To the Graduate Council:

I am submitting herewith a thesis written by Chris Allen Pickett entitled " An Ultrasonic Velocity Measurement System for Verifying Material Properties". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

Robert E Bodenheimer
R. E. Bodenheimer, Major Professor

We have read this thesis
and recommend its acceptance:

Asa O. Bishop, Jr.

William J. McCloy

Accepted for the Council:

Carolyn Winkel
Associate Vice Chancellor
and Dean of the Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis as partial fulfillment of the requirements for a Master of Science degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under the rules of the Library. Brief quotations from this thesis are allowable without special permission, provided accurate acknowledgement of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Chris A. Pickett

Date July 23, 1992

AN ULTRASONIC VELOCITY MEASUREMENT SYSTEM FOR VERIFYING MATERIAL PROPERTIES

A Thesis

Presented for the

Master Of Science

Degree

The University of Tennessee, Knoxville

Chris Allen Pickett

August 1992

DEDICATION

The author would like to dedicate this thesis to his parents, Ronald and Beverly, whose early guidance and support made an university education possible.

ACKNOWLEDGEMENTS

The author would like to acknowledge the cooperation of the following co-workers and supervisors whose encouragement and support helped make this thesis a reality. Zane W. Bell, for his early work with analytic signal, Eugene L. Bird, for metallurgically processing samples, Michael G. Duncan, for several discussions on the use of the Hilbert transform, William H. Hopwood, Jr. for his support and encouragement, Joan F. Hughes, for her collaboration with the experimental design, Keith A. Kitzke, for his support and assigning the project, John W. Koger, for providing financial support for the project, M. William Moyer, for early work involving the use of the cross-correlation method, and James R. Younkin, for providing a disk drive enclosure in a moment of desperation.

The author would also like to especially thank the efforts of his advisors: Drs. Robert E. Bodenheimer, Asa O. Bishop, and William J. McClain, whose guidance and support were essential to the completion of this project. In concluding, the author would like to recognize the tremendous tolerance and support of his wife Vicki, who collectively persevered through the entirety of this project.

ABSTRACT

Virtual programming methods were used to develop signal processing algorithms that can efficiently obtain precision time measurements from digitized ultrasonic signals. These algorithms are precision-wise improvements over the traditional "cursor-to-cursor" time measurements frequently used with the majority of today's digital storage oscilloscopes (DSOs). Each algorithm uses a different technique or a variation of a similar technique for ascertaining the transit time of an ultrasonic pulse. Once the transit time is obtained, it is mathematically combined with the material thickness (or the equivalent sound path distance) to acquire either the longitudinal or shear ultrasonic velocity.

Precision ultrasonic velocity measurements have been shown to be sensitive to the microstructural variations that exist within materials (variations that occur as result of material type and metallurgical processing) [1,2]. In many cases, ultrasonic velocity measurements can also be correlated to a specific mechanical property (i.e. yield strength, tensile strength, elongation, etc...). Accordingly, any improvements achieved in the precision or resolution of the ultrasonic time measurement directly ameliorates the ultrasonic velocity measurement, resulting in a more proficient method for (ultrasonically) verifying a material's mechanical properties.

This thesis describes the implementation and testing of a combination cross-correlation, analytic signal technique. Experimental results have shown that this technique provides the best combination of precision and resolution of the algorithms tested. By incorporating this algorithm into a computer system with the appropriate peripheral equipment (DSO, ultrasonic transducer, and pulser/receiver unit), a system capable of nondestructively (ultrasonically) verifying mechanical properties can be constructed. These types of systems can also, with the appropriate modifications, be implemented as "in-process" type measurements.

TABLE OF CONTENTS

LIST OF FIGURES

1. INTRODUCTION

1.1 Traditional Mechanical Property Measurement Methods

The determination of a material's mechanical properties has historically involved the creation and destruction of specially-fabricated tensile specimens. To fabricate these tensile specimens, additional material must be produced, processed, machined, and eventually sacrificed (in destructive mechanical property tests) to obtain the pertinent mechanical property information. The American Society of Testing and Materials (ASTM) is the national organization which develops and defines standardized mechanical property measurement methods that are used by the majority of industries in this country. In almost every case, these ASTM tests require that a physical change or alteration be induced into the material being tested, be it a small prick from a microhardness test or a complete fracture from a pull with a stress-strain gauge [3]. Additionally, some manufacturing processes require extra samples to be produced and prepared so that electron micrographs or photomicrographs of the material's microstructure can be made. These types of analyses furnish precise information, which generally provides additional assistance in confirming a mechanical property measurement. However, in all instances, regardless of the testing method, traditional mechanical property measurements always require some portion of material to be physically altered or destroyed. In other words, traditional mechanical testing methods are always *destructive*.

1.2 Today's Drivers Toward Nondestructive Determination of Mechanical Properties

In today's world of rapid growth in the material sciences, detailed knowledge of a

material's mechanical properties has become increasingly important. Many industrial drivers are now requiring that this "knowledge" be obtained by a *nondestructive* method(s). Verification of mechanical properties generally involves the fabrication of tensile specimens (or some sort of sacrificial specimens), which are designed to accommodate specific kinds of mechanical testing equipment (i.e., stress-strain gauges). Many manufacturers do not have the resources to mechanically test every part in a production run. Either extra material would be required for testing purposes or portions of every part would have to be sacrificed. For these reasons, industries have implemented statistical sampling methods of quality control (i.e., testing every tenth part, testing one part in every lot of a hundred, etc...), which reduce costs and, when implemented properly, can assure a relatively high-quality production batch. Unfortunately, some industries are required to deal with rare or hazardous types of materials, where even a statistical sampling program can be tremendously expensive. These materials represent problems that are very germane to today's world; problems that deals with the concerns and difficulties associated with the disposal and storage of the potentially hazardous wastes amassed from destroyed tensile specimens. These wastes may or may not be recoverable and, in some instances, may be caustic to both humans and the environment.

More and more frequently, production processes are also requiring that materials have very precise mechanical properties. These types of production processes usually represent industries which manufacture specialized components where a mechanical property failure in a piece part could represent a catastrophic failure to the larger apparatus (e.g., NASA'S Space Shuttle). The criteria discussed in this section describe only some of technical and procedural drivers that many industries are facing. These drivers are compelling industries to develop and implement nondestructive method(s) of mechanical property verification.

1.3 An Ultrasonic Technique for Mechanical Property Verification

The mechanical properties that always seem to be of major interest to material scientists are the ones that govern elastic behavior. These properties are affected by three basic characteristics: the type of material, the method of processing, and the sequence of processing (for multi-processed materials). By using a nondestructive (e.g., ultrasonic, x-ray, etc...) measurement for mechanical property verification, the amount of waste and costs associated with mechanical property testing can be significantly reduced.

Ultrasonic techniques used in determining mechanical properties rely heavily upon high-precision time measurements which, are mathematically combined with precision thickness measurements to obtain either the shear (transverse) or longitudinal ultrasonic velocity. Precision ultrasonic velocity measurements have been shown to be directly correlated with a specimen's mechanical properties and, in some cases, to the degree and type of metallurgical processing [1]. Implementing an ultrasonic inspection as an in-process-type measurement can also help reduce wastes by allowing processing corrections (i.e., re-processing) to be administered before manufacturing costs are driven up and potentially recyclable material is lost.

This thesis describes some previous work and some new efforts, and also relates some new techniques for making precision ultrasonic time measurements. Detailed experiments were designed and conducted with two types of uranium alloys . The goal of these experiments are to quantify the capabilities of the ultrasonic technique for verifying the mechanical properties of uranium alloys. A secondary goal, if possible, is to implement the ultrasonic inspection as an in-process-type measurement.

2. PREVIOUS EFFORTS AND NEW WORK

2.1 An Ultrasonic Method for Evaluating the Solution Quenching Process for Uranium-Titanium Alloys

A previous implementation of a high resolution ultrasonic velocity measurement system was developed by the author in 1988 [1]. This system was designed and used to verify the solution quench of uranium-titanium (U-Ti) alloyed parts. A description of the particulars of the ultrasonic technique, along with an explanation and verification of the technique's corresponding hypothesis are described in this section.. The results from an experimental study, designed to quantify the capabilities of the ultrasonic technique and two other nondestructive methods -- mechanical stress leveling and material density measurements, are also described.

Most metallurgical processes are designed to produce specific microstructural changes within a material, changes which when properly implemented yield the desired physical (mechanical) property. These changes can sometimes be observed ultrasonically when the material's microstructure is large compared to the wavelength of the ultrasonic signal. Rose [2] proposed using ultrasonic velocity measurements to detect the microstructural changes that occur in the region surrounding stainless steel inertia welds (also called the heat effected zone, which is defined as the area near the welded interface that has been microstructurally altered by the heat from the welding process). He showed that these microstructural changes produced a measurable shift in the ultrasonic velocity, which can be used to indicate the quality of the weld. Based on this study, one can hypothesize that any alteration or change in the metallurgical process that produces a microstructural change within a part also produces a corresponding change (or shift) in the ultrasonic velocity which, if measurable, may provide a nondestructive means of verifying

the quality of the metallurgical process. A high-resolution, high-precision ultrasonic velocity measurement system was developed to test this hypothesis.

Obtaining an accurate ultrasonic velocity from the direct measurement of the specimen length and the transit time of an ultrasonic pulse would seem to be a relatively simple task, but this procedure is actually only a recent achievement. The difficulty has been in accurately resolving very small time intervals. This can be further complicated by small ultrasonic signal-to-noise ratios and the dispersive nature of many materials, which tend to degrade significantly the quality of the ultrasonic signal.

Fortunately, digital storage oscilloscopes (DSOs) with extremely fast rise times and broad flat frequency responses now exist for these types of measurements. Figure 1

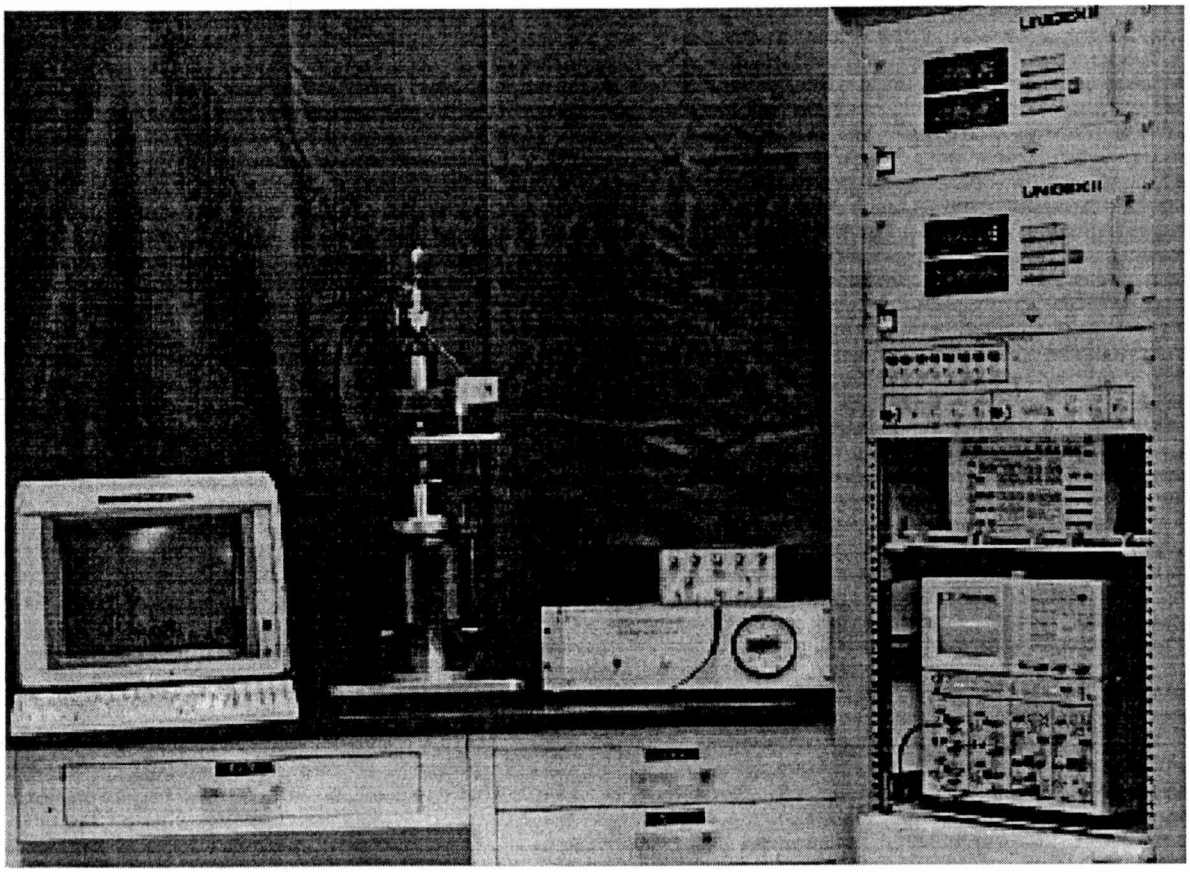


Figure 1: The U-Ti Ultrasonic Velocity Measurement System

depicts a Tektronix 7854 DSO as the heart of the ultrasonic velocity measurement system developed to verify the solution quenching of uranium-titanium (U-Ti) parts. The Tektronix 7854 DSO is capable of digitizing up to 1024 points per waveform and can be controlled by a computer via an IEEE-488 instrument bus. In the ultrasonic velocity measurement system shown in Figure 1, the Tektronix 7854 DSO is used primarily for displaying and acquiring ultrasonic waveforms.

Figure 2 is a blowup of the mechanism shown in Figure 1, used for pressure loading the ultrasonic transducer on to a specimen. This device is used to ensure adequate signal coupling (coupling substances such as water, oils, etc..., are used in ultrasonic contact testing to improve the sonic impedance match between the transducer and the specimen). Pressure loading also helps reduce the problems associated with thickness variations in the couplant. If the thickness of the couplant is either not uniform or too thick, timing errors can result. Pressure loading allows the couplant to be squeezed sufficiently thin, reducing any thickness irregularities, which improves the consistency of the timing measurement. The ultrasonic transducer whose frequency determined by the material's microstructure (grain size), is pulsed by a Panametrics 5055PRX pulser/receiver unit, which supplies short 300 volt pulses to the piezoelectric element in the transducer. The transducer's piezoelectric element responds with an ultrasonic vibration that reverberates at a frequency directly related to thickness of the piezoelectric element. Ultrasonic signals are injected into a specimen by the transducer, which also receives the corresponding reflections from discontinuities or interfaces within the specimen. These signals are displayed and digitized by the Tektronix 7854 DSO, which transmits them via an IEEE-488 bus to a Digital Equipment Corporation (DEC) PDP-11/23 microcomputer running a real-time operating system (RT-11). Several "in-house" written FORTRAN programs and subroutines (see Appendix A) are used to control the waveform acquisition and processing [4]. The resultant processed waveform is transmitted back to the Tek 7854

DSO for display and operator verification. A software algorithm is then used to determine and display the signal peaks on the DSO, along with the resultant waveform. This algorithm, developed to determine the ultrasonic propagation time, is described in the subsequent paragraph.

An ultrasonic rf-waveform is digitized (1024 levels), and is sent to the computer for processing where the analytic signal is determined [5-11]. The ultrasonic propagation

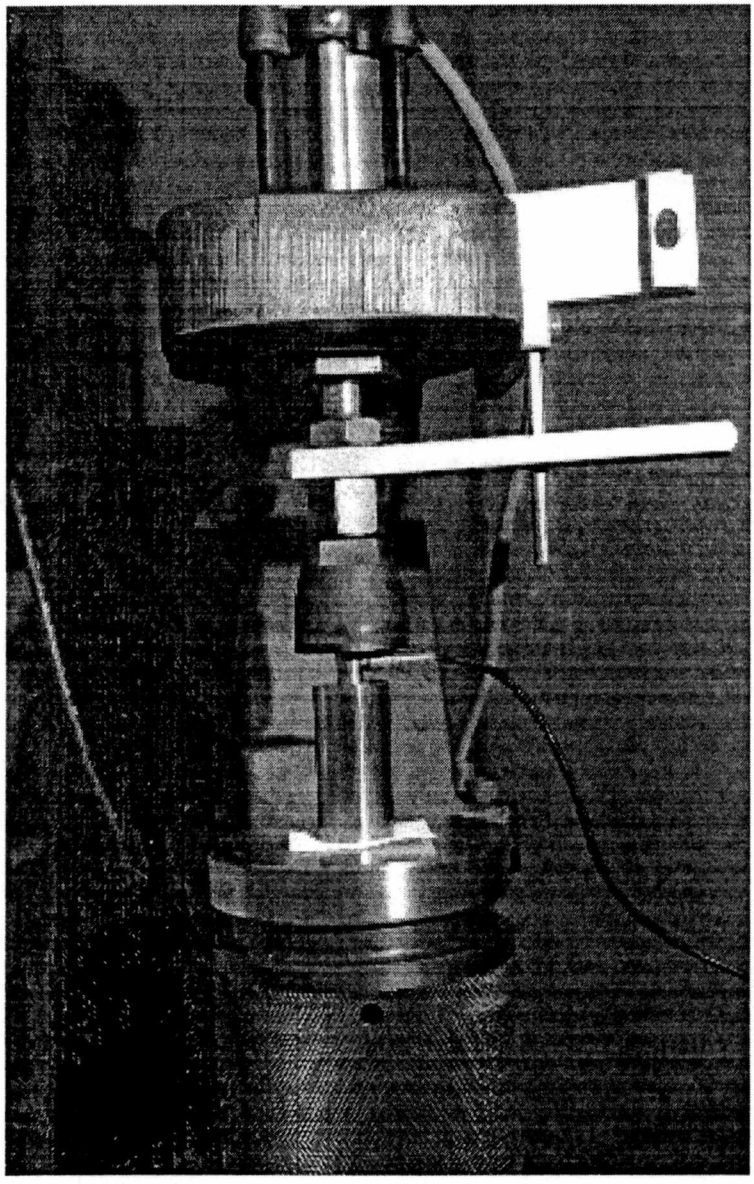


Figure 2: The Ultrasonic Transducer Loading Mechanism

times are determined from the peaks of the analytic signal. Previous studies have shown that the analytic signal provides better time resolution and tends to be a more repeatable measurement than traditional rf-waveform measurements [5,6]. The following paragraphs and calculations describe some of the results from previous studies, showing how the theory is used to determine the analytic signal from an ultrasonic rf-waveform.

Determination of the Analytic Signal

In 1981, Gammell proposed an alternative to the waveform rectification methods that had traditionally been used for detecting the rate of arrival of ultrasonic signals [5]. The proposed technique involved using the envelope of the analytic signal which could be determined from the ultrasonic rf-waveform by means of a Hilbert Transform. He cited earlier studies by Heyser [8], who in 1971 investigated the relationships between the analytic signal and the rate of arrival of acoustic energy in a study of the audio transducers used in loudspeakers. Heyser showed that the square of the magnitude of the analytic signal is proportional to the instantaneous rate of arrival of the components of energy (i.e., the kinetic energy, the potential energy, and/or a linear combination of the two). He also showed that the maximum magnitude of the Hilbert Transform occurred at a time corresponding to the instant of energy arrival. Since the analytic signal magnitude is directly related to the rate of energy arrival and is not modulated by the resonant frequency of the transducer, Gammell and others were able to show that the analytic signal provides a smoother, more readable signal, for detecting interface locations (see page 16).

Gammell advocated using the magnitude of the analytic signal as an improved method for ultrasonic B-scan imaging. Bell [7] developed a software program to determine the analytic signal from ultrasonic rf-waveforms, and he used this algorithm to produce improved ultrasonic B-scan and C-scan images. Bell also described an alternative

hardware implementation to Gammell's method [5] for an analytic signal processor that is based on a circuit described by Weaver [7]. Duncan [9] later published a paper describing another implementation of a real-time hardware design of an analytic signal processor, which he built specifically for processing ultrasonic signals. Both of these papers contain results confirming the use of the analytic signal as an improved ultrasonic method of interface detection. The text and equations that follow describe briefly the mathematical theory used for obtaining an analytic signal from a digitized waveform; some illustrations of its use with ultrasonic signals are also provided.

Analytic signals are complex-valued signals that have one-sided spectral density functions, where the real part coincides exactly with the original real-valued signal. Their spectra contain no negative frequency components, and their name derives from the fact that they are restricted to the real axis of an analytic function of a complex variable (i.e., they satisfy the Cauchy-Riemann conditions for analyticity). The properties of analytic signals are deduced from the properties of causal signals by exchanging time with frequency.

Hilbert Transforms are used to represent the relationships between the real and imaginary parts of the Fourier Transform of a complex function. These complex functions that represent discrete time signals are usually well-behaved functions. Their z-transforms are analytic functions within their regions of convergence, meaning that their z-transforms have an unique derivative that is continuous at every point within the region of convergence. The Cauchy-Riemann equations, that relate the partial derivatives of the real and imaginary parts of a complex function are complete and sufficient tests for determining analyticity of a function. There are also integral relationships that exist between the real and imaginary parts of a complex function that are analytic, and, in mathematics, these relationships are known as the *Poisson Integrals*. However, in signal processing theory these relationships are commonly referred to as the *Hilbert Transform relations* [10].

The derivation of the Hilbert Transform is based on the principle of causality, where causality conditions are applied to the Fourier Transform of a complex sequence and are used to relate the real and imaginary parts. This principle (causality) basically means that $\mathbf{X}(\omega) = 0$ for $\omega < 0$. However, since the Fourier Transform is periodic we cannot require $\mathbf{X}(\omega)$ to be zero for all $\omega < 0$. For these cases, causality requires that the Fourier Transform be zero in the second half of each period (i.e., the z-transform is zero in the bottom half of the unit circle from $-\pi \leq \omega < 0$). Therefore, for a sequence $\mathbf{x(n)}$ which has a Fourier Transform of $\mathbf{X}(\omega)$, the requirement would be that: $\mathbf{X}(\omega) = 0$ for $-\pi \leq \omega < 0$. This implies that the sequence $\mathbf{x(n)}$ corresponding to $\mathbf{X}(\omega)$ must be a complex sequence. Therefore $\mathbf{x(n)}$ can be expressed as the sum of its real and imaginary parts:

$$\mathbf{x(n) = x_R(n) + jx_I(n)} \qquad \mathbf{(2.1).}$$

In analog signal theory, the corresponding function to this analytic function would be called the ***analytic signal***. An analytic signal is a complex time function having a Fourier Transform that equals zero for negative frequencies. Although, analyticity has no meaning for sequences, but since any sequence $\mathbf{x(n)}$ can be modeled as a band-limiting analog signal $\mathbf{x_a(t)}$ where:

$$\mathbf{x_a(t)|_{t=n} = x(n)} \qquad \mathbf{(2.2).}$$

Therefore, if

$$X_a(j\omega) = X(e^{j\omega}) \quad \text{for} \quad 0 \leq \omega < \pi$$
$$= 0 \quad \text{for} \quad -\pi \leq \omega < 0 \qquad (2.3),$$

then the signal $x_a(t)$ is an analytic function of t. Under these conditions a sequence will also correspond to an analytic signal , and the Fourier Transform relations corresponding to the real and imaginary parts of $x(n)$ can be written as:

$$X_R(e^{j\omega}) = 1/2[\ X(e^{j\omega}) + X^*(e^{-j\omega})]$$

and

$$jX_I(e^{j\omega}) = 1/2[\ X(e^{j\omega}) - X^*(e^{-j\omega})] \qquad (2.4).$$

Since $X(e^{j\omega})$ is zero for $-\pi \leq \omega < 0$ and there is no overlap between the nonzero portions of $X(e^{j\omega})$ and $X^*(e^{-j\omega})$, means that $X(e^{j\omega})$ can be recovered from either $X_R(e^{j\omega})$ or $X_I(e^{j\omega})$ (see eqns. 2.4) as follows:

$$X(e^{j\omega}) = 2X_R(e^{j\omega}) \quad \text{for} \quad 0 \leq \omega < \pi$$
$$= 0 \quad \text{for} \quad -\pi \leq \omega < 0$$

or

$$X(e^{j\omega}) = 2jX_I(e^{j\omega}) \quad \text{for} \quad 0 \leq \omega < \pi$$
$$= 0 \quad \text{for} \quad -\pi \leq \omega < 0 \qquad (2.5).$$

The equations for $X_R(e^{j\omega})$ and $X_I(e^{j\omega})$ lead directly to following relationships:

$$X_I(e^{j\omega}) = -jX_R(e^{j\omega}) \quad \text{for} \quad 0 \leq \omega < \pi$$
$$= jX_R(e^{j\omega}) \quad \text{for} \quad -\pi \leq \omega < 0 \qquad (2.6),$$

which can be written as:

$$X_I(e^{j\omega}) = H(e^{j\omega})\, X_R(e^{j\omega}) \qquad (2.7),$$

where $H(e^{j\omega})$ is defined as:

$$H(e^{j\omega}) = -j \quad \text{for} \quad 0 \le \omega < \pi$$
$$= j \quad \text{for} \quad -\pi \le \omega < 0 \qquad (2.8).$$

According to these equations $x_I(n)$ can be obtained by processing $x_R(n)$ with the discrete system frequency response, $H(e^{j\omega})$. $H(e^{j\omega})$ has unity magnitude with a phase angle of $-\pi/2$ from $0 \le \omega < \pi$ and $+\pi/2$ from $-\pi \le \omega < 0$. Such a system is referred to as a 90-degree phase shifter or a Hilbert Transformer [10].

The Hilbert Transform relations that exist between the real and imaginary parts of a discrete analytic signal are given by:

$$x_R(n) = -\sum_{m=-\infty}^{\infty} x_I(n-m)h(m)$$

and

$$x_I(n) = \sum_{m=-\infty}^{\infty} x_R(n-m)h(m) \qquad (2.9),$$

where $h(m)$ is determined by:

$$h(m) = \frac{1}{2\pi}\int_{-\pi}^{0} je^{j\omega m}d\omega - \frac{1}{2\pi}\int_{0}^{\pi} je^{j\omega m}d\omega$$

$$= \frac{2}{\pi m}\sin^2\left(\frac{\pi m}{2}\right) \quad \text{for} \quad m \neq 0$$

$$= 0 \qquad \text{for} \quad m = 0 \qquad (2.10).$$

An alternative form of writing **x(n)**, in terms of magnitude and phase is as:

$$\mathbf{x(n) = A(n)e^{j\phi(n)}} \qquad \mathbf{(2.11)}$$

where

$$\mathbf{A(n) = [x_R^2(n) + x_I^2(n)]^{1/2}} \qquad \mathbf{(2.12)}$$

and

$$\mathbf{\phi(n) = \arctan\left[\frac{x_I(n)}{x_R(n)}\right]} \qquad \mathbf{(2.13).}$$

A(n) (also called the envelope **x(n)**) represents the magnitude of sequence and **ϕ(n)** is referred to as the phase. Heyser showed that the square of the real part of **A(n)** coincides with the kinetic energy of the signal while the square of the imaginary part represents the potential energy. Therefore, **A(n)** squared represents the total energy in the signal, which is what is needed to determine the arrival times of ultrasonic pulses.

Earlier we discussed that Gammell and others were able to demonstrate that the peak of the total energy **A(n)** function provides a better indication of echo magnitude and location [5-11]. Let's now look at some examples with actual ultrasonic waveforms that confirm their results. Figure 3 is a depiction of the results from each intermediary signal processing step that is used to obtain the analytic signal from an ultrasonic rf-waveform. In the first step the Fourier Transform is determined from the time domain signal **x(t)** (Figure 3a); this results in a frequency domain function **|X(f)|** (see Figure 3b). At this point all negative frequency components are set to zero (Figure 3c). The remaining function is inverse Fourier Transformed and whose magnitude is the Hilbert Transform or the analytic signal (as shown in Figure 3d).

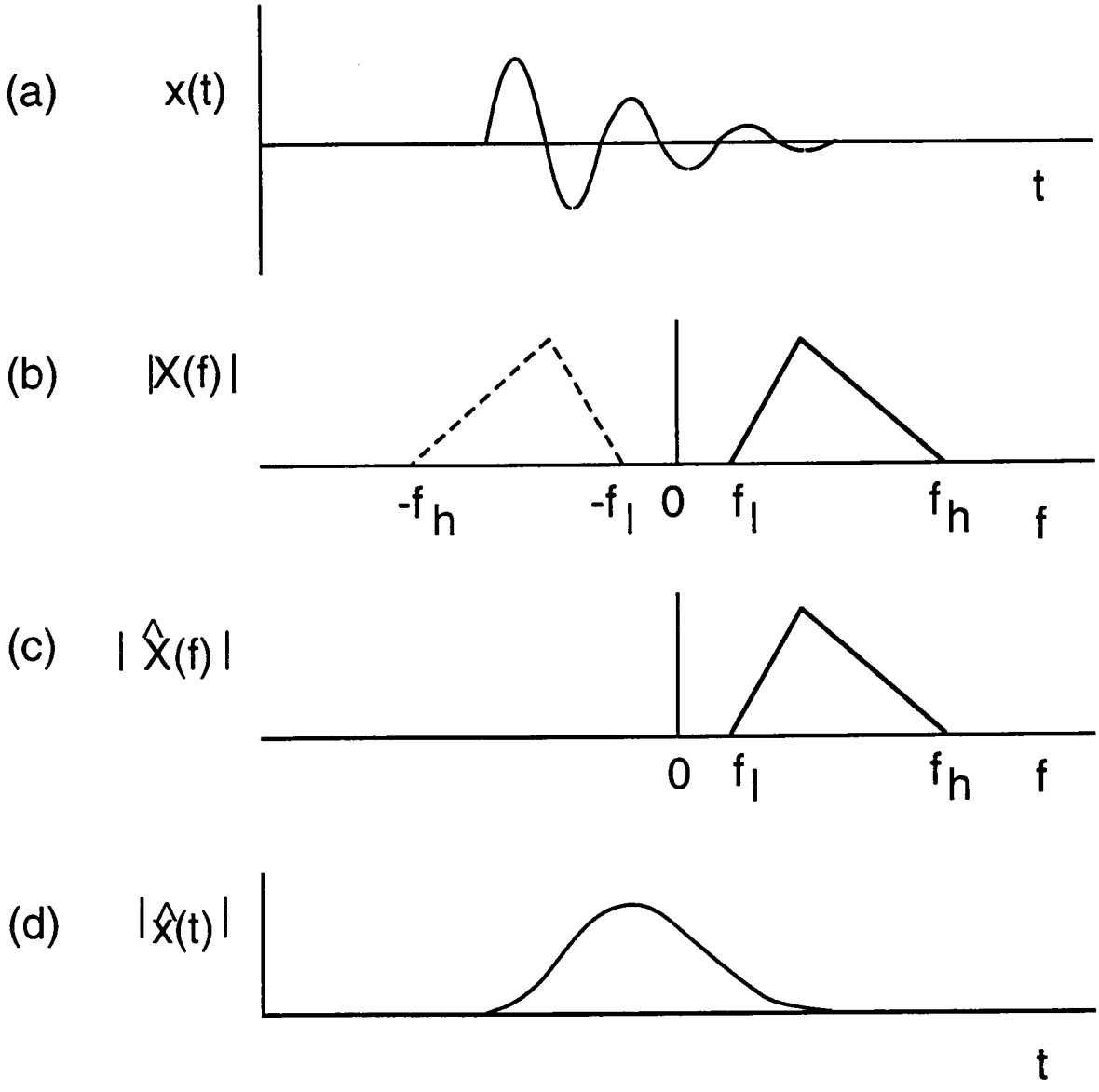


Figure 3: The Signal Processing Steps used to Obtain the Analytic Signal [9]

The following figures (Figures 4 and 5) demonstrate the usefulness of the analytic signal algorithm described above for ultrasonic inspections. Figure 4 shows a front surface reflection (i.e., an ultrasonic rf-waveform) obtained from a flat reflector and its corresponding analytic signal. Figure 5 shows an ultrasonic waveform obtained from a specimen with a closely spaced front surface defect. No indication of this defect can be seen in the ultrasonic rf-waveform; but when the corresponding analytic signal is

determined, an easily identifiable defect signal is obtained. The signal from this defect relates directly in time to the defect's distance from the front surface. Therefore, if the ultrasonic velocity of the specimen is known, the precise depth of this defect can be determined.

When the analytic signal is calculated from an ultrasonic waveform as is shown in Figure 5, the time obtained between the two signal peaks are used, along with the material thickness, to calculate the ultrasonic velocity. The reader should be aware, that sometimes a mode-converted signal can appear in the analytic signal spectrum. This occurs when an ultrasonic longitudinal wave is reflected from an internal interface at an angle different than the direction of travel. This is a normal effect that commonly occurs when propagating a longitudinal signal into a narrow specimen (narrow with respect to the diameter of the ultrasonic transducer). An example of this phenomenon is shown in Figure 21 (on page 49).

Ultrasonic Mechanical Property Measurements

The ultrasonic velocity, either longitudinal or shear, is generally calculated by using the two-way propagation time **t** (i.e., the time it takes for the ultrasonic signal to travel from the transducer, through the specimen, and back to the transducer) and the thickness of the specimen **D** (the one-way distance the ultrasonic signal travels in a specimen). The equation below represents the basic formula used for obtaining ultrasonic velocities:

$$\text{Velocity} = \frac{2D}{t} \qquad (2.14).$$

One should note, that the ultrasonic shear velocity requires the averaging of the transit

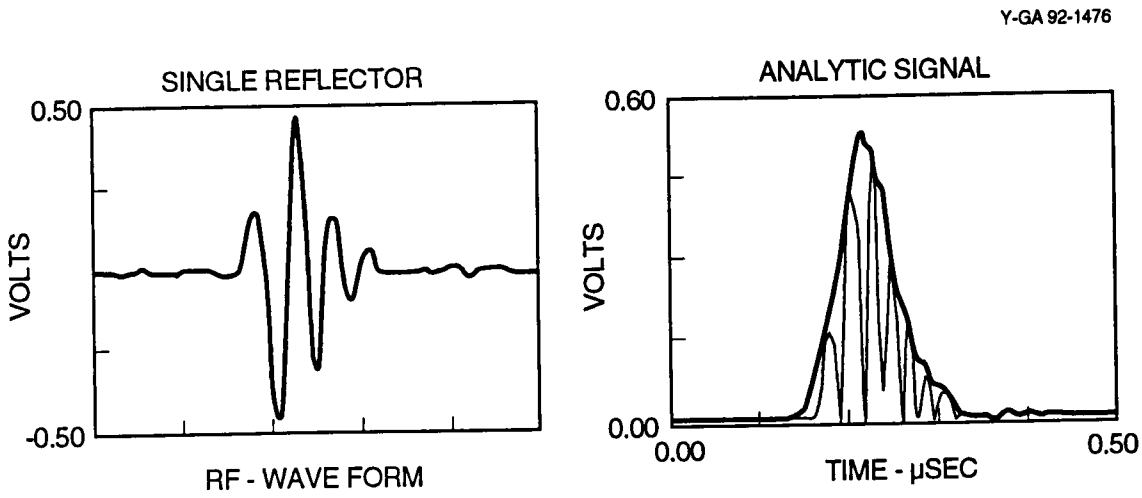


Figure 4: The Analytic Signal Determined from a Front Surface Reflection

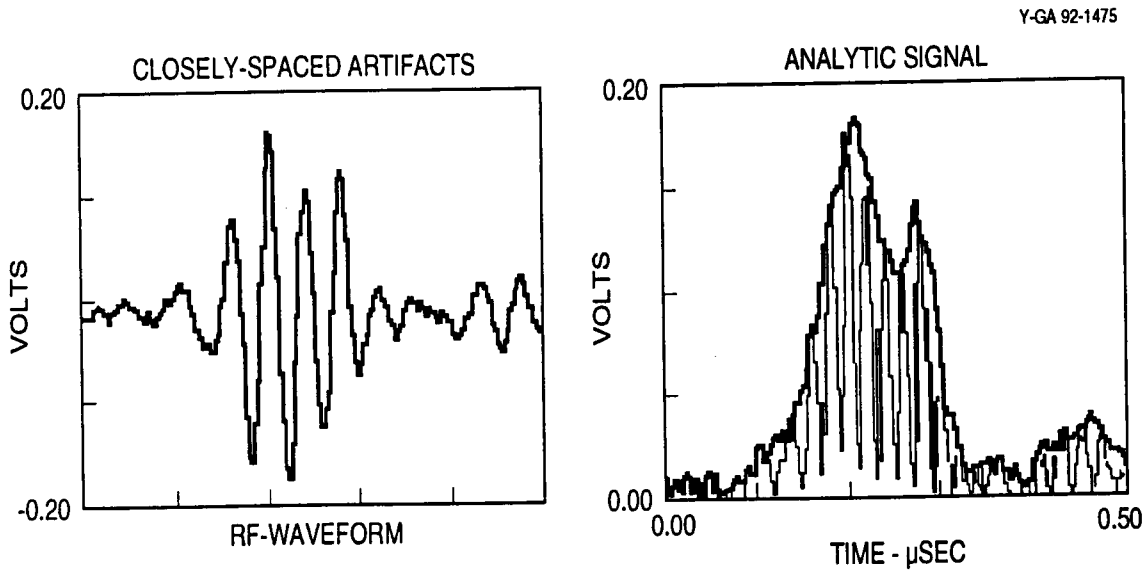


Figure 5: The Analytic Signal Determined from a Specimen with a Closely Spaced Front Surface Defect

times measured at both the zero-degree and ninety-degree transducer orientations. This is to account for signal polarization effects that occur within anisotropic specimens. Once the ultrasonic longitudinal and shear (transverse) velocities have been determined and if the

Table I: Equations for Ultrasonically Estimating a Material's Mechanical Properties [12].

Name	Symbol	Equation	Definition
Poisson's Ratio	σ	$= \frac{1-2(V_S/V_L)^2}{2-2(V_S/V_L)^2}$	**The ratio of lateral contracting strain to elongation strain**
Elastic Modulus	E	$= V_L^2 \rho \frac{(1+\sigma)(1-2\sigma)}{(1-\sigma)}$	**Applied load per unit area cross section / Increase in length per unit length**
Shear Modulus	G	$= V_S^2 \rho$	**Tangential force per unit area / Angular Deformation**
Bulk Modulus	K	$= \frac{V_L}{3(1-2\sigma)}$	**Compressive force per unit area / Change in volume per unit volume**

where ρ is the material density and V_L and V_S are the longitudinal and shear ultrasonic velocities.

material density is known, mathematical estimates of a material's mechanical properties can be determined by using the equations listed in Table I. One of the major differences between these ultrasonic estimations and actual mechanical property measurements is that the ultrasonic measurements are made essentially at the origin of the mechanical stress strain curve, whereas actual mechanical property measurements are made near the elastic limit of the mechanical stress-strain curve. This situation usually results in an offset or discrepancy between the two measurements.

Experimental Verification of Technique

Several uranium-titanium (U-Ti) specimens were prepared by a prototypical production process. These parts were then ultrasonically tested after each step in the metallurgical processing cycle. The processing steps required are listed below in sequential order.

1. ***Heat Treatment*** at an elevated temperature directly followed by ***Solution Quench*** at room temperature.
2. ***Stress leveling*** - a process for inducing mechanical strain into a part.
3. ***Aging*** - a process used to increase the yield strength of a part.

The heat treatment/quench process cannot be separated into two distinct processes. Partial cooling will occur if the parts are not quenched immediately after heat treatment. This produces inconsistent quenching within the part and reduces the completeness of the microstructural transformation. Figures 6 and 7 are 100X photomicrographs which illustrate the microstructural differences that occur when parts do and do not receive an adequate solution quench.

The U-Ti processing cycle (listed above) allows ultrasonic velocity measurements to be made at only the following intervals in the metallurgical process.

1. Before Heat Treatment /Quench
2. After Heat Treatment /Quench
3. After Stress Leveling
4. After Aging

Figures 8 and 9 are plots of the ultrasonic longitudinal and shear velocities (with 95% or the 2σ (sigma) tolerance limits) measured from over one hundred U-Ti specimens at each of the four processing steps. The plots illustrate the distinctness and relative consistency of the velocity change after each processing step. The largest velocity change occurs between the before heat treatment/quench and the after heat treatment/quench steps, which is nice, since the quenching process is the process that needs to be monitored.

Figures 8 and 9 also show the effect on the ultrasonic velocities from a set of parts that missed the stress leveling process (Treatment 4). These parts were heat treated and quenched, then mistakenly aged without any stress-leveling. The ultrasonic inspection quickly revealed that these parts were different from parts that went through the normal processing cycle. This type of observation substantiates the potential for using ultrasonic velocity measurements as a method for screening "good" parts from "bad" parts and/or for indicating the previous processing history of unknown parts.

Figure 6: Microstructure from Material that did not Receive an Appropriate Quench

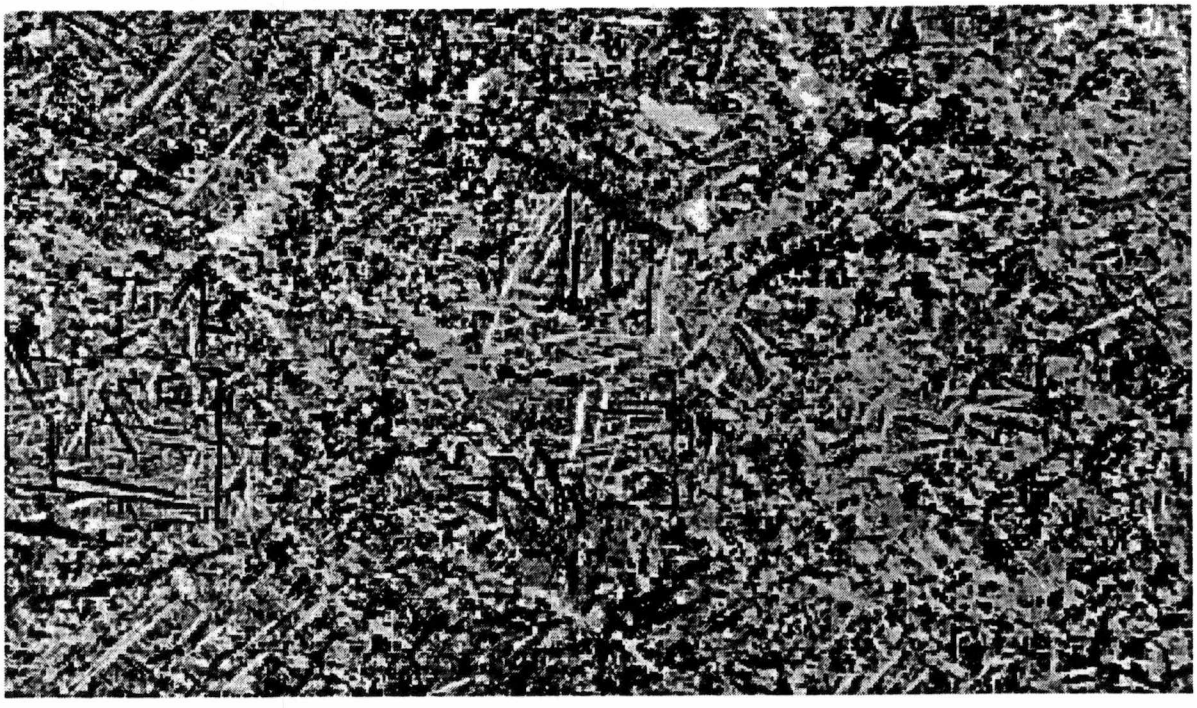


Figure 7: Microstructure from Material that did Receive an Appropriate Quench

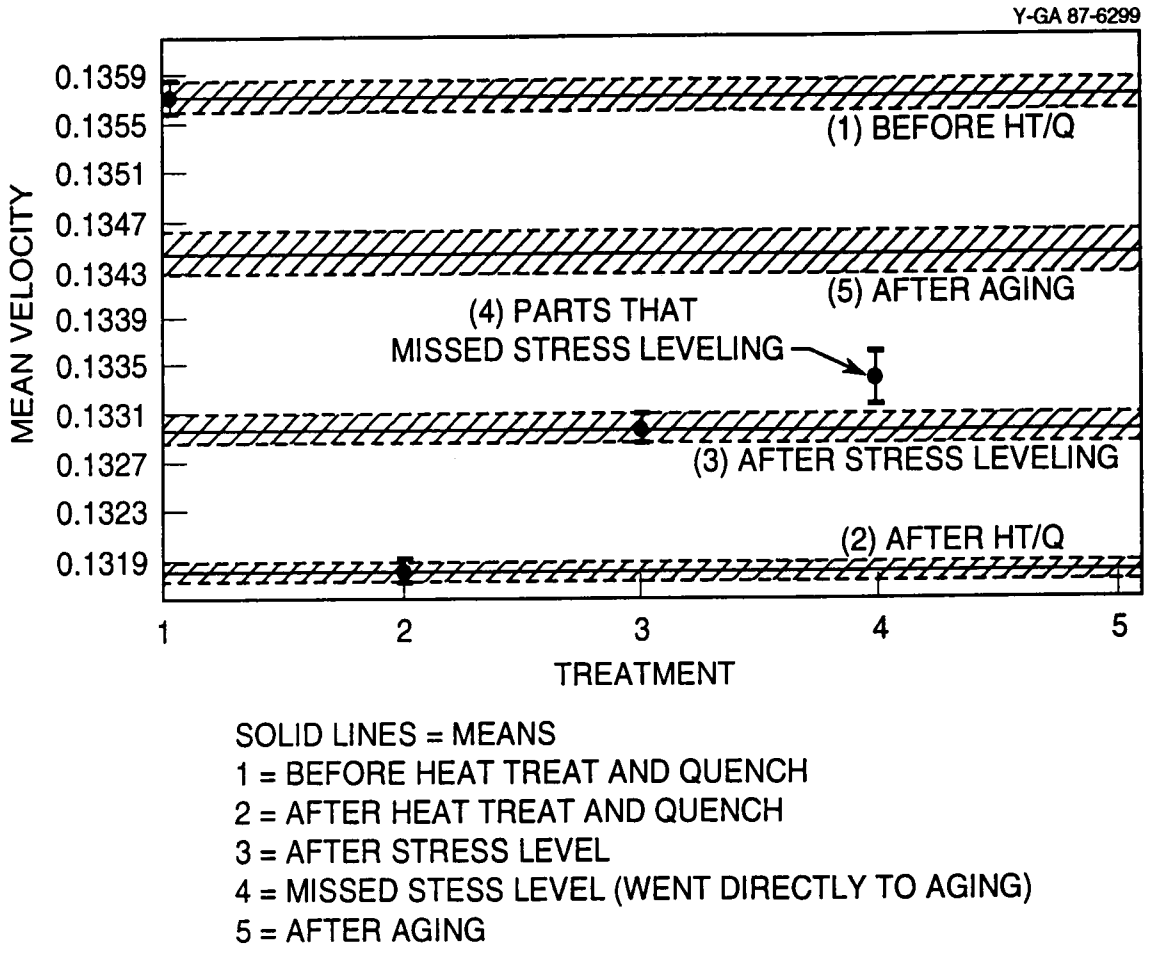


Figure 8: Ultrasonic Longitudinal Velocities (in/μs) After Each Processing Step

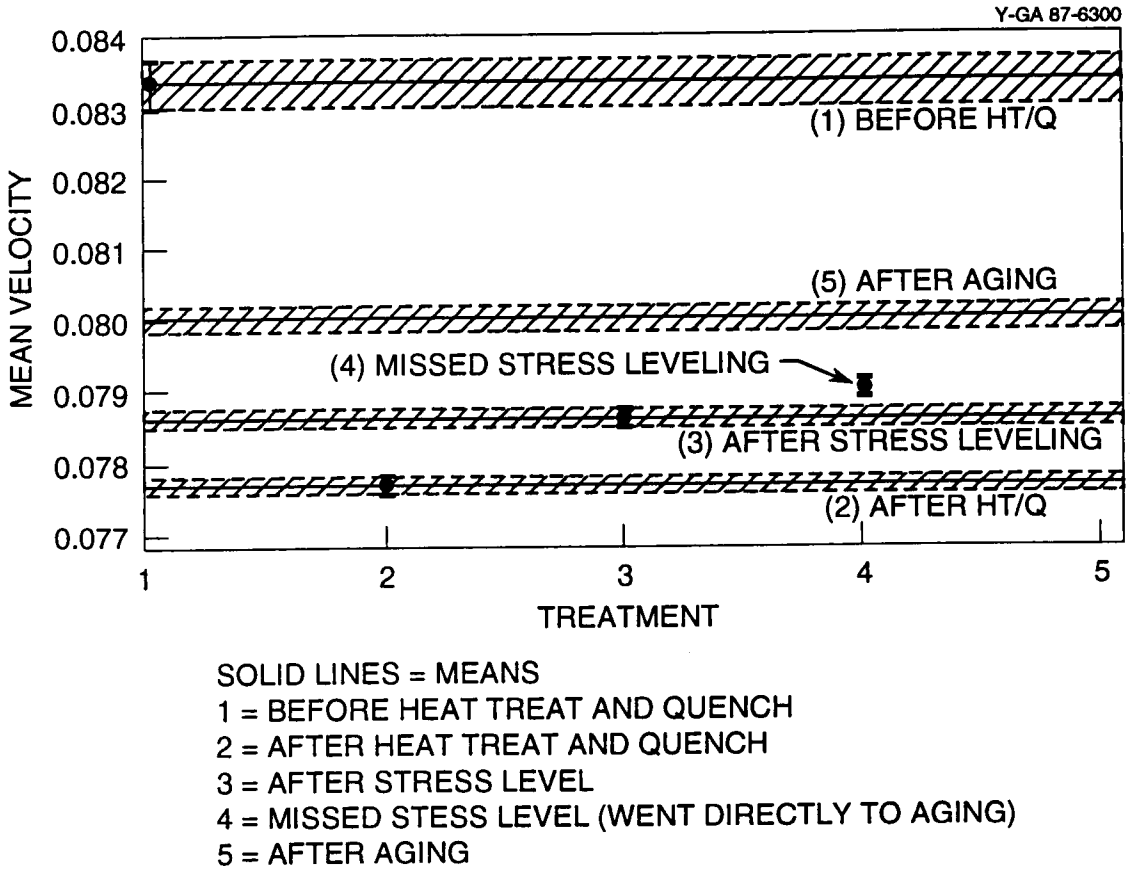


Figure 9: The Ultrasonic Shear Velocities (in/μs) After Each Processing Step

A Statistically Designed Experiment to Determine the Best Nondestructive Technique

U-Ti parts must receive immediate and rapid part quenching after heat treatment; otherwise, the parts may not yield the appropriate mechanical properties. If rapid uniform cooling does not occur, the microstructural transformation cannot go to completion, resulting in parts that crack and do not meet production specifications.

A statistical experiment was conducted to determine whether an ultrasonic velocity measurement, a material density measurement, or the mechanical stress-leveling data would be the best indicator of whether or not a part received an acceptable quench. Fifteen specially processed parts were created for this experiment. The 15 parts represented three replications of five different heat treatment/quench combinations. These combinations are as defined in Table II. The combinations listed in Table II represent situations that were the most likely to occur during the actual production process. For example, since the heat treatment/quench process is not two separate processes, Quench Types A (in Table II) are

Table II: The Heat Treatment/Quench Combinations used in the Experiment

Part Type	Heat Treatment	Quench Rate
A	No	None
B	Yes	1.5 in/minute
C	Yes	5.5 in/minute
D	Yes	14.0 in/minute
E	Yes	Nominal

representative of parts that would miss the entire heat treatment/quench step, while the other quench types represent distinct states of experimentally controlled quenching which may transpire after heat treatment.

Some feasibility studies were conducted prior to beginning of this experiment to establish a range of quench rates that could easily be reproduced during the experiment. The objective was to find three quench rates that were discernible and exist between the immediate (rapid) quenching of the production process and slowest quench rate (air-cooled). These rates were determined as those listed in Table II. Ultrasonic velocity data, depicted in Figure 10, shows that these are uniquely distinguishable quench rates. The velocities in Figure 10 are longitudinal velocities which represent the degree of microstructural transformation that has taken place as a result of the quenching process.

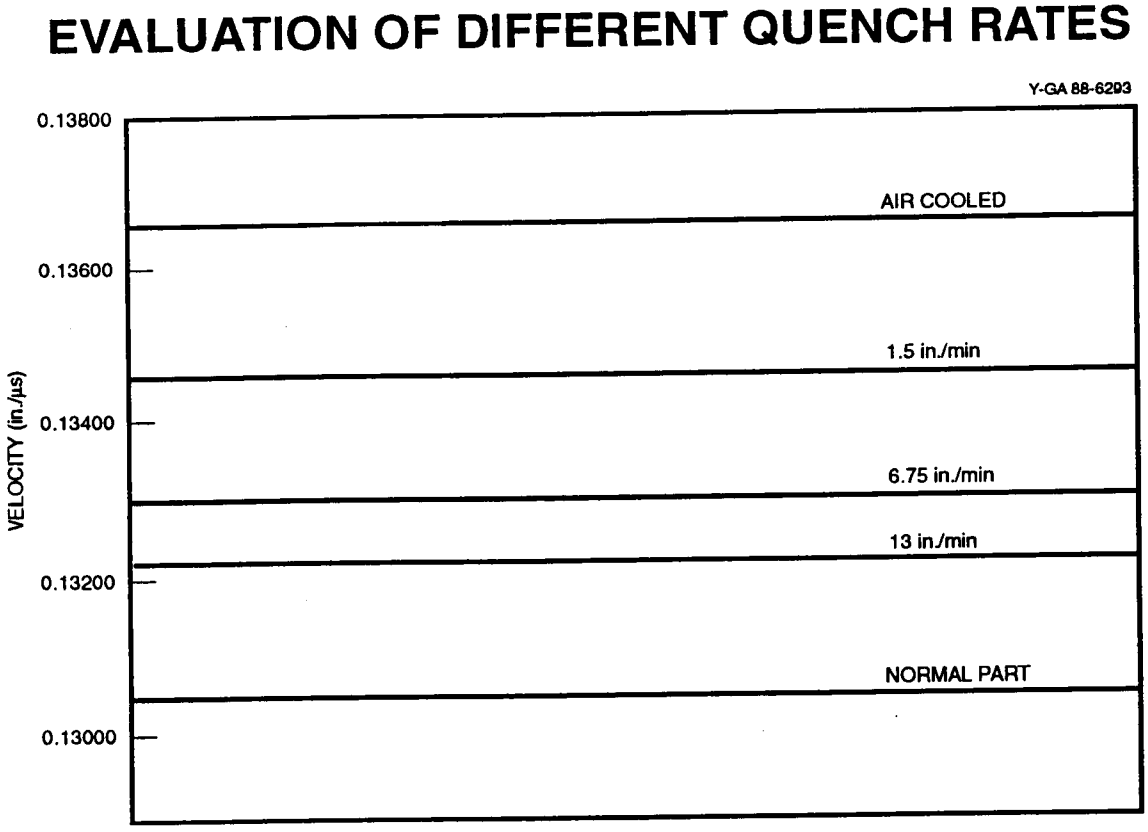


Figure 10 : Ultrasonic Longitudinal Velocities Measured at Various Quench Rates

Figures 6 and 7 (on page 20) are 100x magnifications that illustrate complete and partially complete microstructural transformations from two separate parts, one that received an adequate solution quench and one that did not.

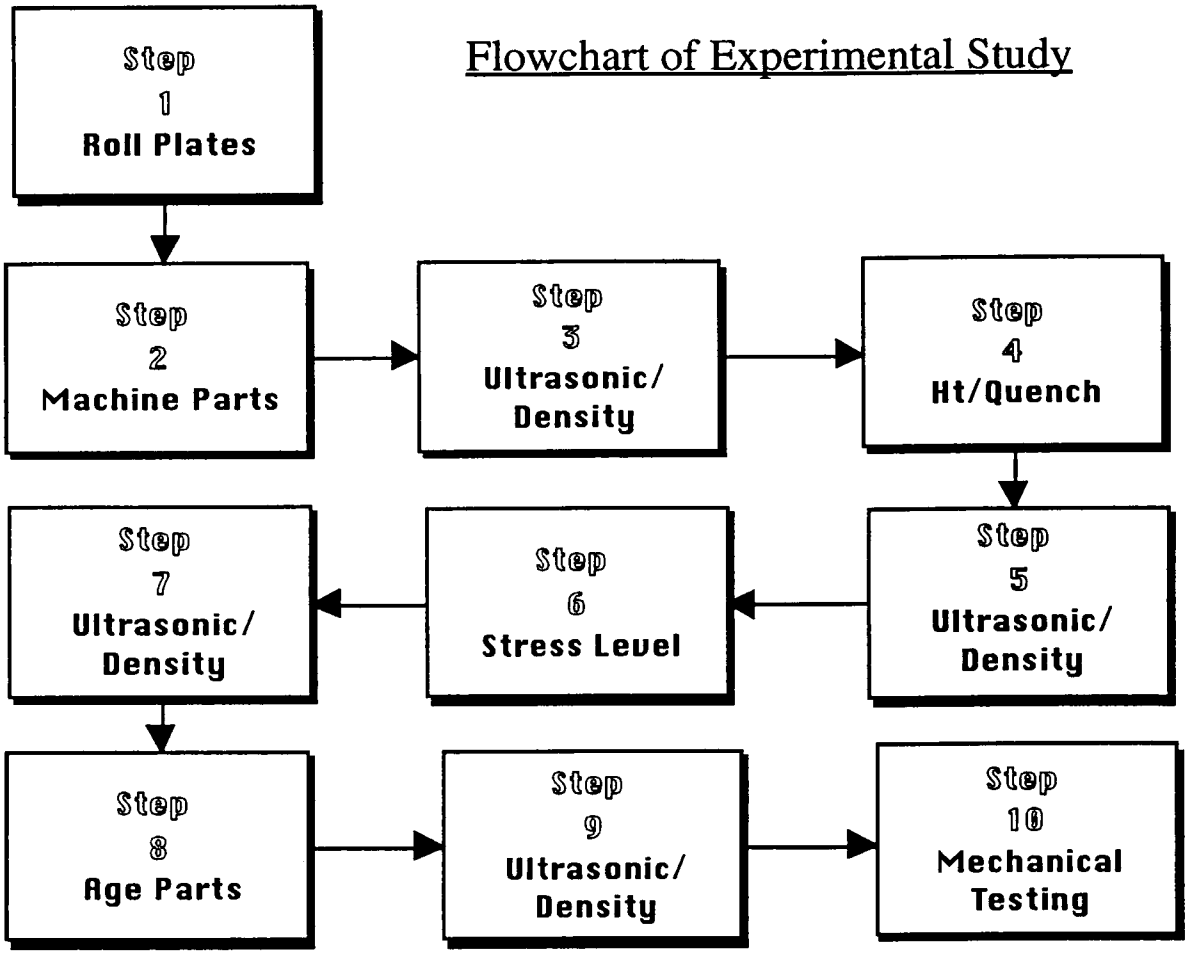


Figure 11 : A Block Diagram Flowchart of the Experimental Study

A block diagram illustrating the progression of this statistically designed experiment is shown in Figure 11. This diagram represents the sequence of events for the entire study, including the fabrication and processing of the 15 test specimens, along with indications of the appropriate intervals for collecting nondestructive data (ultrasonic and density). Stress leveling data were obtained during the actual stress leveling of the specimens. Traditional

(destructive) mechanical property tests were conducted as the final step of the plan, using 10 of the 15 specimens (the remaining 5 were held for standards) to obtain quantitative data on the following properties:

Compressive Yield Strength,
Tensile Strength, and the
Percent Elongation.

The results indicated that the ultrasonic and stress leveling measurements were the most sensitive to the quenching process, when the measurements were made directly after quenching. Figures 12, 13, 14, and 15 show the results from these measurements, including the results from density testing. One can easily see from these figures, that the ultrasonic longitudinal velocity results represent the best method for distinguishing between quench types. The mechanical property measurements indicated that the tensile strengths and compressive yields were within specification for all parts types except the parts in "A" group (no heat treatment/quench). The rate of quenching had the most significant effect on the elongation measurements (see Figure 15). Both the "A" and "B' quench groups failed to meet the desired specifications (NOTE: one part in the "B" group was within specification; however, the experimental criteria that was employed determined that if any part in the quench group was not within specification, then the whole group was not within specification). Using the elongation data (the property most affected by the quenching process), along with the longitudinal velocity data, a pass/fail ultrasonic test was designed and utilized to verify the quench of U-Ti parts.

Summary of the U-Ti Quench Verification Study

This work indicated that with the aid of computers and modern DSOs, ultrasonic velocity measurements can be used as a nondestructive means for verifying mechanical properties and for determining whether or not a part receives the appropriate processing. The technique also demonstrated the capability to verify the previous processing history or sequence for unknown parts when the process was previously (ultrasonically) characterized. Indications are that this type of technique can be used to verify other types of material processing as long as the metallurgical process produces a microstructural change within the material. The next section delineates the details of another experiment (not yet fully completed) which is designed to monitor the effects of combinational metallurgical processing on uranium-niobium materials.

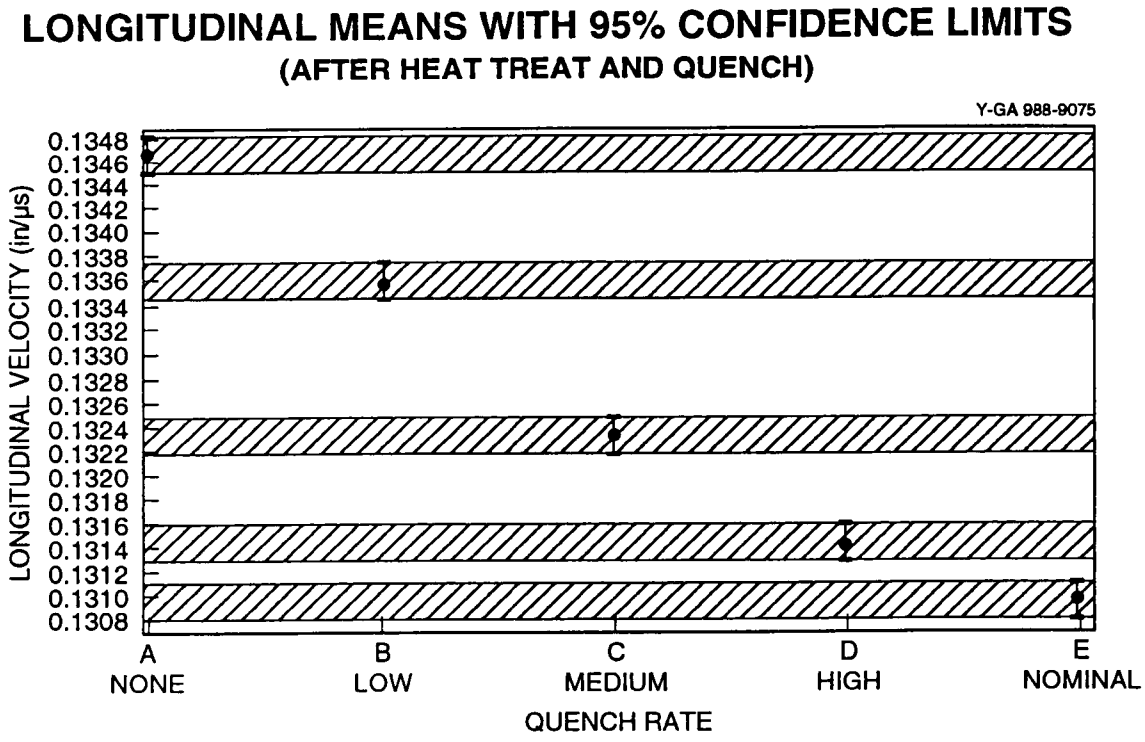


Figure 12: Ultrasonic Longitudinal Velocities as a Function of Quench Rate

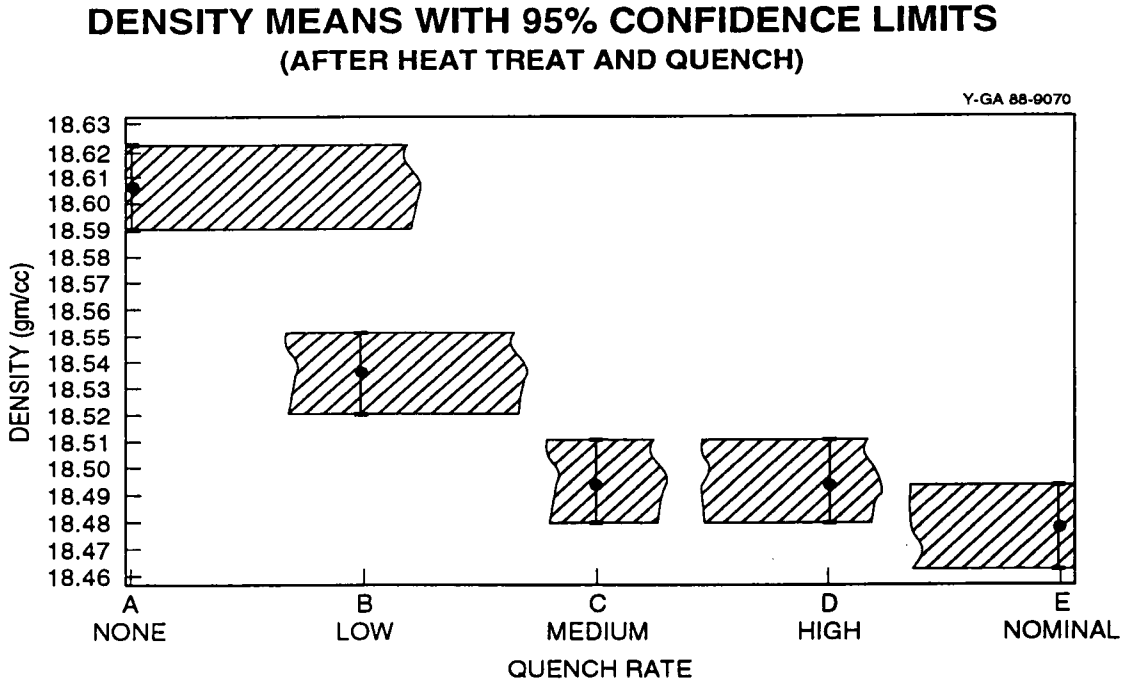


Figure 13: Density Measurements as a Function of Quench Rate

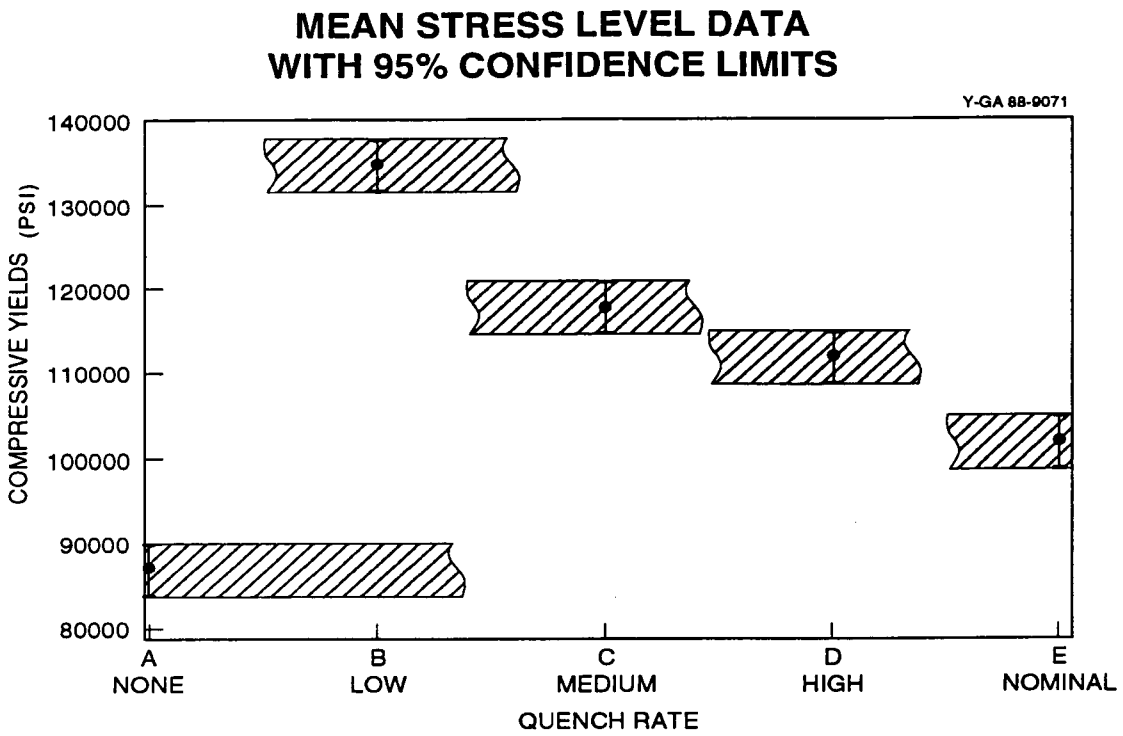


Figure 14: The Mechanical Stress Leveling Data as a Function of Quench Rate

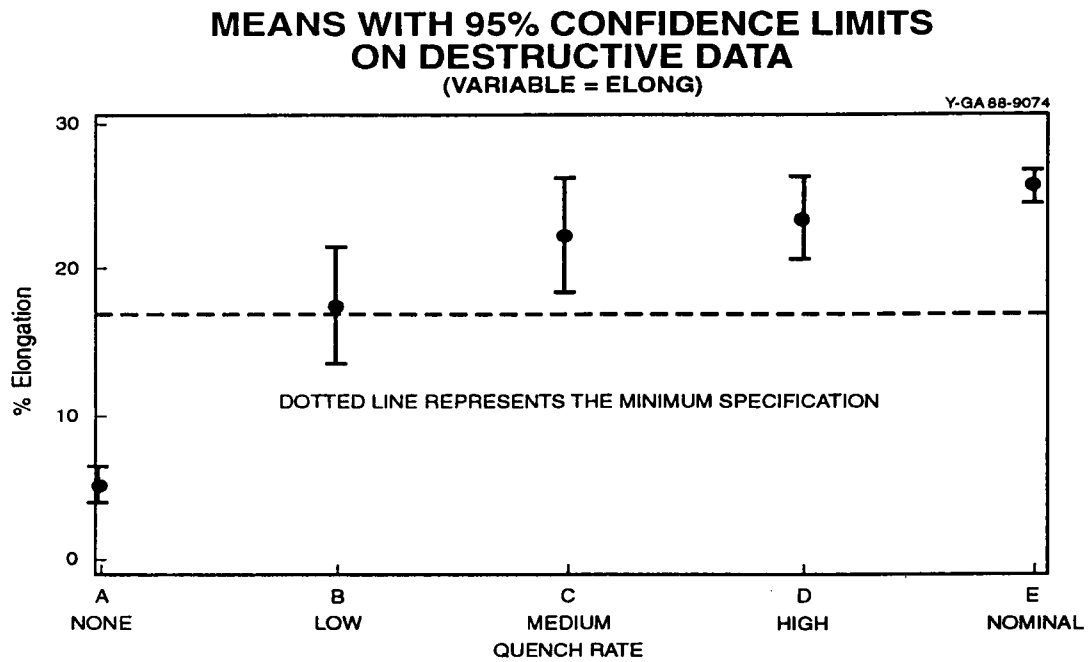


Figure 15: The Elongation Measurements as a Function of Quench Rate

2.2 New Work: A Study to Evaluate the Effectiveness of the Ultrasonic Method at Determining the Mechanical Properties of Uranium-Niobium Alloys

A new study has recently begun at the Oak Ridge Y-12 Plant, which is part of the Department of Energy's (DOE) Waste Minimization Program. This effort is focussed on reducing the amounts of uranium-niobium (U-Nb) scrap produced during the manufacturing and quality testing processes. As part of this program, an ultrasonic (nondestructive) test has been developed to determine whether it can be used to verify the mechanical properties of U-Nb parts. The current or traditional method for verifying the mechanical properties of these parts involves the creation and destruction of mechanical test specimens, which, along with the associated scrap, feed directly into the plant's waste stream. By using a nondestructive ultrasonic measurement for mechanical property verification, the amount of waste normally associated with mechanical property testing can be significantly reduced, eliminating the need for any future handling or disposal.

The ultrasonic measurement technique relies on obtaining a high-resolution time measurement which, along with a precision thickness measurement, are mathematically combined to obtain either the shear or longitudinal ultrasonic velocities. Previous studies have shown that ultrasonic velocity measurements have a strong correlation with both mechanical properties and the degree and type of metallurgical processing a part receives [1]. The goal of this experiment is to quantify the capabilities of the ultrasonic technique at verifying the mechanical properties of U-Nb parts. A secondary goal, if possible, is to implement the ultrasonic inspection as an in-process-type measurement. This can help reduce material waste by allowing process corrections (i.e., re-processing) to be administered before manufacturing costs are run up and potentially recyclable material is lost.

Similar experiments (as discussed in Section 2.1) were successfully conducted using ultrasonic velocity measurements to verify the degree of quenching for uranium-titanium alloys [1]. This work demonstrated that longitudinal ultrasonic velocities seem to be more sensitive at detecting processing variations than shear ultrasonic velocities. Correlations between with mechanical properties also indicated that longitudinal ultrasonic velocities provided statistically more stable results (i.e., a more uniform distribution).

This section discusses the details of an experiment designed to measure the effectiveness of using ultrasonic longitudinal velocity measurements to verify the mechanical properties of U-Nb parts. This experiment was designed specifically, to accommodate the two of metallurgical processing schemes used to produce U-Nb components.

Experimental Feasibility Work

Some initial feasibility work was conducted to determine if a high-resolution ultrasonic velocity measurement would be sensitive enough to detect the material processing variations associated with the U-Nb alloys. For these initial studies, only a limited number and type of samples were available for experimentation. The samples were processed (as determined by a metallurgist) by one of three methods, all with normal solution heat treatments and then with either no aging (unaged), aged at 300 degrees Celsius for 2 hours, or aged at 200 degrees Celsius for 3 hours. Repeated ultrasonic measurements on these test samples produced the following average longitudinal ultrasonic velocities for each of the three aging groups:

1. Unaged	0.1165 in/μs
2. 300 degrees Celsius for 2 hours	0.1203 in/μs
3. 200 degrees Celsius for 3 hours	0.1175 in/μs

The results indicate that ultrasonic velocity measurements have, in some cases, less than 1% change from one aging type to another, but yet remain distinctly stable between all parts within the same (aging) group. The results from this feasibility study indicate that ultrasonic velocity measurements are sensitive to variations in the aging process of U-Nb parts. However, a more detailed study [13] is required to better quantify these measurements, and to ascertain precisely how sensitive they are to the variations in solution heat treatments plus, the combinational variations associated with both heat treatment and aging processes. Finally, it must be determined whether or not these measurements can be correlated to specific mechanical properties.

Design of an Experimental Matrix-Type Study

As mentioned earlier, all U-Nb parts manufactured at the Oak Ridge Y-12 Plant are produced according to one of three specified processes:

1. Heat Treatment/ Quench Aging (HTQA) process
2. Heat Treatment/ Quench No Aging (HTQU) process, and
3. A Special Process Forming Method (SPF).

The only basic difference between the HTQA processing method and the HTQU processing method, is that the HTQU processing method does not require the aging step. In this section, the experimental study described, focusses on components manufactured

by either the HTQA or HTQU methods. Since the SPF method is relatively new, it is not included in this experimental design, but a similar experimental study may be required in the future to evaluate this process.

Designing this experiment, as is in any experiment, is based on determining exactly what it is that needs to be measured. In this case, a request was made to determine whether or not an ultrasonic method exists that can adequately verify that a U-Nb part possesses the desired mechanical properties. According to this request, what is desired is a direct nondestructive measurement which can certify the mechanical properties of U-Nb components. Unfortunately, a direct (ultrasonic) measurement of mechanical properties is not possible, since ultrasonic mechanical property measurements are based on calculations (see Table I) involving the specimen's acoustic velocity and material density. Additionally, the mechanical property estimates based on these calculations are usually made when the specimen is in a relaxed condition (i.e., at the origin of the stress-strain curve), as opposed to destructive mechanical property testing where measurements are made near the specimen's elastic limit. For these reasons, direct comparisons of ultrasonic mechanical property measurements with measurements made by mechanical testing methods, almost always yield a discrepancy or an offset. However, prior work has indicated that ultrasonic velocity measurements, can be correlated with a specimen's mechanical properties The goal of this study is to develop similar correlations that allows the mechanical properties of U-Nb components to be estimated by means of an ultrasonic (nondestructive) measurement.

For the reasons previously stated, an experimental study was designed [13} to quantify any correlations that may exist between ultrasonic mechanical property measurements and those destructively obtained from tensile specimens (taken from parts or processed test coupons). In order to satisfy the statistical design requirements of this experiment, it was determined that a total of 107 parts (or test coupons) would need to be

fabricated. This was accomplished by using 2 billets of U-Nb material, which were rolled into 2 plates producing a total of six rectangular plates with dimensions of 22.5 inches by

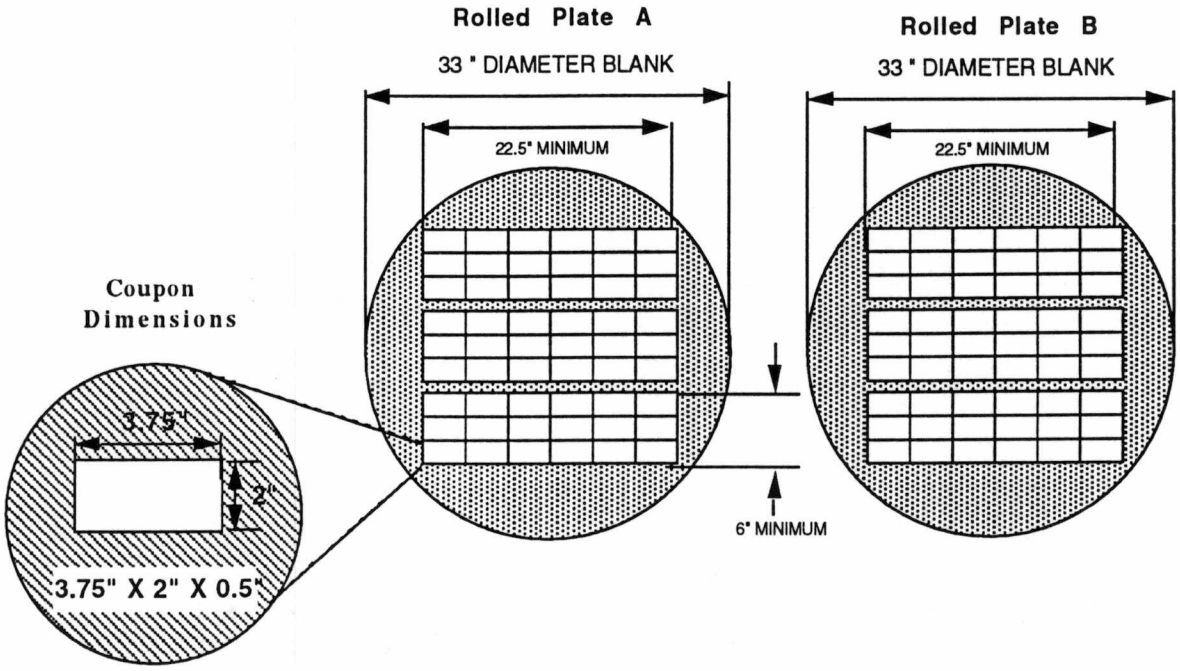


Figure 16: A Depiction of the Relative Dimensions and Locations of Test Coupons and Sawed Plates

6 inches by 0.5 inches. Three separate plates were sawed from each rolled plate and subsequently sectioned into eighteen, 3.75 inch by 2 inch by 0.5 inch test coupons (for a total 108 coupons). The coupons were cut from the sawed plates by an electron discharge machine (EDM), to ensure smooth edges and reduce or eliminate the likelihood of having machining stresses inflicted into the test coupons (as is sometimes the case with coarse cutting methods). Figure 16 illustrates the locations of the sawed plates and coupons on rolled plates A and B, along with the dimensional details. Figure 17 is a flowchart illustration of the entire material fabrication process from billets to tensile specimens.

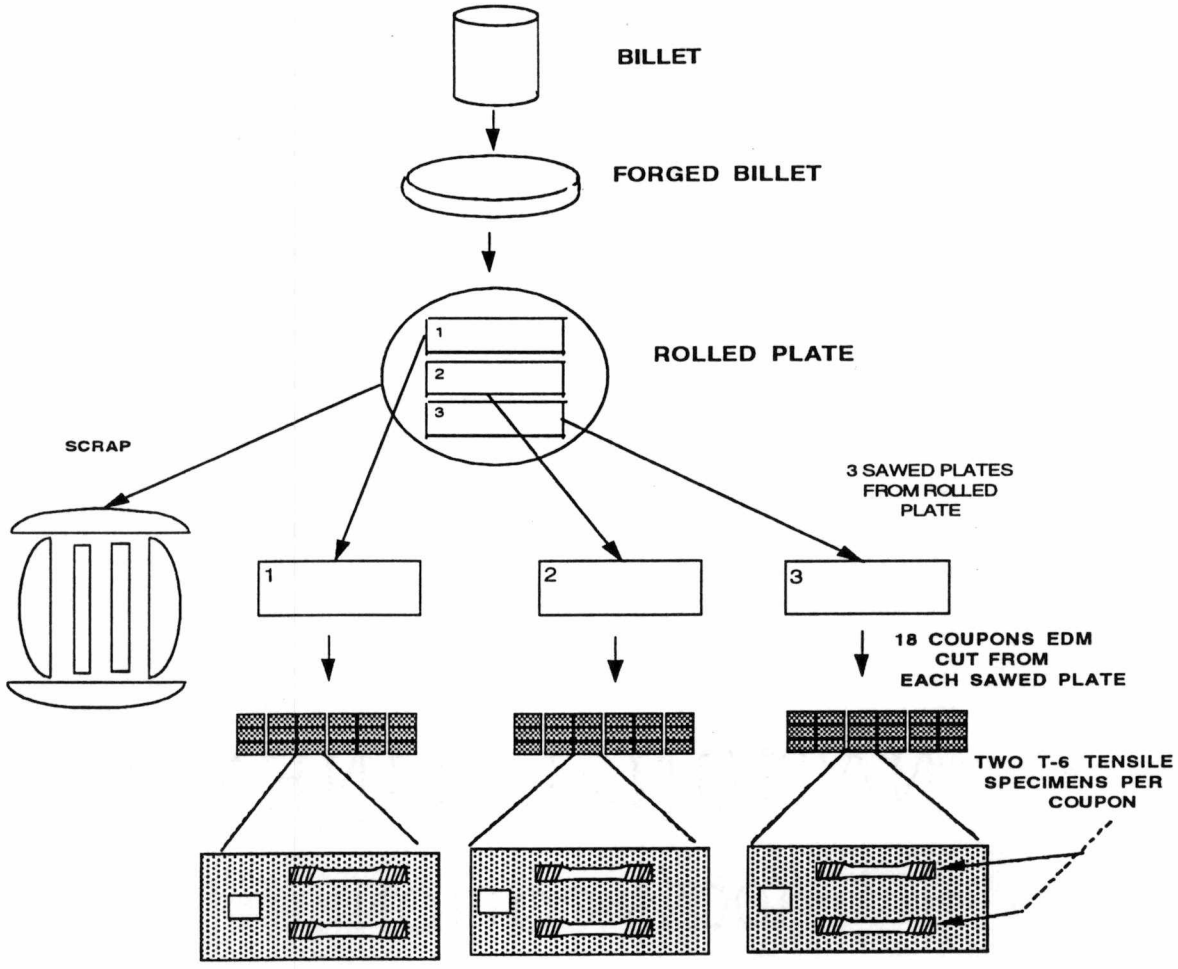


Figure 17: A Flowchart Illustrating the Fabrication Process from Billet to Tensile Specimens

All excess material cut from billets A and B was cut into test blanks (coupons) and used for experimental heat treatment and aging studies. These studies are designed to determine what heat treatment and aging parameters are needed to produce coupons with specific mechanical properties. Knowledge of these parameters allows test coupons to be reproduced possessing a desired mechanical property. To ensure a successful study, test samples must be manufactured with a variety of distinct mechanical properties. The study must also emulate, as closely as possible, all potential heat treatment and aging situations

that are most likely to occur in the production environment.

Experimental Procedures

Appendix B contains the Program Evaluation and Review Technique (PERT) chart that identifies the individual task steps and work flow associated with this experiment. All major task steps and projected milestones, along with estimates of the associated start and completion dates are listed on this chart. As indicated previously, the experiment requires that 107 test coupons be divided into three experimental test groups. These groups are defined as follows:

Group #1 consists of coupons that are contrived to evaluate the effects associated with the solution heat treatment and quenching process on the ultrasonic measurement. This group represents parts processed by the HTQU specifications. The heat treatment/ quench parameters for this group of parts are determined from the experimental work on the scrap. There are 72 coupons used for this portion of the study, including, an additional 35 coupons which are used to represent the nominal heat treatment condition. These 35 coupons will later be classified as **Group #2.** The five heat treatments that will be evaluated and the number of coupons per treatment are specified below:

A - No heat treatment/quench (18 total parts)
B - (parameters to be determined from experimental work on scrap) (18 total parts)
C - (parameters to be determined from experimental work on scrap) (18 total parts)
D - (parameters to be determined from experimental work on scrap) (18 total parts)
E - (nominal heat treatment/quench) (35 total parts that are to be used in the aging (**Group #2**) portion of this study)

Of the 18 coupons used per heat treatments A, B, C, and D, twelve will be used in the combinational portion of the study **Group #3** (defined below), 4 will be mechanically tested and 2 will be held as replacements. Data will be obtained from the 35

nominally heat treated and quenched **E**- coupons (which will subsequently be used in the aging study (**Group #2**)).

The **Group #2** coupons will be used to evaluate the effects on the ultrasonic velocity measurement directly related to variations in the aging process. This group represents parts processed by the HTQA specifications. The 35 test coupons used in this portion of the study will each receive a nominal heat treatment and quench, and then be aged as follows:

Aging V - Unaged (same as **HT/Q E**-coupons). (7 total parts)
Aging W - Underaged.(7 total parts)
Aging X - Nominal (Normal) aged.(7 total parts)
Aging Y - Slightly overaged.(7 total parts)
Aging Z - Overaged.(7 total parts)

The aging types listed above are generically referred to as V, W, X, Y, and Z during the course of this experiment. The exact specifications defining each of these aging types are determined from existing data and from the experimental studies conducted with the scrap. Initially, 4 of the 7 coupons from each aging batch will be mechanically tested, while the remaining 3 will be held for use as spares and/or potential ultrasonic calibration standards. Note, the **Aging V**-coupons are the same as the **HT/Q E**-coupons; both categories represent the same processing condition (nominal heat treatment, no aging). This overlap in the experiment, provides an opportunity to obtain additional information pertaining to the measurement variability of both the ultrasonic and density measurement techniques.

The **Group #3** coupons are used to evaluate the effects on the ultrasonic measurement associated with combinational processing situations where both the heat treatment and the aging processes deviate. This phase of the experiment utilizes 48 parts from the heat treatment/quench group (**Group #1**). These parts are used to complete the combinational matrix illustrated in Figure 18. This matrix contains all possible combinations of heat treatment and aging occurrences that may exist within the parameters

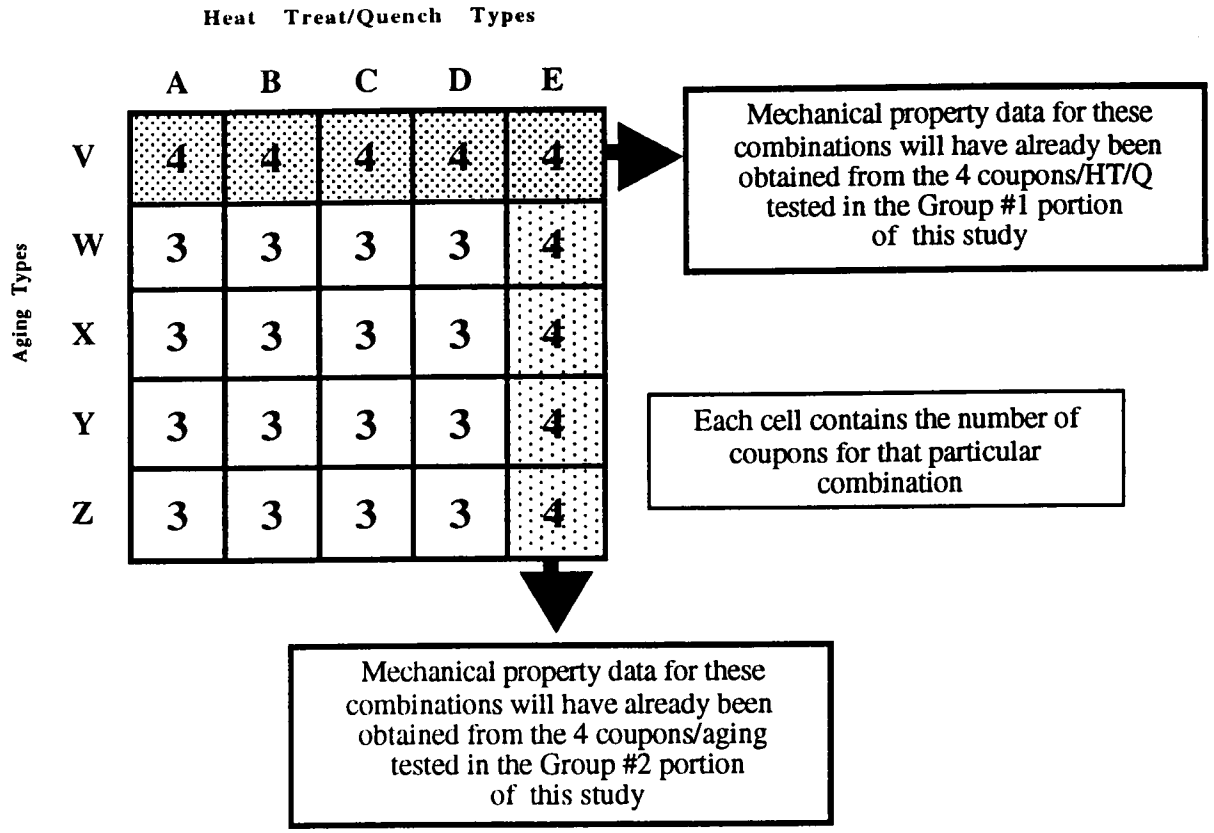


Figure 18: The Combinational Processing Matrix for **Group #3** Parts

of this study. The number in each matrix cell represents the number of test coupons available for this portion of the study. All parts in the matrix are fabricated into tensile specimens and are mechanically tested. The **Group #3** coupons are held and aged until all the **Group #2** coupon testing has been completed. This helps avoid any potential confusion that may be associated with the designated agings for the **Group #2** and the **Group #3** coupons.

Labeling the Parts (Test Coupons)

A labeling scheme was designed for maintaining the identity of each coupon and to indicate the test group to which each coupon belongs. This scheme consists of using a 4-digit letter number combination on each coupon. The first digit is a number which refers to the number of the plate from which the coupon was obtained. The second digit is a letter which refers to the processing type (e.g., heat treatment or aging) that the coupon has been designated to receive. The following two digits, are numbers which represent the number (01 through 18) or location of the coupon on the plate. Figure 19 depicts the labeling scheme with the actual markings that have been established for each coupon. These labels have been compiled into randomized lists which represent the testing and processing order(s) for each coupon test group.

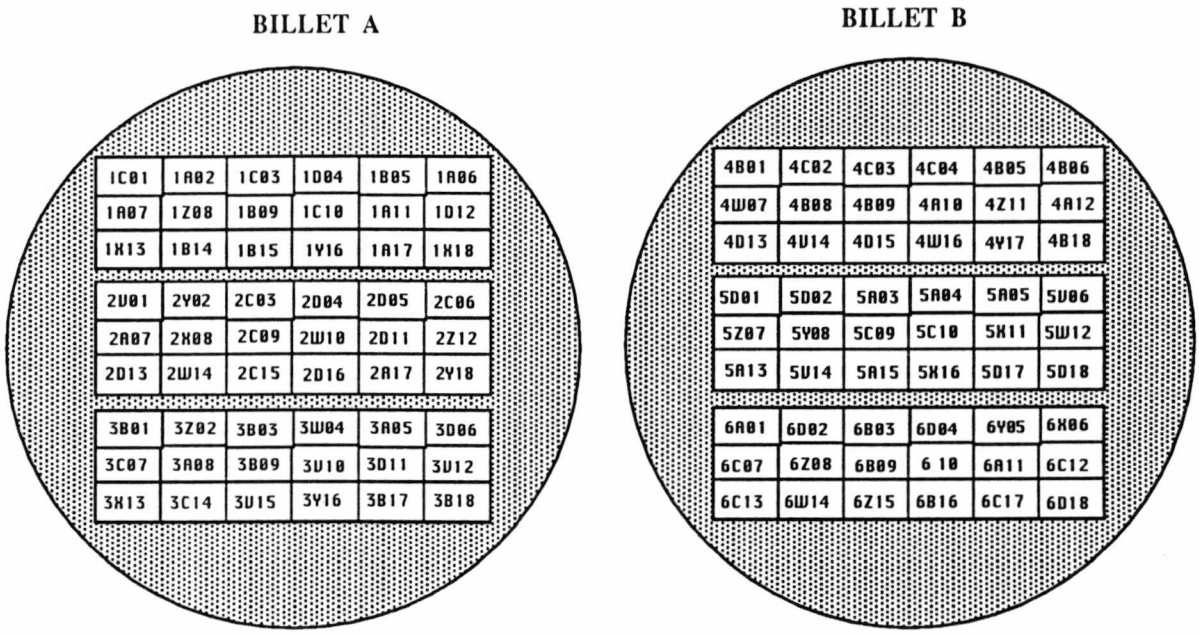


Figure 19: A Depiction of the Proposed Coupon Labeling Scheme

A Step-by Step Description of the Complete Experimental Scheme

The PERT chart portrayed in Appendix B is a step-by-step illustration of the entire experimental study. It provides functional descriptions for each task, a representation of the project flow from milestone to milestone, and estimates of all commencement and completion dates. Each block represents a major job function or milestone. The connecting lines delineate the relationships between each block (or job function) and, over the entire chart, illustrate the work flow for the entire study. Simply put, the chart provides a relatively easy method for monitoring project status.

Summary

A study has been designed to measure the effectiveness of using nondestructive ultrasonic velocity measurements to verify the mechanical properties of components manufactured from U-Nb. The initial part of this study involves the creation of 107 experimental test coupons. These coupons are cut from rolled U-Nb plates and separated into three different experimental test groups. The first group is processed and tested to evaluate the effects (i.e., mechanical property variations) associated with different types of heat treatment. Coupons used in the second group, represent parts that are processed and tested to evaluate the mechanical property changes that occur with variations in the aging process. The third group is designed to evaluate the mechanical property variations associated with combinational changes in both the heat treatment and the aging processes.

Ultrasonic velocity data and density measurements are acquired from each test coupon before and after each metallurgical process. After all metallurgical processing has been completed, mechanical property (MP) data are obtained from tensile specimens taken from specified sets of test coupons. The MP data are then correlated with both the ultrasonic and

density data. The goal is to determine whether or not this correlation is sufficiently significant to permit the establishment of an acceptable inspection technique. If a suitable inspection technique exists, an ultrasonic test will be designed to certify nondestructively the mechanical properties of U-Nb parts, resulting in a new non-waste producing method of mechanical property certification. This experiment has temporarily been put on hold until new funding is available, but in the interim, a new ultrasonic velocity measurement method and system (described in the following sections) has been developed.

2.3 The Ultrasonic Velocity Measurement System

A new ultrasonic velocity measurement system has been devised for testing the uranium-niobium alloys described in the preceding experiment. This system is illustrated in Figure 20; and is similar to the system configuration described in Figure 1 of Section 2.1. The major changes are (1) a significant reduction in the size of the computer and (2) a sufficient increase in the capabilities and functionality of the oscilloscope. These differences can primarily be attributed to the technological improvements that have occurred since the early 1980's (the vintage of the technology described in Section 2.1). The Macintosh IIci personal computer (Figure 20) runs a multi-tasking operating system and can be configured with a hard disk and RAM ranging anywhere from 50 to 100 times the storage capacity of the DEC PDP 11/23 microcomputer (used with the system described in Section 2.1). The primary advantage of the Tektronix 11403A Oscilloscope is the ability to digitize up to 10240 points per waveform, an improvement of ten times the capacity of the Tek 7854 oscilloscope. The other components shown in Figure 20 are essentially the same, but the reduced size of the computer and the enhanced capacity of the oscilloscope provide the potential for building, at least, a cartable system that can be used for in-process-type ultrasonic measurements.

The Macintosh (Mac) IIci personal computer depicted in Figure 20 has been configured with a National Instruments NuBus-to-IEEE-488 card, 17 MegaBytes (MB) of RAM, and 240 MB of disk storage. The Tektronix 11403A oscilloscope comes equipped with an IEEE-488 instrument port for easy attachment to most computers. The Panametrics 5055PRX pulser/receiver unit is the same one used in the system described in Section 2.1. A 5 MHz longitudinal contact transducer with a 0.5 inch diameter element was determined the appropriate transducer for this project. However, rough part surface conditions may warrant the use of a 2.25 MHz transducer

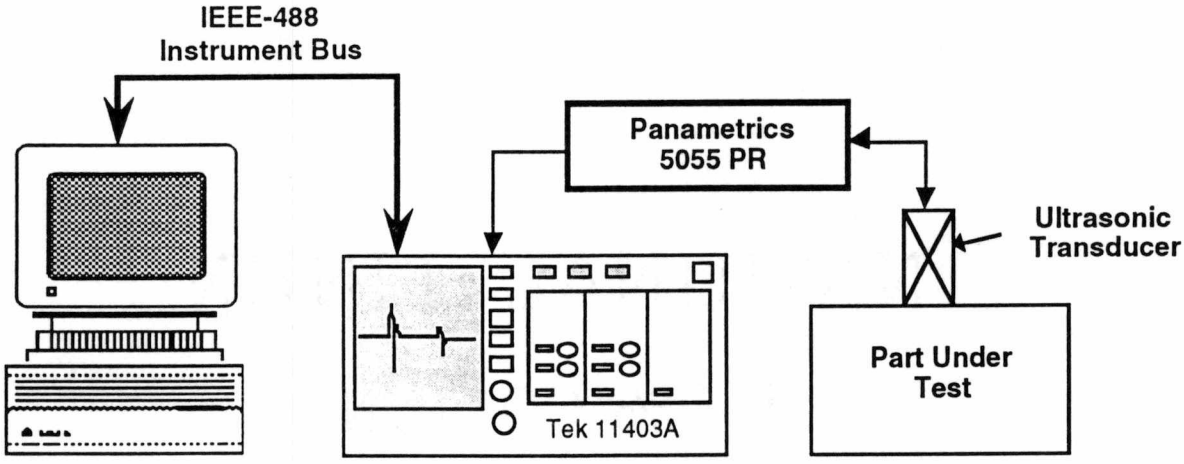


Figure 20: The Ultrasonic Velocity Measurement System Devised for Inspecting U-Nb Alloys

The ultrasonic velocity measurement system shown in Figure 20 was assembled to make the same type of measurements as the system used for the U-Ti work in Section 2.1. Previous work indicated that, because of the need to monitor multiple processing effects and to correlate data with additional mechanical property measurements, an improved ultrasonic time measurement would be required. The following sections describe the algorithms developed to determine the ultrasonic signal propagation times. Prior to describing those algorithms, an overview of the LabVIEW (virtual programming &

software development) environment must be provided [14-18].

2.4 Virtual Programming Methods

2.4.1 The Virtual Programming Philosophy

Virtual programming methods seem to be the natural evolution of computer programming. Historically, as computers and operating systems have evolved, so have the programming environments, although at a slower rate. The only method for programming some of the earliest computers involved manually setting banks of switches. These machines were capable of only relatively simple calculations, and programming them could sometimes take days or weeks to get a correctly working algorithm. As computers evolved, more and more efficient methods of programming developed, ranging from machine-coded assembly languages with single line editors to early versions of many of the higher level programming languages that are used today (e.g., FORTRAN, BASIC, etc....). After each evolution, the programming environment provided tools which were easier to use and functionally more powerful.

The graphical user interface (GUI), popular with many of today's PCs and workstations, has spawned another evolution in new programming methods, one of which is called ***virtual programming*** (which should be considered a higher-level language implementation of languages like FORTRAN, C, etc...). Virtual programming uses graphical icons or symbols to represent functional blocks of routines that perform specific function(s). Virtual programming environments provide the tools needed to create and interconnect these symbols. The following sections describe how National Instruments Inc. implemented a virtual programming environment for instrument control and testing with their LabVIEW software package.

2.4.2 The LabVIEW Implementation

In 1987, shortly after the release of the Apple MacIntosh II series computers, National Instruments Inc. felt that they finally had the appropriate hardware platform and operating system environment to implement a revolutionary new product for instrument and process control, called LabVIEW. LabVIEW was developed and designed with a virtual programming type environment, with the intent of removing the cumbersomeness that is sometimes inherent with many of today's popular programming languages. Its primary objective was to reduce the time and effort required for developing data acquisition and instrument control programs.

In the LabVIEW programming environment, the application programs that are created are called ***virtual instruments*** and referred to as VIs. A VI is virtual software implementation of an instrument. VIs consist of three main components: the front panel, the block diagram, and the icon/connector [18]. The front panel serves as the user interface for the VI. It is usually designed to resemble the front (or control) panel of the equipment or instrumentation that requires computer control. Block diagrams are used to represent the source code for each VI; they are created using a graphical (or symbol-based) programming language called G, developed by National Instruments Inc. Icons are the graphical symbols that are used to represent VIs. Connectors serves as data ports, allowing data to pass from diagram to connector and visa-versa. The icon/connector pair represents something analogous to a subroutine call, where a VI is used as a subVI and called by another VI.

There are two windows (i.e., the panel window and the diagram window) that appear on the screen when LabVIEW is executed; these are used to create (or program) a VI: . The panel window, as the name suggests, is used to build the front panel, and the

diagram window is used for constructing the block diagram. These windows are both designed with standard Macintosh features, but only one window can be active at a time. The front panel (the panel window) is built by adding objects for input called **controls** and objects for output called **indicators**. Controls represent instrument input devices and are the means for supplying data to a VI. Indicators represent output devices and are used to display the data generated by a VI. The front panel allows up to 12 controls and indicators per panel (additional controls or indicators require additional panels). When a VI is used as a subVI, the controls and indicators receive and return data to the calling VI in a fashion equivalent to a subroutine call in a conventional programming environment. LabVIEW, version 2.2, has the following types of controls and indicators available for use when building a front panel:

NUMERIC - used to enter and display numeric quantities

BOOLEAN - used to enter and display boolean (TRUE/FALSE) values

STRING - used to enter and display ASCII character strings

ARRAY & CLUSTER - used for grouping and displaying sets of data

CHARTS - used to plot numeric data real time in chart form

GRAPHS - used to plot blocks of data and to generate interactive plots

TABLE - used to enter and display data in spreadsheet form.

The block diagram (diagram window) is created by "wiring" (connecting) program modules (including other VIs or subVIs) to the control and indicator nodes. The "wiring" function is a graphical means of editing the program. It is similar to using the drawing tools that exist with many windows-based drawing programs (Appendix C contains some examples of LabVIEW programs).

The concept that defines how a LabVIEW program works is called **dataflow** [18].

This concept is based on the premise that program execution cannot occur until data is present at all of the input terminals. When the data are present, execution occurs and data are passed to the output terminals. Dataflow contradicts the control flow methods of conventional programming where instructions are executed in sequence. Dataflow programs are data driven, whereas control flow programs are instruction driven. Hopefully, the examples that follow will make some of these concepts more clear, but for those who require more information the author recommends obtaining the material listed in the reference list from National Instruments, Inc.[14-18].

2.4.3 LabVIEW and the IEEE-488 Instrument Bus

The IEEE-488 Instrument Bus was designed by Hewlett-Packard (HP) in the early 1970's to interconnect and control its line of programmable instruments. It became a national standard in the mid-1970's; it is also commonly referred to as the General Purpose Interface Bus (or GPIB). It is fundamentally used as link or interface system through which other interconnected electronic devices can communicate. National Instruments (NI) has been supplying GPIB products and solutions for non-HP systems and platforms for more than a decade. LabVIEW contains a GPIB library of commands (VIs) that can be used with their GPIB plug-in board for the Apple Macintosh II family of computers. The LabVIEW GPIB VI library of routines are compatible with either the IEEE-488.1 or the IEEE-488.2 specifications of the standard. The following list is a description of the GPIB VIs available with LabVIEW [15]:

GPIB Initialization	Configures characteristics of the GPIB interface
GPIB Write	Sends data bytes to a single GPIB device
GPIB Read	Reads data bytes from a GPIB device

GPIB Trigger	Triggers a single device
GPIB Clear	Clears a single device
GPIB Serial Poll	Serial polls a single device
GPIB Wait	Waits for a GPIB event to occur
GPIB Status	Indicates the status of the GPIB Controller
GPIB Misc	Performs specialized GPIB functions
Wait for GPIB SRQ	Waits for assertion of SRQ (Service Request) line

Further details illustrating the use of the commands are described in the LabVIEW programs contained in the following sections (see the Read Waveform VI in appendix C). More descriptive details on the use of these programs can also be obtained from the manuals accompanying the LabVIEW software (see references 8-12).

3. SIGNAL PROCESSING METHODS

3.1 Traditional Peak to Peak Cursor Measurements

Digital Oscilloscopes (DSOs) have been offering an increasing number of waveform processing and analysis functions since their inception. One of the more traditional (or most common) features has been on-screen cursor measurements. Cursor measurements can be made by moving the DSO's screen cursors either manually or by computer to a specific waveform location(s), where the waveform information (i.e., amplitude and time) can be displayed simultaneously and/or acquired. DSOs with two or more screen cursors usually allow the simultaneous display of both the Δx (which generally refers to the time difference) and the Δy (the amplitude difference) values between the cursors. These values have traditionally been used for ascertaining from the peaks of either an ultrasonic rf-waveform or a rectified ultrasonic rf-waveform the propagation time of the ultrasonic signal (See Figure 21). Although, on-screen cursor measurements (either automated or manual) may be good enough for some types of ultrasonic measurements, cursor measurements have some inherent problems. These problems are related to the digitizing process of the DSO.

When any analog signal is digitized (e.g., during a DSO acquire process), there is some natural uncertainty in the digitized value due primarily to the finite resolution of the digital conversion process. This uncertainty is commonly referred to as the ***quantization error***. The quantization error results from the discrete transfer function of the digital converter; a function which resembles a staircase shape. The width of each step of this staircase function is represented by Q for quantum size. All digital converters (analog-to-digital) have an irreducible error associated with them, called the quantization noise. This error results from the nature of conversion process (the staircase transfer function), which

cannot distinguish the difference between analog values whose difference is less than Q (the width of an individual stair on the transfer function). Therefore, an output error exists from the digital conversion process, that will always be as much as plus or minus Q/2.

Y-GA 87-4706

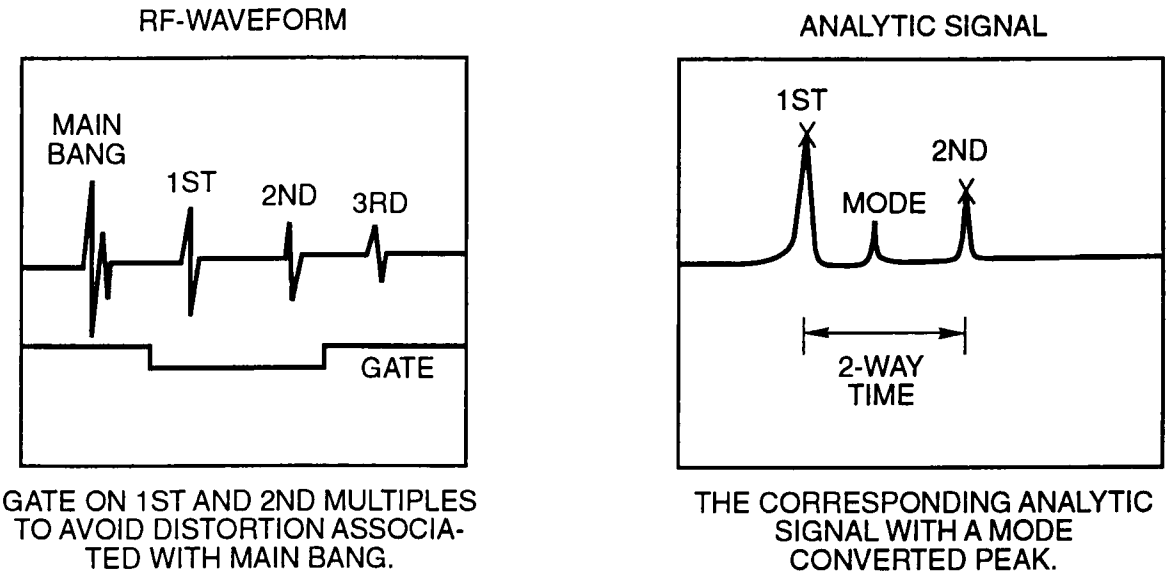


Figure 21: Portion of the Ultrasonic Waveform used for Obtaining Propagation Time and its Corresponding Analytic Signal

There are additional sources of error that can also effect the digital conversion process; these primarily deal with the linearity and accuracy of the conversion process. Digital conversion is not a perfect process and with the potential for conversion errors, some analyses (i.e., signal peak determination) can become potentially difficult tasks.

When digitally-acquired signals are expanded so that the individual points that make up the waveform can be seen, one notices that the waveform appears to have some sort of white noise function superimposed onto the signal. This function makes the signal appear "grassy" and is, at least in part, caused by the problems associated with the digital conversion process (described above). This feature directly affects the ability to obtain accurate, precise, and repeatable measurements of ultrasonic signal peaks. In the next

section, a discussion of some signal smoothing algorithms that can be used to improve the determination of ultrasonic waveform peaks are described.

3.2 Waveform Smoothing Algorithms

Other popular features that are common with many of today's DSOs, are waveform smoothing functions. These functions are designed to remove the "grassiness" (referred to in the previous section) from the digitally-acquired waveform. The majority of the waveform smoothing algorithms (included with many of today's DSOs) use a moving average technique to smooth the waveform. This technique involves averaging each point in the digital waveform with the adjacent points that directly precede and follow the point being determined. New values are determined for all points in the waveform. When the process has completed the waveform is considered "smoothed". The more points used in the smooth, the smoother and less defined the resultant waveform. This is the inherent problem or the trade-off associated with smoothing algorithms. As a waveform becomes smoother it also loses definition, and distinct characteristics such as signal peaks flatten out. This causes difficulties in accurately determining signal peaks and generally results in less repeatable time measurements (i.e., the signal gets time-shifted from the smooth).

Fortunately, other types of waveform smoothing algorithms exist that do not cause time shifting of peaks. One of these techniques is used in the USVEL program listed in Appendix A; it uses weighted moving average algorithm with coefficients that were determined in a paper by Savitzky and Golay [19]. Savitzky and Golay are chemists that were looking for a method to accurately determine the wavelength peaks of chemical absorption spectra. Their method works better than the previously described moving average method. However, other distortions can be produced that affect the measurement, especially when the signals are different from the spectra shapes used by Savitzky and

Golay. Irregular signal shapes are common with ultrasonic signals, whose waveform shapes are determined many times by the setup (i.e., transducer type and excitation pulse) and the material through which they propagate. For these reasons, the type of waveform smoothing algorithm used should always be verified experimentally. The ultrasonic velocity measurements that are obtained for mechanical property verification must be very precise (or repeatable), or in other words, they must have a very tight measurement spread; the accuracy of the measurement is of lesser concern. Accuracy is not as important as repeatability, because the goal of the ultrasonic inspection is to obtain a threshold(s) velocity value which can be used to determine acceptance or non-acceptance of a material. Besides, there are no tables listing standard ultrasonic velocity values which can be used to verify the accuracy of partially processed materials. The next sections describe a smoothing technique that was determined (heuristically); this is then used with an algorithm that does a cross-correlation of the analytic signal.

3.3 Time Between Peaks Measurement Using the Analytic Signal

Section 2.1 discussed how the analytic signal can be obtained from an ultrasonic rf-waveform and how the signal propagation time is obtained from measuring the time between the peaks in the analytic spectrum. Figure 21 is a depiction of this algorithm applied to an ultrasonic rf-waveform using the software listed in Appendix A, where more than one echo is present in the waveform. Figure 21 also shows how to gate on the ultrasonic rf-waveform so that the distortions associated with the Main Bang signal are avoided. These distortions can induce errors in the timing measurement, and its use should be avoided whenever possible. The calculated analytic signal (in Figure 21) also shows a mode-converted signal peak in the spectrum. This results from propagating a longitudinal signal into a narrow specimen (i.e., narrow with respect to the diameter of the

ultrasonic transducer). If this mode-converted signal becomes large when compared to the subsequent interface peak in the spectrum, problems can occur the peak-find algorithm does not account for mode-converted peaks (i.e., the time determined between peaks will be the time between the first peak and a mode converted peak, not the time between the two interface peaks). This problem can be eliminated or significantly reduced by modifying the peak-find algorithm or by using a smaller diameter transducer. The peak-find algorithm used in the programs in Appendix A requires that the mode-converted peak be smaller in amplitude than the second interface peak. Other algorithms developed involve splitting the ultrasonic analytic signal spectrum in a manner designed to avoid the mode-converted signal. Unfortunately, these techniques require prior knowledge of where the mode-converted signal can occur. Mode conversion is an effect that must be considered when using automated methods of determining ultrasonic propagation times.

The measurement of signal peaks in the analytic signal have a maximum resolution that is related to the digitizing limits of the scope and the size of the specimen being measured. The time it takes an ultrasonic signal to propagate from transducer through a specimen and back to the transducer is determined by two things: (1) the properties of the specimen and (2) the length of the specimen. For example, assume that it takes an ultrasonic pulse 10 μs to travel through a specimen and that the DSO has a maximum digitizing capability of 1024 points per waveform (as is the case with the Tek 7854 DSO). This generally requires the displayable range of the DSO to be set at around 12 μs, in order to adequately display both interface peaks. Therefore, the maximum time resolution obtainable from a measurement of this type is:

$$\frac{12\ \mu s}{1024} \approx 11.7 \quad \textbf{ns/point.}$$

The next section demonstrates how the application of a cross-correlation technique to

separate portions (the signal peaks) of the analytic signal spectrum, can increase the maximum obtainable time resolution. For this technique, the maximum obtainable resolution is limited only by the digitizing capacity of the DSO and the pulse width of the ultrasonic signal.

3.4 Cross-Correlation of the Analytic Signal

In the previous section, an estimate of the maximum time resolution obtainable with 1024 point digitization of an (example) ultrasonic analytic waveform was calculated. This section describes the improvements in time resolution that can be gained by applying a cross-correlation algorithm to individual sections of the ultrasonic analytic waveform.

The previous algorithm digitized the entire (displayed) ultrasonic waveform as one piece. The cross-correlation technique allows the waveform to be split into two separate sections, one containing the first signal peak and the other containing the second signal peak. These peaks can then be individually "windowed" (spread out within the maximum displayable range of the DSO) and digitized as individual sections. Using this technique, the maximum obtainable time resolution is limited to the width of the individual signal peaks in the ultrasonic rf-waveform. The width of these peaks represent the limit of how far the signal can be spread out within the displayable range of the DSO. Using the example described in the previous section (i.e., 10 μs waveform with 1 μs (a typical value) pulse widths), the maximum obtainable time resolution for this waveform at 1024 point digitization would be:

$$\frac{1\ \mu s}{1024} = 1\ \textbf{ns/point.}$$

This value represents an improvement of approximately 12 times the resolution obtained

using the previous (display of the entire analytic waveform) method. The amount of improvement in resolution becomes greater for longer specimens (which have longer times between pulses), since ultrasonic pulse widths remain fairly constant within materials of the same type.

To implement a cross-correlation algorithm, the first interface pulse in the ultrasonic rf-waveform must be windowed and digitized. The corresponding analytic signal for the first pulse is then determined and stored. An identical process is then executed on the second pulse in the ultrasonic rf-waveform. The two stored analytic waveforms each contain time information corresponding to the time range at which they were digitized. When both analytic waveforms are acquired, they are immediately cross-correlated (i.e., with an algorithm similar to equation 3.1, where $\mathbf{x}(\tau)$ corresponds to the first peak and $\mathbf{y}(\mathbf{t}+\tau)$ corresponds to the second peak) to produce a resultant waveform referred to as the cross-correlated analytic signal (CCAS). The peak of the CCAS corresponds to

$$\mathbf{R}_{xy}(\mathbf{t}) = \int_{-\infty}^{\infty} \mathbf{x}(\tau)\mathbf{y}(\mathbf{t}+\tau)\, \mathbf{d}\tau \qquad (3.1)$$

the time difference (with a resolution improvement coinciding to the value determined in the preceding paragraph) between the first and second signal peaks in an ultrasonic analytic waveform. This entire measurement takes less than ten seconds running on the system described in Figure 20. Using this method allows the individual to acquire only the portions of the ultrasonic waveform that need to analyzed. This eliminates the acquisition and analysis of the sections of waveform that are of no interest to the experimenter.

The LabVIEW program (entitled Anal. Cross Corr. (ACC)) that implements the cross-

correlation algorithm is listed in Appendix C. The program listing for ACC consists of both a front panel and a block diagram. A similar listing is also included in Appendix C for the Read Waveform program, which was developed to acquire waveforms from the Tektronix 11403A DSO. The block diagrams for both programs consist of individual symbols (or icons) that have been designed to perform a specific function. The symbols represent individual VIs, which are part of one of the many libraries supplied with the LabVIEW software.

The ACC program can acquire displayed or stored waveforms from Tek 11403A DSO and simultaneously display them on the program's front panel. After the waveforms are acquired and displayed, the program determines the analytic signal (via the Hilbert Transform) for both waveforms, which are also displayed on the front panel. The analytic waveforms on then cross-correlated and displayed, along with the resultant peak time (see front panel of ACC shown in Appendix C).

An interesting comparison can be made between the programs listed in Appendix A and Appendix C. Appendix A represents some of the FORTRAN routines that were written to perform analytic signal measurements with the Tek 7854 DSO. Appendix C represents the LabVIEW routines (both of them) that were required to implement the analytic signal algorithm twice and perform a cross-correlation. This is a very graphic example of the power associated with a virtual programming environment that contains an extensive command library!!

4. MEASUREMENT COMPARISONS

Some individual comparisons were made between the analytic signal method and the CCAS method. Ultrasonic longitudinal propagation times were obtained using each method from a stainless steel block with flat and parallel surfaces. A 1024 point digitizing

rate was used to acquire the ultrasonic waveforms displayed on each DSO (the Tek 7854 and the Tek 11403A).

After making 100 repeated measurements with each method, the results indicated that the analytic signal method had an average resolution of approximately 12 nanoseconds between each point in the 1024 point waveform. The times measured between the two interface peaks in the analytic spectrum had an average standard deviation of plus or minus 324 nanoseconds for 100 separate measurements.

The CCAS technique recorded an average resolution of approximately 0.9 nanoseconds between the individual points in a 1024 point waveform. Using this same technique, an average measurement standard deviation of plus or minus 14 nanoseconds was achieved, from the 100 separate measurements of the stainless steel block. These numbers correspond to an improvement of greater than 12 in measurement resolution and greater than 23 in measurement repeatability. The range of these numbers will vary when using different types of ultrasonic inspection equipment and/or when testing different types and lengths of materials.

5. SUMMARY

A cartable ultrasonic velocity measurement system, capable of verifying material properties and metallurgical processing conditions, was designed and built. The system uses an improved algorithm, that was developed for ascertaining the propagation times of ultrasonic signals. This algorithm does a cross-correlation of the individual signal peaks in the ultrasonic analytic signal spectrum. Preliminary results have indicated that significant improvements in measurement resolution and precision can be achieved using this method. The portability of the system allows in-process characterizations of certain types of metallurgical processes. These characterizations permit re-processing corrections to be

implemented before potentially recyclable material is lost.

Two additional aspects of this thesis need to mentioned. One is the ability to verify material properties and characterize metallurgical processes by using only an ultrasonic velocity measurement. When making material property measurements, the material cost savings alone (i.e., from reductions in the number of tensile specimens, material waste, etc...) can more than pay for the hardware used with this system. Another aspect worth noting, is the efficiency of using a virtual programming environment. The effort and number of routines required to implement an algorithm are significantly reduced by using the LabVIEW software.

Lastly, the algorithms developed in this thesis also have applications in other disciplines, that require accurate determination of signal peaks (e.g., from rectified waveforms, electromagnetic spectra, etc...).

LIST OF REFERENCES

LIST OF REFERENCES

[1] Pickett, C. A., Ultrasonic Verification of the Material Processing for Uranium-Titanium Alloys, Review in Progress in Quantitative Nondestructive Evaluation. Vol. 8B, D. O. Thompson and D.E. Chimenti, Eds., Plenum Publishing, New York, 1988.

[2] Rose, J. H., Ultrasonic Characterization of Solid-Solid Bonds from Microstructural Changes, Review in Progress in Quantitative Nondestructive Evaluation. Vol. 7B,D. O. Thompson and D.E. Chimenti, Eds., Plenum Publishing, New York, 1987.

[3] The American Society for Nondestructive Testing, Materials and Processes for NDT Technology, Columbus, Ohio, 1981.

[4] Pickett, C. A., Ferguson, J. R., Hughes, J. F., The Software Configuration Control Manual for the Ultrasonic Velocity Measurement System used to Characterize Uranium-Titanium Parts, Martin Marietta Energy Systems, Oak Ridge, Tennessee, Report Y/DW-1127/R1, December 1991.

[5] Gammell, P. M., Analogue Implementation of Analytic Signal Processing for Pulse-Echo Systems, Ultrasonics, November 1981.

[6] Gammell, Paul M., Improved Ultrasonic Detection Using the Analytic Signal Magnitude, Ultrasonics, March 1981.

[7] Bell, Zane W., Use of the Analytic Signal in Ultrasonic Imaging, Review in Progress in Quantitative Nondestructive Evaluation. Vol. 4A, D. O. Thompson and D.E. Chimenti, Eds., Plenum Publishing, New York, 1985.

[8] Heyser, R.C., Determination of Loudspeaker Siganl Arrival Times: Part III, Journal of Audio Eng. Soc., Vol. 19 , 1971.

[9] Duncan, Michael G., Real-Time Analytic Signal Processor for Ultrasonic Nondestructive Testing, IEEE Transactions on Instrumentation and Measurement, Vol. 39, No. 6, December 1990.

[10] Oppenheim, Alan V.and Schafer, Ronald W., Digital Signal Processing, Prentice-Hall, Englewood Cliffs, New Jersey, 1975.

[11] Sippel, Teresa M., Moses, Dwane J., and Gammell, Paul M., Quantitative Separation of Overlapping Echoes Using the Analytic Signal Magnitude, Review in Progress in Quantitative Nondestructive Evaluation. Vol. 7A, D. O. Thompson and D.E. Chimenti, Eds., Plenum Publishing, New York, 1987.

[12] Schreiber, Edward, Anderson, Orson L., and Soga, Naohiro, Elastic Constants and Their Measurement, McGraw-Hill, Inc., New York, New York, 1977.

[13] Pickett, C. A., Bird, E. L., Hodge, W. E., Marsicek, M. J., Thompson, J. E., Hughes, J. F., Chadwick, R. L., and, Coates, C. W., A Study to Ultrasonically Verify the Mechanical Properties of Uranium-0.6% Niobium Parts, Martin Marietta Energy Systems, Oak Ridge, Tennessee, Report Y/DW-1126/R1, December 1991.

[14] National Instruments, LabVIEW 2: Getting Started Manual, National Instruments Corporation, Austin, Texas, 1991.

[15] National Instruments, LabVIEW 2: GPIB and Serial Port VI Library Reference Manual, National Instruments Corporation, Austin, Texas, 1991.

[16] National Instruments, LabVIEW 2: Analysis VI Library Reference Manual, National Instruments Corporation, Austin, Texas, 1991.

[17] National Instruments, LabVIEW 2: Data Acquisition VI Library Reference Manual, National Instruments Corporation, Austin, Texas, 1991.

[18] National Instruments, LabVIEW 2: User Manual, National Instruments Corporation, Austin, Texas, 1991.

[19] Savitzky, A. and Golay, J.E., Smoothing and Differentiation of Data by Simplified Least Squares Procedures, Analytical Chemistry, July 1964.

APPENDICES

Appendix A

The FORTRAN Source Code Listing for the Ultrasonic Velocity Measurement System

```
      PROGRAM USVEL
C-----------------------------------------------------------------------------------------------
C
C     Programmer:
C           C.A. Pickett
C           Y-12 Development Division
C           Building 9203, MS-8084
C
C
C     Date Written: 4-MAY-87
C
C     Date last edited: 14-OCT-88
C-----------------------------------------------------------------------------------------------
C
C     Software program name: USVEL
C
C     Description:
C
C     This program is used to determine the longitudinal and shear
C     ultrasonic velocities of a sample, using the analytic signal.
C     The mechanical properties of the sample can also be calculated
C     after these measurements are made. The date is outputted to a
C     line printer for any integer number of measurements.
C
C     The system requires a TEKTRONIX 7854 Oscilloscope and a Tektronix
C     4105 graphics terminal.
C
C     On the IEEE 488 bus the Tek 7854 scope device address is 10.
C
C
C-----------------------------------------------------------------------------------------------
C
C     Application Subroutines Called:
C
C           ERASE     -- erases the terminal screen
C           QGENC     -- encodes array into data for Tek 7854
C           QSCOPE    -- sends commands to Tek 7854 scope
C           QSENDX    -- acquires waveform and sends to computer
C           QGREAD    -- writes waveform to Tek 7854 scope
C           STAT      -- checks current status of 7854 scope
C           WBANL     -- calculated the analytic signal
C           RRDTIM    -- determines the time between analytic peaks
C           CRT       -- moves the screen cursor to a specific location
C
C     TEKLIB 4105 Terminal Application Subroutines:
C
C           CEDIT     -- puts terminal in edit mode
C           CTEK      -- puts terminal in Tektronix (graphics) mode
C           DIAIND    -- specifies Dialog Index colors
C
C     System subroutines called:
```

```
C
C           EXIT    -- exits from program
C           SCOPY   -- defines a character string
C           PBUF    -- loads print string into printer buffer
C           DATE    -- reads current date from system
C           TIME    -- reads current time from system
C
C-------------------------------------------------------------------------------
C     Defines virtual arrays for waveform storage
C-------------------------------------------------------------------------------
C
      VIRTUAL X(1024), Y(1024), X1(1024), SARRAY(8200)
C
C-------------------------------------------------------------------------------
C
      REAL LTIME, LNGAVE, LTOTAL, LDIFF, LSDEV
C
      COMMON/A/N,XMAX,YMIN,YMAX
      COMMON/WN/ J1,J2
      COMMON/WAVE/PREAMB
      COMMON/WAVE1/STRING
C
C-------------------------------------------------------------------------------
C     Byte Statements
C-------------------------------------------------------------------------------
C
      BYTE CLEOS(4)              ! Contains data to clear screen
      BYTE SARRAY                ! Byte Virtual array for wave form data
      BYTE PREAMB(200)
      BYTE STRING (2200)         ! Character String Storage Array
      BYTE YES
      BYTE IFLAG(14)
      BYTE PNUM(40)              ! Array for Part Number data
      BYTE OPNAM(30)             ! Array for Operator's Name
      BYTE COMTS(80)             ! Array for additional comments
      BYTE DAT(9)                ! Array for date characters
      BYTE TIM(8)                ! Array for time characters
      BYTE HP16(4)               ! Contains printer setup data
C
C-------------------------------------------------------------------------------
C     Dimension Statements
C-------------------------------------------------------------------------------
C
      DIMENSION AVETHK(99                ! Average thickness/sample point
      DIMENSION SHRTIM(99,2)             ! Both shear 0 and 90 degree times
      DIMENSION VSH1(99)                 ! Shear 0 degree time
      DIMENSION VSH2(99)                 ! Shear 90 degree time
      DIMENSION AVESHR                   ! Average of VSH1 and VSH2
      DIMENSION VLONG(99)                ! Longitudinal Velocity
      DIMENSION VSHR(99)                 ! Shear Velocity
      DIMENSION ND(3),IND(3),ICRD(3)     ! Dialog index values
```

```
      DIMENSION LTIME(99)                    ! Longitudinal propagation time
      DIMENSION ICHECK(7)
C
C-----------------------------------------------------------------------------------------------
C     Data Statements
C-----------------------------------------------------------------------------------------------
C
      DATA ND/7,0,0/                         ! values for yellow dialog index
      DATA ICRD/3,0,0/                       ! values green dialog index
      DATA IND/1,0,0/                        ! values for white dialog index
      DATA CLEOS/27,'[','0','J'/             ! <ESC> [ 0 J  (erase to end of screen)
      DATA HP16/27,'[','4','w'/              ! <ESC> [4 w  (16 characters/inch)
C
C-----------------------------------------------------------------------------------------------
C
      CALL CEDIT                             ! terminal set to edit mode
      CALL ERASE                             ! erase entire screen
      CALL STAT                              ! Checks status of 7954
C
      N=1024                                 ! default set for 1024 point waveform
      CALL SCOPY('1 0 2 4 >P/W',STRING, 12)          ! defines string to be sent
      CALL QSCOPE(12)                                ! sends string to scope
C
C-----------------------------------------------------------------------------------------------
C     Reset initial values
C-----------------------------------------------------------------------------------------------
C
      CALL CTEK                                      ! put terminal in Tek mode
      CALL DIAIND(ND)                                ! set dialog index
3
C
      TYPE 4
4     FORMAT(10X,' PROGRAM NAME:  USVEL', 20X,'VERSION 1.0',/)
C
5     CALL SCOPY(SCOPE',STRING,5)                    ! Put scope in SCOPE mode
      CALL QSCOPE(5)
      CALL CTEK
      CALL DIAIND(ND)
      CALL CEDIT                                     ! terminal set to edit mode
      CALL CRT(6,1)                                  ! erase portion of screen
      TYPE 8,CLEOS
8     FORMAT('+',4A1,$)
C
6     FORMAT(I5)
C
C-----------------------------------------------------------------------------------------------
C     Define Menu Options
C-----------------------------------------------------------------------------------------------
C
      CALL CRT(10,20)
      TYPE 10                                                !Main menu
```

```
10    FORMAT(' -1 -- QUIT'/,19X,
     1'  1 -- ENTER THICKNESS MEASUREMENTS'/,19X,
     1'  2 -- LONGITUDINAL VELOCITY MEASUREMENT'/,19X,
     1'  3 -- SHEAR VELOCITY MEASUREMENT'/,19X,
     1'  4 -- PRINT TIME AND VELOCITY REPORT'/,19X,
     1'  OPTION?')
C
      READ  (5,15,ERR=5)  IOPT
15    FORMAT(I2)
      IF(IOPT.GT.4  .OR. IOPT .LT. -1 .OR. IOPT.EQ.0)  GO TO 5
      IF(IOPT.EQ.-1)  GO TO 900
      CALL CTEK
      CALL DIAIND(ICRD)
      CALL CEDIT
C
      GOTO  (30,40,44,59)  IOPT
C
C-------------------------------------------------------------------------------------------
C     Option 1 --- Enter Thickness Measurements
C-------------------------------------------------------------------------------------------
C
30    CALL CRT(6,1)
      TYPE  8,CLEOS
C
      TYPE *,' ENTER PART NUMBER (Title):, AND /OR BRIEF DESCRIPTION'
      ACCEPT  400,PNUM
400   FORMAT(40A1)
      TYPE *,'  ENTER YOUR NAME:'
      ACCEPT  401,OPNAM
401   FORMAT(30A1)
C
      CALL CRT (6,1)
      TYPE 8,CLEOS
      TYPE 31
31    FORMAT(' HOW MANY POINTS DO YOU WISH TO MEASURE?'/
     1 ' DEFAULT=1'/,$)
      ACCEPT 32,NPTS                          ! NPTS = Number of points
32    FORMAT (I2)
      IF(NPTS.LT.1) NPTS=1
C
      CALL CRT(6,1)
      TYPE 8,CLEOS
      TYPE 33
33    FORMAT(' HOW MANY THICKNESS MEASUREMENTS PER POINT WILL
     1  BE MADE?'/' DEFAULT=1'/,$)
      ACCEPT 32,MPT                           ! MPT = measurements per point
      IF(MPT.LT.1) MPT=1
C-------------------------------------------------------------------------------------------
      PAUSE ' SET UP FOR THICKNESS MEASUREMENTS'
C-------------------------------------------------------------------------------------------
      DO 34 I=1,NPTS
```

```
      DO 35 J=1,MPT
            CALL CRT(6,1)
            TYPE 8,CLEOS
38          TYPE 36,I                  ! I = Point Number
36          FORMAT(' ENTER THICKNESS (in inches) FOR POINT:',I2)
            ACCEPT 37, THICK
37                FORMAT (F6.3)
            IF(THICK.EQ.0) GO TO 38
            TOTAL=TOTAL+THICK  ! Sum thickness for each measurement
35    CONTINUE
       AVETHK(I)=TOTAL/MPT        ! Calculate average thickness/point
       TOTAL=0                    ! Reset total for next point
34    CONTINUE
      GO TO 5                     ! Return to main menu
C
C-------------------------------------------------------------------------------------------
C     Option 2 and 3 --- Longitudinal/Shear Velocity Measurements
C-------------------------------------------------------------------------------------------
C
40    CALL CRT(6,1)
      TYPE 8,CLEOS
      LFLAG=1                     ! Longitudinal Measurement Flag=1
      LNGTOT=0                    ! Reset to 0
      PAUSE ' SET UP FOR LONGITUDINAL TIME MEASUREMENT'
      GO TO 404
C
44    CALL CRT (6,1)
      TYPE 8,CLEOS
      IF(LFLAG.EQ.1) GO TO 42     ! Check for longitudinal measurement
      PAUSE ' MUST FIRST MAKE LONGITUDINAL MEASUREMENTS'
      IF(LFLAG.NE.1) GO TO 5      ! If not made, return to menu
42    LFLAG=0                     ! Set Shear Measurement Flag=0
      SHRTOT=0
      PAUSE ' SET UP FOR SHEAR TIME MEASUREMENT'
C
404   DO 410 I=1,NPTS
      CALL SCOPY('SCOPE',STRING,5)
      CALL QSCOPE (5)
      CALL CEDIT                  ! Put terminal in edit mode
      CALL CRT (6,1)
      TYPE 8,CLEOS                ! Erase terminal screen
       IORT=1                     ! Flag to define shear orientation
       IF(IOPT.EQ.3) GO TO 422
       TYPE 420,I
420    FORMAT ('APPLY LONGITUDINAL TRANSDUCER TO POINT # ',I2,/)
C
C-------------------------------------------------------------------------------------------
C     Digitize Waveform and Determine Time Between Peaks
C-------------------------------------------------------------------------------------------
C
430   PAUSE ' Set up Scope with Good rf-Waveform'
```

```
      CALL QSENDX(X,Y,SARRAY,ICHECK(4))          ! Acquire waveform and send
      JWSAV=J2
C
C-----------------------------------------------------------------------------------------
C     Calculate Analytic Signal
C-----------------------------------------------------------------------------------------
C
      CALL CEDIT                                 ! Put in edit mode
      CALL CRT (6,1)
      TYPE 8,CLEOS                               ! Erase screen
      CALL SCOPY ( 'BOTH OFF',STRING,8)          ! Defines character string
      CALL QSCOPE(8)                             ! Send string to scope
C
      DO 450 J=1,N
450     Y1(J)=Y(J)
        CALL WBANL(Y1,N)                         ! Calculate analytic signal
C
      DO 460 K=3,N-2                             ! Smooth analytic waveform
460     Y1(K)-(3*Y1(K+1)
     1          +17*Y1(K)+12*Y1(K-1(-3*Y1(K-2))/35   ! Do a least-squares smooth
C
      CALL QGENC(Y1,SARRAY)                      ! Encode waveform data
      JWSAV=J2
      CALL QGREAD(SARRAY)                        ! Write waveform to scope
      CALL SCOPY)'0 WFM ENTER 1 *',STRING,15)
      CALL QSCOPE                                ! Send string
C
C-----------------------------------------------------------------------------------------
C     Calculate time between 2 Peaks
C-----------------------------------------------------------------------------------------
C
      CALL RRDTIM(DX,X,Y1)                       ! DX= time between peaks
C
      TYPE*,' Is this a reasonable time reading?  (D:DY,N)'
      ACCEPT 480, CHR
480   FORMAT (A1)
      CALL SCOPY('OFF',STRING,3)                 ! Turn cursers off
      CALL QSCOPE(3)
      IF(CHR.EQ.'N') GO TO 430
 C
      IF(IOPT.EQ.2) LTIME(I)=DX                  ! Longitudinal time
      IF(IOPT.NE.3) GO TO 410
      SHRTIM))(IORT)=DX                          ! Shear time
      IF(IORT.EQ.2) GOT TO 410
C
      CALL CEDIT
      CALL CRT (6,1)
      TYPE 8, CLEOS
      PAUSE ' ROTATE SHEAR TRANSDUCER 90-DEGREES'
      IORT=IORT+1                                ! Increment shear orientation flag
      GO TO 430
```

```
410  CONTINUE
C
     GO TO 5
C-----------------------------------------------------------------------------------------------
C    Option 4 -- Calculate Velocities and Print out Test Report
C-----------------------------------------------------------------------------------------------
C
59   CALL CRT(6,1)
     TYPE 8,CLEOS
     IF(NPTS.NE.0) GO TO 60
     TYPE *, 'YOU FORGOT TO ENTER THICKNESS DATA!!'
     PAUSE
     GO TO 5
C
60   CALL CRT (6,1)
     TYPE 8,CLEOS
     TYPE *,' ENTER ANY ADDITIONAL COMMENTS (80 CHARACTERS)'
     ACCEPT 61,COMTS
61   FORMAT(80A1)
C
     CALL CRT (6,1)
     TYPE 8, CLEOS
     PRINT 498,HP16
498  FORMAT(1X,4A1)                          ! sets printer up for 16 char/inch
C
     NT=2
     TYPE 499,NT
499  FORMAT ('CURRENT TEST TYPE=',I2)
     TYPE 500
500  FORMAT(/,' WHAT TYPE OF TIME MEASUREMENT WAS MADE?'/
     1' 1 -- Through-Transmission'/
     1' 2 -- Pulse-Echo'/
     1'      Option? (D:  No Change)',$)
C
     ACCEPT 6,NT
     IF(NT.LT.1) NT=2
     IF(NT.GT.2)  GO TO 60
C
C-----------------------------------------------------------------------------------------------
C    Calculate Ultrasonic Velocities
C-----------------------------------------------------------------------------------------------
C
     LNGTOT=0                                 ! Set totals to zero
     SHRTOT=0
C
     DO 510 I=1,NPTS
      IF(LFLAG.EQ.1)  GO TO 505               ! Long, Calculations Only
C
       AVESHR(I)=(SHRTIM(I,1)+SHRTIM(I,2))/2  ! Average shear time
       VSHR(I)=NT*AVETHK(I))/AVESHR(I)        ! Shear velocity
       VSH1 (I)=(NT*AVETHK(I))/SHRTIM(I,1)    ! Shear-0 degree velocity
```

```
      VSH2(I)=(NT*AVETHK(I))/SHRTIM (I,2)          ! Shear-90 degree velocity
      SHRTOT=SHRTOT+VSHR(I)                        ! Total for all shear velocities
C
505   VLONG(I)=(NT*AVETHK(I))/LTIME(I)             ! Longitudinal Velocity
      LNGTOT=LNGTOT+VLONG(I)                       ! Total of all Long. velocities
510   CONTINUE
C
      LNGAVE=LNGTOT/NPTS                           ! Average Long, Velocity
      SHRAVE=SHRTOT/NPTS                           ! Average Shear Velocity
C
      IF(NPTS.EQ.1) GO TO 522                      ! Std Dev=0, for 1 point
C
      DO 520 I-1,NPTS                              ! Calculate standard deviations
        IF(LFLAG.EQ.1) GO TO 515
       SDIFF=VSHR(I)-SHRAVE)**2
       STOTAL=STOTAL=SDIFF
C
515    LDIFF=(VLONG(I)-(I)-LNGAVE)**2
       LTOTAL=LTOTAL+LDIFF
520   CONTINUE
C     LSDEV=(TOTAL/(NPTS-1))**0.5                  ! Longitudinal Std. Dev.
      SSDEV=(STOTAL/NPTS-1))**0.5                  ! Shear Std. Dev.
C
522   CALL DATE(DAT)
      CALL TIME(TIM)
C-------------------------------------------------------------------------------------------------
C     Print out Data in Test Report Format
C-------------------------------------------------------------------------------------------------
C
      IF(LFLAG).EQ.0) GO TO 630                    ! Don't type data on screen
      CALL  CRT(6,1)
      TYPE 8,CLEOS
      TYPE 604
C
      TYPE 599                                     ! Print heading
599   FORMAT('+',27X,'ULTRASONIC TIME MEASUREMENTS')
C
      TYPE 604                                     ! Skip 3 lines
604   FORMAT(' ',//)
C
      TYPE 605                                     ! Type Dist./Time Titles
605   FORMAT('+',1X,'POINT',3X,'DISTANCE (in)',3X,'LTIME(us)',3X,
      1'SHEAR-0(us)',3X,'SHEAR-90(us)',3X,'AVE SHEAR (us)')
C
620   DO 625 K=1,NPTS
        TYPE 622, K, AVETHK(K),LTIME(K)
622      FORMAT(3X,I2,5X,F8.3,5X,F10.3,9X,'NA',13X,'NA',
      1 13X,'NA',/)
625   CONTINUE
C
630   PRINT 604
```

```
      PRINT 604                                          ! Print out Part Number Data
      PRINT 600,PNUM,DAT,TIM,OPNAM
600   FORMAT('1',12X,' Part Number (Title):  ',1X,40A1,20X,9A1,10X,8A1/
      1,12X,'  Operator Name:  ',1x,30A1)
      IF (LFLAG.EQ.1) GO TO 669
C
C-----------------------------------------------------------------------------------------------
C     Print time and distance only when shear and long, velocities taken
C-----------------------------------------------------------------------------------------------
C
      DO 626 N=1,3
      PRINT 627                                          ! Print Heading
627   FORMAT('+',50X,'ULTRASONIC TIME MEASUREMENTS')
626   CONTINUE
C
      DO 629 M=1,3
      PRINT 628                                          ! Type Dist./Time Titles
628   FORMAT('+',12X,'POINT',12X,'DISTANCE (in)', 10X,'LTIME(us)',11X,
      1'SHEAR-0(US)',9X,'SHEAR-90(us)',10X,'AVE SHEAR(us)')
629   CONTINUE
C
      DO 611 K=1,NPTS                                    ! Print thick/time data
      TYPE 610, K, AVETHK(K),LTIME(K),SHRTIM(K,1),SHRTIM(K,2),
      AVESHR(K)
610   FORMAT(14X,I2,15X,F8.3,13X,F10.3,10X,F10.3,
      1 12X,F10.3,/)
611   CONTINUE
C
C-----------------------------------------------------------------------------------------------
C
669   PRINT 604
      DO 675 I=1,3                                       ! Print Heading
         PRINT 670
670      FORMAT ('+',48X,'ULTRASONIC VELOCITY CALCULATIONS')
675   CONTINUE
C
      PRINT 604
      DO 685 J=1,3                                       ! Print Velocity Titles
      PRINT 680
680   FORMAT('+',12X,'VLONG (in/us)',12X,'VSHR-O (in/us)',
      1 12x,'VSHR-90 (in/us)',12X, 'VSHEAR (in/us)')
      CALL PBUF
6856  CONTINUE
C
      IF(LFLAG.EQ.1) GO TO 710
C
      DO 700 K=1,NPTS                                    ! Print Velocity Data
      PRINT 705,K,VLONG(K),VSHI1(K),VSH2(K),VSHR(K)
705   FORMAT(14X,I2,15X,F8.5,17X,F8.5,19X,F8.5,19X,F8.5/)
      CALL PBUF
700   CONTINUE
```

```
C
      PRINT 707,LNGAVE,SHRAVE,LSDEV,SSDEV
707   FORMAT(/,13X,'AVERAGES=',9X,F8.5,71X,F8.5,/,13X,'STD DEV=,
      19X,F8.5,71X,F8.5)
      CALL PBUF
      GO TO 749
C
710   DO 715 K=1,NPTS                          ! Print longitudinal velocity only
      PRINT 712,K, VLONG(K)
712   FORMAT  14X,I2,15X,F8.5,21X,'NA',24X,'NA',25X,'NA'/)
      CALL PBUF
      CONTINUE
C
      PRINT 730,LNGAVE,LSDEV
730   FORMAT(/,13X,'AVERAGE=',10X,F8.5,/,13X,'STD DEV=',10X,F8.5)
      CALL PBUF
C
749   PRINT 750,COMTS
750   FORMAT(/,13X,'COMMENTS:',1X,80A1)
      CALL PBUF
      PAUSE
      GO TO 5                                  ! Return to main menu
C
C-------------------------------------------------------------------------------
C     Option -1 -- Quit
C-------------------------------------------------------------------------------
C
900   CALL CTEK                                ! Make sure terminal in Tek mode
      CALL DIAIND(IND)                         ! Reset Dialog index parameters
      CALL CEDIT                               ! Return Terminal to edit mode
      CALL ERASE                               ! Erase screen
      CALL EXIT                                ! Exit from program
      STOP
      END
```

```
      SUBROUTINE RRDTIM(DX,X,Y1,SARRAY)
C-------------------------------------------------------------------------------------------------
C
      COMMON /A/N,XMIN,XMAX,YMIN,YMAX,TOP,LEFT,BOTM
      VIRTUAL X(1),Y1(1),SARRAY(1)
      DIMENSION XV(51), YV(51)
      BYTE EVAL(12),EV(24),YES,TOP(64),LEFT(16),BOTM(16)
      COMMON/WAVE/PREAMB
      COMMON/WN/J1,J2
      COMMON/WAVE1/STRING
      BYTE PREAMB(1),STRING(1),STRING
C
C-------------------------------------------------------------------------------------------------
C
900   XMX1=0,0
      XMX2=0,0
      YMX1=0,0
      YMX2=0,0
      DO 905 I=2,N                                    !GET MAX PEAK
        IF(Y1(I).GE.YMX1) GO TO 910
       GO TO 905
910    YMX1=Y1(I)                                     !Save max
       IPK1=I                                         !Save index of max
905   CONTINUE
C
C-------------------------------------------------------------------------------------------------
C     Calculate a delay after peak,  Don't look for 2nd peak until after
C     delay.
C-------------------------------------------------------------------------------------------------
C
      NVP=N/20                                        !Choose initial guess
      IF(MOD(NVP,2).EQ.0)NVP=NVP+1                    !make guess odd
C
C-------------------------------------------------------------------------------------------------
C     GET END OF PEAK
C-------------------------------------------------------------------------------------------------
C     1ST LOOK FOR 0.707*MAX
C-------------------------------------------------------------------------------------------------
C
      DO 915 I=IPK1,1,-1                              !look for start of peak
        IF(Y1(I).LT.0.707*YMX1)GO TO 920
915   CONTINUE
920   IPA=1                                           !Start of peak (Min val=1)
      IF(IPK1-IPA.GT.NVP/2)IPA=IPK1-NVP/2             !If wide peak limit to NVP/2
C
      DO 925 I=IPK+1,N                                !Look for end of peak
        IF(Y1(I).LT.O.707*YMX1) GO TO 930
925   CONTINUE
930   IPAE=1                                          !End of peak (Max val=N)
C
      NP1=IPAE-IPA                                !Width of peak for Parabolic fit
```

```
      IF(NP1.GT.NVP)NP1=NVP
      IXE=IPK1+5*NP1/2                    !Est delay=peak delay +2,5* width
C
C-----------------------------------------------------------------------------
C     NOW GET 3 SUCCESSIVE INCREASING POINTS
C-----------------------------------------------------------------------------
C
      DO 940 I=IXE,N
         IF(Y1(I+1).GT.Y1(I)).AND.(Y1(I+2).GT.Y1(I+1)
     1  .AND.(Y1(I+3).GT.Y1(I+2)))GO TO 945
940   CONTINUE
945   IXE1=I
      AX1=X(IPK1)
      AX2=X(1XE1)
C
C-----------------------------------------------------------------------------
C     IDEL=IXE1-IPK1                      ! calculated # of points delay
      DELAY=AX2-AX1                       ! calculated delay not used in rtmeas
      DELAY = 15.                         ! Set delay = 15.0 microseconds
C
C-----------------------------------------------------------------------------
C
      TYPE 950,DELAY
950   FORMAT(' DELAY = ',F10.4,' usec'/
     1 ' Change? (Y,D:N) ',$
      ACCEPT 4, YES
4     FORMAT(1A1)
      IF(YES.NE.'Y') GO TO 958
      TYPE *,'Enter Delay in usec'
      ACCEPT 955,DELAY
955   FORMAT(F10.0)
      DDX=X(2)-X(1)
      IDEL=DELAY/DDX
      IXE1=IPK1+IDEL
C
C-----------------------------------------------------------------------------
C     GET NEXT PEAK
C-----------------------------------------------------------------------------
C
958   DO 960 I=IXE1,N
         IF(Y1(I).GT.YMX2) GO TO 965
        GO TO 960
965     YMX2=Y1(I)
        IPK2=1
960   CONTINUE
C
      DO 970 I=IPK1,IPK2-NVP/2,-1
         IF(Y1(I).LT.0.707*YMX) GO TO 975
970   CONTINUE
975   IPB=I
C
```

```
      DO 980 I=IPK1+1,N
         IF (Y1(I).LT.0.707*YMX2)GO TO 985
980   CONTINUE
C
985   IPBE=I
      NP2=IPBE-IPB
      IF(NP2.GT.NVP)NP2=NVP
      IST1=IPA
C
      DO 990 I=1,NP1
         XV(I)=X(I+IST1-1)
990      YV(I)=Y1(I+IST1-1)
C
      CALL PFIT(XV,YV,NP1,XV1,YV1)
      IST2=IPBE
      IF(IST2.GT.N)IST2=N
C
      DO 995 I=1,NP2
      J=IST2-I+1
      K=NP2-I+1
      XV(K)=X(J)
995   YV(K)=Y1(J)
C
      CALL PFIT(XV,YV,NP2,XV2,YV2)
      XMX1=X(IPK1)
      XMX2=X(IPK2)
      DX=XMX2-XMX1
C
      DX=XV2-XV1                                        !time between peaks
C
      TYPE 1005,XV1,YV1,XV2,YV2,DX
1005  FORMAT(/' Parabolic Fit'/
      1 ' First   Peak at   X=',F10.4,'us Y=',F10.4,'v'/
      1 ' Second Peak at X=',F10.4, us Y=',F10.4,'v'/
      1 ' Time between Peaks =',F10.5,' usec')
C
C-------------------------------------------------------------------------------------------------
C     PUT CURSERS ON PEAKS
C-------------------------------------------------------------------------------------------------
C
      CALL SCOPY('CRS1',STRING,4)
      CALL QSCOPE(4)
      YENC=YV1
      IF(YENC.GT.YMX1) YENC=YMX1-,0005
      ENCODE(12,1025,EVAL)YENC
1015  FORMAT(F12.5)
C
      DO 1020 K=1,12          !Load encoded Peak into EV with spaces between char
         K1=K*2-1
         K2=K*2
         EV(K1)=EVAL(K)
```

```
        EV(K2)=' '
1020 CONTINUE
C
      DXX=DX*1,E-06                                    !Delay is in usec
      CALL SCOPY(EV,STRING,23)
      CALL SCOPY('>VCRD',STRING(24),6)
      CALL QSCOPE(29)
      XALL SCOPY('CRS2-1',STRING,6)
      CALL QSCOPE (6)
C
      ENCODE(12,1025,EVAL)DXX                          !Encode delay
1025 FORMAT(F12.10)
C
      DO 1030 K=1,12          ! Load encoded Delay into EV with spaces between char
         K1=K*2-1
         K2=K*2
         EV(K1)=EVAL(K)
         EV(K2)- ' '
1030 CONTINUE
C
      CALL SCOPY(EV,STRING,23)
      CALL SCOPY('>HCRD',STRING(24),6)
      CALL QSCOPE(29)
C
1035 IAS=1
      CALL CTEK
      RETURN
      END
```

```
      SUBROUTINE WBANL(Y,N2)
C-------------------------------------------------------------------------------
C
C     Programmer:
C                         Z. W. Bell
C                         Y-12 Development Division
C                         Building 9203
C
C     Date Written:       2-DEC-83
C
C     Date Last Editted:          4-JAN-84
C
C-------------------------------------------------------------------------------
C +
C     Software Program Name: WBANL
C
C     Arguments: Y - N2 point virtual array with a rf-waveform
C
C     Description:
C
C     This subroutine is used to convert an rf-waveform file into
C     an analytic signal.
C
C -
C-------------------------------------------------------------------------------
C
C     BANL is called by:
C
C     Application Subroutines Called:
C               WFFT
C
C     System subroutines called:
C               DBLE
C               SNGL
C               CABS
C
C-------------------------------------------------------------------------------
C     VIRTUAL ARRAYS
C-------------------------------------------------------------------------------
      VIRTUAL Y(1)
C-------------------------------------------------------------------------------
C     DOUBLE PRECISION VARIABLES
C-------------------------------------------------------------------------------
      DOUBLE PRECISION DDATA,DVAL
C-------------------------------------------------------------------------------
C     COMPLEX ARRAYS
C-------------------------------------------------------------------------------
      COMPLES F(1024),CVAL
C-------------------------------------------------------------------------------
C     MAIN COMPUTATION LOOP
C
```

```
C     GET RECORD AND REMOVE DC OFFSET
C-----------------------------------------------------------------------------------------------
      IFX=0
      DDATA=0,DO
      DVAL=N2
      VAL=N2
      CVAL=CMPLX(VAL,0.0)
      DO 9 J=1,N2
            DDATA=DDATA=DBLEY(Y(J))
9     CONTINUE
      SDATA=SNGL(DDATA/DVAL)
      DO 3 J=1,N2
3           F(J)=CMPLX(Y(J)-SDATA,0.)
C-----------------------------------------------------------------------------------------------
C     COMPUTE ANALYTIC SIGNAL
C
C     COMPUTATION OF ANALYTIC SIGNAL FROM FFT
C     USES COMPLEX FFT TO COMPUTE IFFT
C-----------------------------------------------------------------------------------------------
      ALN=ALOG(VAL)/ALOG(2.)
      LN=ALN
      IT=N2/64+1+N2/256
      TYPE 5,N2,IT
5     FORMAT(I5,' Pt Waveform. Wait ',i2,' sec for Analytic Signal')
      CALL WFFT(F,LN)
      N3=N2/2
      DO 15 J=1,N3
      F(J)=CVAL*CONJG(F(J))
15    F(J+N3)=(0.,0.)
      CALL WFFT(F,LN)
C-----------------------------------------------------------------------------------------------
C     F CONTAINS THE COMPLEX CONJUGATE OF THE ANALYTIC SIGNAL
C     WHICH IS OK SINCE WE ONLY NEED THE MAGNITUDE
C-----------------------------------------------------------------------------------------------
C     OUTPUT RECORD
C-----------------------------------------------------------------------------------------------
16    CONTINUE
      DO 4 J=1,N2
            Y(J)=CABS(F(J))
4     CONTINUE
C
      RETURN
      END
```

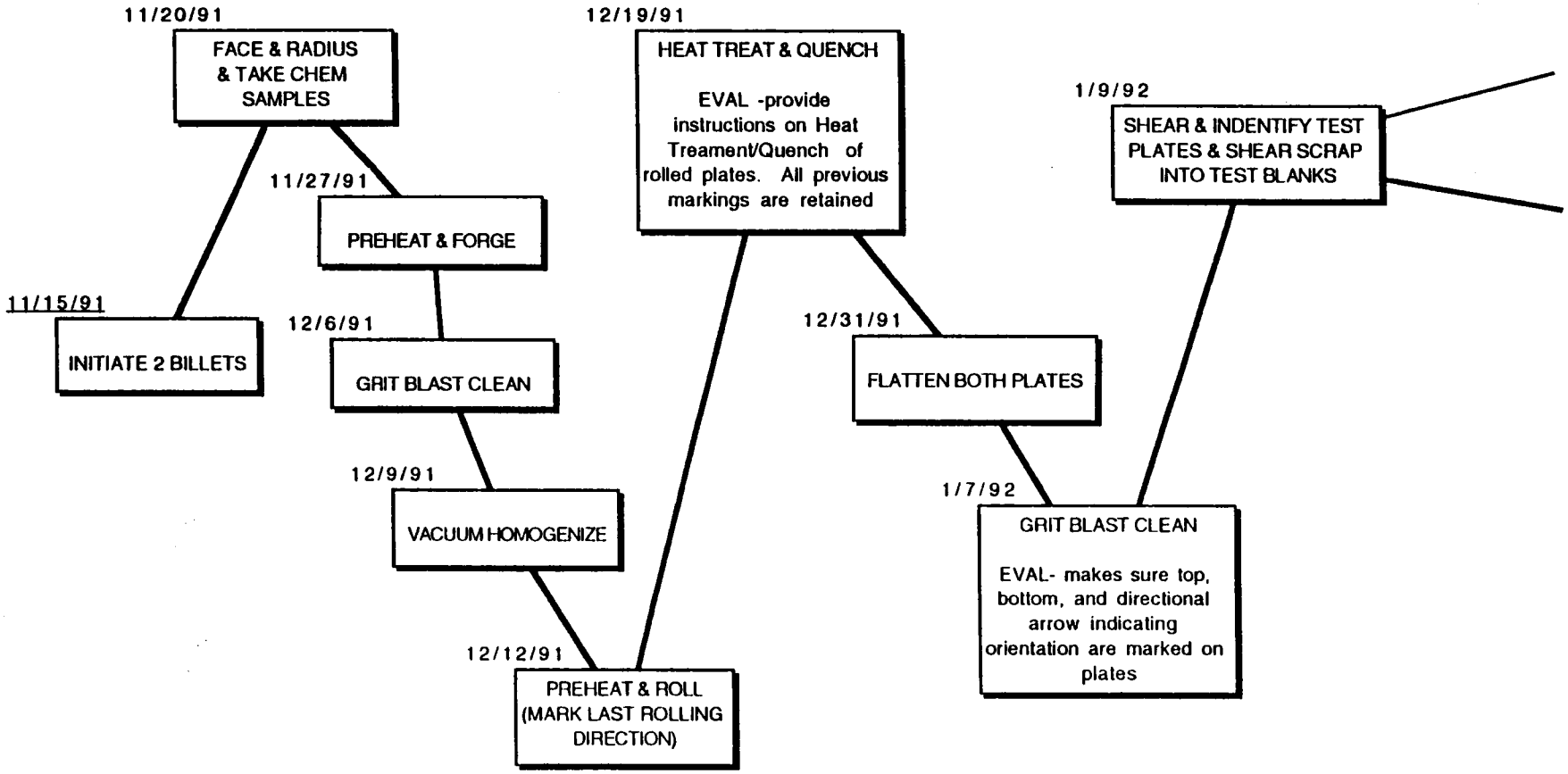
```
      SUBROUTINE WFFT(F,LN)
C-----------------------------------------------------------------------------------------------
C
C     Programmer:
C               Z. W. Bell
C               Y-12 Development Division
C               Building 9203
C
C     Date written:  2-DEC-83
C
C     Date last editted:  4-JAN-84
C-----------------------------------------------------------------------------------------------
C
C     Software program name:  WFFT
C
C     Arguments:
C               F       -       Complex array for data
C               LN      -       Base 2 LOG of number of points in F
C
C     Description:
C
C
C     This subroutine is used to calculate the complex FFT.
C     The routine from GONZALEZ AND WINTZ
C
C-----------------------------------------------------------------------------------------------
C
C     FFT is called by:  BANL
C
C     Application Subroutines Called:  NONE
C
C     System subroutines called.
C               MPLX
C               COS
C               FLOAT
C               SIN
C
C-----------------------------------------------------------------------------------------------
C     COMPLEX VARIABLES
C-----------------------------------------------------------------------------------------------
      COMPLES F91),U,W,T
C-----------------------------------------------------------------------------------------------
C     DATA STATEMENTS
C-----------------------------------------------------------------------------------------------
      DATA PI/3.141592654/
C-----------------------------------------------------------------------------------------------
      N=2**LN
      NV2=N/2
      NM1=N-1
      J=1
C-----------------------------------------------------------------------------------------------
```

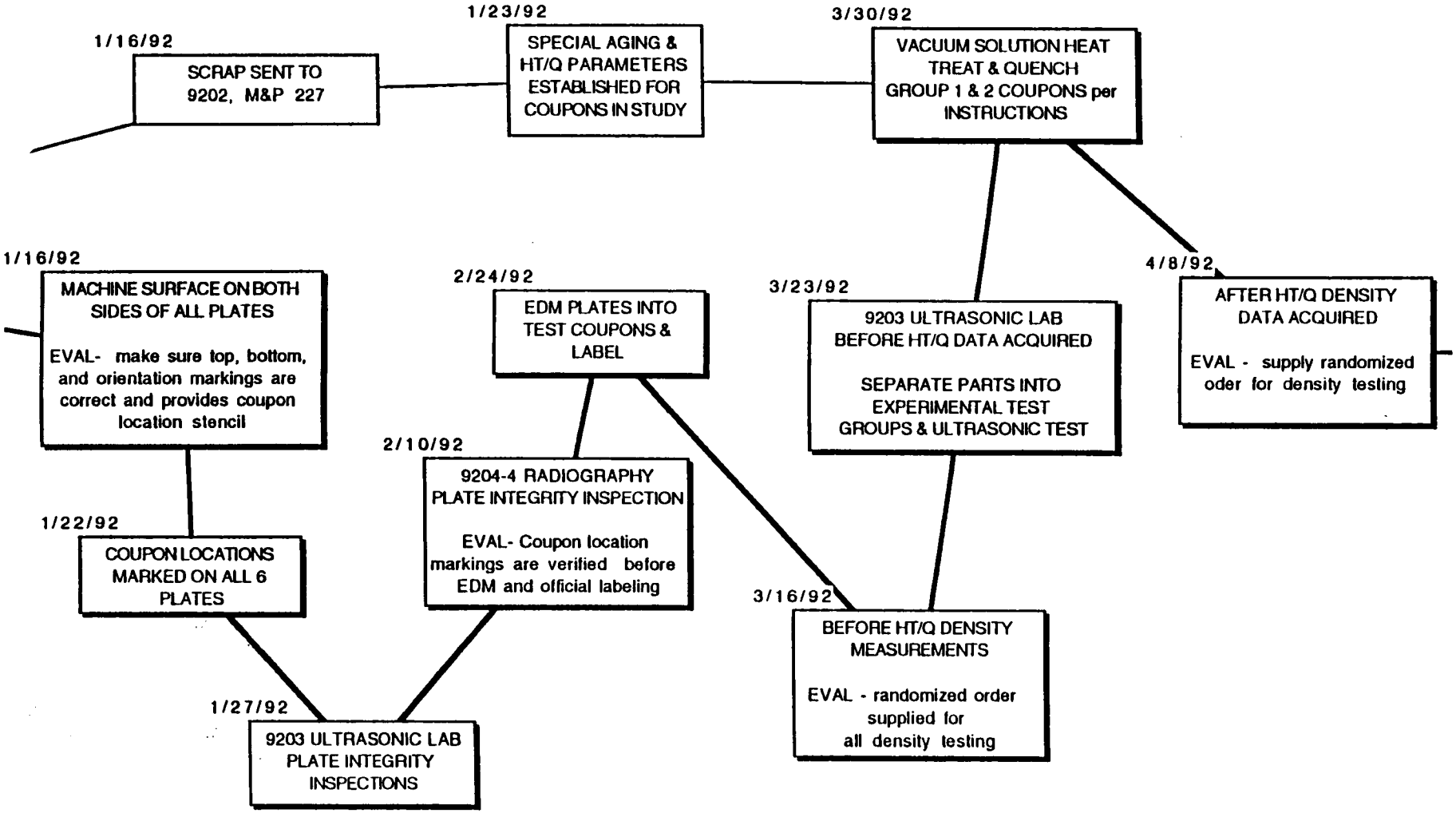
```
C     DO THE BIT REVERSAL
C-----------------------------------------------------------------------------------------------
      DO 3 I=1,NM1
      IF(I.GE.J) GO TO 1
      T=F(J)
      F(J)=F(I)
      F(I)=T
1     K=NV2
2     IF(K.GE.J) GO TO 3
      J=J-K
      K=K/2
      GO TO 2
3     J=J+K
C-----------------------------------------------------------------------------------------------
C     COMPUTE THE BUTTERFLIES
C-----------------------------------------------------------------------------------------------
      LE=1
      DO 5 L=1,LN
      LE1=LE
      LE=LE+LE
      U=(1.0,0,0)
      W=CMPLX(COS(PI/LE1),-SIN(PI/LE1))
      DO 5 J=1,LE1
      DO 4 I=-J,N,LE
      IP=I+LE1
      T=F(IP)*U
      F(IP)=F(I)-T
4     F(I)=F(I)+T
5     U=U*W
C-----------------------------------------------------------------------------------------------
C     SCALE BY N
C-----------------------------------------------------------------------------------------------
      DO 6 I=1,N
6     F(I)=F(I)/FLOAT(N)
      RETURN
      END
```

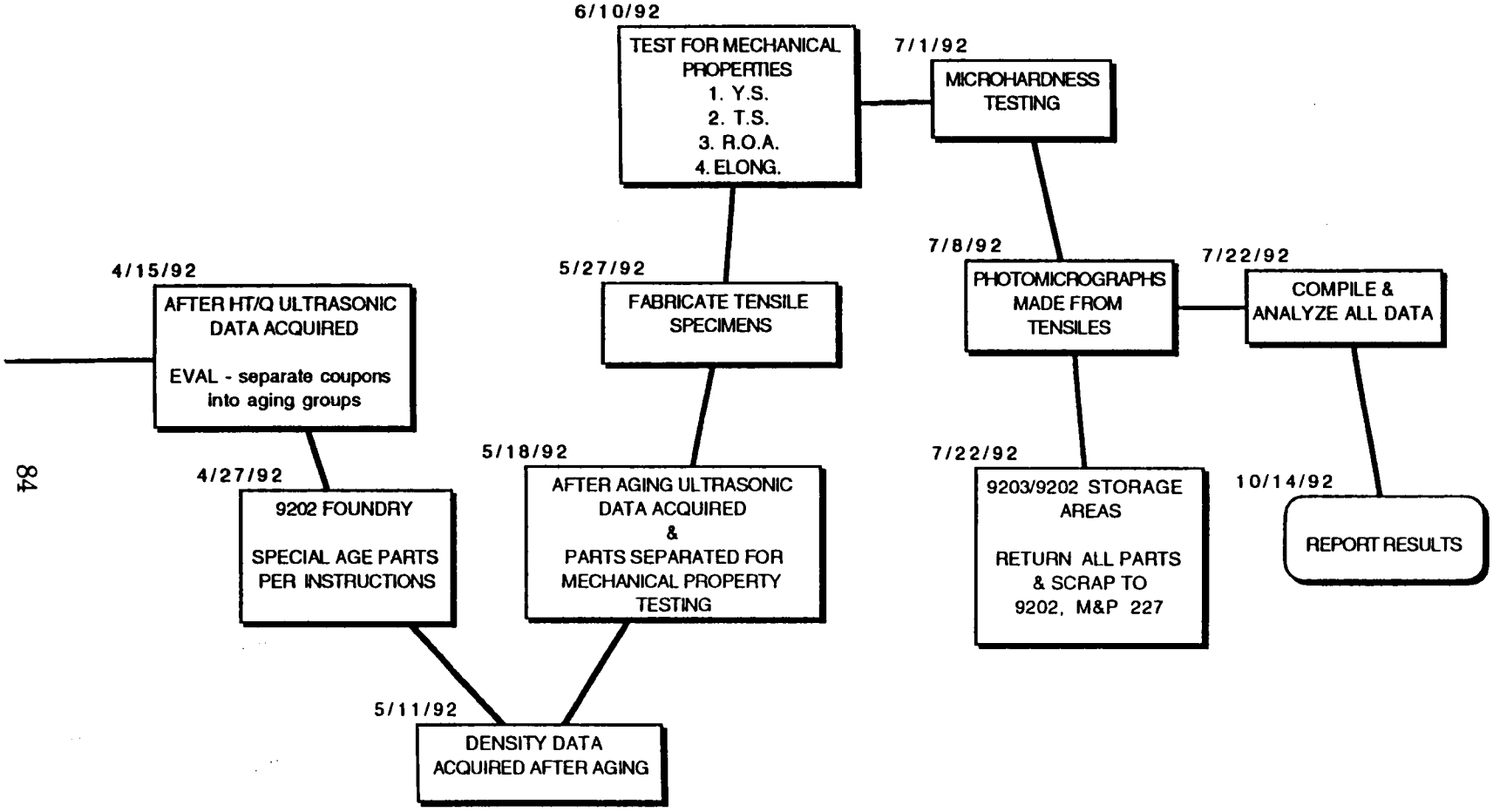
Appendix B

A PERT Chart Representation of an Experimental Study Designed to Evaluate the Capabilities of an Ultrasonic Method for Verifying the Mechanical Properties of U-Nb Parts.

ULTRASONIC MECHANICAL PROPERTY VERIFICATION STUDY

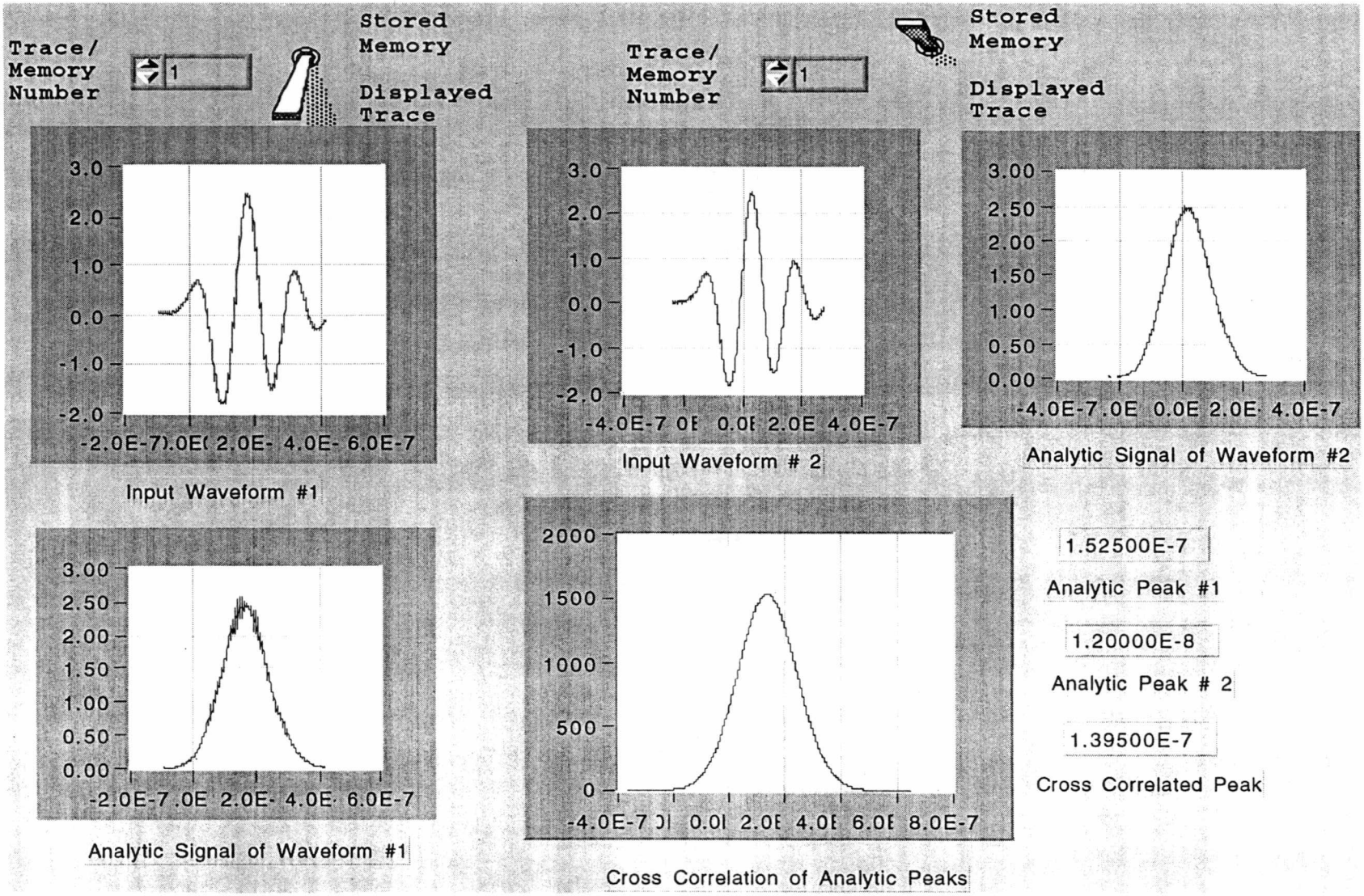



1/16/92
SCRAP SENT TO 9202, M&P 227
1/23/92
SPECIAL AGING & HT/Q PARAMETERS ESTABLISHED FOR COUPONS IN STUDY
3/30/92
VACUUM SOLUTION HEAT TREAT & QUENCH GROUP 1 & 2 COUPONS per INSTRUCTIONS
1/16/92
MACHINE SURFACE ON BOTH SIDES OF ALL PLATES
EVAL- make sure top, bottom, and orientation markings are correct and provides coupon location stencil
2/24/92
EDM PLATES INTO TEST COUPONS & LABEL
3/23/92
9203 ULTRASONIC LAB BEFORE HT/Q DATA ACQUIRED
SEPARATE PARTS INTO EXPERIMENTAL TEST GROUPS & ULTRASONIC TEST
4/8/92
AFTER HT/Q DENSITY DATA ACQUIRED
EVAL - supply randomized oder for density testing
1/22/92
COUPON LOCATIONS MARKED ON ALL 6 PLATES
2/10/92
9204-4 RADIOGRAPHY PLATE INTEGRITY INSPECTION
EVAL- Coupon location markings are verified before EDM and official labeling
3/16/92
BEFORE HT/Q DENSITY MEASUREMENTS
EVAL - randomized order supplied for all density testing
1/27/92
9203 ULTRASONIC LAB PLATE INTEGRITY INSPECTIONS

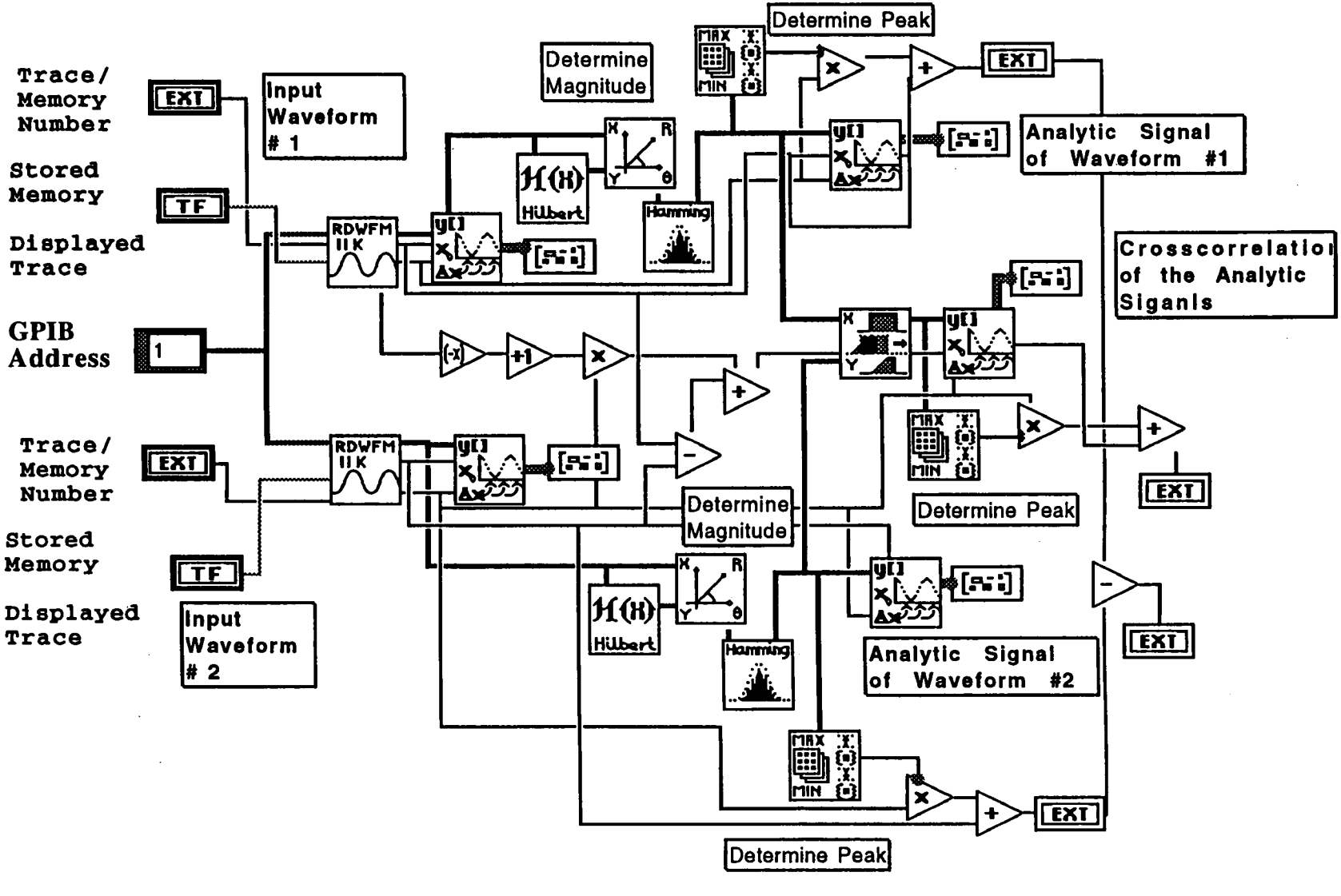

6/10/92
TEST FOR MECHANICAL PROPERTIES
1. Y.S.
2. T.S.
3. R.O.A.
4. ELONG.
7/1/92
MICROHARDNESS TESTING
4/15/92
AFTER HT/Q ULTRASONIC DATA ACQUIRED
EVAL - separate coupons into aging groups
5/27/92
FABRICATE TENSILE SPECIMENS
7/8/92
PHOTOMICROGRAPHS MADE FROM TENSILES
7/22/92
COMPILE & ANALYZE ALL DATA
4/27/92
9202 FOUNDRY
SPECIAL AGE PARTS PER INSTRUCTIONS
5/18/92
AFTER AGING ULTRASONIC DATA ACQUIRED
&
PARTS SEPARATED FOR MECHANICAL PROPERTY TESTING
7/22/92
9203/9202 STORAGE AREAS
RETURN ALL PARTS & SCRAP TO 9202, M&P 227
10/14/92
REPORT RESULTS
5/11/92
DENSITY DATA ACQUIRED AFTER AGING

Appendix C

The LabVIEW Programs: for Obtaining Ultrasonic Propagation Times by a Cross-Correlation of the Analytic Signal and for Reading Waveforms from the Tektronix 11403A Oscilloscope

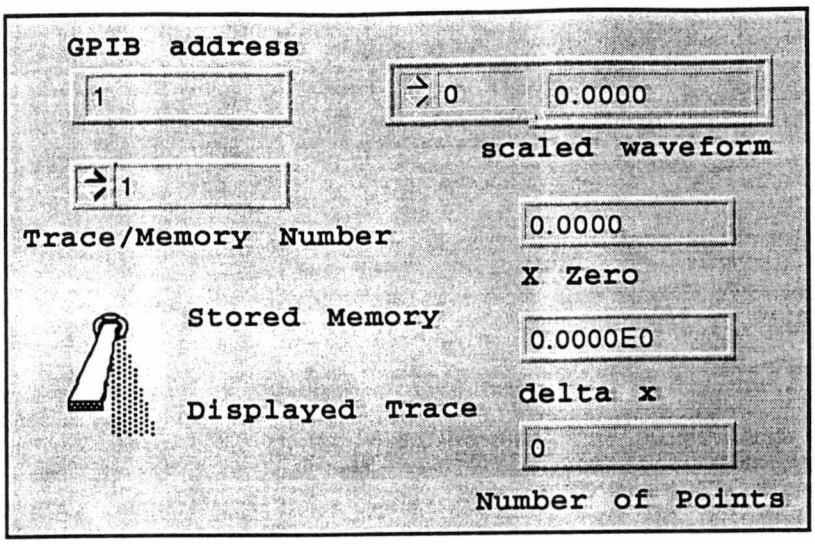


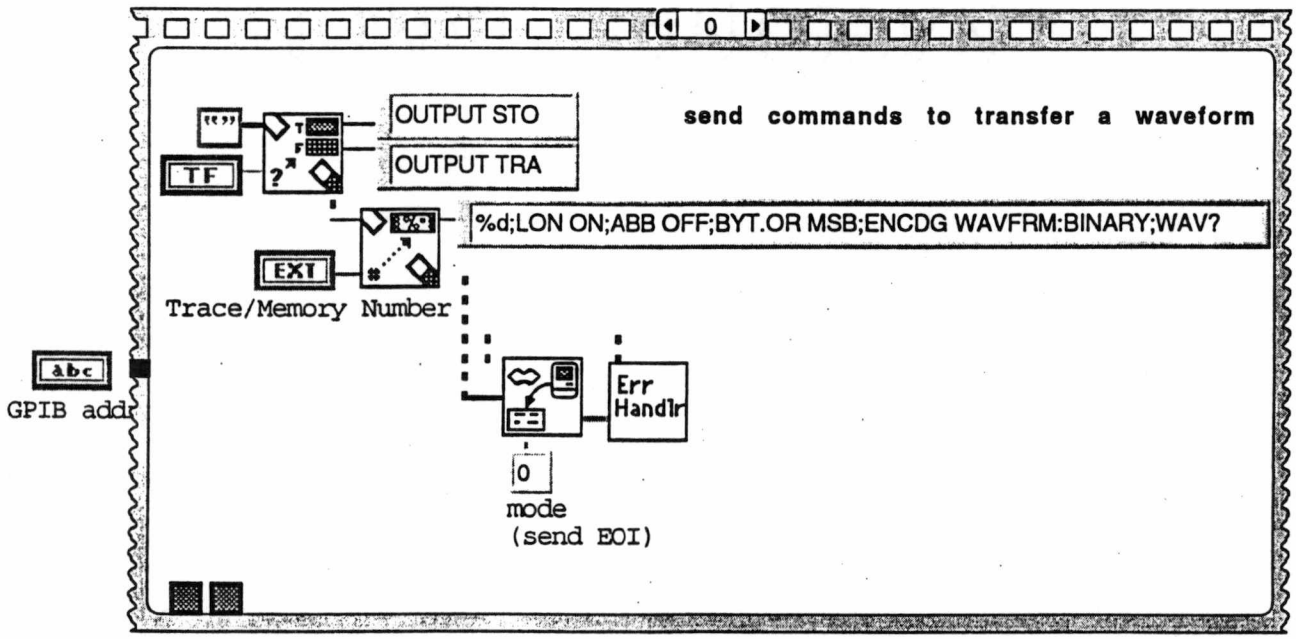
The Front Panel Developed for the Analytic Signal Cross Correlate Virtual Instrument

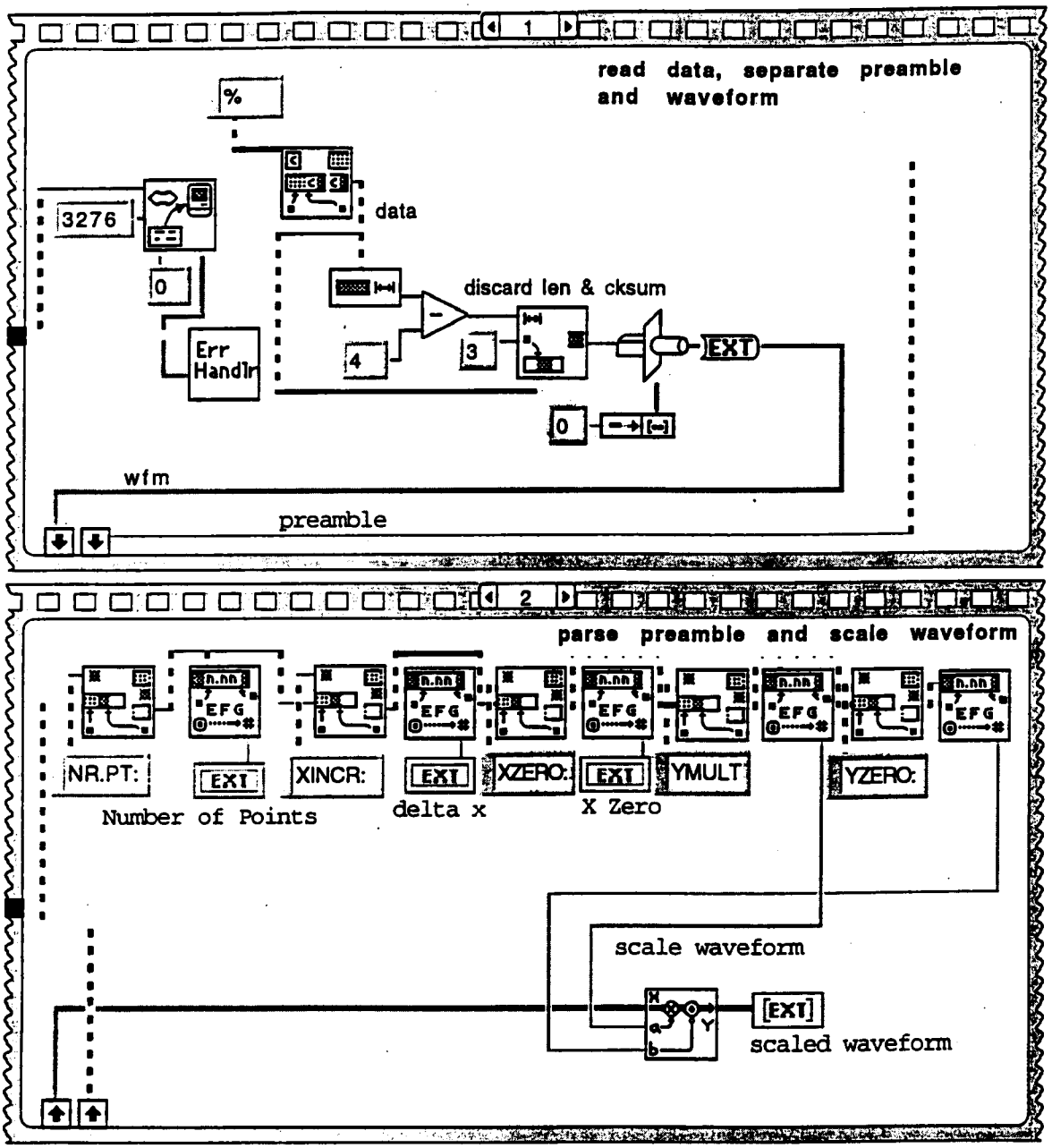


The Block Diagram used with the Analytic Signal Cross Correlate Virtual Instrument

The Front Panel and Block Diagrams for the Read Waveform Virtual Instrument






1
read data, separate preamble and waveform
%
3276
0
Err Handlr
data
discard len & cksum
4
3
EXT
0
wfm
preamble
2
parse preamble and scale waveform
NR.PT:
EXT
Number of Points
XINCR:
EXT
delta x
XZERO:
EXT
X Zero
YMULT
YZERO:
scale waveform
EXT
scaled waveform

VITA

Chris Allen Pickett was born in Mansfield, Ohio on May 8, 1958. He attended primary and secondary schools in Madison Township (a municipality located just outside the city limits), and in June of 1976 graduated from Madison Comprehensive High School. The following September he began studies at Bowling Green State University in Bowing Green, Ohio, where in June of 1980 he graduated with a Bachelor of Science degree in Physics with a minor in Mathematics.

In October of 1980, he accepted a position with the Union Carbide Corporation (presently Martin Marietta Energy Systems) in Oak Ridge, Tennessee, where he was assigned to work as a Development Engineer in the Materials Evaluation Group of the Y-12 Development Division. During his first year on the job, he registered for admission to the University of Tennessee to pursue a Master of Science degree in Physics. During this same period and prior to registering for his first class, he became captivated with the rapid transformations occurring with computers in the workplace. This fascination provided the impetus for him to change his major from Physics to Electrical and Computer Engineering (practicing engineers commonly refer to this phenomenon as *"seeing the light"*). So in the Fall of 1981, he began, as part-time student at the University of Tennessee, the quest for a Master of Science degree in Electrical and Computer Engineering. By the Spring of 1986, he had completed enough undergraduate course work to merit a Bachelor of Science degree in Electrical and Computer Engineering. He continued (part-time) at the University of Tennessee until he was able to conclude his quest for the Master of Science degree in the Summer of 1992.

In November of 1991, the author received a new assignment with Martin Marietta Energy Systems. He now works in the Health, Safety, Environment, and Accountability

(HSEA) Division, where he serves as group leader for the Measurements & Technical Support Group of the Nuclear Materials Control & Accountability Department.

The author is a member of Sigma Pi Sigma (National Physics Honor Society), Eta Kappa Nu (Electrical Engineering Honor Society), ASNT (American Society for Nondestructive Testing), and a former member of The American Physical Society. He is an ASNT Level III certified ultrasonic inspector and has five publications to his credit