex301ReadLoop) = true
      InHex301Temp = InHex301Temp - 2 ^ Hex301ReadLoop
    ELSE
      Hex301(Hex301ReadLoop) = false
    END IF
  NEXT Hex301ReadLoop
  RETURN
```

```

InspectPart:
  GOSUB ClearViewPort
  LOCATE 13, 34
  PRINT "INSPECT PART";
  GOSUB GetPartSerialNumber
  IF PartSerialNumber = nul OR tmpASC = 27 THEN GOTO InspReturn
  :
  :   Display Part Serial Number
  :
  LOCATE 30, 1
  PRINT "Serial #: "; PartSerialNumber;
  :
  :   Save File Header and initialize InspRecord
  :
  GOSUB GetDateTime
  InspRecord.PSN = PartSerialNumber
  InspRecord.DTS = DateTimeString
  InspRecord.PF = nul
  tmp$ = nul
  FOR SubScript = 1 TO 200
    [ tmp$ = tmp$ + CHR$(RejectTable(SubScript))
  NEXT
  InspRecord.RT = tmp$
  InspRecord.DAT = nul
  :
  :   Open COM Port
  GOSUB ComOpen
  :
  :   ResetTOT for Robot timeout
  :
  GOSUB ResetTOT
  :
  :   Set Robot activity flag
  RobotActiveFlag = true
  :
  :   Select Robot Program #1
  :
  RobotBitSubScript = 3
  GOSUB RobotBitSetTrue
  RobotBitSubScript = 4
  GOSUB RobotBitSetTrue
  GOSUB RobotControl
  :
  :   Start Robot Execution
  :
  RobotBitSubScript = 2
  GOSUB RobotBitSetTrue
  GOSUB RobotControl
  :
  :   Clear Robot Control Bits
  :
  RobotBitSubScript = 2
  GOSUB RobotBitSetFalse
  RobotBitSubScript = 3
  GOSUB RobotBitSetFalse
  RobotBitSubScript = 4
  GOSUB RobotBitSetFalse
  GOSUB RobotControl
  :
  :   Graphic Screen
  :
  GOSUB DrawGraphicScreen
  :
  :   Display Inspection Point Status
  :
  FOR InspPoint = 1 TO 17
    [ LOCATE 8 + InspPoint, 75
      PRINT USING "##"; InspPoint;
  NEXT
  :
  :   Clear PartDefectFlag
  :
  PartDefectFlag = false

```

```

: Inspect 17 InspPoints
FOR InspPoint = 1 TO 17
: Clear InspRepeatFlag
InspRepeatFlag = false
LOCATE 8 + InspPoint, 75
COLOR 15
PRINT USING "##"; InspPoint;
COLOR colorf
: Program Entry Point for reinspection
InspRepeatEntryPoint:
: Adjust Panametrics EPOCH 2002 for inspection
GOSUB ZeroTransducer
: Set dB Level for inspection
GOSUB SendStar
PRINT #6, USING "DB=##.#"; Decibel
GOSUB ReadResponse
: Get Inspection data dump
GOSUB GetAdump
: Redraw Graphic Screen
GOSUB DrawGraphicScreen
: Display Inspection Point #
LOCATE 30, 60
PRINT USING "Inspection Point: ##"; InspPoint;
: Is there a defect????
DefectFlag = false
FOR SubScript = 1 TO 200
LINE (SubScript * 2 - 1, 254) - (SubScript * 2, 254 - AdumpValue(SubScript) * 4), 2, B
IF RejectTable(SubScript) > 0 AND AdumpValue(SubScript) > RejectTable(SubScript)
THEN
LINE (SubScript * 2 - 1, 254 - RejectTable(SubScript) * 4) - (SubScript * 2, 254
- AdumpValue(SubScript) * 4), 4, B
DefectFlag = true
END IF
NEXT
GOSUB DrawRejectLine
: If defect found, reinspect InspPoint
IF NOT InspRepeatFlag AND DefectFlag THEN
LOCATE 30, 33
PRINT "Insp: ";
COLOR 15
LOCATE 30, 39
PRINT "Retesting";
COLOR colorf
InspRepeatFlag = true
GOTO InspRepeatEntryPoint
END IF
: Move Robot to next InspPoint
RobotBitSubScript = 1
GOSUB RobotBitSetTrue
GOSUB RobotControl
: Display & Save DefectFlag
IF DefectFlag THEN
LOCATE 8 + InspPoint, 75
COLOR 4
PRINT USING "##"; InspPoint;
COLOR colorf
LOCATE 30, 33

```

```

PRINT "Insp:          ";
COLOR 4
LOCATE 30, 39
PRINT "FAILED";
COLOR colorf
IF InspPoint = 1 THEN
    InspRecord.PF = "f"
ELSE
    InspRecord.PF = LEFT$(InspRecord.PF, InspPoint - 1) + "f"
END IF
; Set PartDefectFlag
;
PartDefectFlag = true
ELSE
LOCATE 8 + InspPoint, 75
COLOR 2
PRINT USING "##"; InspPoint;
COLOR colorf
LOCATE 30, 33
PRINT "Insp:          ";
COLOR 2
LOCATE 30, 39
PRINT "PASSED";
COLOR colorf
IF InspPoint = 1 THEN
    InspRecord.PF = "p"
ELSE
    InspRecord.PF = LEFT$(InspRecord.PF, InspPoint - 1) + "p"
END IF
END IF
; Convert Data to string and Save for data file
;
tmp$ = nul
FOR SubScript = 1 TO 200
    tmp$ = tmp$ + CHR$(AdumpValue(SubScript))
NEXT
IF InspPoint = 1 THEN
    InspRecord.DAT = tmp$
ELSE
    InspRecord.DAT = LEFT$(InspRecord.DAT, (InspPoint - 1) * 200) + tmp$
END IF
; Clear Robot Control Bit
;
GOSUB RobotBitSetFalse
GOSUB RobotControl
; Wait until Robot Clears [sets False] positon ready bit
;
DO
    GOSUB ClockDisplay
    GOSUB Hex301Read
LOOP WHILE Hex301(0)
NEXT
; Clear Robot activity flag
;
RobotActiveFlag = false
; Close COM Port
;
GOSUB ComClose
; Save Inspection Signal Level
;
InspRecord.DB = Decibel
; Open Data File
;
DataFile$ = RTRINS(PartSerialNumber) + ".INS"
OPEN DataFile$ FOR BINARY AS #1
; Save Data to file
;
PUT #1, i, InspRecord

```



```

:
: Close Data File
CLOSE #1
: Rerun Part?
:
IF PartDefectFlag THEN
  LOCATE 28, 30
  COLOR 15
  PRINT "Rerun Part [y/N]: ";
  COLOR colorf
  DO
    tmp$ = UCASE$(INKEY$)
    IF tmp$ = CR$ THEN tmp$ = "N"
  LOOP WHILE tmp$ <> "Y" AND tmp$ <> "N"
  PRINT tmp$;
  IF tmp$ = "Y" THEN
    LOCATE 28, 30
    PRINT SPACES(20);
    LOCATE 30, 38
    PRINT SPACES(11);
    LOCATE 30, 78
    PRINT SPACES(2);
    RerunFlag = true
  ELSE
    RerunFlag = false
  END IF
ELSE
  RerunFlag = false
END IF
IF RerunFlag THEN GOTO InspectPart
InspectReturn:
RETURN

```

```

IntroScreen:
s$ = "1100000011000002220022200000033333333000000444444440000055555555"
s$ = s$ + "110000001100000002220000000033000000000004400000000005550000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "11000000110000000002200000000033000000000004400000000005500000000"
s$ = s$ + "0111111110000002220022200000033333333000000444444440000055555555"

FOR i = 1 TO LEN(s$)
  IF VAL(MID$(s$, i, 1)) THEN
    MID$(s$, i, 1) = CHR$(178)
  ELSE
    MID$(s$, i, 1) = CHR$(32)
  END IF
NEXT
GOSUB ScreenHeader
TIMER STOP
row = 11
column = 5
COLOR colorf - 2
FOR i = 0 TO 11
  LOCATE row + i, column
  PRINT MID$(s$, i * 70 + 1, 70);
NEXT
COLOR colorf
TIMER ON
LOCATE 25, 14
PRINT "Ultrasonic Inspection Cell Control Software (UICCS)";
COLOR 15
LOCATE 27, 24
PRINT "<< Press any Key to Continue >>";
COLOR colorf
row = 11
column = 5
RANDOMIZE TIMER
IntroScreenFlag = true
IntroScreenColor = 12
DO
  IF colorf = 14 AND IntroScreenColor <> LastIntroScreenColor THEN
    TIMER STOP
    COLOR IntroScreenColor
    FOR i = 0 TO 11
      LOCATE row + i, column
      PRINT MID$(s$, i * 70 + 1, 70);
    NEXT
    LastIntroScreenColor = IntroScreenColor
    COLOR colorf
    TIMER ON
  END IF
  tmp$ = INKEY$
LOOP WHILE tmp$ = nul
IntroScreenFlag = false
GOSUB ScreenHeader
RETURN

```

```

InvalidEntry:
  LOCATE 21, column + 17
  PRINT "****Invalid Entry****";
  BEEP
  SLEEP 2
  LOCATE 21, column + 17
  PRINT " ";
  ErrorFlag = true
  RETURN

NoVGA:
  |
  | Error Routine for computers without VGA graphics
  |
  PRINT "This program requires a VGA graphics card to run."
  PRINT
  GOTO byebyeend
  |
  | This program should never process the next two lines
  |
  RESUME
  RETURN

ReadResponse:
  GOSUB ResetTOT
  ResponseString$ = nul
  |
  | Wait for EOB$ character or timeout
  |
  DO
    ResponseString$ = ResponseString$ + INPUT$(LOC(6), #6)
    IF INSTR(ResponseString$, EOB$) > 0 THEN EXIT DO
  LOOP WHILE TimeOutTimer < 2
  |
  | Check for timeout
  |
  IF INSTR(ResponseString$, EOB$) = 0 THEN
    ERROR 255
    STOP
  END IF
  RETURN

```

```

ReportMenu:
  COLOR colorf
  ReportMenuSelection = false
  DO WHILE ReportMenuSelection <> 4
    GOSUB ClearViewPort
    s$ = "R E P O R T   M E N U"
    LOCATE 10, 40 - LEN(s$) / 2
    PRINT s$;
    column = 26
    LOCATE 13, column
    PRINT "1. Print Inspection Summary";
    LOCATE 15, column
    PRINT "2. Print Today's Inspection Summary";
    LOCATE 17, column
    PRINT "3. <<Unavailable>>";
    LOCATE 19, column
    PRINT "4. Return to Main Menu";
    LOCATE 21, column
    COLOR 15
    PRINT "Enter Selection: ";
    COLOR colorf
    PRINT CHR$(178);
    LOCATE 21, column + 17
    GOSUB ResetTOT
    '
    ' Get selection or force return to main menu
    '
  DO
    ReportMenuSelection$ = INKEY$
    IF TimeoutTimer > 60 THEN ReportMenuSelection$ = "4" ' Force menu exit
  LOOP WHILE ReportMenuSelection$ = nul
  PRINT ReportMenuSelection$;
  selection = VAL(ReportMenuSelection$)
  IF selection > 0 AND selection < 5 THEN
    IF SoundFlag THEN SOUND 1000, .5
    SELECT CASE selection
      CASE 1
        ReportSummaryTodayFlag = false
        GOSUB ReportSummary
      CASE 2
        ReportSummaryTodayFlag = true
        GOSUB ReportSummary
      CASE 3
        REM GOSUB
      CASE 4
        EXIT DO
    END SELECT
    ReportMenuSelection = 4
    selection = true ' force continued looping
  ELSE
    GOSUB InvalidEntry
  END IF
LOOP
IF SoundFlag THEN SOUND 2000, .5
RETURN

```

```

ReportSummary:
LOCATE 25, 33
PRINT "<<Processing>>";
GOSUB ReportSummaryInit
GOSUB GetDateTime
OPEN "UICCS.PRT" FOR OUTPUT AS #5
LineNumber = 1
PageNumber = 1
DateTimePrint$ = DATE$ + " " + TIME$
PRINT #5, ""
FOR RecordNumber = 1 TO MaxRecordNumber
  GET #3, RecordNumber, Sort1
  Filename$ = RTRIM$(Sort1) + ".INS"
  OPEN Filename$ FOR RANDOM ACCESS READ AS #1 LEN = 3643
  GET #1, 1, InspRecord
  CLOSE #1
  IF (ReportSummaryTodayFlag AND LEFT$(InspRecord.DTS, 8) = LEFT$(DateTimeString, 8)) OR
    (NOT ReportSummaryTodayFlag) THEN
    IF LineNumber = 60 THEN
      PRINT #5, CHR$(12)
      LineNumber = 1
    END IF
    IF LineNumber = 1 THEN
      Print Report Header
      PRINT #5, ""
      PRINT #5, TAB(22); "ULTRASONIC INSPECTION REPORT SUMMARY"; TAB(70);
      PRINT #5, USING "Page: ###"; PageNumber
      PRINT #5, TAB(30); DateTimePrint$
      IF ReportSummaryFlag THEN
        PRINT #5, TAB(30); "Today's Records Only"
      ELSE
        PRINT #5, TAB(31); "Cumulative Records"
      END IF
      PRINT #5, ""
      PRINT #5, ""
      PRINT #5, "Serial #          Summary"          dB      Inspection Pts
      PRINT #5, "-----"
      LineNumber = 10
      PageNumber = PageNumber + 1
    END IF
    PRINT #5, InspRecord.PSM; TAB(11); TAB(28);
    PRINT #5, USING "##.# "; InspRecord.DB;
    PassFailFlag = false
    FOR i = 1 TO 17
      tmp$ = MID$(InspRecord.PF, i, 1)
      IF tmp$ = "F" THEN PassFailFlag = true
      PRINT #5, tmp$; " ";
    NEXT
    PRINT #5, TAB(73);
    IF PassFailFlag THEN
      PRINT #5, "FAIL"
    ELSE
      PRINT #5, "Pass"
    END IF
    LineNumber = LineNumber + 1
  END IF
NEXT
PRINT #5, CHR$(12);
CLOSE
IF PageNumber = 1 AND LineNumber = 1 THEN
  LOCATE 25, 20
  PRINT "Request Terminated - No matching Records";
  IF SoundFlag THEN
    FOR Scan = 1 TO 20
      SOUND 1300, .4
      SOUND 1000, .4
      SOUND 700, .4
    NEXT
  END IF

```

```

ELSE
  SHELL "COPY UICCS.PRT PRN:"
END IF
KILL "UICCS.TMP"
KILL "UICCS.PRT"
RETURN

ReportSummaryInit:
  : Write Directory to File
  :
  SHELL "DIR *.INS > UICCS.DIR"
  :
  : Read in directory and save filenames (serial numbers)
  :
  OPEN "UICCS.DIR" FOR INPUT AS #2
  OPEN "UICCS.TMP" FOR RANDOM AS #3 LEN = 8
  RecordNumber = 0
  DO WHILE NOT EOF(2)
    LINE INPUT #2, tmp$
    IF MIDS(tmp$, 10, 3) = "INS" THEN ' filename extension
      RecordNumber = RecordNumber + 1
      PutPSN = tmp$
      PUT #3, RecordNumber, PutPSN
    END IF
  LOOP
  CLOSE #2
  KILL "UICCS.DIR"
  MaxRecordNumber = RecordNumber
  :
  : Sort Filenames (Serial Numbers)
  :
  IF MaxRecordNumber > 5000 THEN
    :
    : Sort to Disk
    :
    DO
      SortFlag = false
      FOR RecordNumber = 1 TO MaxRecordNumber - 1
        GET #3, RecordNumber, Sort1
        GET #3, RecordNumber + 1, Sort2
        IF Sort1 > Sort2 THEN
          PUT #3, RecordNumber, Sort2
          PUT #3, RecordNumber + 1, Sort1
          SortFlag = true
        END IF
      NEXT
    LOOP WHILE SortFlag = true
  ELSE
    :
    : Sort in memory
    :
    FOR RecordNumber = 1 TO MaxRecordNumber
      GET #3, RecordNumber, Sort(RecordNumber)
    NEXT
    DO
      SortFlag = false
      FOR RecordNumber = 1 TO MaxRecordNumber - 1
        IF Sort(RecordNumber) > Sort(RecordNumber + 1) THEN
          SWAP Sort(RecordNumber), Sort(RecordNumber + 1)
          SortFlag = true
        END IF
      NEXT
    LOOP WHILE SortFlag = true
    FOR RecordNumber = 1 TO MaxRecordNumber
      PUT #3, RecordNumber, Sort(RecordNumber)
    NEXT
  END IF
  RETURN

```

```

ResetTOT:
  TimeOutTimer = 0
  RETURN

RobotBitSetFalse:
  RobotBit(RobotBitSubScript) = false
  RETURN

RobotBitSetTrue:
  RobotBit(RobotBitSubScript) = true
  RETURN

RobotBitToggle:
  IF RobotBit(RobotBitSubScript) THEN
    GOSUB RobotBitSetFalse
  ELSE
    GOSUB RobotBitSetTrue
  END IF
  RETURN

RobotControl:
  ; Calculate CmdValue for controlling DIO8-P interface board
  ;
  CmdValue = 0
  IF RobotBit(1) THEN CmdValue = CmdValue + 1
  IF RobotBit(2) THEN CmdValue = CmdValue + 2
  IF RobotBit(3) THEN CmdValue = CmdValue + 4
  IF RobotBit(4) THEN CmdValue = CmdValue + 8
  IF RobotBit(5) THEN CmdValue = CmdValue + 16
  IF RobotBit(6) THEN CmdValue = CmdValue + 32
  IF RobotBit(7) THEN CmdValue = CmdValue + 64
  IF RobotBit(8) THEN CmdValue = CmdValue + 128
  ;
  ; Make sure .3 seconds have elapsed since last OUT &H300
  ; Note: This is required so that the HITACHI M5030 has
  ;       time to read the control line
  ;
  DO
  LOOP UNTIL RobotDelayTimer + .3 < TIMER OR TIMER < RobotDelayTimer
  ; Send control signal to HITACHI M5030 via DIO8-P interface board
  ;
  OUT &H300, CmdValue
  ;
  ; Save time for robot delay loop
  ;
  RobotDelayTimer = TIMER
  GOSUB DebugDisplayIO
  RETURN

```

```

ScreenHeader:
  COLOR colorf
  CLS 0
  IF DebugFlag THEN
    LOCATE 1, 70
    PRINT DisplayBoxTop$;
    LOCATE 2, 70
    PRINT DisplayBoxMiddle$;
    LOCATE 3, 70
    PRINT DisplayBoxMiddle$;
    LOCATE 4, 70
    PRINT DisplayBoxMiddle$;
    LOCATE 5, 70
    PRINT DisplayBoxBottom$;
    GOSUB DebugDisplay10
  END IF
  LOCATE 1, 27
  PRINT "University of Northern Iowa";
  LOCATE 2, 23
  PRINT "Department of Industrial Technology";
  LOCATE 3, 30
  PRINT "Metal Casting Center";
  LOCATE 4, 27
  PRINT "Cedar Falls, IA 50614-0178";
  GOSUB ClockDisplay
  LOCATE 6, 21
  PRINT "Copyright 1991-1992, All Rights Reserved";
  LOCATE 7, 34
  PRINT "Version 0.51";
  TIMER ON
  RETURN

SendStar:
  ResponseLength = 1
  |
  | Clear COM Input Buffer
  |
  IF LOC(6) > 0 THEN Response$ = INPUT$(LOC(6), #6)
  |
  | Send attention character [*]
  |
  PRINT #6, Star;
  |
  | Wait for a response w/timeout
  |
  GOSUB ResetTOT
  DO
  |
  | IF TimeOutTimer > 2 THEN EXIT DO
  LOOP WHILE LOC(6) < ResponseLength
  |
  | Read COM Buffer
  |
  ResponseStar$ = INPUT$(LOC(6), #6)
  |
  | Is acknowledgement correct [*]
  |
  IF ResponseStar$ <> "*" THEN
    IF ErrorFlag THEN
      ERROR 255
      STOP
    ELSE ' Try again
      ErrorFlag = true
      GOSUB SendStar ' Recursive call
      |
      | Clear ErrorFlag if second try succeeds
      |
      ErrorFlag = false
    END IF
  END IF
  RETURN

```



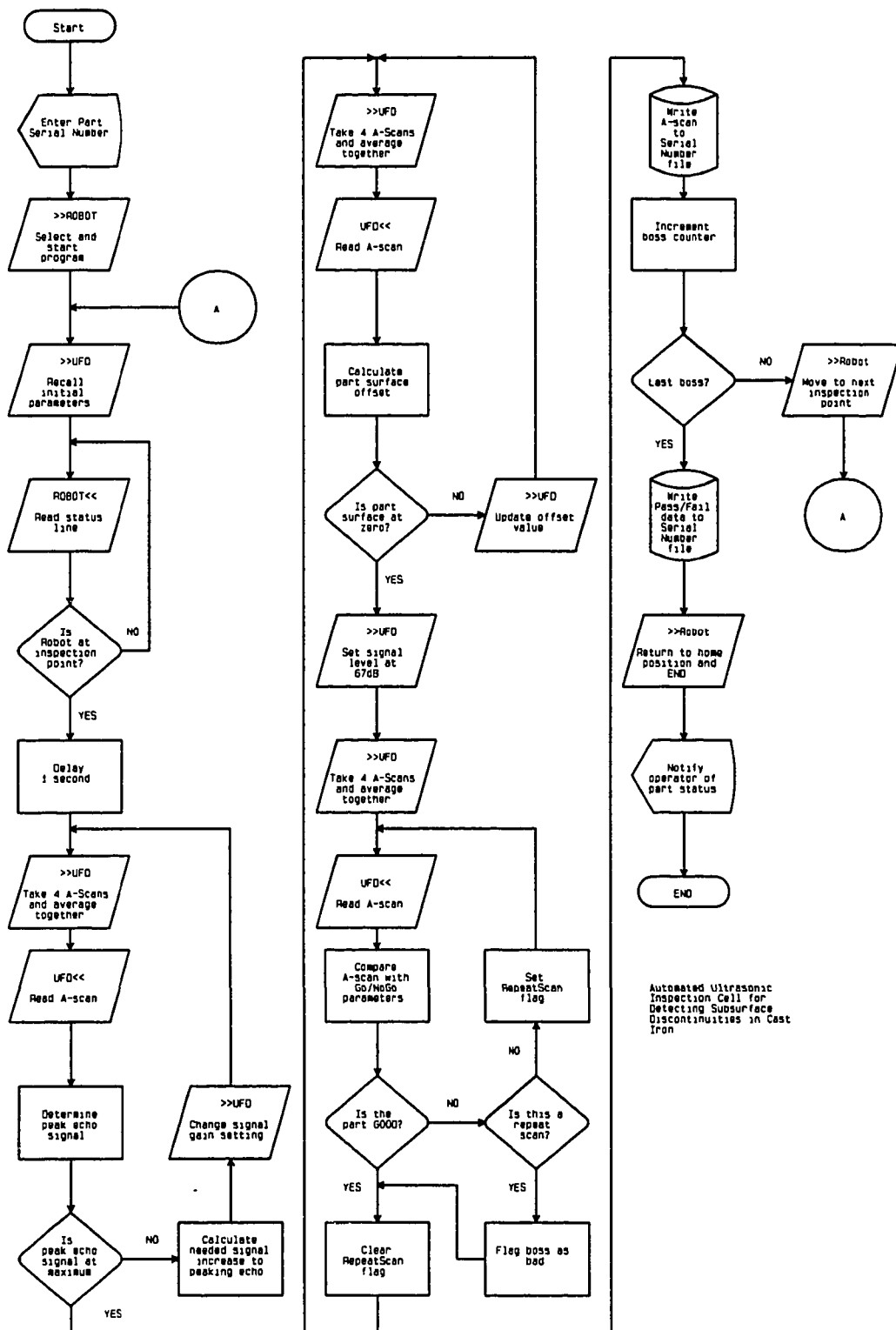
```

ZeroTransducer:
  DB = 0
  AdumpPeak = 0
  ReaddB = 0
  |
  |   Reset EPOCH 2002 display
  |
  |   GOSUB SendStar
  |   PRINT #6, "DISP=S"
  |   GOSUB ReadResponse
  |   GOSUB SendStar
  |   PRINT #6, "RCL=1"
  |   GOSUB ReadResponse
  |   GOSUB SendStar
  |   PRINT #6, "DISP=G"
  |   GOSUB ReadResponse
  |
  |   Set starting subscript range
  |
  |   SubscriptStart = 1
  |   SubscriptEnd = 200
  |
  |   Wait until Robot is in position
  |
  | DO
  |   GOSUB Hex301Read
  | LOOP WHILE NOT Hex301(0)
  |
  |   Wait 1 Second for robot to settle (it bounces at the end of motion)
  |
  |   SettleTimer! = TIMER
  | DO
  |   LOOP UNTIL SettleTimer! + 1 < TIMER OR TIMER < SettleTimer!
  |
  |   Zero Transducer
  |
  | DO
  |   GOSUB dBchange
  |   GOSUB GetAdumpPeak
  |   IF AdumpPeak > 20 THEN
  |     SubscriptStart = AdumpPeakPosition - 10
  |     IF SubscriptStart < 1 THEN SubscriptStart = 1
  |     SubscriptEnd = AdumpPeakPosition + 10
  |     IF SubscriptEnd > 200 THEN SubscriptEnd = 200
  |   END IF
  |   GOSUB dBcalculate
  | LOOP WHILE AdumpPeak < 63 OR DB > 3 OR DB < 0
  |   GOSUB SendStar
  |   PRINT #6, "DB=?"
  |   GOSUB ReadResponse
  |   FrontdB = VAL(MID$(ResponseString$, INSTR(ResponseString$, CHR$(10) + "DB=") + 4))
  |
  |   Left justify Top Surface
  |
  |   GOSUB SendStar
  |   PRINT #6, "ZERO=?"
  |   GOSUB ReadResponse
  |   FrontZeroOffset = VAL(MID$(ResponseString$, INSTR(ResponseString$, CHR$(10) + "ZERO=") + 6))
  |   SubscriptStart = 1
  |   LOOPFlag = false
  | DO
  |   |
  |   |   SET ZERO OFFSET
  |   |
  |   |   IF LoopFlag THEN
  |   |     GOSUB SendStar
  |   |     IF FrontZeroOffset < 100 THEN
  |   |       s$ = "ZERO=##.##"
  |   |     ELSE
  |   |       s$ = "ZERO=###.##"
  |   |     END IF
  |   |     PRINT #6, USING s$; FrontZeroOffset
  |   |     GOSUB ReadResponse
  |   |     GOSUB GetAdumpPeak
  |   |
  |   |
  |

```

```
ELSE
  LoopFlag = true
END IF
SubscriptEnd = AdumpPeakPosition + 10
IF SubscriptEnd > 200 THEN SubscriptEnd = 200
SELECT CASE AdumpPeakPosition
  CASE IS > 3
    FrontZeroOffset = FrontZeroOffset + AdumpPeakPosition / 19
  CASE ELSE
    FrontZeroOffset = FrontZeroOffset + .1
END SELECT
LOOP WHILE AdumpPeakPosition > 1
RETURN
```

**APPENDIX D**  
**CELL OPERATION FLOW CHART**



Automated Ultrasonic Inspection Cell for Detecting Subsurface Discontinuities in Cast Iron