



Development of apparatus for in situ erosion monitoring of surfaces immersed in high temperature fluidized beds

by Robb Edward Larson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

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Abstract:

The topic of this thesis is the development of an instrument to accurately measure the wall thickness of a heated, hollow, cylindrical 304 stainless steel specimen, in situ. The instrument was designed to measure thickness from the internal bore of the specimen, when the exterior wall of the specimen was subjected to a heat source with a temperature representative of the combustion level temperature of a high temperature fluidized bed combustor. The evolution of this device included design, testing and validation of two interim configurations for testing of planar specimens, and two mature configurations designed to measure cylindrical specimen wall thickness. The different instrument versions each utilized a type of 10-MHz ultrasonic transducer, cooled by circulating water, operating in one case with a contact type transducer with a high-temperature compatible protective extension tip and in the second case operating with a non contact immersion type transducer. All configurations utilized a pulse/echo time of flight measurement technique for thickness determination, with the signal directed through an externally heated specimen. Data was obtained via a digitizing oscilloscope, linked to a computer controlled data acquisition system for program control and data processing. Temperature vs. ultrasonic wave speed relationships for the specimens were first experimentally determined, based upon the average of inside surface and exterior surface temperatures. This data was subsequently used to predict specimen thickness. The final configurations typically returned thickness measurements accurate to within .0635 mm (.0025 inch), when compared to a nominal ambient temperature measurement and normalized to a reference temperature, throughout an average specimen temperature range of from 8 °C to 650 °C.

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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NOMENCLATURE

α	thermal expansion coefficient, in/in/ $^{\circ}$ F
$^{\circ}$ C	degrees Centigrade
CRT	cathode ray tube
dc	direct current
E	thickness measurement error
$^{\circ}$ F	degrees Farenheight
HP-IB	Hewlett Packard Interface Bus
in	inch
kHz	kilohertz, i.e. 10^3 cycles per second
L	length, m
L_a	specimen thickness at ambient temperature, m
$L_{a,i}$	specimen thickness at ambient temperature, in
L_h	elevated temperature specimen thickness, m
$L_{p,ref}$	predicted thickness at T_{ref} , m
L_{ref}	specimen thickness adjusted to T_{ref} , m
m	meter
MHz	megahertz, i.e. 10^6 cycles per second
mm	millimeter
m/s	meters per second

NOMENCLATURE-continued

MSU	Montana State University
P	time period between waveform signal voltage peaks, seconds
RTV	room temperature vulcanizing
T	temperature, °C.
T _{ave}	average specimen temperature, °C.
T _{ave,F}	average specimen temperature, °F.
T _a	ambient temperature, °C.
T _{a,F}	ambient temperature, °F.
T _{in}	temperature measured at inside surface of specimen, °C.
T _{ref}	reference temperature, 9.16 °C. (48.5 °F.)
T _{out}	temperature measured at outside surface of specimen, °C.
V	sonic wave velocity, m/s
V _a	ambient temperature wave velocity, m/s
V.D.C.	volts, direct current
V _h	elevated temperature wave velocity, m/s

ABSTRACT

The topic of this thesis is the development of an instrument to accurately measure the wall thickness of a heated, hollow, cylindrical 304 stainless steel specimen, *in situ*. The instrument was designed to measure thickness from the internal bore of the specimen, when the exterior wall of the specimen was subjected to a heat source with a temperature representative of the combustion level temperature of a high temperature fluidized bed combustor. The evolution of this device included design, testing and validation of two interim configurations for testing of planar specimens, and two mature configurations designed to measure cylindrical specimen wall thickness. The different instrument versions each utilized a type of 10-MHz ultrasonic transducer, cooled by circulating water, operating in one case with a contact type transducer with a high-temperature compatible protective extension tip and in the second case operating with a non contact immersion type transducer. All configurations utilized a pulse/echo time of flight measurement technique for thickness determination, with the signal directed through an externally heated specimen. Data was obtained via a digitizing oscilloscope, linked to a computer controlled data acquisition system for program control and data processing. Temperature vs. ultrasonic wave speed relationships for the specimens were first experimentally determined, based upon the average of inside surface and exterior surface temperatures. This data was subsequently used to predict specimen thickness. The final configurations typically returned thickness measurements accurate to within .0635 mm (.0025 inch), when compared to a nominal ambient temperature measurement and normalized to a reference temperature, throughout an average specimen temperature range of from 8 °C to 650 °C.

CHAPTER 1

INTRODUCTION

Fluidized bed combustor research and development has recently become a subject of increased emphasis in the energy industry, due primarily to the potential for reduced pollutant emissions when compared to the more conventional stoker fired and pulverized coal fired combustors. An additional advantage of the fluidized bed design, according to Makansi and Schweiger (1987), is the possible utilization of several different fuel types such as bio-mass, industrial waste and byproducts, and coal. However, current fluidized bed combustor efficiency is often lower than comparable units already in place. Continued investigation into the optimization of this technology is therefore an important step towards the implementation of the fluidized bed combustion process.

Heat exchangers within fluidized bed combustors typically utilize an array of horizontal tubes immersed directly in the fluidized bed. Heat transferred to the tubes is used for steam generation or for heating of process fluids. Erosion of the external surfaces of these heat exchanger tubes within fluidized bed combustors, brought on by the corrosive and erosive high-temperature operating environment, is a

problem in the development of this versatile energy technology. The occurrence of erosion in fluidized beds, particularly when operating near the upper range of bed temperatures (approximately 850 °C) and the as yet unpredictable nature of that erosion has dampened the initial enthusiasm and acceptance of this technology by industry, according to papers published by Johnson, et al., 1989, and Reimann, 1990. Observance of this problem has led to a number of studies which attempted to model tube wastage, including Podolski, et al., 1989 and Deffenbaugh, et al., 1988. An effort to develop heat exchanger tubes that were wastage resistant was undertaken by Grace, et al., 1989.

Down time resulting from failed heat exchanger tubes, or due to excessively restrictive maintenance schedules based upon worst-case erosion rates, is an area where implementation of accurate *in situ* erosion monitoring technology can improve the efficiency of the fluidized bed combustor system. Such a measurement system could also prove valuable in the ongoing effort to understand and reduce heat exchanger tube wastage in fluidized bed combustor facilities.

The research described here involved the development, fabrication and testing of an instrument designed to perform *in situ* monitoring of the wall thickness of a specially constructed cylinder while the cylinder was exposed to external heating. The apparatus was designed to provide accurate tube wall thickness measurements during high temperature operation of a fluidized bed combustor facility; however, for the purposes of this research a natural gas and oxygen torch with a special heating tip (Smith Welding Equipment, Minneapolis MN, part no. ST630) provided the

temperatures representative of fluidized bed operation. Preliminary testing of planar specimens within the Montana State University electrically heated fluidized bed facility demonstrated that the type of heat source utilized to achieve elevated temperatures did not adversely affect the ability of the system to deliver accurate thickness prediction data, as reported by George, et al., 1990.

Ultrasonic measurement was determined to be the ideal method of dimensional inspection for the purposes of this research, due to the maturity of the technology involved, the high degree of accuracy possible with proper component selection and design, and availability of components from commercial sources. The heart of the system was the ultrasonic transducer, basically a device capable of generating and receiving high frequency vibrations. Ultrasound is, by definition, sound generated above the range of human hearing, about 20 kHz; however, the frequency range normally employed in ultrasonic nondestructive testing and thickness gaging is between 100 kHz and 50 MHz (Panametrics, 1991).

A diagram of a typical ultrasonic dimensional inspection apparatus is shown in Figure 1. Ultrasonic dimensional inspection involves utilizing a series of discrete electrical pulses delivered from a powered pulser/receiver unit to cause the piezoelectric crystal based ultrasonic transducer to emit a sound pulse from its front face. The sound pulse propagates through the coupling media (water in the case of an immersion type transducer used in one of the systems developed here) until it encounters some discontinuity or media interface, such as a solid surface. At the interface, a portion of the signal is reflected back to the transducer, which converts

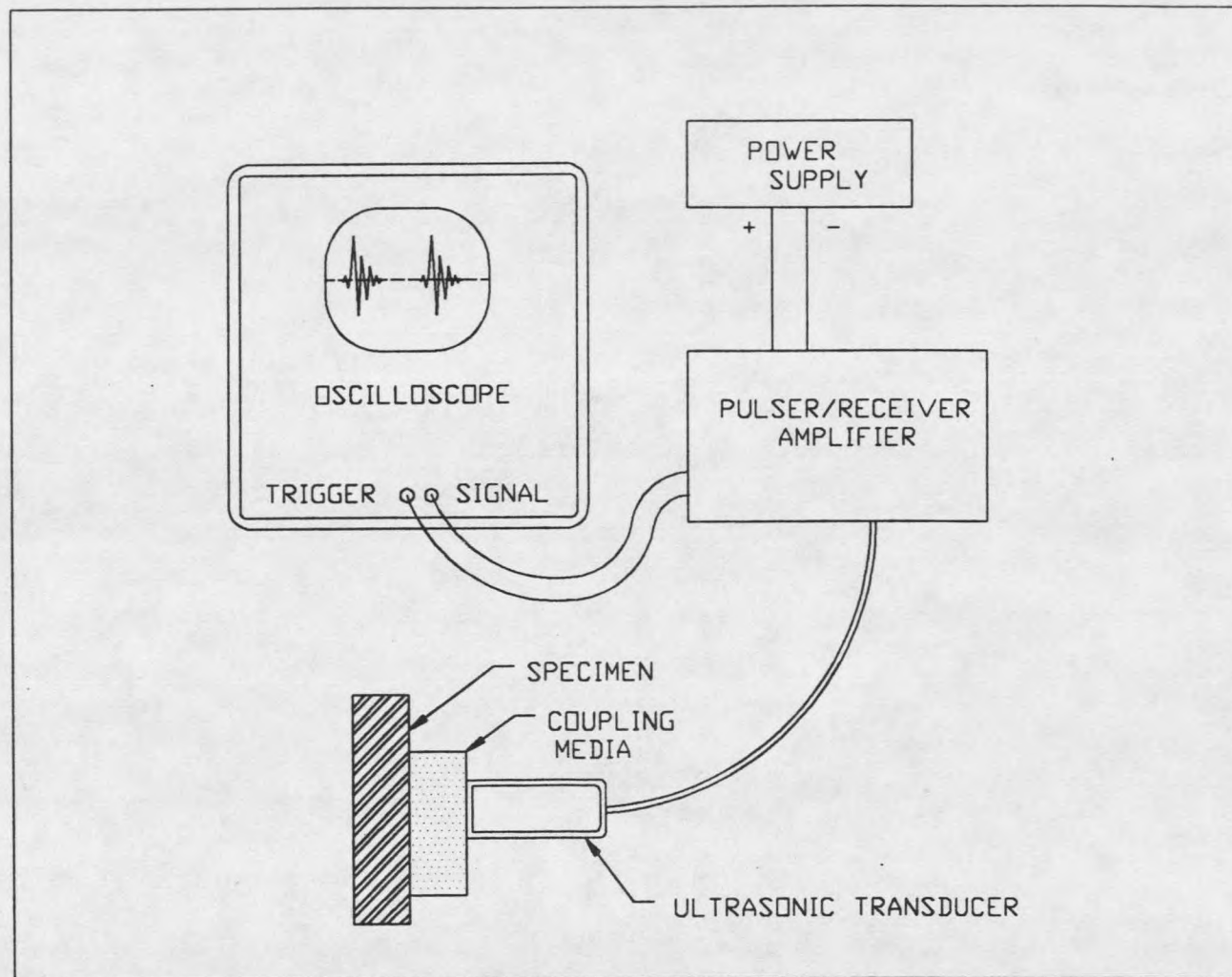


Figure 1. Typical Ultrasonic Dimensional Inspection Apparatus.

this sound pressure to an electrical signal and returns it to the pulser/receiver. The remainder of the signal continues through the object. In the case of thickness measurement, the sound pulse encounters a second media interface, which again results in an echo returning through the coupling media to the transducer. The echo in turn is partially reflected back by the first interface; this sequence continues until the energy of the propagating sound wave is dissipated. Return signals from the transducer are passed from the pulser/receiver unit to the oscilloscope, where the waveform is displayed on a CRT screen. A typical waveform is shown in Figure 2.

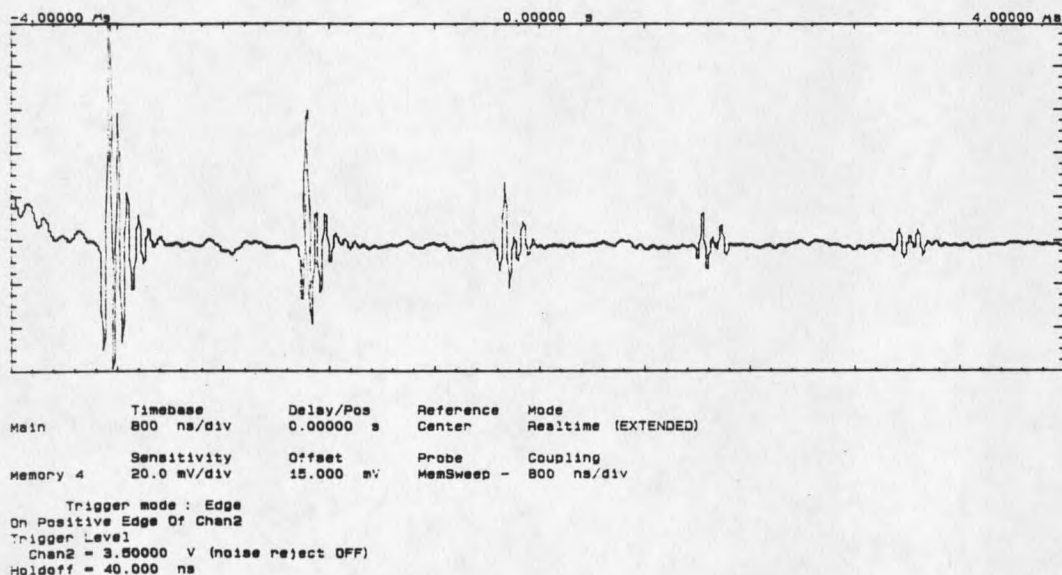


Figure 2. Sample Oscilloscope Waveform.

This displayed waveform is then analyzed to obtain the time delay measurement (period) between two adjacent signal peaks.

The time span between two consecutive peaks is the time period for two complete passes of the signal through the object; if the wave speed through the object is known, the thickness of the object can be calculated as follows;

$$(1) \quad L = V \times P / 2$$

Many styles and designs of ultrasonic transducers are commercially available, each tailored to specific tasks. Features include single or dual beam configurations, angle beam or normal incident beam types, longitudinal or shear wave generating designs and immersion (fluid coupled) or contact varieties. Most of these variations are available in a wide variety of frequencies.

A key feature of an ultrasonic transducer is the frequency of the sound pulse it emits. Higher frequencies produce shorter wavelength signals, and can provide greater accuracy (resolution) in dimensional inspection applications; however, frequency dependent attenuation effects increase linearly with distance from the transducer face and with the square of the frequency of the signal produced by the transducer. The intended application must therefore be carefully considered when selecting a transducer frequency. The transducers selected for this investigation were all operating at 10 MHz, and used a straight beam orientation to introduce longitudinal ultrasonic waves into the test specimens.

Initial research focused upon planar specimen testing, at room temperature and at elevated temperature, to define and develop the ultrasonic measurement techniques necessary for cylindrical specimen testing. Once the procedure was

perfected in planar testing, the research was expanded to include cylindrical specimen thickness measurement at elevated temperature.

Two versions of the mature system were developed, each of which demonstrated the capability to ascertain wall thicknesses for the instrumented cylinder, which was basically a "dummy" heat exchanger tube. The device provided *in situ* real time thickness determination, and can therefore accurately monitor thickness while tube external surface erosion is occurring.

A compilation of wall thickness data taken over a period of time is an effective means to gather erosion rate information: The ability to determine tube wall thickness and tube erosion rate is a step towards optimization of the maintenance schedule and operational parameters (i.e. particle size, bed temperature, etc.) of a fluidized bed combustor facility.

CHAPTER 2

DATA ACQUISITION SYSTEM

For cylindrical specimen testing, the data acquisition system was configured as shown in Figure 3.

The system consisted of the following components:

1. A Hewlett Packard HP9836 computer with dual 5.25 inch floppy disk drives.
2. A Hewlett Packard HP3497A Data Acquisition Control Unit.
3. A Hewlett Packard HP3456A Digital Voltmeter. [Accuracy (0 - 0.1 volt range) $\pm$ (.0022 % +24 counts), 6 decimal places carried, integrated over 10 power line cycles. Input resistance $>10^{10}$ ohms.]
4. Two Hewlett Packard HP9121 dual 3.5 inch floppy disk drive units.
5. A Hewlett Packard HP9153C hard disk drive.
6. A Hewlett Packard HP54502A Digitizing Oscilloscope. [400 MHz bandwidth, risetime 3.5 nanoseconds, dual cursor accuracy (dc) $\pm$ 2% of scale $\pm$.032 x volts/division, time base reference accuracy 0.01%, repetitive delta time accuracy $\pm$ (2% x seconds/division + 0.01% x delta time + 250 picoseconds).]

7. A Hewlett Packard HP6236B Triple Output Power Supply unit. [0+/- 20 volts, 0-0.5 amps, 1 volt resolution, or 0-6 volts, 0-2.5 amps, 0.2 volt resolution.]
8. An MSU fabricated pulser/receiver unit. [Transducer driver section; <100 nanoseconds risetime, 380 millivolt peak @ 15 V.D.C. input, 2.5 kHz. Receiver section; 10 MHz, variable attenuation. Trigger section; 7-15 microsecond variable delay, 380 millivolts peak @ 15 V.D.C. input, 2.5 kHz.]
9. Computer programs to control functions of the apparatus.
10. A Hewlett Packard Thinkjet printer.
11. HP-IB cables for communication interface.

Data acquisition system operation depended upon the mode in which it was operating; wave speed determination mode or thickness measurement mode. Each mode was controlled by a separate computer program. (ref: appendix A.) An overview of operation of the data acquisition system is included in following chapters.

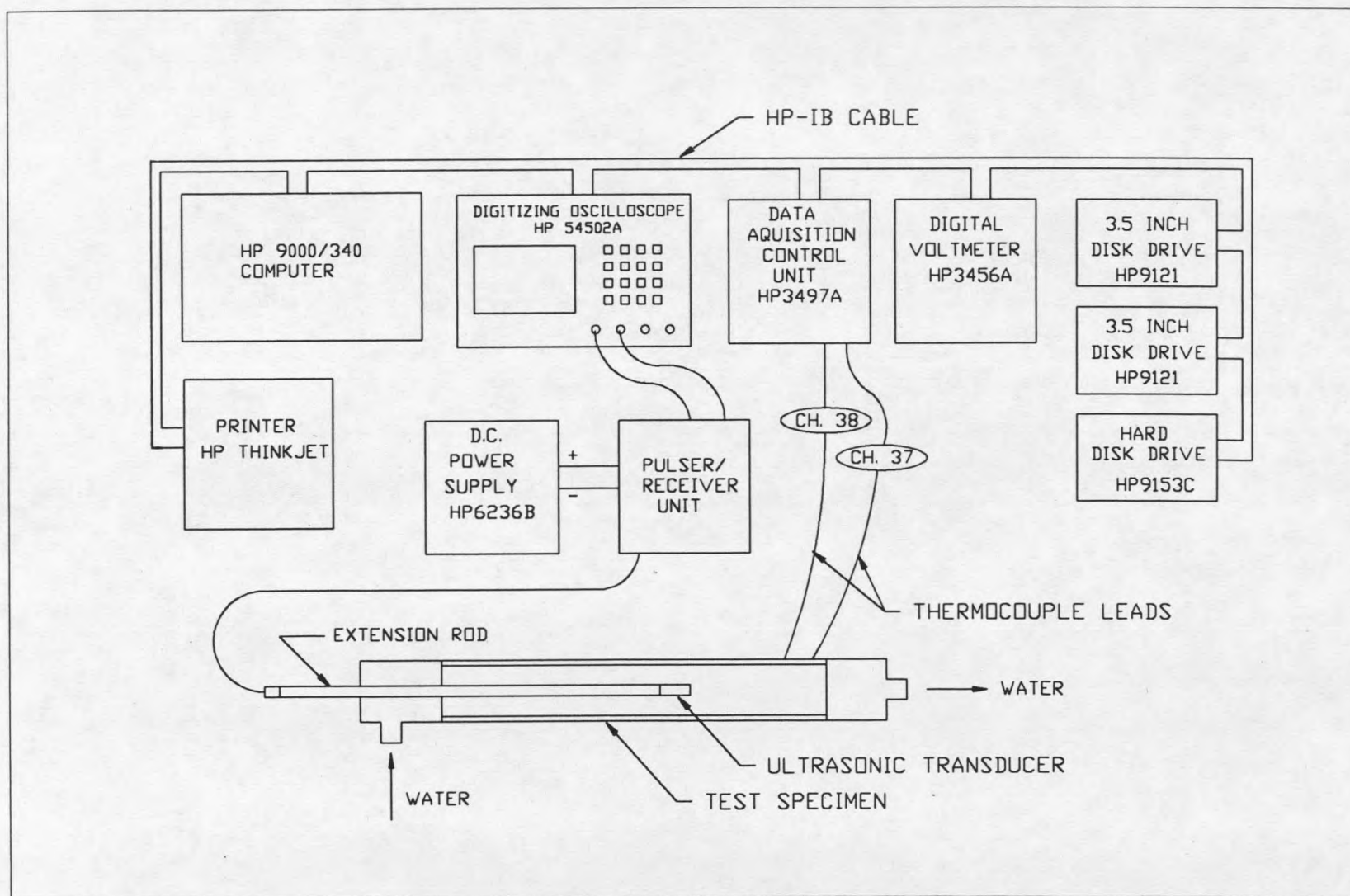


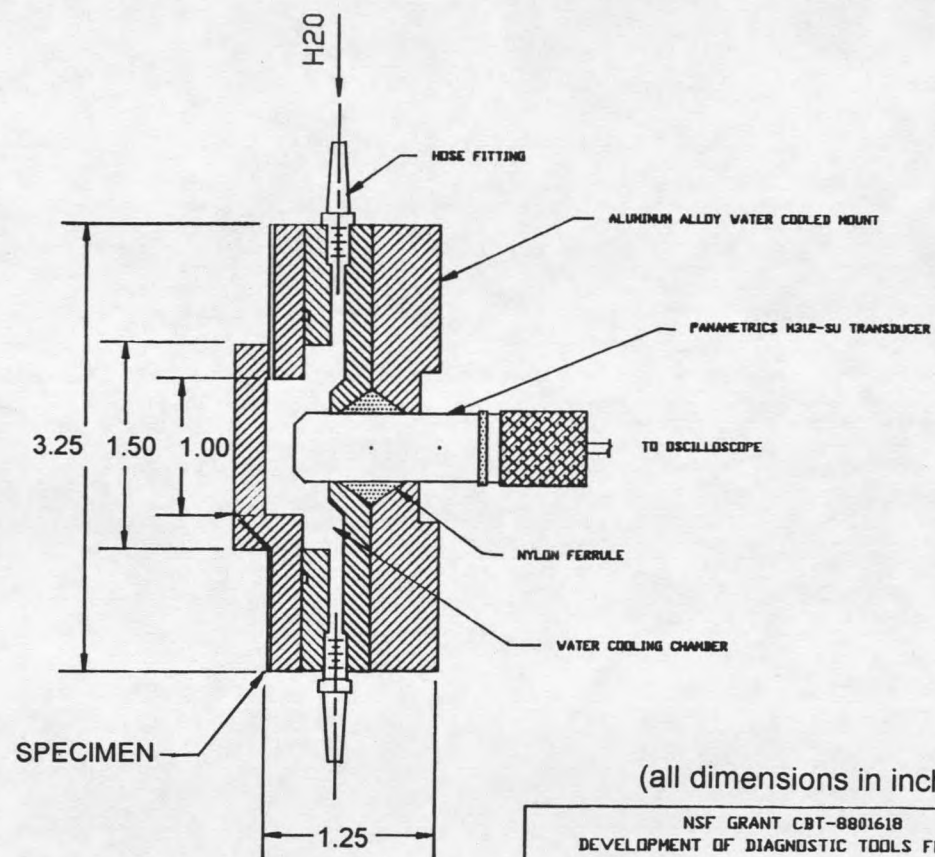
Figure 3. Data Acquisition System Apparatus.

CHAPTER 3

PLANAR TESTING , NONCONTACT TRANSDUCER

Initial research in the subject area was performed using a Panametrics model 312-SU unfocused 10 MHz immersion-type ultrasonic transducer to measure the thickness of planar stainless steel specimens (George, et al., 1990). The transducer was installed in a specially fabricated holder bolted to the test specimen. This hardware is described in Figure 4. The mount provided for transducer cooling using flowing tap water and also positioned the transducer face at approximately 6.5 mm standoff from the planar specimens. Standoff distance could be varied in order to isolate a front and back face echo pair within the field of view of the oscilloscope. Data acquisition equipment used was as described in Chapter 3, Figure 3, with the exception that a Gould model 1425 storage oscilloscope with model 125 waveform processor was used in place of the Hewlett Packard 50502A digitizing oscilloscope for the early testing.

Three different thickness specimens were prepared, with 3.9116, 4.0894, and 4.4958 mm thickness respectively as determined with an Ames dial indicator, with 0.013 mm resolution. Each specimen in turn was placed in the holder, the data



(all dimensions in inches)

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TEMPERATURE FLUIDIZED BEDS.

ULTRASONIC TRANSDUCER MOUNT

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date 9/5/89

scale: REDUCED COPY
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Figure 4. Noncontact Planar Test Apparatus.

acquisition system was connected to the specimen and to the transducer, and water flow was turned on. Voltage output peaks of interest were isolated, and the average echo pulsetimes were recorded for each of the three test specimens. Wave velocity was calculated from echo pulsetimes and measured specimen thickness data, per;

$$(2) \quad V_a = 2 \times L_a / P$$

The three wave velocities were then averaged to establish the wave velocity of 316 stainless steel at ambient conditions (15.5 °C). Test specimens of three thicknesses were then tested over a range of elevated temperatures, from 16 °C to 260 °C., and the wave speed vs. average specimen temperature relationship for the 316 stainless steel specimens was established as shown in Figure 5.

Once this relationship was determined, the thickness of the specimen was calculated from the measured echo pulsetime and the average specimen temperature. 316 Stainless steel specimens of six known thicknesses. (measured by dial indicator) were randomly tested. The specimen design is described in Figure 6. The results of thickness measurements are shown in Figures 7 and 8.

Thickness measurement error was defined as;

$$(3) \quad E = L_{p,ref} - L_{ref}$$

Error versus temperature for six tested planar specimens is shown in Figure 9. The few data points outside the dashed "limits of error" line in Figure 9 were caused by an electronic failure within the Gould model 1425 storage oscilloscope.

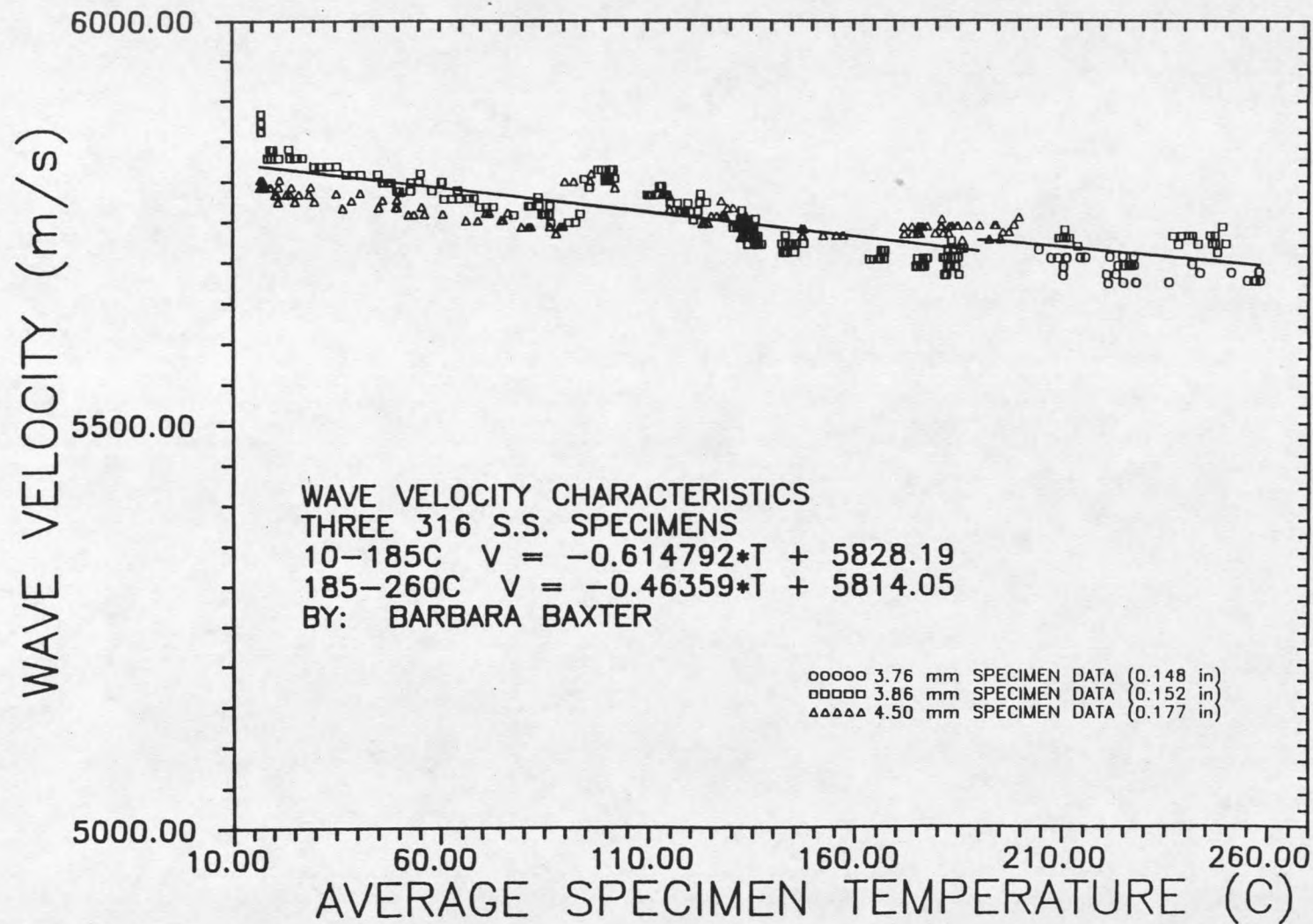


Figure 5. Planar Specimen Wave Speed Correlation.

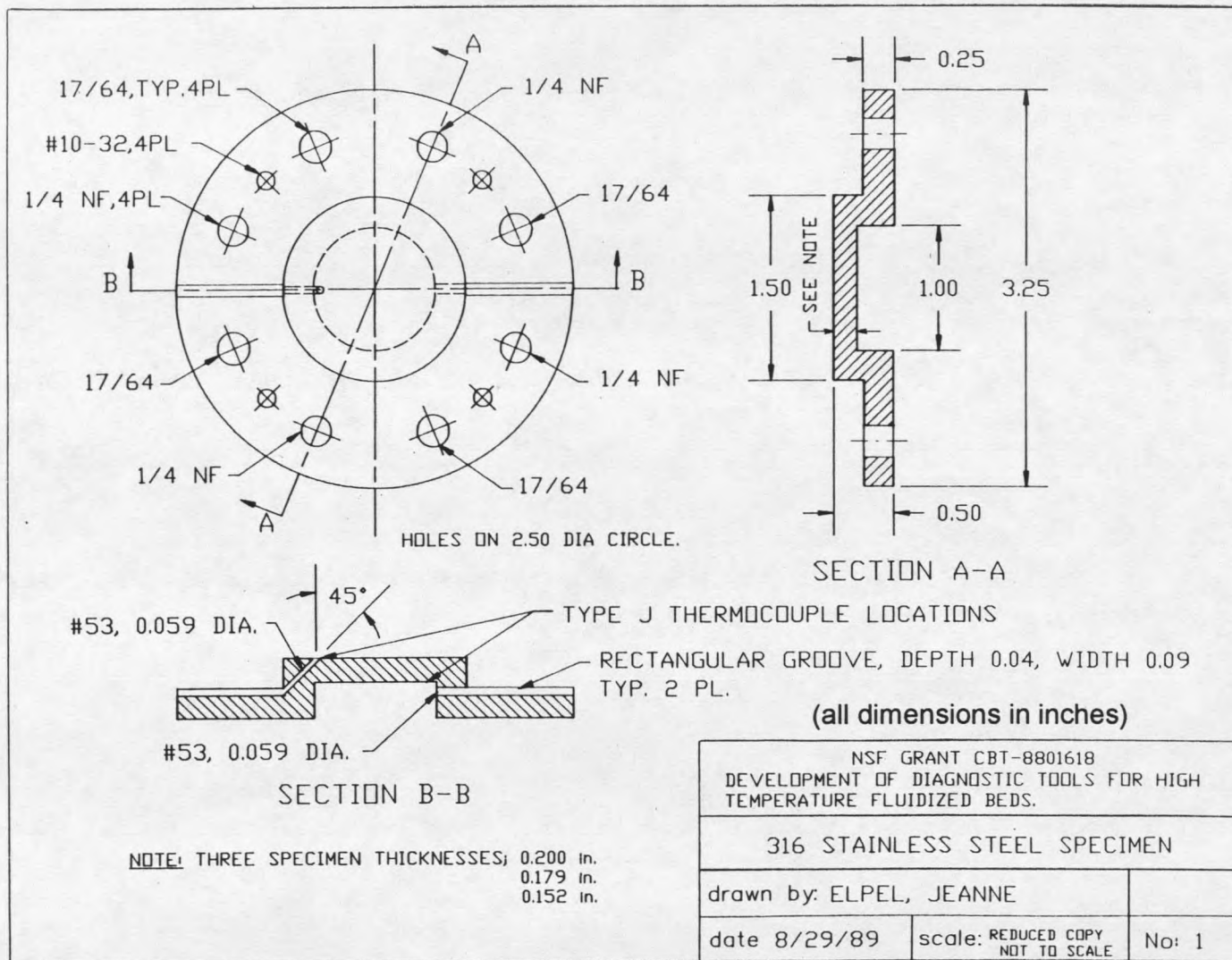


Figure 6. Planar Test Specimen Design.

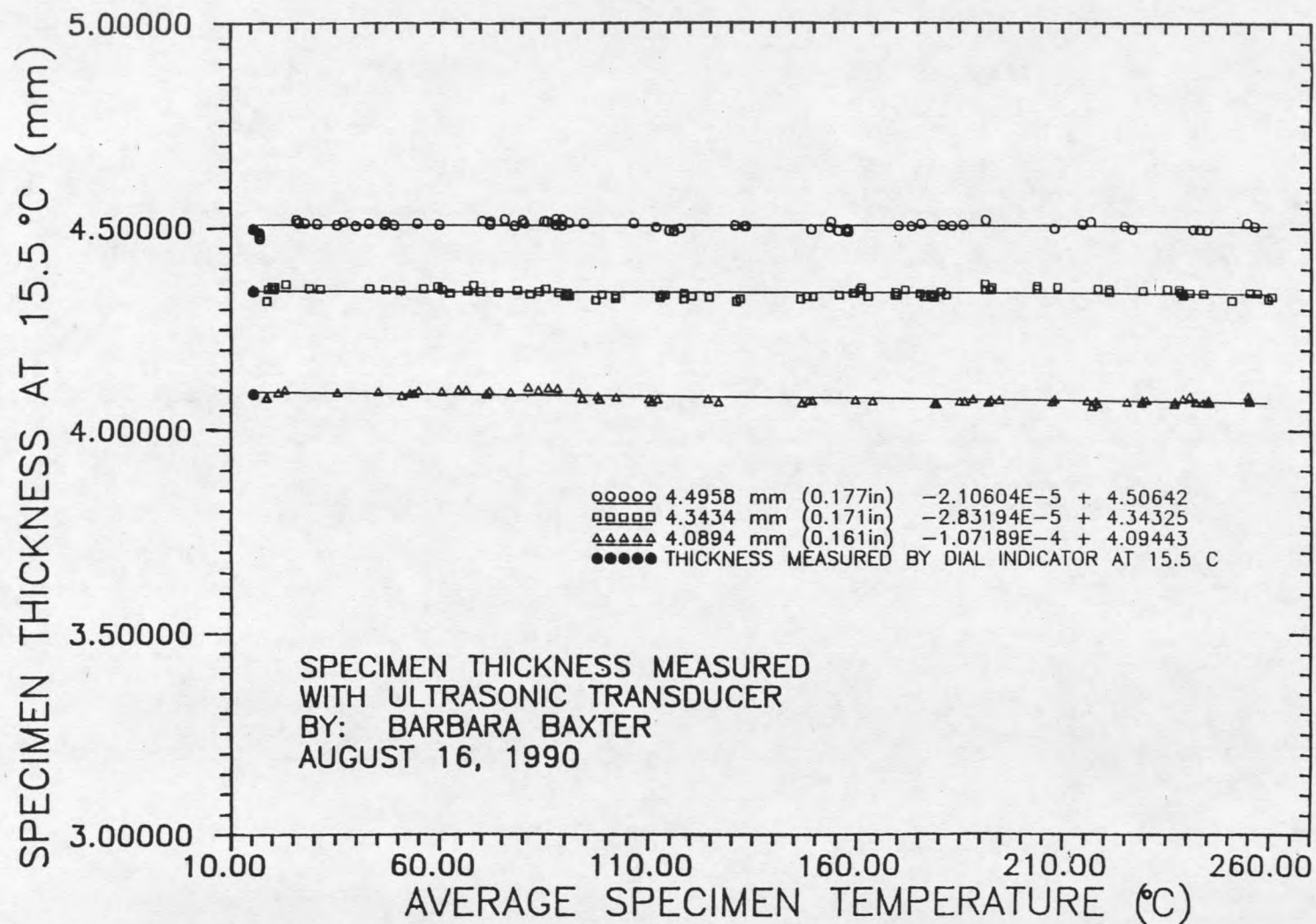


Figure 7. Thickness Measurements for Planar Specimens.

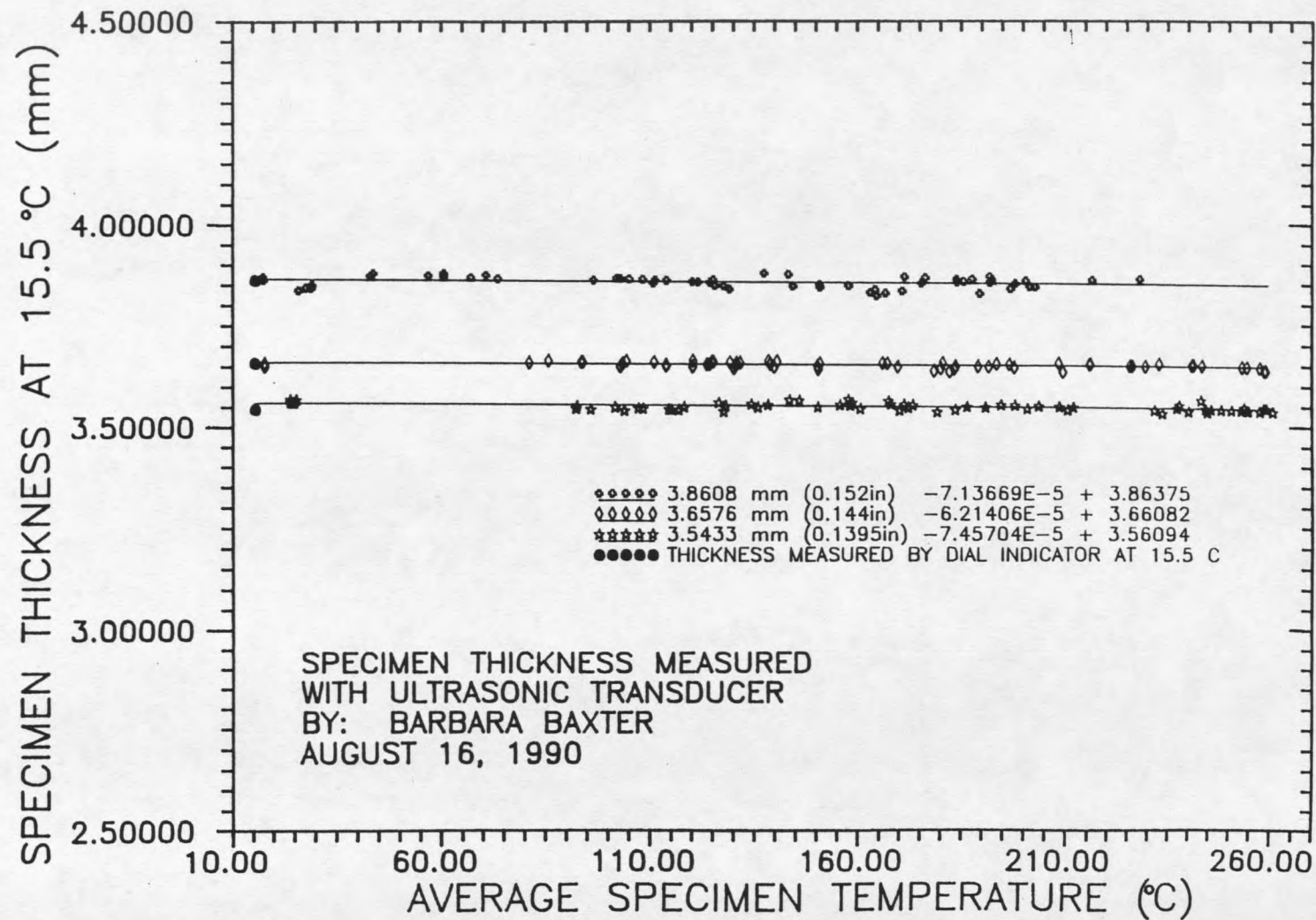


Figure 8. Thickness Measurements for Planar Specimens.

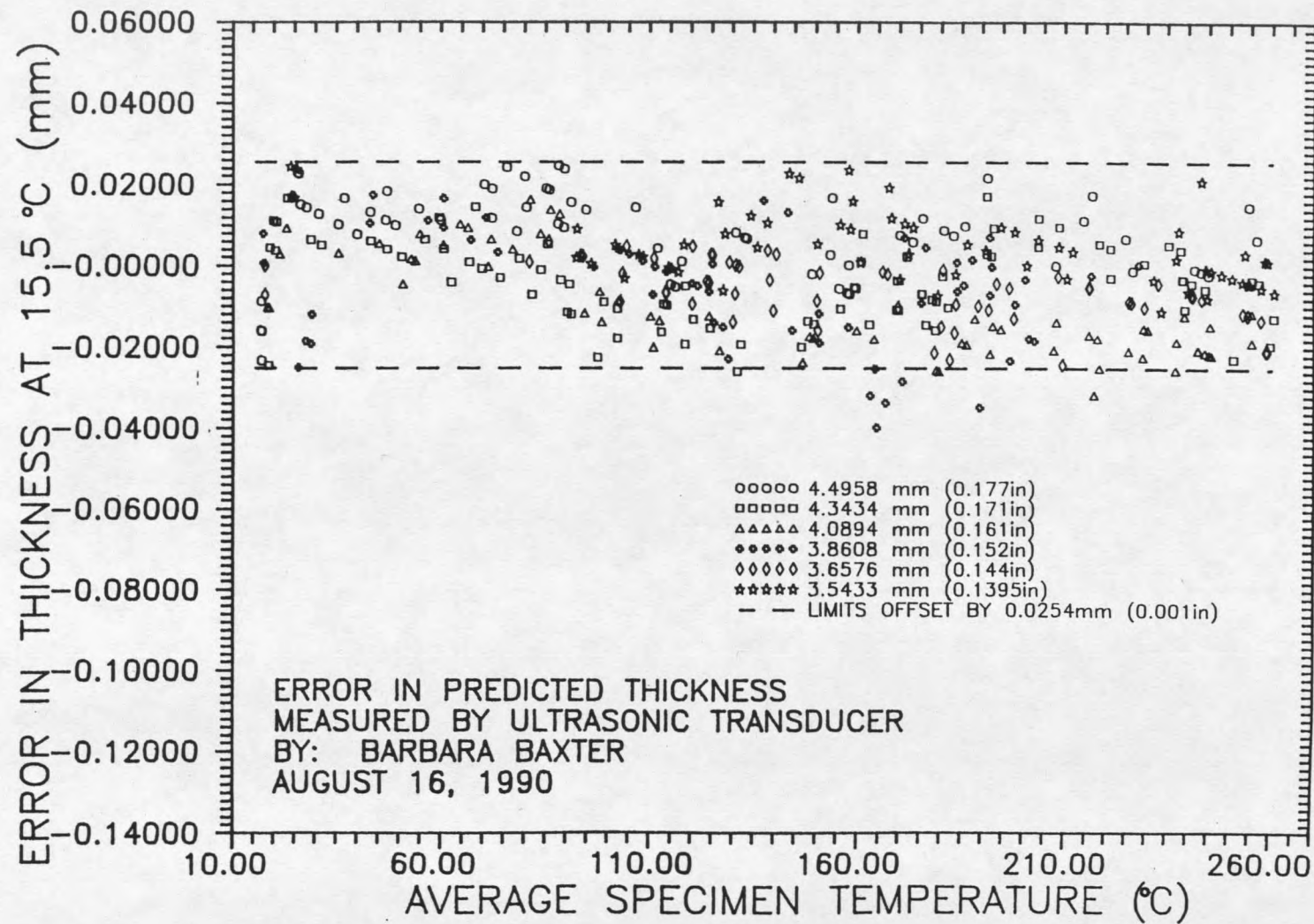


Figure 9. Measurement Error versus Temperature for Planar Specimens.

CHAPTER 4

CYLINDRICAL TEST SPECIMEN DESIGN

The capability of the ultrasonic transducer based system to accurately determine the wall thickness of a hollow cylindrical specimen at an elevated temperature was the focus of this research. The configuration of the cylindrical test specimen was integral to the successful demonstration of this capability.

Since the cylindrical test specimen was to represent a single heat exchanger tube from a fluidized bed combustor heat exchanger, the test specimen was designed to exactly replace one of the tubes within an actual fluidized bed combustor test facility. Design parameters from the Oregon State University High Temperature Fluidized Bed facility were used as the basis for the test specimen design, based primarily upon the accessibility of that unit for applied research and testing (ref: Appendix F for specifications). Although the systems developed in this research for cylindrical specimen testing were not tested in the actual fluidized bed combustor heat exchanger during this research phase, the configuration is compatible with the Oregon State University facility in the event that further study is undertaken in the future.

Critical to the function of the system was the ability to accurately determine the temperature of the steel specimen wall, since the ultrasonic wave speed through any media is dependent on the temperature of the media. Also, as temperature increases, the specimen experiences thermal growth dependent upon the coefficient of thermal expansion of the specimen material and the range of temperatures experienced. The coefficient of thermal expansion was obtained by performing a linear curvefit of a graph describing thermal expansion versus temperature for 304 series stainless steel, from Peckner & Bernstein, 1977, shown in Figure 10.

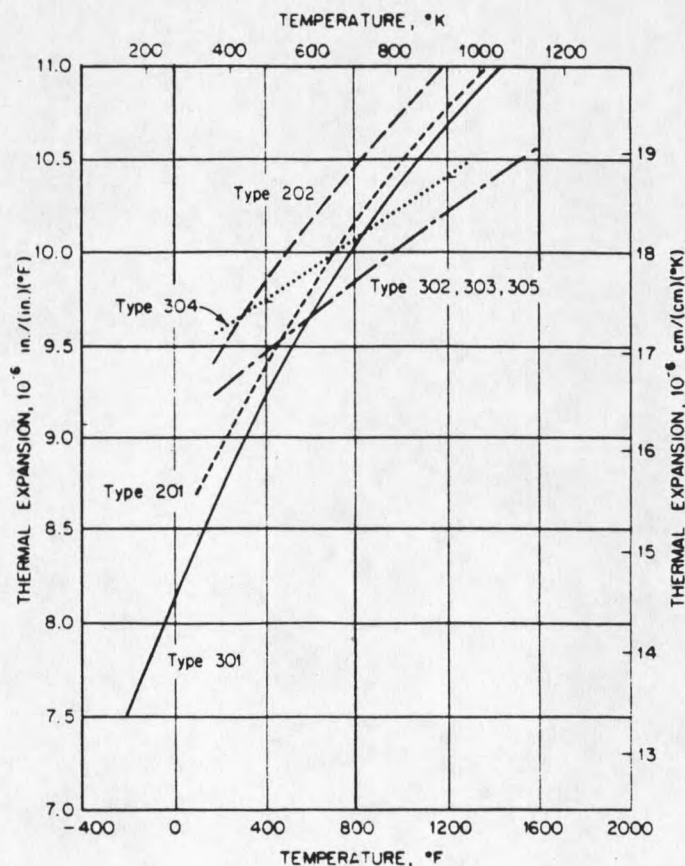


Figure 10. Thermal Expansion Relationships for Steel.

The temperature profile of the specimen wall was far from uniform during elevated temperature testing, due to the torch flame impinging on the exterior wall and the tap water coolant stream providing a constant cooling source on the interior wall. It was assumed for the purposes of determining material properties that a linear temperature profile through the specimen wall would give a reasonable approximation of wall temperatures. The average of interior and exterior surface temperatures was therefore chosen as the characteristic temperature upon which to base thermal expansion and wave speed calculations. The fact that accurate thickness measurements were obtained throughout the test series, based upon wave speed correlations created from average specimen wall temperature values, supports the assumption of a relatively linear temperature profile for wall temperature. No claim of an exact linear profile is made, however, nor was any attempt made to determine the actual temperature profile.

Based on the above considerations, test specimen design therefore included two type "E" constantan/chromel welded junction thermocouples for each test location, silver brazed to the internal and external surfaces of the test specimen. The cylindrical test specimen is described in Figures 11, 12, 13 and 14.

For demonstration of system performance, two different wall thickness steps were machined into the cylindrical test specimen. Thermocouple wires were located in channels machined longitudinally on the external surface of the test specimen, and were covered by a close fitting cover secured to the main body of the test specimen with screws.

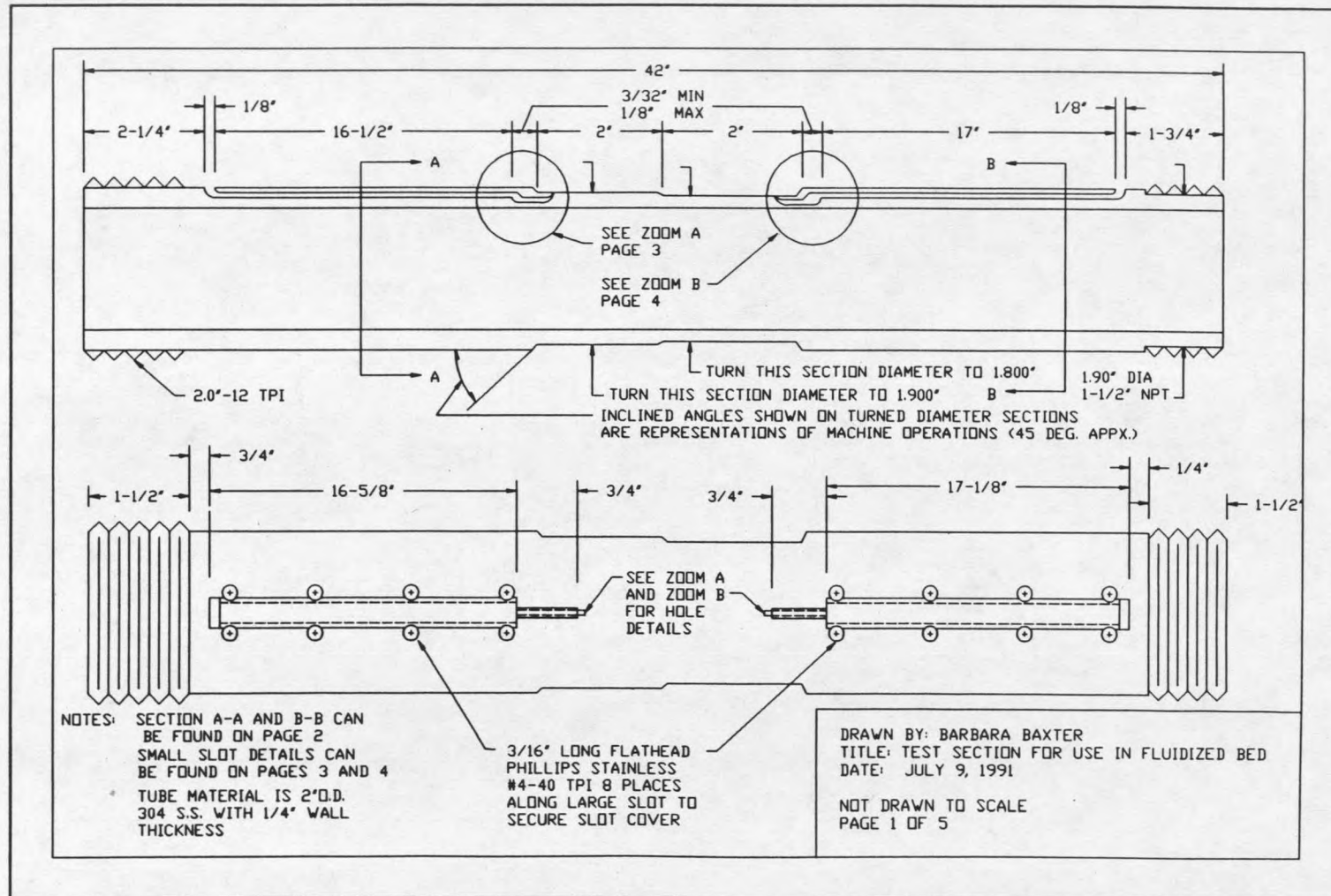


Figure 11. Cylindrical Test Specimen Design.

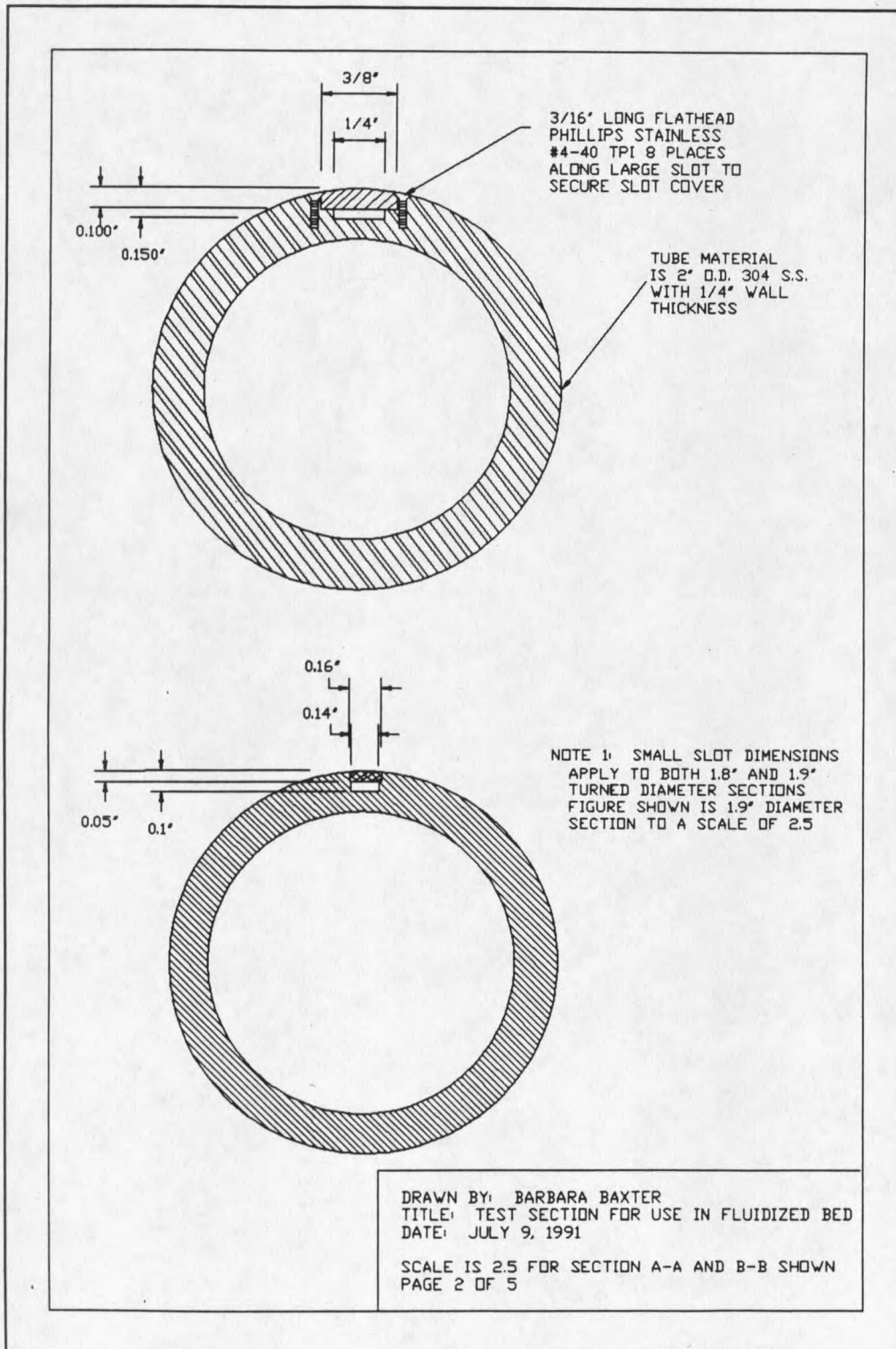


Figure 12. Cylindrical Test Specimen Design.

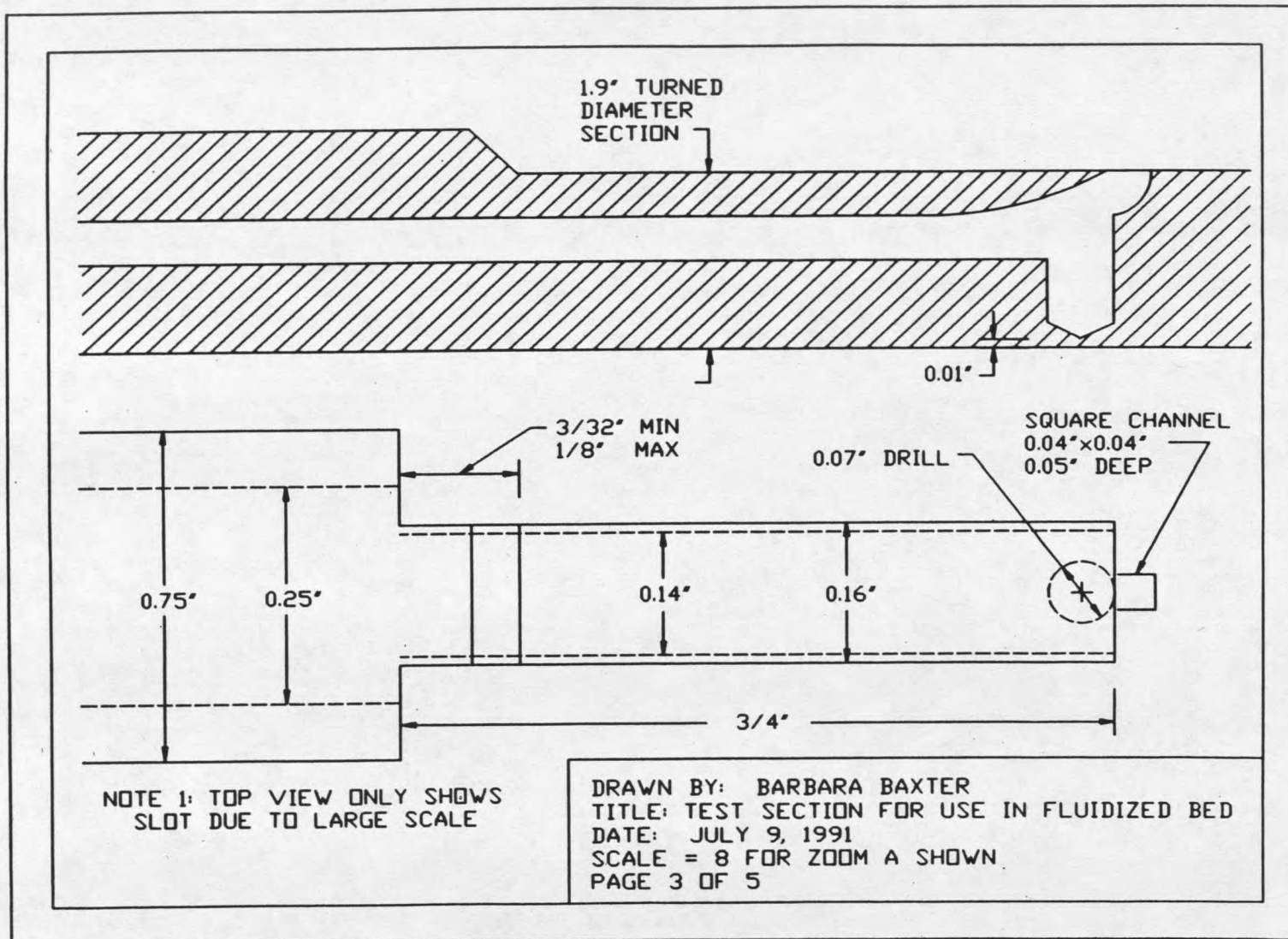


Figure 13. Cylindrical Test Specimen Design.

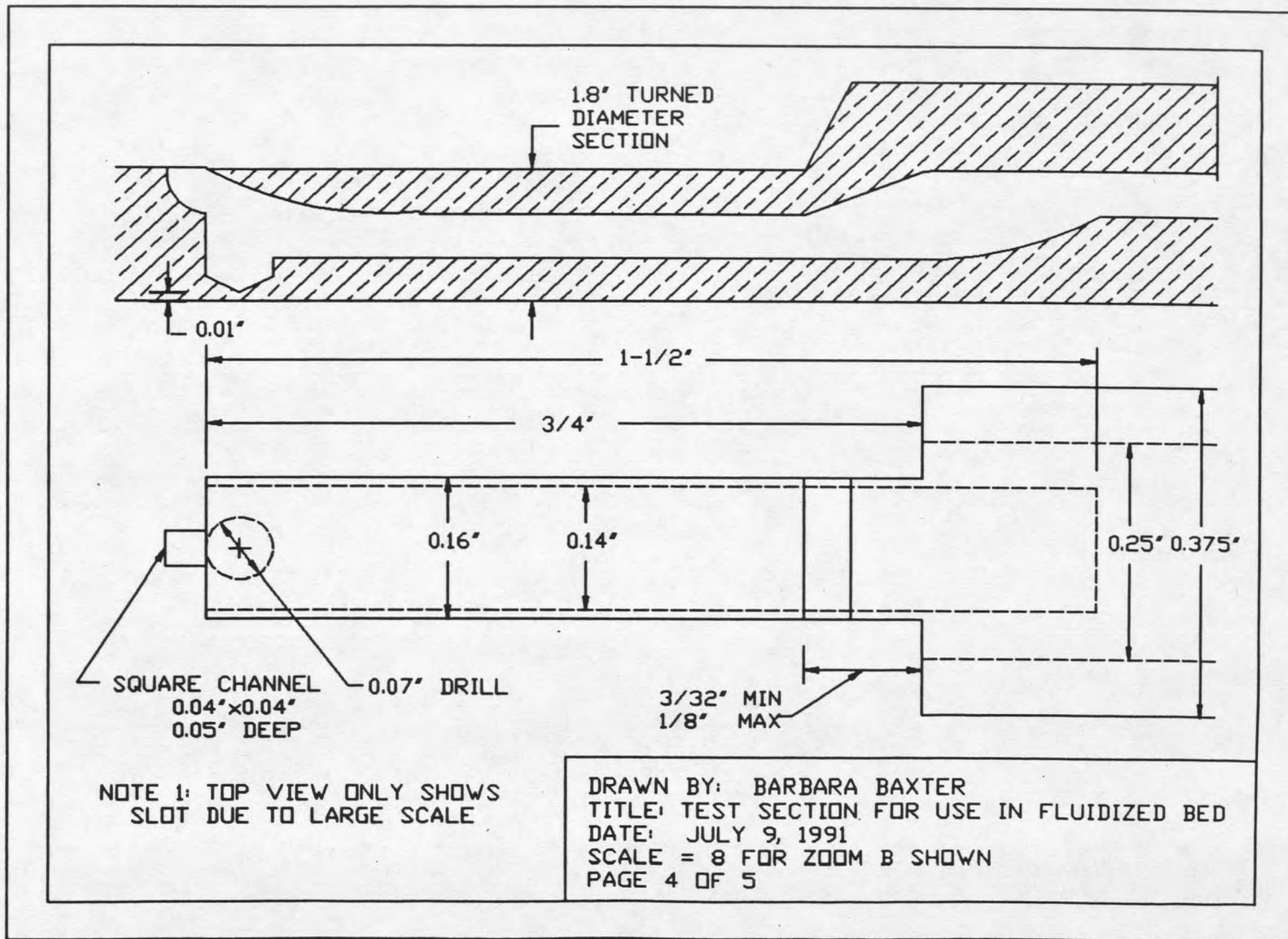


Figure 14. Cylindrical Test Specimen Design.

CHAPTER 5

CYLINDRICAL TESTING, NONCONTACT TRANSDUCER

The apparatus based upon the noncontact immersion transducer was then adapted for testing of cylindrical specimens. A Panametrics model F120 "Immersion Search Tube" extension rod of 18.74 mm (.738 inch) diameter served to position the transducer axially within the cylindrical test specimen. A Panametrics model F102 45 degree angle acoustic mirror was used to provide an acoustic signal normally incident to the internal diameter of the test specimen, and a Panametrics model V311-SU "Videoscan" 10 MHz immersion-type ultrasonic transducer, focused at 54.22 mm (2.138 inches) in water, was selected to provide good sensitivity in the curved internal bore of the test specimen. The apparatus is shown in Figure 15.

Wave Speed Determination

Ultrasonic wave speed data for the specimen was first obtained by performing the following series of steps:

1. Since manual (micrometer or dial indicator) measurements of the test segment of the test specimen were impossible to perform with available measurement

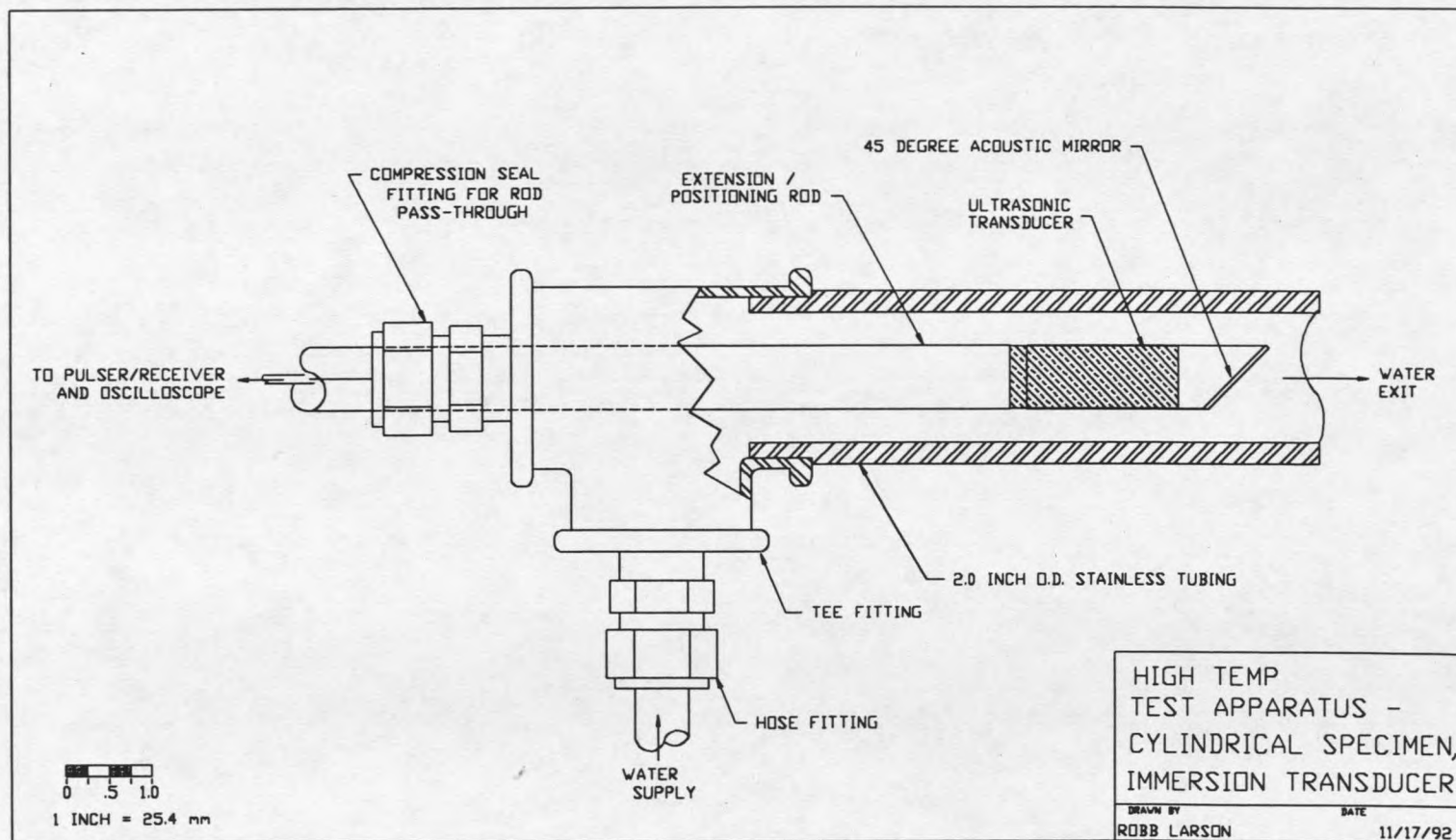


Figure 15. Noncontact Cylindrical Test Apparatus.

equipment due to the configuration of the test specimen, the ambient (tap water) temperature wave speed was determined using a specimen machined from the same 304 stainless steel stock as the primary instrumented test specimen. This wave speed calibration test specimen is shown in Figure 16.

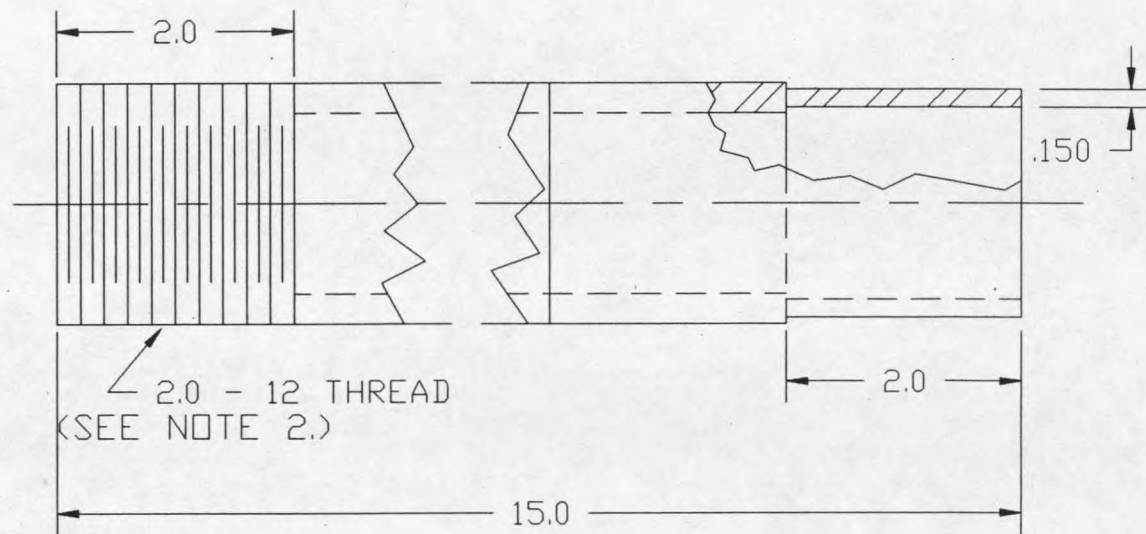
The test specimen was installed into the tee fitting, and water supply turned on. Once temperature equilibrium was reached, the thickness of the machined portion of this specimen was measured manually with a ball end micrometer with .013 mm resolution (L.S. Starrett Co., Athol, MA, part no. 576R). The temperature of the specimen was determined using a type J thermocouple bonded to the specimen exterior, and manually recorded as "T_a".

The ultrasonic transducer was positioned so that the measurement location was identical to that where micrometer thickness measurements were taken. The data acquisition system was activated, the waveform of interest identified on the oscilloscope display, and the period between voltage peaks was manually recorded as "P".

Wave speed at ambient (tap water) temperature was then calculated from the known specimen thickness and the pulse-echo time period, as follows;

$$(4) \quad V_a = 2 \times L_a / P$$

2. The instrumented cylindrical test specimen was then connected to the data acquisition system; the coaxial cable was connected between the pulser/receiver unit and the ultrasonic transducer extension rod, and specimen thermocouple wires



NOTES:

1. MATERIAL: MAKE FROM 304 STAINLESS STEEL PIPE, 2.0 INCH O.D.
2. THREADS TO MATCH PREVIOUS FITTING: MAINTAIN PREPENDICULARITY.
3. REMOVE BURRS AND SHARP EDGES.

(ALL DIMENSIONS IN INCHES)

WAVE SPEED
CALIBRATION TUBE

PART NO. SKRL921121

DRAWN BY: ROBB LARSON DATE: 11/21/92

Figure 16. Wave Speed Calibration Test Specimen.

were connected to the appropriate contacts within the thermocouple card in the data acquisition system control unit. The system was activated, the computer booted, and the controlling program "Phase2" was loaded into computer memory from one of the disk drives. The natural gas/oxygen heating torch was connected to a regulated oxygen supply and natural gas line, and installed in a clamp stand mount. The water supply for system cooling was then connected and turned on.

3. By means of the interactive program, the time period between the waveform voltage peaks was determined: The oscilloscope waveform was visually scanned by the operator for a signal pair of acceptable clarity, the signal pair representing the ultrasonic echo from the inside and the outside faces of the specimen. Once identified, the approximate location on the displayed oscilloscope waveform where each of the two peaks occurred was input into the controlling program. The program instructed the digitizing oscilloscope to search for signal peaks within two time bands centered around the peak locations input by the operator. The digitizing oscilloscope then marked the identified peaks of interest, and determined the time period between peak voltages.

4. Voltage values from the type E thermocouples silver soldered to the inside and outside faces of the specimen were sampled by the digital voltmeter, converted to temperature readings by the controlling program, and averaged to obtain the average specimen temperature as follows;

$$(5) \quad T_{ave} = (T_{in} + T_{out}) / 2$$

This temperature, "T_{ave}", was checked to verify that it was within 1 °C. of that used as "T_a" for the wave speed calibration test specimen thickness measurement, to ensure calibration accuracy.

5. The wave speed calculated per equation (4) for the specimen at uniform tap water temperature was then utilized to determine the baseline temperature thickness measurement of the machined instrumented test specimen, at a random location within one of the two test zones. Thickness was determined by;

$$(6) \quad L_a = V_a \times P / 2$$

This baseline thickness value was recorded to disk and also saved by the controlling program, and used as a basis for subsequent wave speed calculations.

6. With ambient temperature thickness calculated by the controlling program, the specimen was subjected to external heating. Pulse echo times and average specimen temperature were recorded at random temperature increments, from ambient temperature (no heating) to a working limit of approximately 270 °C. average specimen wall temperature. This was the temperature at which the detected waveform became unstable and the oscilloscope screen display of the waveform disappeared.

The value for α , the thermal expansion coefficient, was calculated at each increment of average specimen temperature, per the first order polynomial curvefit of the thermal expansion curve for 304 stainless steel shown in Figure 10. The curvefit equation is defined as equation (7);

$$(7) \quad \alpha = 8.33 \text{ E-}10 \times T_{a,F} + 9.41165 \text{ E-}6$$

Specimen thickness at the elevated temperature was calculated, and used in calculating the wave speed for each increment of temperature increase, as follows;

$$(8) \quad L_h = L_{a,i} \times .0254 \times [1 + \alpha \times (T_{ave,F} - T_{a,F})]$$

$$(9) \quad V_h = 2 \times L_h / P$$

The wave speed and temperature data were then recorded to disk for this data point. The specimen external wall temperature was changed by adjusting the torch oxygen supply or relocating the torch with respect to the specimen surface. The program was cycled back to the beginning, and data recorded for each increment of temperature increase between room temperature and the upper temperature limit reached for each test run.

7. These data values were transferred to an IBM compatible computer system, where a graphing program was utilized to plot temperature and wave speed data to create a wave speed versus temperature curve for the specimen. The program used for this data processing was "Easyplot 2.12M", by Stuart Karon, copyright 1988 & 1991, MIT & Spiral Software, (Ref: S/N 21201273). A third order polynomial curvefit of the data was performed to obtain an algebraic expression of the relationship for subsequent use in the thickness measurement program. This data was plotted and is displayed in Figure 17.

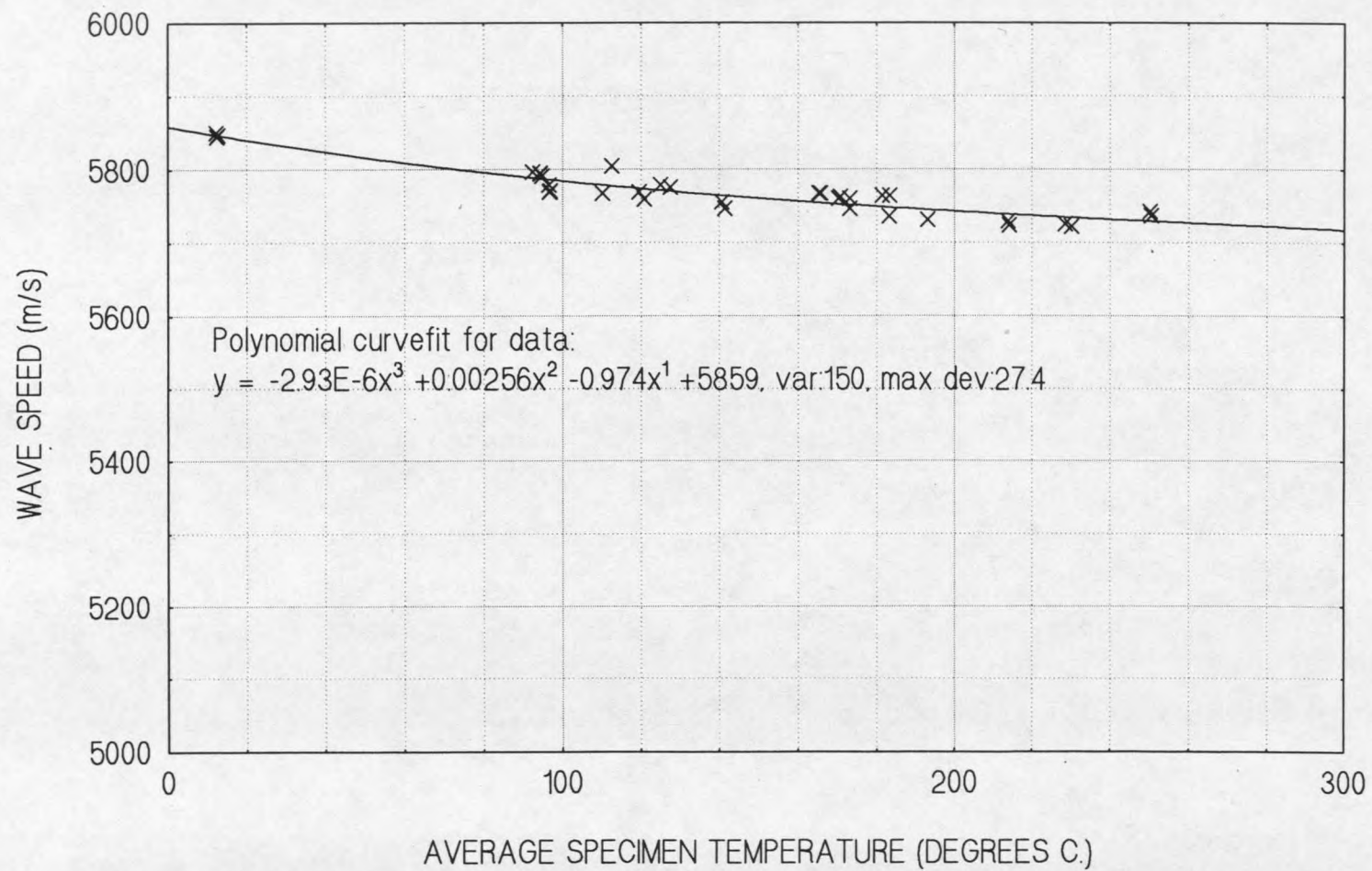


Figure 17. Wave Speed versus Temperature for 304 Stainless Steel.

Thickness Measurement

Wall thickness measurements at random locations within the cylindrically machined portions of the test specimen were performed as follows:

1. The coaxial cable was connected between the pulser/receiver unit and the ultrasonic transducer extension rod, and specimen thermocouple wires were connected to the appropriate contacts within the thermocouple card in the data acquisition system control unit. The system was activated, the computer booted, and the controlling program "Nonpred" was loaded into computer memory from one of the disk drives. The natural gas/oxygen heating torch was installed in the mount, and the water cooling system was connected.

2. Voltage values from the type E thermocouples silver soldered to the inside and outside faces of the specimen were sampled by the digital voltmeter and converted to temperature readings by the controlling program, and then averaged to obtain the average specimen temperature per equation (5). The oscilloscope waveform was visually scanned by the operator for a signal pair of acceptable clarity. Once identified, the approximate location of the primary and secondary waveform peaks was input into the program. The program instructed the digitizing oscilloscope to search for signal peaks within two time bands centered about the times input by the operator, corresponding to ultrasonic echoes from the front and back faces of the specimen. The digitizing oscilloscope then marked the identified peaks of

interest, and determined the time lapse between peak voltages. A typical test waveform displayed in Figure 18.

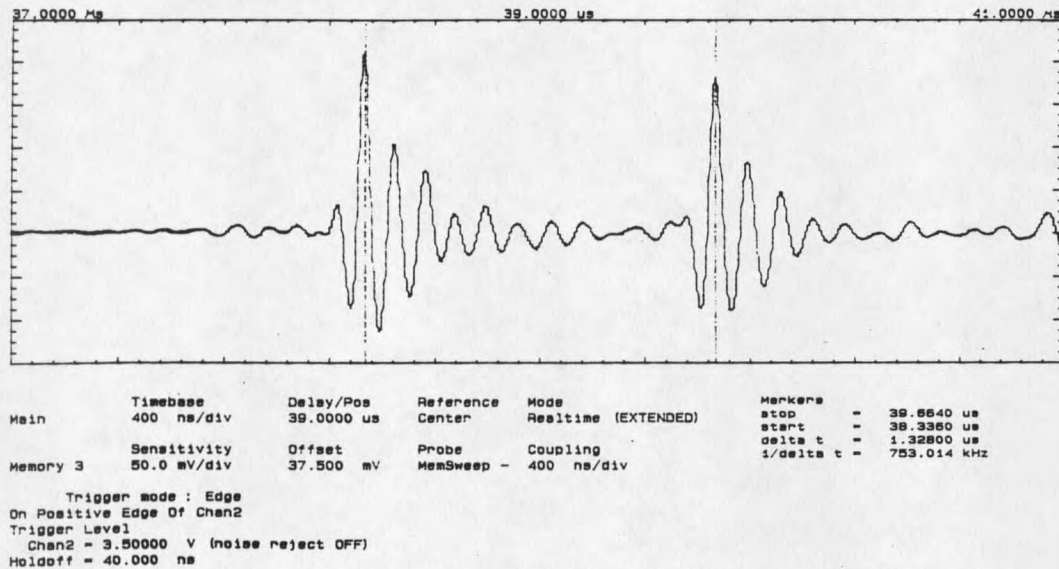


Figure 18. Typical Oscilloscope Waveform.

3. The wave speed for the baseline average temperature was calculated by the program, by evaluating the wave speed curvefit equation at the averaged specimen temperature, as follows;

$$(10) \quad V_a = -2.93 \text{ E-6} \times T_{ave}^3 + .00255 \times T_{ave}^2 - .974 \times T_{ave} + 5859$$

This wave speed was compared to the time lapse between ultrasonic specimen surface echoes to determine the baseline thickness of the specimen at the point of measurement, calculated as follows;

$$(11) \quad L_a = V_a \times P / 2$$

This thickness was used as a baseline thickness to compare with all subsequent thickness measurements at this location within the specimen.

4. The heating torch was ignited following instructions from the manufacturer (as shown in Appendix E), and placed so that the imbedded thermocouples and the specimen measurement site were heated uniformly. Again, voltage values from the type E thermocouples were sampled by the digital voltmeter, converted to temperature readings by the controlling program, and averaged to obtain the average specimen temperature. The wave speed for the average temperature was again calculated from the wave speed versus temperature third order polynomial curvefit equation;

$$(12) \quad V_h = -2.93 \text{ E-6} \times T_{ave}^3 + .00255 \times T_{ave}^2 - .974 \times T_{ave} + 5859$$

5. The oscilloscope waveform was visually scanned by the operator, and the time band within which each peak occurred was input into the program. The program instructed the digitizing oscilloscope to search for signal peaks within the two time bands input by the operator, corresponding to ultrasonic echoes from the front and back faces of the specimen. The digitizing oscilloscope then marked the identified peaks of interest, and determined the time period between peak voltages. The elevated temperature thickness was calculated per;

$$(13) \quad L_h = V_h \times P / 2$$

This elevated temperature thickness was normalized to a reference thickness at a reference temperature of 9.16 °C. (48.5 °F.) using the α value calculated as follows;

$$(14) \quad L_{ref} = L_h \times .0254 / (\alpha \times (T_{ave,F} - 48.5) + 1)$$

Thickness and temperature data were recorded to disk, and then the specimen wall temperature was changed by varying the oxygen supply or re-locating the torch with respect to the specimen surface. The program was cycled back to the beginning, and data recorded for each increment of temperature increase between coolant temperature and the upper temperature limit reached for each test.

6. Data value files were transferred to an IBM compatible computer system, where a graphing program was utilized to plot temperature and thickness data to create a thickness versus temperature curve for the specimen. These plots are shown in Figures 19 and 20.

Measurement error, or "deviation from nominal" was defined as follows;

$$(15) \quad E = L_{p,ref} - L_{ref}$$

Plots of error versus average specimen temperature are shown in Figures 21 and 22. Error values plotted are relative to a reference temperature of 9.16 °C. (48.5 °F.)

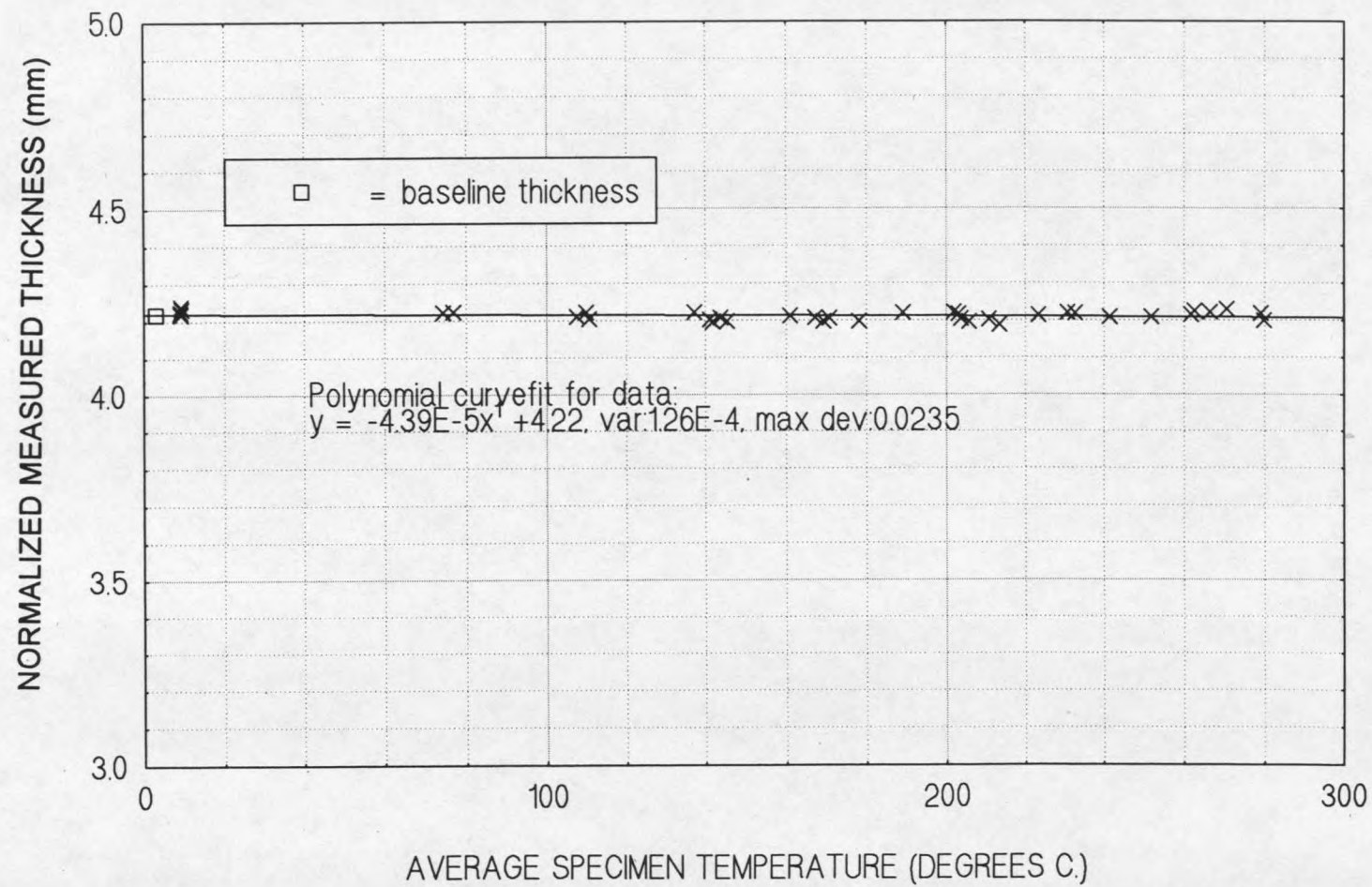


Figure 19. Measured Wall Thickness versus Average Specimen Temperature.

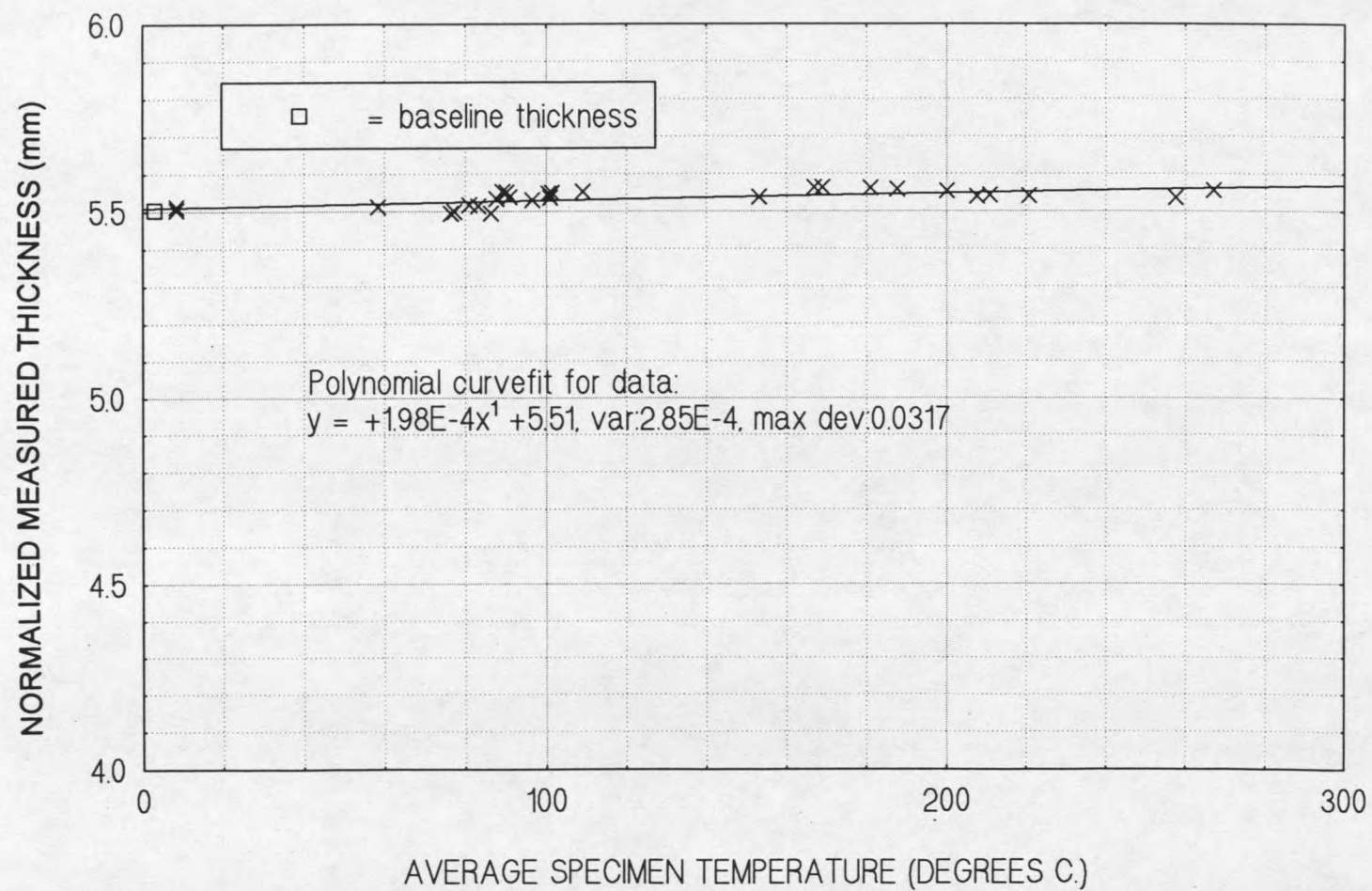


Figure 20. Measured Wall Thickness versus Average Specimen Temperature.

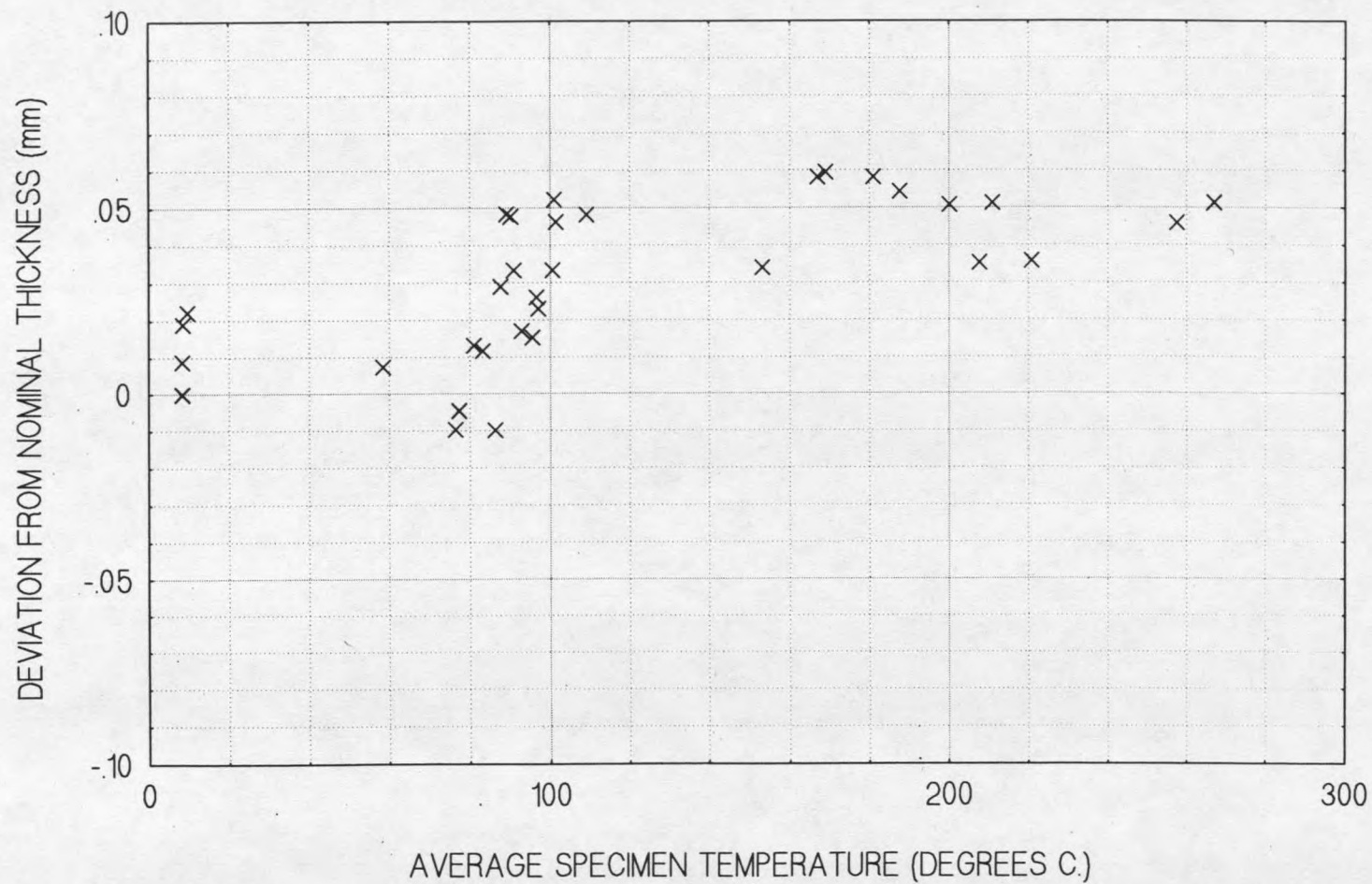


Figure 21. Measurement Error versus Temperature, Cylindrical Tests.

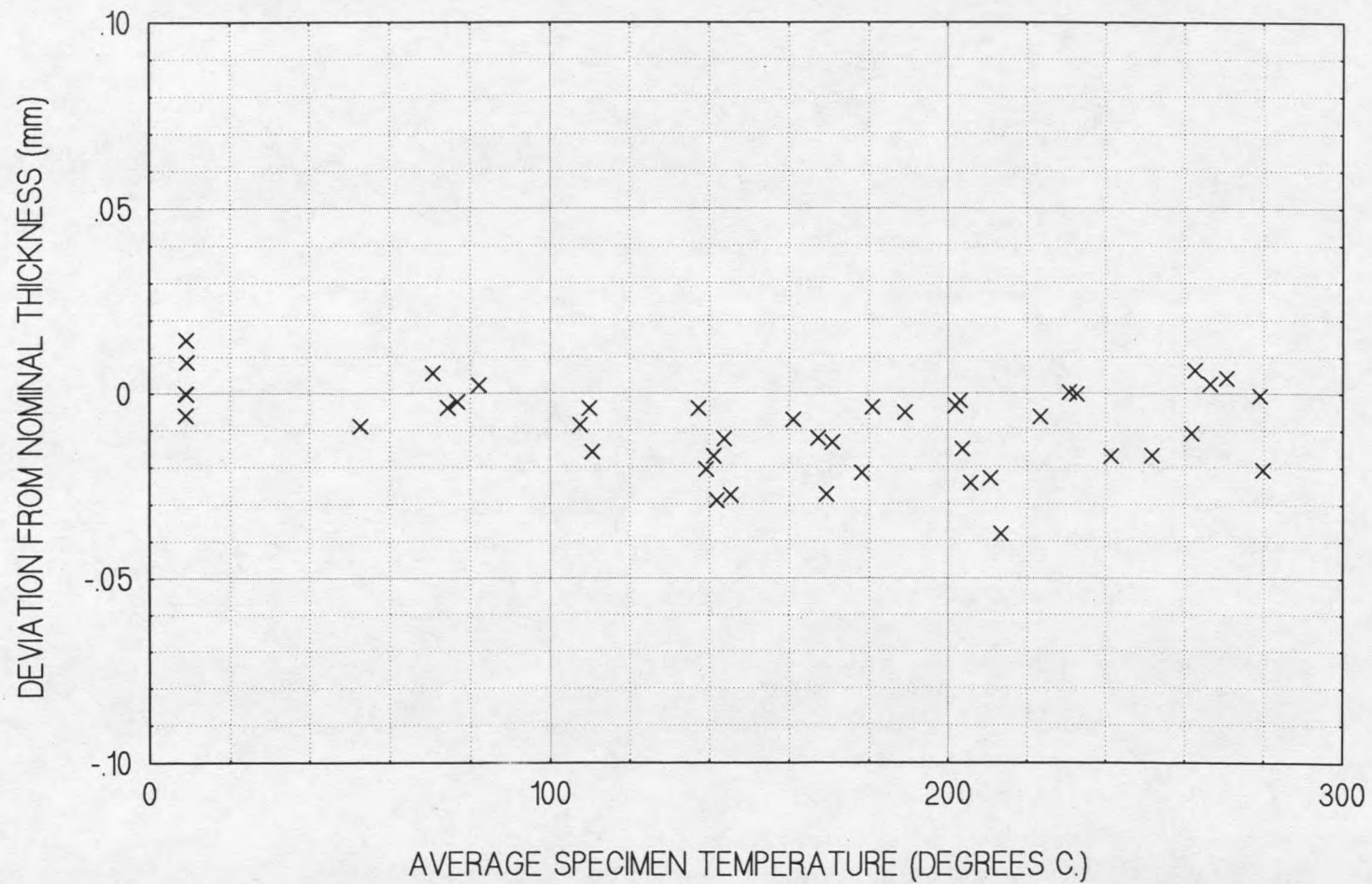


Figure 22. Measurement Error versus Temperature, Cylindrical Tests.

CHAPTER 6

PLANAR TESTING, CONTACT TRANSDUCER

The noncontact transducer based system performed well within the temperature band from ambient tap water temperature to about 270 °C. average specimen temperature. Above this temperature, however, a problem of signal degradation and eventual loss of signal was encountered.

The signal loss was attributed to formation of a sheet of microbubbles (surface boiling) on the interior surface of the test specimen. Ultrasonic signal transmission requires a nearly incompressible medium; when (compressible) air bubbles were present as a result of specimen interior surface boiling, the acoustic signal from the fluid coupled transducer as viewed on the oscilloscope display began to become unstable. Waveform instability increased with increasing specimen temperature, until the signal attenuation resulting from the boiling of the fluid on the internal face of the test specimen precluded successful thickness detection. This occurred at approximately 270 °C. average specimen wall temperature, with the internal specimen wall temperature typically at about 160 °C., and the exterior surface of the cylindrical specimen at approximately 380 °C. A new development phase was

therefore initiated in an attempt to raise the useful maximum working temperature limit of the apparatus.

Several possible techniques to expand the useful temperature range of the system were considered. These included mechanical devices, electronic hardware, and advanced signal processing methods. Initially, data processing and signal conditioning methods appeared to hold the greatest promise for reducing the ultrasonic "noise" from the bubble formation.

Bilgutay, et al, 1989, describes a process of spatial processing for coherent noise reduction in ultrasonic imaging, whereby a polarity thresholding algorithm is used to enhance the signal return from the target. The more common diversity methods of repositioning the transducer (spatial diversity) and varying the frequency used (frequency diversity) are both somewhat effective when the noise source is incoherent (time variant) such as the bubble sheet encountered here, and were investigated as possible solutions.

Also considered was a simpler technique known as time gating. This common method of noise filtering is employed by several ultrasonic equipment manufacturers in their product lines (Panametrics, 1991), and suppresses signals received from the transducer that fall outside a time band which is known to contain the waveform of interest, i.e. the echoes from the specimen. However, each of these techniques was unlikely to solve the problem of signal breakdown at some critical specimen temperature corresponding to a high density of surface bubble formation, and another approach was pursued.

The possibility of raising the maximum working temperature for the system by pressurizing the cooling system, perhaps in conjunction with the use of a higher boiling point fluid, was considered but discarded for the same reasons as the data processing techniques.

The approach chosen was to return to the ultrasonic measurement technique, common at low or moderate temperatures, of utilizing a contact type transducer: i.e., eliminating the fluid path between the transducer and the specimen. This was accomplished at the elevated temperatures involved in this study by utilizing a high-temperature compatible extension tip to acoustically couple the transducer to the specimen. The transducer was still cooled via a cold water stream.

A Panametrics V-203RM contact type replaceable delay line transducer was selected for use in this application. The transducer was equipped with a replaceable extension tip suitable for room temperature operation. A Panametrics DLHT-3G high temperature compatible extension tip was also procured, reported to perform adequately when subjected to intermittent contact with specimens of temperatures of up to 480 °C. In addition to the commercially procured tips, extension tips of aluminum oxide machineable ceramic, aluminum, nylon, teflon, polypropylene, steel and polyethylene were fabricated in an attempt to match or exceed the performance of the commercial tips. Tapered configurations, contoured tip shapes, and several different length tips were formed and tested. Some of these experimental tips are shown in Figure 23.

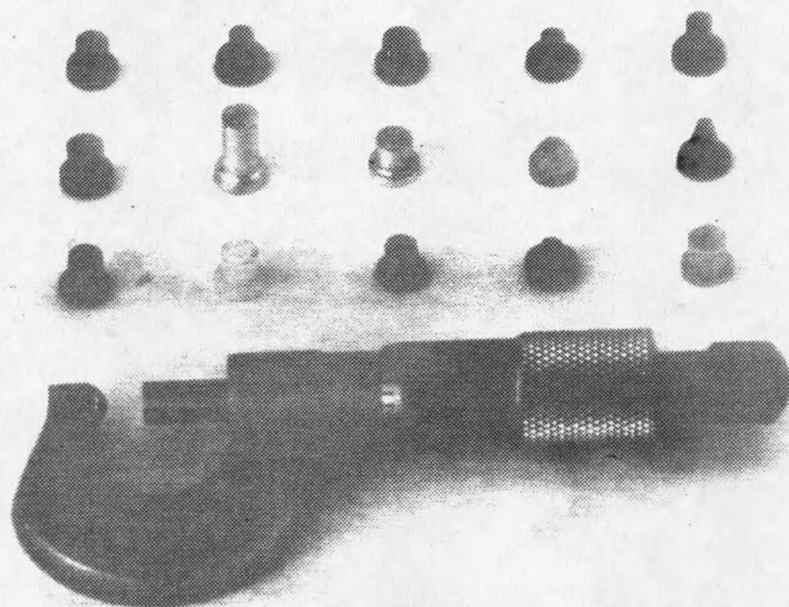


Figure 23. Experimental Contact Transducer Extension Tips.

Comparative testing of the signal quality showed that a custom machined and contoured tip of 15% graphite filled DuPont "Vespel" polyimide, a machineable commercial plastic resin, provided the best relative signal level and signal to noise ratio of the materials deemed adequate for high temperature exposure.

The transducer was mounted in a specially fabricated mount, with water providing limited cooling to the transducer. The body of the transducer was instrumented with a constantan-chromel thermocouple bonded to the backshell, to monitor temperature. The test arrangement and machined tip detail is described in Figure 24.

The actual testing of the planar configuration was primarily a demonstration that the contact transducer with the high temperature extension tip could produce a

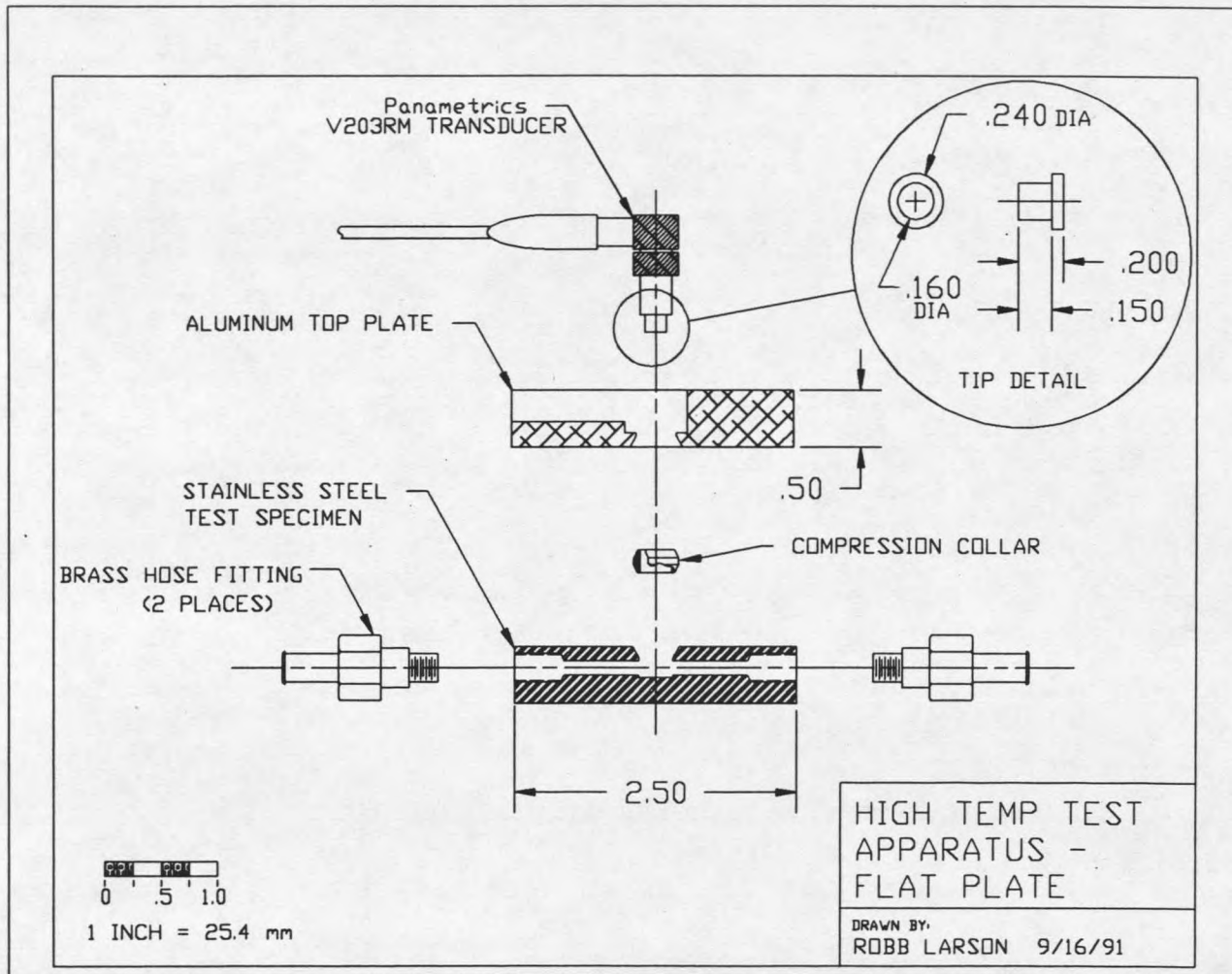


Figure 24. Planar Test Apparatus, Contact Transducer.

coherent signal when the specimen was heated in a manner similar that used for the non-contact transducer planar specimen tests. During the elevated temperature testing, the pulse-echo signal was coherent and strong up to the recommended temperature exposure limit of the transducer, as monitored from the thermocouple bonded to the body of the transducer. The tests were halted when the backshell temperature reached the manufacturers recommended exposure limit. Specimen inner surface temperature was 156 °C. at this point, indicating that surface boiling was taking place.

Thickness measurements were not made in the planar specimen configuration, nor were wave speed versus temperature correlations made, since the tests with the noncontact device indicated that the transition from a planar specimen to a cylindrical specimen involved only limited procedural changes.

CHAPTER 7

CYLINDRICAL TESTING, CONTACT TRANSDUCER

Once planar specimen performance was successfully demonstrated using the contact type transducer, a cylindrical test mount was fabricated and tested. A spring loaded cradle was fabricated to hold the contact transducer with high temperature extension tip in the correct orientation with respect to the test specimen internal diameter. The position of the transducer within the specimen was controlled via an extension/positioning rod, which also housed the transducer cable potted in silicone RTV sealant. The positioning rod passed through a watertight tee fitting which also supplied cooling water flow through the cylindrical specimen. The device is shown in Figure 25.

The extension tip was altered slightly to transmit a stronger echo through the cylindrical inside face of the specimen by contouring the contact face to match the inside diameter of the test section. All other tip characteristics were the same as those which were used for planar testing. The same cylindrical test specimen which was used for noncontact transducer cylindrical testing was again used with the contact transducer device.

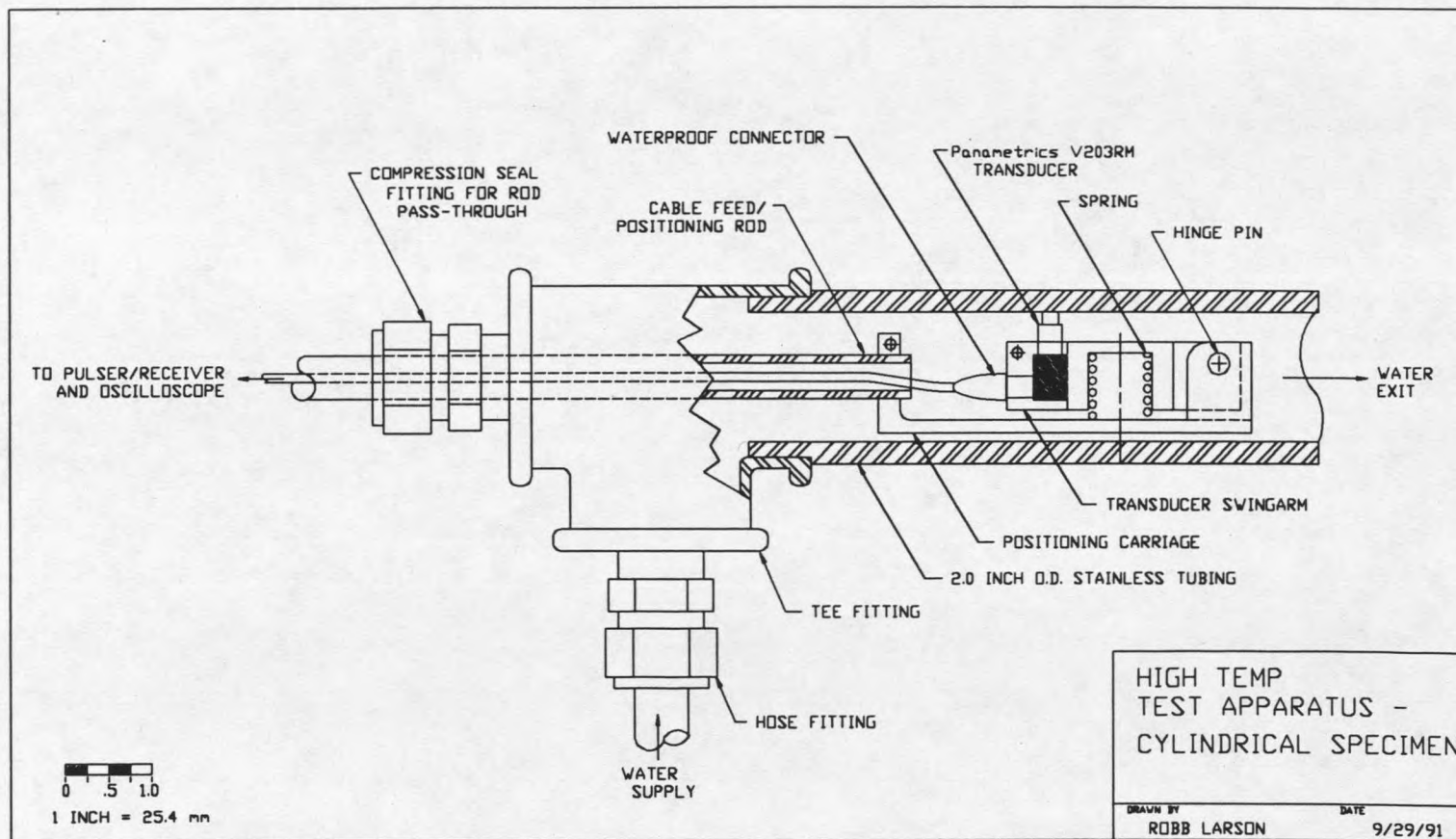


Figure 25. Cylindrical Test Apparatus, Contact Transducer.

Using methodology analogous to that used for the noncontact transducer cylindrical specimen testing, ultrasonic wave speed data for the specimen was first obtained.

The step by step procedure used to gather wave speed versus temperature data was identical to that used for the noncontact transducer based system in wave speed determination mode, with the exception that the controlling computer program used was entitled "Contact1," and that the maximum average specimen wall temperature reached during the wave speed calibration test sequence was in excess of 600 °C. The entire procedure was detailed in Chapter 5.

The wave speed versus temperature plot for the contact transducer is shown in Figure 26. The third order polynomial curve fit of this plot resulted in the following equation for wave velocity as a function of temperature;

$$(16) \quad V_h = -2.66 \text{ E-7} \times T_{ave}^3 + 2.69 \text{ E-4} \times T_{ave}^2 - .537 \times T_{ave} + 5806$$

The step by step procedure used to gather thickness measurement data was also identical to that used for the noncontact transducer based system in thickness measurement mode, with the exception that the controlling computer program used was entitled "Conpred." That procedure was also described in Chapter 5; therefore the detailed operating procedures will not be repeated here.

Thickness measurements accurate to within .033 mm (.0013 inch) were made with the device at an average specimen temperature of 651 °C. (1207 °F.) The

internal wall temperature at this point was 546 °C. (1014 °F.) and the external wall of the specimen reached 760 °C. (1400 °F.)

Excursions to higher temperatures were successfully made, but not with consistent results or repeatability. At temperatures above 650 °C. average wall temperature, the voltage levels of the waveform peaks displayed on the digitizing oscilloscope began to decrease, and occasionally were beneath the maximum sensitivity capability of the oscilloscope. When this occurred, the waveform peaks were not detectable by the oscilloscope peak search function. The root cause of this reduced signal at elevated temperatures was not identified, but was suspected to be temperature sensitive attenuation effects of the transducer and extension tip material. It was noted that as the test temperature limit (760 °C. outer specimen wall temperature) was approached, the tips of the stainless steel wire channel covers began to melt, indicating that the test specimen had also reached the upper limit of its useful temperature range.

Thickness measurement and deviation from nominal thickness plots created from the contact transducer system data are shown in Figures 27, 28, 29 and 30.

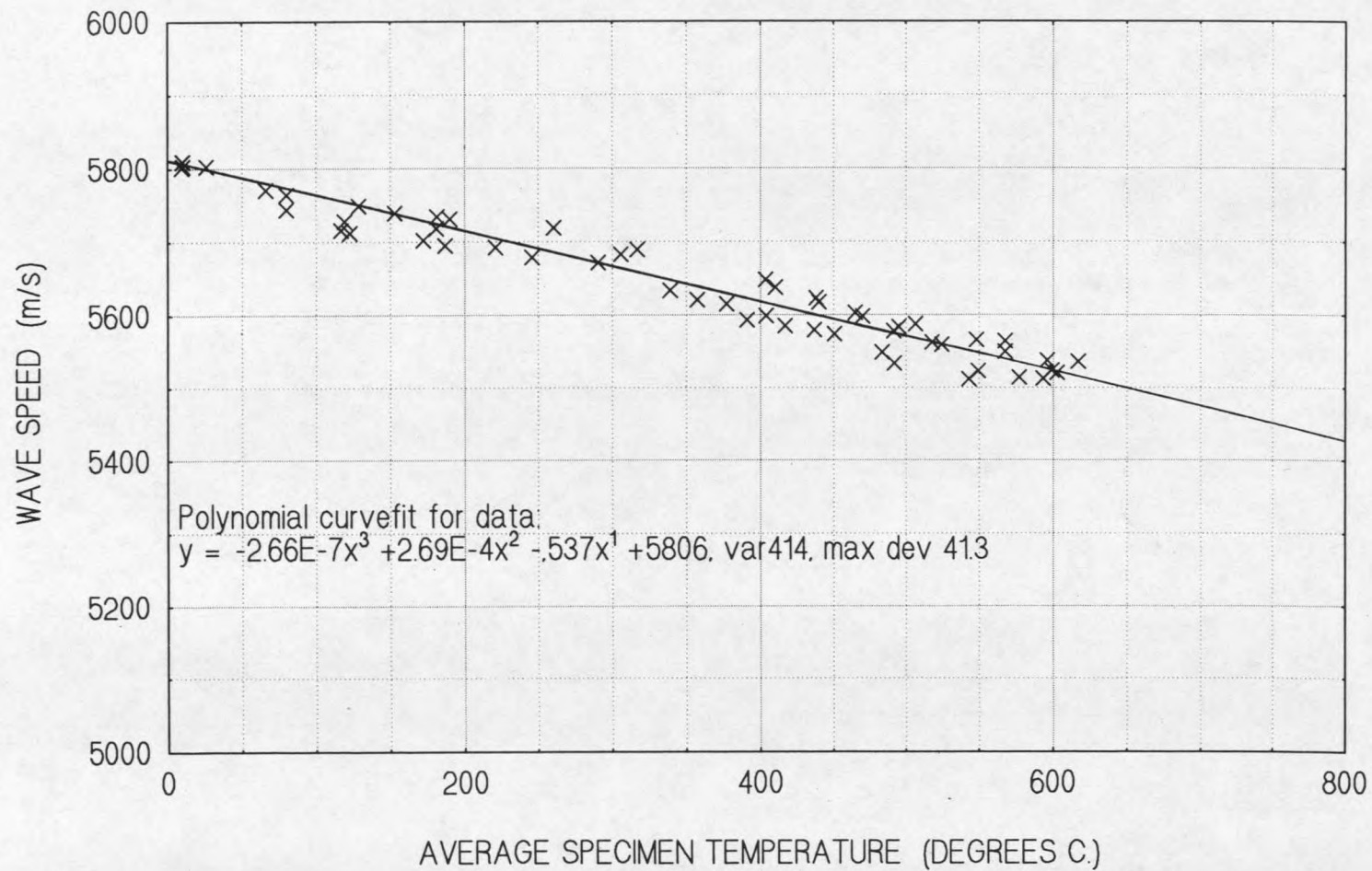


Figure 26. Wave Speed versus Temperature for 304 Stainless Steel.

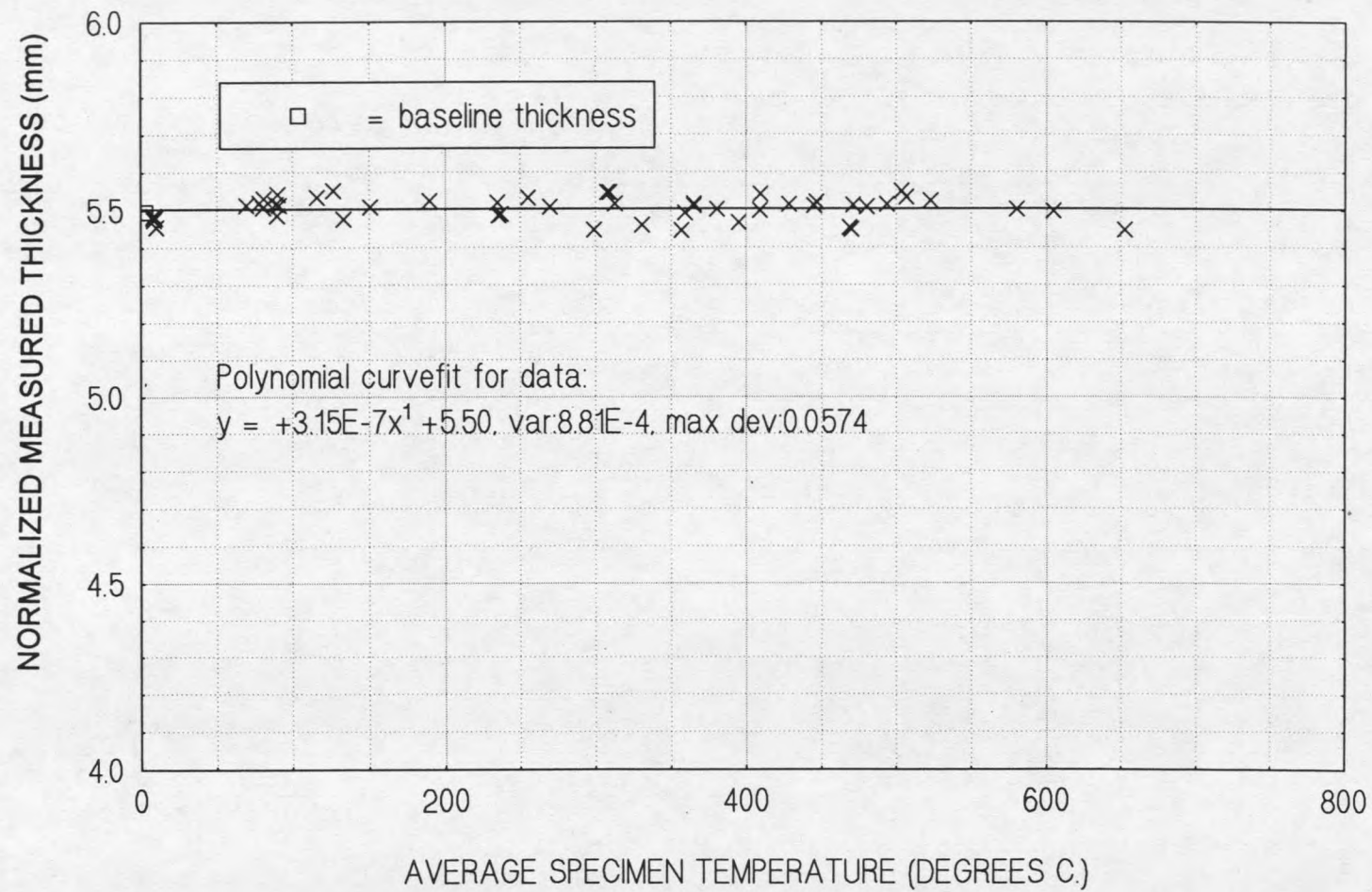


Figure 27. Measured Wall Thickness versus Average Specimen Temperature.

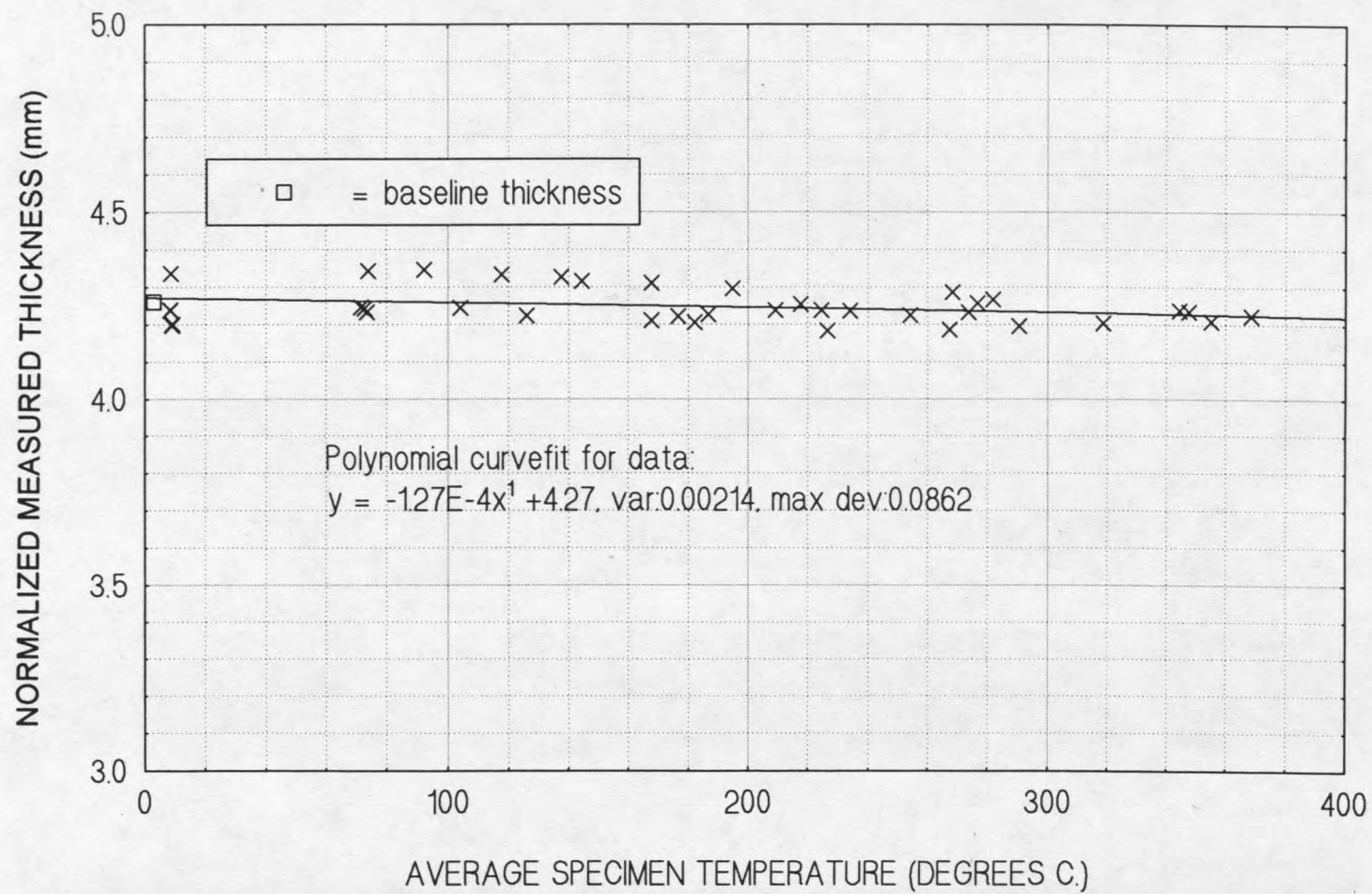


Figure 28. Measured Wall Thickness versus Average Specimen Temperature.

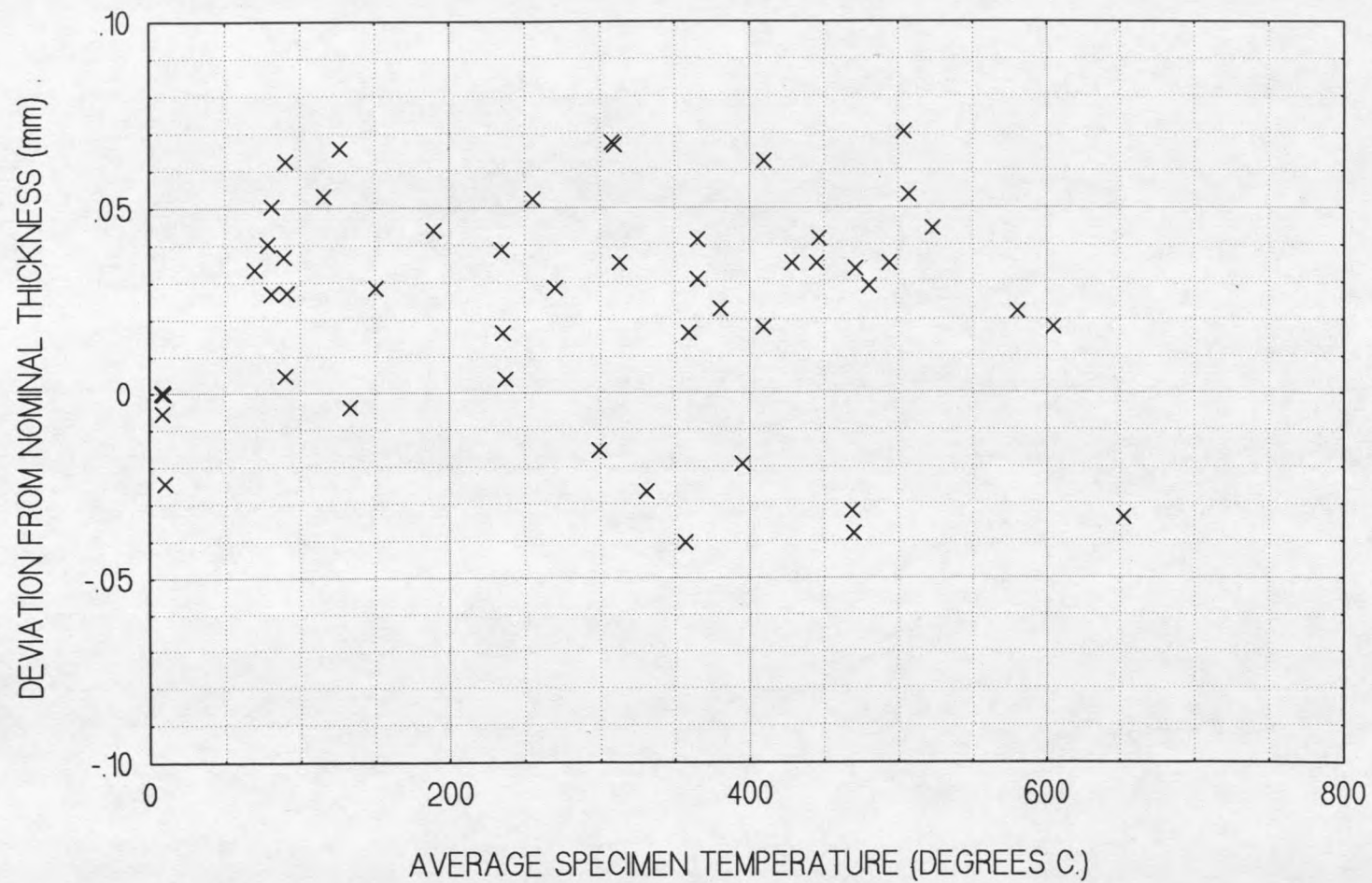


Figure 29. Measurement Error versus Temperature, Cylindrical Tests.

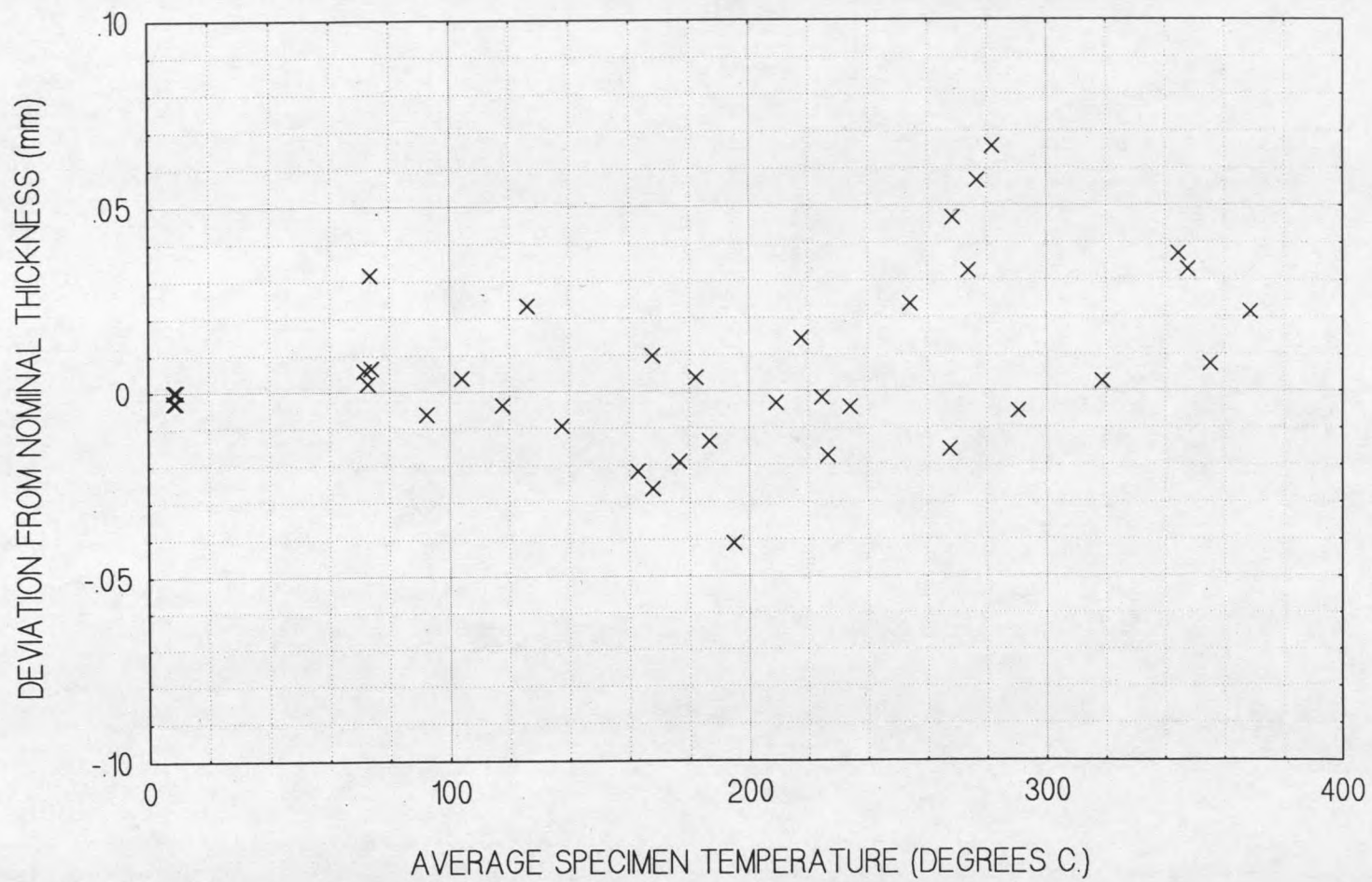


Figure 30. Measurement Error versus Temperature, Cylindrical Tests.

CHAPTER 8

SUMMARY AND CONCLUSIONS

The results of the experiments performed with both versions of the developed system indicated that it is feasible to adapt conventional ultrasonic transducer measurement equipment for use at the elevated temperatures typical of fluidized bed combustor heat exchanger applications (bed temperatures up to 850 °C.) The noncontact transducer based system gave slightly better uniformity of thickness measurements than the contact transducer based version, but failed to perform at average specimen temperatures above 270 °C. which were easily handled with the contact transducer device.

For the noncontact transducer based system, 57 of the 71 normalized thickness measurement data points recorded, were within ± 0.05 mm of the normalized nominal measured specimen thickness. This result gives an 80% confidence level that measurement accuracy is within ± 0.05 mm of the nominal measurement, throughout a useful average specimen temperature range of from approximately 8 °C. to 270 °C. A 99% confidence level was attained at a tolerance of ± 0.058 mm:

70 of the 71 data points recorded for this system were within the ± 0.07 mm tolerance.

For the contact transducer based system, 79 of the 90 normalized thickness measurement data points recorded were within ± 0.05 mm of the normalized nominal measured specimen thickness. This result gives an 88% confidence level that accuracy of measurement is within ± 0.05 mm of the nominal measurement throughout the useful average specimen temperature range of from approximately 8°C . to 650°C . A 99% confidence level was attained at a tolerance of ± 0.07 mm: 89 of the 90 data points recorded for this system were within the ± 0.07 mm tolerance.

One critically important portion of the experimental procedure was the compilation of wave speed versus temperature data. It is possible that a part of the "error", or "deviation from nominal thickness" readings reported in Chapters 5 and 7, Figures 21, 22, 29 and 30, could be attributed to inaccuracies in the wave speed versus temperature data upon which thickness measurements depended. Additionally, the assumption that the average wall temperature of the specimen would give good thickness measurement correlations may have introduced a substantial portion of the error noted in the measurement data. A library of curves which accurately describe the temperature versus wave speed relationship for test materials of interest would be a prerequisite to the fielding of a commercial version of this type of system.

Several design flaws and procedural problems became apparent during the test sequence, primarily with the contact transducer based version of the system. This could probably be attributed to the fact that while three key components in the noncontact transducer system (the noncontact transducer, the extension rod and the acoustic mirror) were procured from industrial sources as mature systems, only the contact type transducer was commercially obtained for the second system. The extension rod and the entire spring-loaded cradle assembly was designed and fabricated at Montana State University specifically to test the hypotheses of this thesis. A first generation device such as the contact transducer version of this system typically suffers from minor design problems.

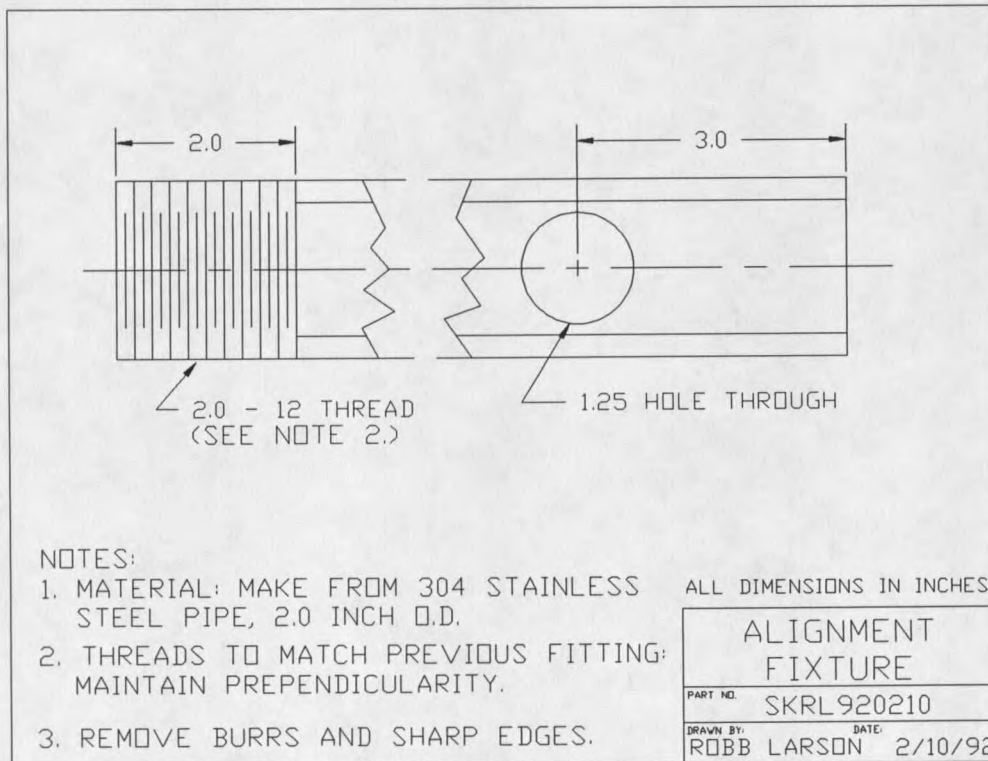


Figure 31. Contact Transducer Alignment Fixture.

One problem with the contact transducer assembly was the need to carefully adjust the position of the transducer within the swingarm so that the axis of the transducer face was exactly perpendicular to the interior wall of the test specimen. A special alignment fixture, shown in Figure 31, was fabricated to assist in this task, but it was nevertheless a time consuming portion of the test sequence. As the location of the transducer was varied as testing progressed, the high temperature extension tip was abraded by the relatively rough interior of the tube. This caused a mis-alignment of the transducer with the specimen, and the alignment procedure was again required. A second generation of the contact transducer device should incorporate either a multi-bar link system to achieve permanent alignment of a spring loaded swingarm, or perhaps the spring could be omitted and replaced with a mechanical cam release to permit repositioning of the transducer without tip contact. This type of system would prolong extension tip life by eliminating tip abrasion and would also reduce heat transfer through the tip material.

The cylindrical test specimen also exhibited some design flaws during elevated temperature testing. As noted in Chapter 7, the thin tips of the stainless steel thermocouple wire channel covers were prone to melting from impingement of the torch flame during the highest test temperatures. This exposed the thermocouple wires to direct flame contact, which invariably caused short circuiting and erroneous thermocouple temperature readings after a brief period of exposure. This occurrence required the rebuilding of the thermocouple wire covers several times during elevated temperature testing, at which time the thermocouples were also replaced.

Condensation of moisture on the exterior also presented a problem during the test runs. The cold tap water stream inside the test specimen chilled the entire specimen, except in the area of flame impingement. Surface condensation droplets gathered in the thermocouple wire troughs, and caused short circuiting of the thermocouple wire when the fiberglass insulation of the wires was saturated. This problem is peculiar to the test method; heat exchanger tube surface condensation occurring within an actual fluidized bed combustor heat exchanger would immediately be dissipated by the action of the fluidized bed.

Clearly it would be desirable to test the systems designed for cylindrical specimen thickness measurement within an actual fluidized bed combustor facility. While there is little reason to suspect that substantial problems would be encountered in this next level of testing, such a test would lend further credibility to the results presented here, and perhaps point out the need for further work in this area.

It is apparent that while this system was specifically designed as a device for the *in situ* thickness determination of an externally heated cylindrical specimen representing a heat exchanger tube within a fluidized bed combustor heat exchanger, the technology is readily applicable to any similar design situation. The key in this research was to maintain an acceptable temperature level at the transducer body via a constant coolant stream: it is conceivable that with proper design and experimentation, and inclusion of advanced data processing techniques, the temperature limits of this or a similar system could be extended without loss of system accuracy.

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REFERENCES CITED

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APPENDICES

APPENDIX A

COMPUTER PROGRAMS

This Program is entitled "Phase2." It directs the Hewlett Packard data acquisition system, via interactive communications with the operator, to control the Hewlett Packard oscilloscope and Hewlett Packard digital voltmeter to obtain data necessary to compute ultrasonic wave speed.

```

10  REM      PROGRAM "PHASE2" FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM      WRITTEN BY BARBARA H. SAXTER
40  REM      AND MODIFIED BY ROBB LARSON
50  REM      MONTANA STATE UNIVERSITY
60  REM      DEPARTMENT OF MECHANICAL ENGINEERING
70  REM
80  REM      THIS PROGRAM IS DESIGNED TO OPERATE THE HEWLETT PACKARD
90  REM      DIGITIZING OSCILLOSCOPE 54502A THROUGH THE HP1B
100 REM      THIS PROGRAM SHOULD BE USED IN CONJUNCTION WITH THE
110 REM      STAINLESS STEEL SPECIMEN TEST APPARATUS AND THE REQUIRED
120 REM      HARDWARE TO COMPLETE THE TEST ARRANGEMENT
130 REM      THIS SETUP REQUIRES THE FOCUSSED TRANSDUCER MOUNTED IN
140 REM      THE PIPE TEST SECTION AT ROOM TEMPERATURE AND ELEVATED TEMPS.
150 REM
160 REM      THIS PROGRAM REQUIRES TWO TYPE "E" THERMOCOUPLES. TWO
170 REM      TEMPERATURE MEASUREMENTS WILL BE RECORDED BY THE HP DATA
180 REM      ACQUISITION SYSTEM/300. PLACE THE T-COUPLE ACQ LIBRARY CARD
190 REM      IN SLOT 1 OF THE 3497A CONTROL UNIT. CONNECT CHANNEL 37 TYPE
200 REM      "E" THERMOCOUPLE TO THE INSIDE SURFACE OF THE TEST SPECIMEN
210 REM      (Tin). CONNECT CHANNEL 38 TYPE "E" THERMOCOUPLE TO THE
220 REM      OUTSIDE SURFACE OF THE TEST SPECIMEN (Tout).
230 REM
240 REM
250 REM      FUNCTIONS CALLED FROM THE HP 54502A OSCILLOSCOPE
260 REM
270 REM      TMAX      : TMAX returns the time at which the first maximum
280 REM                  voltage occurs
290 REM      TSTART    : TSTART sets the time marker at specified time
300 REM      VTIME     : VTIME query returns the voltage at a specified time
310 REM      TSTOP     : TSTOP moves the stop marker to the specified time
320 REM      TDELTA    : TDELTA measures the time between start and stop markers
330 REM
340 REM      VARIABLE LIST
350 REM
360 REM      Tmx$       : string variable called in TMAX function
370 REM      Tmax       : numerical value of Tmx$
380 REM      Loop       : time interval in which the second voltage peak occurs
390 REM      Vtm$       : string variable called in VTIME function
400 REM      Volt       : numerical value of Vtm$

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

```

410 REM Voltpeak : maximum voltage variable for comparison of voltage
420 REM Tpeak : time at which Voltpeak occurs
430 REM Tdis : string variable called in TDELTA function
440 REM Period : numerical value of Tdis
450 REM Wave : calculated wavespeed of stainless steel specimen
460 REM Nominal : nominal wall thickness calculated by calibration
470 REM Dpoint(*) : variable array to store data point collection
480 REM File$ : file name to save data on disk
490 REM FS : file string used in function call SAVE_rvect
500 REM Runnum : run number
510 REM Channel : thermocouple channel number
520 REM Voltage1 : voltage for measuring TC temp at active junction
530 REM Vref : reference voltage for TC
540 REM Tref : reference temperature for TC
550 REM Tin(*) : inside temperature array
560 REM Tout(*) : outside temperature array
570 REM Tavef(*) : average temperature (degrees F)
580 REM Tavec(*) : average temperature (degrees C)
590 REM Alpha : thermal expansion coefficient
600 REM Hthick : heated thickness
610 REM Ewave(*) : wave velocity (ft/s)
620 REM Wave(*) : wave velocity (m/s)
630 REM BEGIN PROGRAM
640 REM
650 CLEAR SCREEN
660 OPTION BASE 1
670 DIM Dpoint(50)
680 DIM File$(8)
690 DIM FS(14)
700 DIM Tin(25)
710 DIM Tout(25)
720 DIM Tavef(25)
730 DIM Tinf(25)
740 DIM Toutf(25)
750 DIM Tavec(25)
760 DIM Wave(25)
770 DIM Ewave(25)
780 CALL Sys_init("P")
790 REM RESET THE OSCILLOSCOPE TO ITS DEFAULT PARAMETERS
800 CLEAR 707
810 OUTPUT 707; "*RST"
820 OUTPUT 707; ":DISP:CONNECT ON"
830 OUTPUT 707; ":CHANNEL1:RANGE .32"
840 OUTPUT 707; ":CHANNEL1:OFFSET .025"
850 OUTPUT 707; ":WAVEFORM:RECORD FULL"
860 REM THE TIME RANGE VALUE IS 10 TIMES THE TIME PER DIVISION
870 OUTPUT 707; ":TIMEBASE:RANGE 2000 NS"
880 OUTPUT 707; ":TIMEBASE:REFERENCE CENTER"
890 OUTPUT 707; ":TIMEBASE:DELAY 40.45 US"
900 OUTPUT 707; ":TRIG:SOURCE CHAN2"

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

```

810 OUTPUT T07;"TRIGGER:LEVEL 3.5"
820 OUTPUT T07;"DISPLAY:CONNECT ON"
830 OUTPUT T07;"DISPLAY:TM-R-ER ON"
840 OUTPUT T07;"ACQUIRE:TYPE AVERAGE;COUNT 64"
850 REM
860 REM ESTABLISH WAVESPEED FOR 304 STAINLESS STEEL
870 CLEAR SCREEN
880 PRINT "WHAT SECTION OF THE FULL TUBE IS BEING TESTED ?"
890 PRINT " (1) THICK      wall thickness > 0.174in      v=5541 m/s"
900 PRINT " (2) THIN       wall thickness < 0.174in      v=5784 m/s"
910 INPUT "ENTER SELECTION FROM ABOVE MENU (type 1 OR 2)",Test
920 IF Test=1 THEN Speed=5541
930 IF Test=2 THEN Speed=5784
940 CLEAR SCREEN
950 PRINT "THE FIRST MEASUREMENT FOR THIS PROGRAM MUST BE TAKEN AT"
960 PRINT "ROOM TEMPERATURE (8.5 degrees C, 47.3 degrees F)"
970 PRINT
980 FOR I=1 TO 49 STEP 2
990 C=(I+1)/2
1000 PRINT "DATA ACQUISITION SYSTEM IS TAKING TEMPERATURE MEASUREMENTS"
1010 CALL Dcvs(39,V3)
1020 CALL Dcvs(38,V2)
1030 CALL Dcvs(37,V1)
1040 Tref=i0+V3
1050 Tin(C)=FNThm(V1,"E",Tref)
1060 Tout(C)=FNThm(V2,"E",Tref)
1070 Tave(C)=(Tin(C)+Tout(C))/2
1080 Tinf(C)=Tin(C)+1.8+32
1090 Toutf(C)=Tout(C)+1.8+32
1100 Tavef(C)=Tave(C)+1.8+32
1110 PRINT " INSIDE WALL TEMPERATURE = ";Tin(C); " Degrees C  ";Tinf(C); " Degrees F"
1120 PRINT " OUTSIDE WALL TEMPERATURE = ";Tout(C); " Degrees C  ";Toutf(C); " Degrees F"
1130 PRINT " AVERAGE WALL TEMPERATURE = ";Tave(C); " Degrees C  ";Tavef(C); " Degrees F"
1140 RS=""
1150 INPUT "PRESS <X> TO MEASURE TEMPERATURES AGAIN <RETURN> TO CONTINUE",RS
1160 IF RS="X" OR RS="x" THEN
1170   CLEAR SCREEN
1180   GOTO 1100
1190 ELSE
1200   CLEAR SCREEN
1210   END IF
1220 PRINT USING "10/"
1230 PRINT "PRESS RETURN IF ALL OSCILLOSCOPE SETTINGS ARE APPROPRIATE"
1240 INPUT "MAKE ADJUSTMENTS IF NECESSARY THEN PRESS RETURN TO CONTINUE",RS
1250 CLEAR SCREEN
1260 PRINT "PRESS <local> THEN <delta t/V markers> ON THE OSCILLOSCOPE PANEL TO"
1270 PRINT "USE THE TIME MARKERS TO FIND THE RANGE OF THE PEAKS OF INTEREST"
1280 INPUT "ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED ",
Begin
1290 INPUT "ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED "
,Finish
1300 REM

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

```

1410 CLEAR SCREEN
1420 PRINT "ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF"
1430 PRINT
1440 PRINT "      ";Begin-.008;" AND " ";Begin+.008;" microseconds"
1450 REM
1460 PRINT USING "5/"
1470 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1480 PRINT
1490 PRINT "      ";Finish-.008;" AND " ";Finish+.008;" microseconds"
1500 REM TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE
1510 OUTPUT 707;":STOP"
1520 REM SEARCH WAVEFORM FOR MAXIMUM VOLTAGE PEAKS
1530 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1540 REM
1550 REM THE RANGE OF Loop1 IS THE TIME INTERVAL (in micro seconds)
1560 REM AT WHICH THE FIRST VOLTAGE PEAK OCCURS
1570 LET Voltpeak=0
1580 LET Volt=0
1590 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1600 REM MEASURE THE VOLTAGE AT THE TIME Loop1
1610 OUTPUT 707;":MEASURE:VTIME? "&VAL$(Loop1)&" US"
1620 ENTER 707;Vtm$
1630 LET Volt=VAL(Vtm$)
1640 IF Volt>=Voltpeak THEN
1650 Voltpeak=Volt
1660 Tpeak1=Loop1
1670 ELSE
1680 END IF
1690 NEXT Loop1
1700 REM SET START MARKER AT Tpeak (THE TIME AT THE FIRST VOLTAGE PEAK)
1710 OUTPUT 707;":MEAS:TSTART "&VAL$(Tpeak1)&" US"
1720 REM THE RANGE OF Loop2 IS THE TIME INTERVAL (in micro seconds)
1730 REM AT WHICH THE SECOND VOLTAGE PEAK OCCURS
1740 LET Voltpeak=0
1750 LET Volt=0
1760 FOR Loop2=Finish-.008 TO Finish+.008 STEP .0005
1770 REM MEASURE THE VOLTAGE AT THE TIME Loop2
1780 OUTPUT 707;":MEASURE:VTIME? "&VAL$(Loop2)&" US"
1790 ENTER 707;Vtm$
1800 LET Volt=VAL(Vtm$)
1810 IF Volt>=Voltpeak THEN
1820 Voltpeak=Volt
1830 Tpeak2=Loop2
1840 ELSE
1850 END IF
1860 NEXT Loop2
1870 REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
1880 OUTPUT 707;":MEAS:TSTOP "&VAL$(Tpeak2)&" US"
1890 REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
1900 OUTPUT 707;":MEASURE:TDELTA?"

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

```

1910 ENTER 707;Td1$
1920 Period=VAL(Td1$)
1930 CLEAR SCREEN
1940 PRINT USING "5/"
1950 PRINT "THE TIME PERIOD MEASURED WAS = ";Period;" seconds"
1960 PRINT "THE CALIBRATED WAVESPEED USED = ";Speed;" m/s"
1970 REM
1980 REM CALCULATE THE THICKNESS FROM THE MEASURED PERIOD
1990 REM ESTABLISH NOMINAL THICKNESS IF TAKING FIRST MEASUREMENT
2000 IF I=1 THEN
2010     Nominal=Speed*Period/2
2020     PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
.0254;" in"
2030     R$=""
2040     INPUT "PRESS RETURN TO CONTINUE MAKING MEASUREMENTS",R$
2050 ELSE
2060     PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
.0254;" in"
2070     R$=""
2080     INPUT "PRESS <N> IF NOMINAL THICKNESS IS INCORRECT, PRESS <RETURN> TO C
ONTINUE",R$
2090     IF (R$="N" OR R$="n") THEN
2100         INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
2110     ELSE
2120         END IF
2130     INPUT "PRESS <T> TO MEASURE TIME INTERVAL AGAIN, PRESS <RETURN> TO CONT
INUE",R$
2140     IF (R$="T" OR R$="t") THEN
2150         CLEAR SCREEN
2160         GOTO 1350
2170     ELSE
2180         END IF
2190     END IF
2200 IF I=1 THEN
2210     CLEAR SCREEN
2220     GOTO 2860
2230 ELSE
2240     END IF
2250 REM
2260 REM CALCULATE THERMAL EXPANSION
2270 Alpha=.00000000833*Tavef(C)+.0000094165
2280 Hthick=(Nominal/.0254)*(1+Alpha*(Tavef(C)-47.3))
2290 Mhthick=Hthick*.0254
2300 REM WAVESPEED CALCULATION IS IN m/s
2310 Wave(C)=2*Mhthick/Period
2320 Ewave(C)=2*(Hthick/12)/Period
2330 CLEAR SCREEN
2340 PRINT "THE TIME PERIOD MEASURED AT ";Tavef(C);" F = ";Period;" seconds"
2350 PRINT "THE HEATED WAVESPEED MEASURED WAS = ";Wave(C);" m/s"
2360 PRINT "NOMINAL SPECIMEN THICKNESS = ";Nominal;" m";Nominal/.0
254;" in"
2370 PRINT USING "5/"
2380 R$=""
2390 INPUT "PRESS <P> TO PRINT DATA <RETURN> TO CONTINUE",R$
2400 IF (R$="P" OR R$="p") THEN

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

```

2410     PRINTER IS 701
2420     IF I=3 THEN
2430         PRINT USING "1X,17A,7X,10A,11X,10A"; "SPECIMEN TEMP (F)"; "AVERAGE TEM
P"; "WAVE SPEED"
2440         PRINT USING "7A,6X,6A,6X,3A,5X,3A,10X,4A,7X,3A"; "OUTSIDE"; "INSIDE"; "
(F)"; "(C)"; "ft/s"; "m/s"
2450         PRINT "-----"
2460         PRINT USING "1X,3D.2D,5X,3D.2D,5X,3D.2D,3X,3D.2D,4X,7D.2D,2X,7D.2D";
Tin(C);Tout(C);Tavef(C);Tavec(C);Ewave(C);Wave(C)
2470     ELSE
2480         PRINT USING "1X,3D.2D,5X,3D.2D,5X,3D.2D,3X,3D.2D,4X,7D.2D,2X,7D.2D";
Tin(C);Tout(C);Tavef(C);Tavec(C);Ewave(C);Wave(C)
2490     END IF
2500 ELSE
2510     END IF
2520 PRINTER IS 1
2530 REM RESTART DATA ACQUISITION TO MAKE ANOTHER READING
2540 OUTPUT 707;":RUN"
2550 REM STORE INFORMATION ON DISK
2560 PRINT "DO YOU WANT TO SAVE THIS DATA POINT TO A DISK ? "
2570 RS=""
2580 INPUT "PRESS <enter> TO SAVE      PRESS <X> TO ABORT SAVE",RS
2590 IF RS="X" OR RS="x" THEN
2600     I=I-2
2610     CLEAR SCREEN
2620     GOTO 2660
2630 ELSE
2640     END IF
2650 INPUT "NAME THE DATA FILE...(8 characters or less) DRIVE 703,1",File$
2660 Dpoint(I-2)=Tavec(C)
2670 Dpoint(I-1)=Wave(C)
2680 Runnum=C
2690 F$=File$&"":,703,1"
2700 CALL Save_rvect(Dpoint(*),F$)
2710 Info(1)=Tin(C)
2720 Info(2)=Tout(C)
2730 Info(3)=Tavec(C)
2740 Info(4)=Nominal
2750 Info(5)=Speed
2760 Info(6)=Wave(C)
2770 PRINT "RUN NUMBER ";Runnum-1
2780 INPUT "ENTER FILE NAME FOR DATA STORAGE....(8 characters or less) DRIVE 70
4,1",Data$
2790 F$=Data$&"":,704,1"
2800 CALL Save_rvect(Info(*),F$)
2810 REM
2820 CLEAR SCREEN
2830 PRINT "DATA POINT ";Runnum-1;" HAS JUST BEEN SAVED"
2840 INPUT "PRESS RETURN TO MAKE ANOTHER MEASUREMENT",R$
2850 REM RESTART MEASUREMENT PROGRAM
2860 NEXT I
2870 END

```

Figure 32. Wave Speed Determination Program, Noncontact Test.

This Program is entitled "Nonpred." It directs the Hewlett Packard data acquisition system, via interactive communications with the operator, to control the Hewlett Packard oscilloscope and Hewlett Packard digital voltmeter to obtain data necessary to compute specimen thickness.

```

10  REM  PROGRAM "NONPRED" FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM  THIS PROGRAM WRITTEN BY ROBB E. LARSON
40  REM  MONTANA STATE UNIVERSITY
50  REM  DEPARTMENT OF MECHANICAL ENGINEERING
60  REM
70  REM  CONTAINS PORTIONS OF PROGRAMS
80  REM  ORIGINALLY WRITTEN BY BARBARA H. BAXTER
90  REM  THIS PROGRAM DETERMINES THE WAVE VELOCITY AND PREDICTS
100 REM  THE THICKNESS OF A CYLINDRICAL 304 STAINLESS STEEL SPECIMEN.
110 REM  IT IS WRITTEN FOR USE WITH THE NON-CONTACT TRANSDUCER.
120 REM  THE PROGRAM IS DESIGNED FOR USE OVER A RANGE OF TEMPERATURES.
130 REM  DATA FILES ARE CREATED FOR EASE IN PROCESSING DATA.
140 REM
150 REM  THIS PROGRAM REQUIRES TWO TYPE "E" THERMOCOUPLES. TWO
160 REM  TEMPERATURE MEASUREMENTS WILL BE RECORDED BY THE HP DATA
170 REM  ACQUISITION SYSTEM/300. PLACE THE T-COUPLE ACQ LIBRARY CARD
180 REM  IN SLOT 1 OF THE 3497A CONTROL UNIT. CONNECT CHANNEL 37 TYPE
190 REM  "E" THERMOCOUPLE TO THE INSIDE SURFACE OF THE TEST SPECIMEN
200 REM  (Tin). CONNECT CHANNEL 38 TYPE "E" THERMOCOUPLE TO THE
210 REM  OUTSIDE SURFACE OF THE TEST SPECIMEN (Tout).
220 REM
230 REM
240 REM  FUNCTIONS CALLED FROM THE HP 54502A OSCILLOSCOPE
250 REM
260 REM  TMAX : TMAX returns the time at which the first maximum
270 REM         voltage occurs
280 REM  TSTART : TSTART sets the time marker at specified time
290 REM  VTIME : VTIME query returns the voltage at a specified time
300 REM  TSTOP : TSTOP moves the stop marker to the specified time
310 REM  TDELTA : TDELTA measures the time between start and stop markers
320 REM
330 REM  VARIABLE LIST
340 REM
350 REM  Tmx$ : string variable called in TMAX function
360 REM  Tmax : numerical value of Tmx$
370 REM  Loop : time interval in which the second voltage peak occurs
380 REM  Vtm$ : string variable called in VTIME function
390 REM  Volt : numerical value of Vtm$
400 REM  Voltpeak : maximum voltage variable for comparison of voltage

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

410 REM Tpeak : time at which Voltpeak occurs
420 REM Tdl$ : string variable called in TDELTA function
430 REM Period : numerical value of Tdl$
440 REM Wave : calculated wavespeed of stainless steel specimen
450 REM Nominal : nominal wall thickness calculated by calibration
450 REM Info(*) : variable array to store data point collection
470 REM File$ : file name to save data on disk
480 REM F$ : file string used in function call SAVE_rvect
490 REM Runnum : run number
500 REM Channel : thermocouple channel number
510 REM Voltage1 : voltage for measuring TC temp at active junction
520 REM Vref : reference voltage for TC
530 REM Tref : reference temperature for TC
540 REM Tin(*) : inside temperature array
550 REM Tout(*) : outside temperature array
560 REM Tavef(*) : average temperature (degrees F)
570 REM Tavec(*) : average temperature (degrees C)
580 REM Alpha : thermal expansion coefficient
590 REM Hthick : heated thickness, inches
600 REM Refthick : predicted specimen thickness in inches
610 REM Thickerr : difference between predicted thickness and
620 REM : actual measured specimen thickness, corrected to 48.5 C.
630 REM Refthickm : predicted specimen thickness in meters
640 REM Ewave(*) : wave velocity (ft/s)
650 REM Wave(*) : wave velocity (m/s)
660 REM Mhthick : heated thickness, meters
670 REM BEGIN PROGRAM
680 REM
690 CLEAR SCREEN
700 OPTION BASE 1
710 DIM Info(150)
720 DIM File$(8)
730 DIM F$(14)
740 DIM Tin(25)
750 DIM Tout(25)
760 DIM Tavef(25)
770 DIM Tinf(25)
780 DIM Toutf(25)
790 DIM Tavec(25)
800 DIM Wave(25)
810 DIM Ewave(25)
820 CALL Sys_init("P")
830 REM RESET THE OSCILLOSCOPE TO ITS DEFAULT PARAMETERS
840 CLEAR 707
850 OUTPUT 707; "*RST"
860 OUTPUT 707; ":DISP:CONNECT ON"
870 OUTPUT 707; ":CHANNEL1:RANGE .32"
880 OUTPUT 707; ":CHANNEL1:OFFSET .025"
890 OUTPUT 707; ":WAVEFORM:RECORD FULL"
900 REM THE TIME RANGE VALUE IS 10 TIMES THE TIME PER DIVISION

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

910 OUTPUT 707;":TIMEBASE:RANGE 2000 NS"
920 OUTPUT 707;":TIMEBASE:REFERENCE CENTER"
930 OUTPUT 707;":TIMEBASE:DELAY 40.33 US"
940 OUTPUT 707;":TRIG:SOURCE CHAN2"
950 OUTPUT 707;":TRIGGER:LEVEL 3.5"
960 OUTPUT 707;":DISPLAY:CONNECT ON"
970 OUTPUT 707;":DISPLAY:TMARKER ON"
980 OUTPUT 707;":ACQUIRE:TYPE AVERAGE;COUNT 64"
990 REM
1000 CLEAR SCREEN
1010 PRINT USING "5/"
1020 R$=""
1030 PRINT "IF YOU WANT TO MAKE A CALIBRATION RUN, PRESS <RETURN>"
1040 PRINT "IF YOU WANT TO ENTER THE NOMINAL THICKNESS, PRESS <N>"
1050 INPUT R$
1060 IF R$="N" OR R$="n" THEN
1070     CLEAR SCREEN
1080     INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
1090     GOTO 3480
1100 END IF
1110 PRINT
1120 FOR I=1 TO 150 STEP 6
1130 C=(I+5)/6
1140 PRINT "DATA ACQUISITION SYSTEM IS TAKING TEMPERATURE MEASUREMENTS"
1150 CALL Dcvs(39,V3)
1160 CALL Dcvs(38,V2)
1170 CALL Dcvs(37,V1)
1180 Tref=10+V3
1190 Tin(C)=FNThmc(V1,"E",Tref)
1200 Tout(C)=FNThmc(V2,"E",Tref)
1210 Tavec(C)=(Tin(C)+Tout(C))/2
1220 Tinf(C)=Tin(C)*1.8+32
1230 Toutf(C)=Tout(C)*1.8+32
1240 Tavef(C)=Tavec(C)*1.8+32
1250 PRINT " INSIDE WALL TEMPERATURE = ";Tin(C); " Degrees C   ";Tinf(C); " Degr
ees F"
1260 PRINT " OUTSIDE WALL TEMPERATURE = ";Tout(C); " Degrees C   ";Toutf(C); " De
grees F"
1270 REM CALCULATE WAVE VELOCITY AS A FUNCTION OF AVERAGE TEMPERATURE
1280 REM
1290 REM Wavespeed correlation from 6/23/92
1300 REM
1310 Wavet=-2.93E-6*(Tavec(C)^3)+.00256*(Tavec(C)^2)-.974*Tavec(C)+5859
1320 REM
1330 Ewavet=(Wavet/.0254)
1340 PRINT " AVERAGE WALL TEMPERATURE = ";Tavec(C); " Degrees C   ";Tavef(C); " D
egrees F"
1350 PRINT "Wavespeed used to establish specimen thickness is";Ewavet,"in/sec"
1360 PRINT "                               or ";Wavet,"m/s"
1370 R$=""
1380 INPUT "PRESS <X> TO MEASURE TEMPERATURES AGAIN <RETURN> TO CONTINUE",R$
1390 IF R$="X" OR R$="x" THEN
1400     CLEAR SCREEN

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

1410 GOTO 1140
1420 ELSE
1430 CLEAR SCREEN
1440 END IF
1450 PRINT USING "10/"
1460 PRINT "PRESS RETURN IF ALL OSCILLOSCOPE SETTINGS ARE APPROPRIATE"
1470 INPUT "MAKE ADJUSTMENTS IF NECESSARY THEN PRESS RETURN TO CONTINUE",R$
1480 CLEAR SCREEN
1490 PRINT "PRESS <local> THEN <delta t/V markers> ON THE OSCILLOSCOPE PANEL TO
"
1500 PRINT "USE THE TIME MARKERS TO FIND THE RANGE OF THE PEAKS OF INTEREST"
1510 INPUT "ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED ",
Begin
1520 INPUT "ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED "
,Finish
1530 REM
1540 CLEAR SCREEN
1550 PRINT "ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF"
1560 PRINT
1570 PRINT "      ";Begin-.008;" AND      ";Begin+.008;" microseconds"
1580 REM
1590 PRINT USING "5/"
1600 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1610 PRINT
1620 PRINT "      ";Finish-.008;" AND      ";Finish+.008;" microseconds"
1630 REM TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE
1640 OUTPUT 707;":STOP"
1650 REM SEARCH WAVEFORM FOR MAXIMUM VOLTAGE PEAKS
1660 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1670 REM
1680 REM THE RANGE OF Loop1 IS THE TIME INTERVAL (in micro seconds)
1690 REM AT WHICH THE FIRST VOLTAGE PEAK OCCURS
1700 LET Voltpeak=0
1710 LET Volt=0
1720 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1730 REM MEASURE THE VOLTAGE AT THE TIME Loop1
1740 OUTPUT 707;":MEASURE:VTIME? "&VAL$(Loop1)&" US"
1750 ENTER 707;Vtm$
1760 LET Volt=VAL(Vtm$)
1770 IF Volt>=Voltpeak THEN
1780 Voltpeak=Volt
1790 Tpeak1=Loop1
1800 ELSE
1810 END IF
1820 NEXT Loop1
1830 REM SET START MARKER AT Tpeak (THE TIME AT THE FIRST VOLTAGE PEAK)
1840 OUTPUT 707;":MEAS:TSTART "&VAL$(Tpeak1)&" US"
1850 REM THE RANGE OF Loop2 IS THE TIME INTERVAL (in micro seconds)
1860 REM AT WHICH THE SECOND VOLTAGE PEAK OCCURS
1870 LET Voltpeak=0
1880 LET Volt=0
1890 FOR Loop2=Finish-.008 TO Finish+.008 STEP .0005
1900 REM MEASURE THE VOLTAGE AT THE TIME Loop2

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

1910     OUTPUT 707;":MEASURE:VTIME? "&VAL$(Loop2)&" US"
1920     ENTER 707;Vtm$
1930     LET Volt=VAL(Vtm$)
1940     IF Volt>Vtpeak THEN
1950         Vtpeak=Volt
1960         Tpeak2=Loop2
1970     ELSE
1980         END IF
1990 NEXT Loop2
2000 REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
2010 OUTPUT 707;":MEAS:TSTOP "&VAL$(Tpeak2)&" US"
2020 REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
2030 OUTPUT 707;":MEASURE:TDELTA?"
2040 ENTER 707;Td1$
2050 Period=VAL(Td1$)
2060 CLEAR SCREEN
2070 PRINT USING "5/"
2080 PRINT "THE TIME PERIOD MEASURED WAS = ";Period;" seconds"
2090 PRINT "THE WAVESPEED CALCULATED WAS = ";Wavet;" m/s"
2100 REM
2110 REM CALCULATE THE THICKNESS FROM THE MEASURED PERIOD
2120 REM ESTABLISH NOMINAL THICKNESS FOR CALIBRATION RUN
2130 IF I=1 THEN
2140     Nominal=Wavet*Period/2
2150     PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
2154;" in"
2160     R$=""
2170     INPUT "PRESS RETURN TO CONTINUE MAKING MEASUREMENTS",R$
2180 ELSE
2190     PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
2194;" in"
2200     R$=""
2210     INPUT "PRESS <N> IF NOMINAL THICKNESS IS INCORRECT, PRESS <RETURN> TO C
ONTINUE",R$
2220     IF (R$="N" OR R$="n") THEN
2230         INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
2240     ELSE
2250         END IF
2260     INPUT "PRESS <T> TO MEASURE TIME INTERVAL AGAIN, PRESS <RETURN> TO CONT
INUE",R$
2270     IF (R$="T" OR R$="t") THEN
2280         CLEAR SCREEN
2290         GOTO 1480
2300     ELSE
2310         END IF
2320     END IF
2330 IF I=1 THEN
2340     CLEAR SCREEN
2350     GOTO 3480
2360 ELSE
2370     END IF
2380 REM
2390 REM CALCULATE THERMAL EXPANSION
2400 Alpha=.00000000833*Tavef(C)+.0000094165

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

2410 Hthick=(Nominal/.0254)*(1+Alpha*(Tavef(C)-48.5))
2420 Mthick=Hthick*.0254
2430 REM
2440 REM WAVESPEED CALCULATION IS IN m/s
2450 Wave(C)=2*Mthick/Period
2460 Ewave(C)=2*(Hthick/12)/Period
2470 CLEAR SCREEN
2480 REM CALCULATE SPECIMEN THICKNESS AT AVERAGE TEMPERATURE
2490 Hthick2=Ewave(C)*Period/2
2500 REM CALCULATE SPECIMEN THICKNESS AT REFERENCE TEMPERATURE OF 48.5 F
2510 Refthick=Hthick2/(Alpha*(Tavef(C)-48.5)+1)
2520 Thickerr=Refthick-(Nominal/.0254)
2530 PRINT "THE TIME PERIOD MEASURED AT ";Tavef(C); F = ";Period;" seconds"
2540 PRINT "THE HEATED WAVESPEED MEASURED WAS      = ";Wave(C);" m/s"
2550 PRINT "THE CALCULATED WAVESPEED WAS          = ";Ewave(C);" m/s"
2560 PRINT
2570 PRINT
2580 PRINT "THE CORRECTED NOMINAL THICKNESS AT ";Tavef(C); F = ";Hthick;" in"
2590 PRINT "      (using alpha)                                ";Mthick;" m"
2600 PRINT
2610 PRINT "THE CALCULATED HEATED THICKNESS AT ";Tavef(C); F = ";Hthick2;" in"
2620 PRINT "      (using V vs T curve)                        ";Hthick2*.0254;" m"
2630 PRINT
2640 PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F : "
2650 PRINT "SPECIMEN THICKNESS      Nominal = ";Nominal/.0254
2660 PRINT "      (inches)              Predicted = ";Refthick
2670 Refthickm=Refthick*.0254
2680 PRINT "SPECIMEN THICKNESS      Nominal = ";Nominal
2690 PRINT "      (METERS)           Predicted = ";Refthickm
2700 REM
2710 PRINT
2720 PRINT "Measurement error, corrected to 48.5 degrees C =";Thickerr,"INCH"
2730 R$=""
2740 INPUT "PRESS <P> TO PRINT DATA <RETURN> TO CONTINUE",R$
2750 IF (R$="P" OR R$="p") THEN
2760 REM *****
2770 REM *          OUTPUT INFORMATION
2780 REM *****
2790 PRINTER IS 701
2800 PRINT USING "20A,35A";"";"SPECIMEN THICKNESS PREDICTION DATA"
2810 PRINT
2820 PRINT "OPERATOR:  Larson, Robb E.      RUN NUMBER";C-1
2830 PRINT "MONTANA STATE UNIVERSITY"
2840 PRINT
2850 PRINT "304 STAINLESS STEEL SPECIMEN"
2860 PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) : "
2870 PRINT
2880 PRINT USING "5X,32A,Z.4D,3A";"NOMINAL SPECIMEN THICKNESS      = ";Nominal
2890 PRINT USING "5X,32A,Z.4D,3A";"PREDICTED SPECIMEN THICKNESS = ";Refthick
2900 PRINT

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```

2910 PRINT "          WAVE VELOCITY CORRELATION"
2920 PRINT "    V = -2.93E-6*T^3 +.00256*T^2-.974*T+5859"
2930 PRINT
2940 PRINT "AT RUN ";C-1;" CONDITIONS:"
2950 PRINT USING "5X,38A,Z.5D,3A";"SPECIMEN THICKNESS (nominal) =";Hthick;"
in"
2960 PRINT USING "43A,D.4D";"";Hthick*25.4;" mm"
2970 PRINT USING "25X,18A,Z.5D,3A";"(V vs T curve) = ";Hthick2;" in"
2980 PRINT USING "43A,D.4D";"";Hthick2*25.4;" mm"
2990 PRINT
3000 PRINT "THICKNESS PREDICTION MEASUREMENT ERROR = ";Thickerr;" inch"
3010 PRINT
3020 PRINT USING "5X,27A,D.4D,3A";"TIME PERIOD OF ECHO PULSES = ";Period*100
0000;" us"
3030 PRINT USING "5X,25A,7D.2D,4A";"SPECIMEN WAVE VELOCITY =";Ewave(C);"ft/s"
"
3040 PRINT USING "32A,4D.2D";"";Wave(C);" m/s"
3050 PRINT
3060 PRINT
3070 PRINT USING "13A,3D,19A";" -----RUN";C-1;" CONDITIONS -----"
3080 PRINT
3090 PRINT USING "38A,3D.3D";"SPECIMEN TEMPERATURE outside surface=";Tout(C)
);" F"
3100 PRINT USING "38A,3D.3D";"";Tout(C);" C"
3110 PRINT USING "38A,3D.3D";"SPECIMEN TEMPERATURE inside surface =";Tinf(C)
;" F"
3120 PRINT USING "38A,3D.3D";"";Tin(C);" C"
3130 PRINT USING "30A, 3D.3D";"AVERAGE SPECIMEN TEMPERATURE =";Tavef(C);" F"
3140 PRINT USING "30A,3D.3D";"";Tavef(C);" C"
3150 PRINTER IS 1
3160 END IF
3170 REM RESTART DATA ACQUISITION TO MAKE ANOTHER READING
3180 OUTPUT 707;" :RUN"
3190 REM*****
3200 REM STORE INFORMATION ON DISK
3210 REM*****
3220 REM
3230 PRINT "DO YOU WANT TO SAVE THIS DATA POINT TO A DISK ? "
3240 R$=""
3250 INPUT "PRESS <enter> TO SAVE          PRESS <X> TO ABORT SAVE",R$
3260 IF R$="X" OR R$="x" THEN
3270     I=I-6
3280     CLEAR SCREEN
3290     GOTO 3480
3300 ELSE
3310     END IF
3320 INPUT "NAME THE DATA FILE...(8 chs max, RETURN for previous: DRIVE 703,1)"
,File$
3330 Runnum=C
3340 Info(I)=Nominal
3350 Info(I+1)=Refthick
3360 Info(I+2)=Tavef(C)
3370 Info(I+3)=Hthick
3380 Info(I+4)=Hthick2
3390 Info(I+5)=Thickerr
3400 PRINT "RUN NUMBER ";Runnum-1

```

Figure 33. Thickness Measurement Program, Noncontact Test.

```
3410 F$=File$&"":,703,1"  
3420 CALL Save_rvect(Info(*),F$)  
3430 REM  
3440 CLEAR SCREEN  
3450 PRINT "DATA SET NUMBER";Runnum-1;"OF 25 ALLOWABLE SETS WAS JUST SAVED"  
3460 INPUT "PRESS RETURN TO MAKE ANOTHER MEASUREMENT",R$  
3470 REM RESTART MEASUREMENT PROGRAM  
3480 NEXT I  
3490 END
```

Figure 33. Thickness Measurement Program, Noncontact Test.

This Program is entitled "Contact1." It directs the Hewlett Packard data acquisition system, via interactive communications with the operator, to control the Hewlett Packard oscilloscope and Hewlett Packard digital voltmeter to obtain data necessary to compute ultrasonic wave speed.

```

10  REM    PROGRAM "CONTACT1" FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM    WRITTEN BY ROBB LARSON, 4/6/92
40  REM    MONTANA STATE UNIVERSITY
50  REM    DEPARTMENT OF MECHANICAL ENGINEERING
60  REM
70  REM    THIS PROGRAM CONTAINS PORTIONS OF PROGRAM
80  REM    "PHASE1" WRITTEN BY BARBARA BAXTER, MAY 23, 1991
90  REM
100 REM    THIS PROGRAM IS DESIGNED TO OPERATE THE HEWLETT PACKARD
110 REM    DIGITIZING OSCILLOSCOPE 54502A THROUGH THE HP-IB
120 REM
130 REM    REQUIRED APPARATUS:
140 REM    STAINLESS STEEL CYLINDRICAL TEST SPECIMEN AND
150 REM    HARDWARE TO COMPLETE THE TEST ARRANGEMENT. NOTE: THERMOCOUPLES
160 REM    MUST BE CONNECTED TO CARD TO PRECLUDE RECEIPT OF ERROR MSG.
170 REM
180 REM    THIS SETUP REQUIRES THE CONTACT TRANSDUCER MOUNTED IN
190 REM    THE CYLINDRICAL TEST SECTION
200 REM
210 REM    THIS PROGRAM ESTABLISHES THE INITIAL SETTINGS FOR THE HP 54502A
220 REM    OSCILLOSCOPE AND SEARCHES THE WAVEFORM OF INTEREST TO DETERMINE
230 REM    THE PERIOD BETWEEN THE PEAKS OF MAXIMUM VOLTAGE. THE PROGRAM
240 REM    SEARCHES FOR THE HIGHEST VOLTAGE (the first peak) AND RETURNS
250 REM    THE TIME AT WHICH THAT VOLTAGE OCCURS. THEN THE PROGRAM
260 REM    SEARCHES THE WAVE IN THE RANGE OF THE SECOND VOLTAGE PEAK AND
270 REM    COMPARES THE VOLTAGE LEVELS AT A SPECIFIED TIME INTERVAL AND
280 REM    FINDS THE SECOND TIME MEASUREMENT AT WHICH THE SECOND PEAK
290 REM    VOLTAGE HAS OCCURRED. THE PERIOD BETWEEN THESE TWO VOLTAGE
300 REM    PEAKS IS THEN MEASURED AND RETURNED AS THE MEASUREMENT OF INTEREST.
310 REM
320 REM    THE INTERNAL, EXTERNAL, AND AVERAGE SPECIMEN TEMPERATURES
330 REM    AS WELL AS THE TRANSDUCER BACKSHELL TEMPERATURE ARE DETERMINED.
340 REM    TYPE "E" THERMOCOUPLES ARE USED EXCEPT FOR A TYPE "J" UNIT
350 REM    ON THE TRANSDUCER BACKSHELL.
360 REM
370 REM    FUNCTIONS CALLED FROM THE HP 54502A OSCILLOSCOPE
380 REM
390 REM    TMAX    : TMAX returns the time at which the first maximum
400 REM              voltage occurs

```

Figure 34. Wave Speed Determination Program, Contact Test.

```

410 REM TSTART : TSTART sets the time marker at specified time
420 REM VTIME : VTIME query returns the voltage at a specified time
430 REM TSTOP : TSTOP moves the stop marker to the specified time
440 REM TDELTA : TDELTA measures the time between start and stop markers
450 REM
460 REM VARIABLE LIST
470 REM
480 REM Tmx$ : string variable called in TMAX function
490 REM Tmax : numerical value of Tmx$
500 REM Loop : time interval in which the second voltage peak occurs
510 REM Vtm$ : string variable called in VTIME function
520 REM Volt : numerical value of Vtm$
530 REM Voltpeak : maximum voltage variable for comparison of voltage
540 REM Tpeak : time at which Voltpeak occurs
550 REM Tdl$ : string variable called in TDELTA function
560 REM Period : numerical value of Tdl$
570 REM Wave : calculated wavespeed of stainless steel specimen
580 REM Nominal : nominal wall thickness measured by micrometer
590 REM Thickness: nominal wall thickness of stainless steel specimen
600 REM : this value of thickness is mechanically measured
610 REM Dpoint(*): variable array to store data point collection
620 REM File$ : file name to save data on disk
630 REM F$ : file string used in function call SAVE_rvect
640 REM
650 REM BEGIN PROGRAM ++++++
660 REM
670 CLEAR SCREEN
680 REM
690 OPTION BASE 1
700 DIM Dpoint(75)
710 DIM File$(8)
720 DIM F$(14)
730 REM
740 INPUT "ENTER KNOWN SPECIMEN THICKNESS (In inches) ",Nominal
750 REM RESET THE OSCILLOSCOPE TO ITS DEFAULT PARAMETERS
760 CLEAR 707
770 OUTPUT 707;"*RST"
780 OUTPUT 707;":DISP:CONNECT ON"
790 OUTPUT 707;":CHANNEL1:RANGE .32"
800 OUTPUT 707;":CHANNEL1:OFFSET .025"
810 OUTPUT 707;":WAVEFORM:RECORD FULL"
820 REM THE TIME RANGE VALUE IS 10 TIMES THE TIME PER DIVISION
830 OUTPUT 707;":TIMEBASE:RANGE 8000 NS"
840 OUTPUT 707;":TIMEBASE:REFERENCE CENTER"
850 OUTPUT 707;":TIMEBASE:DELAY 5.0000 US"
860 OUTPUT 707;":TRIG:SOURCE CHAN2"
870 OUTPUT 707;":TRIGGER:LEVEL 3.5"
880 OUTPUT 707;":DISPLAY:CONNECT ON"
890 OUTPUT 707;":DISPLAY:TMARKER ON"
900 OUTPUT 707;":ACQUIRE:TYPE AVERAGE;COUNT 64"

```

Figure 34. Wave Speed Determination Program, Contact Test.

```

910 REM
920 FOR I=1 TO 74 STEP 3
930 PRINTER IS 701
940 CALL Sys_init("P")
950 CALL Devs(39,V4)
960 CALL Devs(36,V1)
970 CALL Devs(37,V2)
980 CALL Devs(38,V3)
990 Tr=10^-14
1000 Ttrans=FNThmc(V1,"J",Tr)
1010 Tinside=FNThmc(V2,"E",Tr)
1020 Toutside=FNThmc(V3,"E",Tr)
1030 Taverage=.5*(Tinside+Toutside)
1040 REM PRINT TEMPERATURES
1050 REM
1060 PRINT "-----"
1070 PRINT "TRANSDUCER BACKSHELL TEMP IS =";Ttrans;"DEGREES C"
1080 PRINT "OUTSIDE WALL TEMP=";Toutside;"DEG C"
1090 PRINT "AVERAGE WALL TEMP=";Taverage;"DEG C"
1100 PRINT "INSIDE WALL TEMP=";Tinside;"DEG C"
1110 PRINTER IS 1
1120 REM
1130 PRINT "-----"
1140 PRINT "TRANSDUCER BACKSHELL TEMP IS =";Ttrans;"DEGREES C"
1150 PRINT "OUTSIDE WALL TEMP=";Toutside;"DEG C"
1160 PRINT "AVERAGE WALL TEMP=";Taverage;"DEG C"
1170 PRINT "INSIDE WALL TEMP=";Tinside;"DEG C"
1180 REM
1190 PRINT "PRESS RETURN IF ALL OSCILLOSCOPE SETTINGS ARE APPROPRIATE"
1200 INPUT "MAKE ADJUSTMENTS IF NECESSARY THEN PRESS RETURN TO CONTINUE",R$
1210 CLEAR SCREEN
1220 PRINT "PRESS <local> THEN <delta t/V markers> ON THE SCOPE PANEL TO"
1230 PRINT "USE THE TIME MARKERS TO FIND THE RANGE OF THE FIRST VOLTAGE PEAK"
1240 INPUT "ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED",H
ere
1250 INPUT "ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED "
,There
1260 REM
1270 PRINT USING "10/"
1280 PRINT "ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF"
1290 PRINT
1300 PRINT "      ";Here-.008;" AND      ";Here+.008;" microseconds"
1310 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1320 PRINT
1330 PRINT "      ";There-.008;" AND      ";There+.008;" microseconds"
1340 REM
1350 REM TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE
1360 OUTPUT 707;":STOP"
1370 REM MEASURE THE TIME AT WHICH THE FIRST PEAK OCCURS
1380 FOR Lp1=Here-.008 TO Here+.008 STEP .0002
1390 REM MEASURE THE VOLTAGE AT THE TIME Lp1
1400 OUTPUT 707;":MEASURE:VTIME? "&VAL$(Lp1)&" US"

```

Figure 34. Wave Speed Determination Program, Contact Test.

```

1410 ENTER 707;Vtm$
1420 LET Volt=VAL(Vtm$)
1430 IF Volt>=Voltpeak THEN
1440     Voltpeak=Volt
1450     Tpeak=Lp1
1460 ELSE
1470     END IF
1480 NEXT Lp1
1490 REM SET START MARKER
1500 OUTPUT 707;"MEASURE:TSTART "&VAL$(Tpeak)&" US"
1510 REM
1520 REM SEARCH SECOND HALF OF WAVEFORM FOR MAXIMUM SECOND PEAK VOLTAGE
1530 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1540 REM
1550 REM THE RANGE OF Loop IS THE TIME INTERVAL (in micro seconds)
1560 REM AT WHICH THE SECOND VOLTAGE PEAK OCCURS
1570 LET Voltpeak=0
1580 LET Volt=0
1590 LET Loop=0
1600 LET Vtm$=""
1610 LET Tpeak=0
1620 FOR Loop=There-.008 TO There+.008 STEP .0002
1630     REM MEASURE THE VOLTAGE AT THE TIME Loop
1640     OUTPUT 707;"MEASURE:VTIME? "&VAL$(Loop)&" US"
1650     ENTER 707;Vtm$
1660     LET Volt=VAL(Vtm$)
1670     IF Volt>=Voltpeak THEN
1680         Voltpeak=Volt
1690         Tpeak=Loop
1700     ELSE
1710         END IF
1720 NEXT Loop
1730 REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
1740 OUTPUT 707;"MEAS:TSTOP "&VAL$(Tpeak)&" US"
1750 REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
1760 OUTPUT 707;"MEASURE:TDELTA?"
1770 ENTER 707;Td1$
1780 Period=VAL(Td1$)
1790 CLEAR SCREEN
1800 PRINTER IS 701
1810 REM
1820 REM convert to farenheight temp to apply thermal expansion coeff...
1830 REM
1840 Tavef=Taverage*1.80+32
1850 Alpha=.00000000833*Tavef+.0000094165
1860 Hthick=Nominal*(1+Alpha*(Tavef-44.6))
1870 REM CONVERT ENGLISH HTHICK TO METRIC MHTHICK
1880 Mhthick=Hthick*.0254
1890 Thickness=Nominal*.0254
1900 Wave=2*Mhthick/Period

```

Figure 34. Wave Speed Determination Program, Contact Test .

```

1810 REM
1820 PRINT USING "5/"
1830 PRINT "THE TIME PERIOD AT TAVERAGE =";Taverage;"DEG C WAS = ";Period;" s
seconds"
1840 PRINT "THE CORRECTED WAVESPEED AT TAVERAGE =";Taverage;"DEG C WAS ";Wave;"
m/s"
1850 PRINT "ROOM TEMP SPECIMEN THICKNESS = ";Thickness;" m, MEASURED AT 74 DEGR
EES F "
1860 PRINT "ROOM TEMP SPECIMEN THICKNESS = ";Nominal;" in"
1870 PRINTER IS 1
1880 PRINT "THE TIME PERIOD AT TAVERAGE =";Taverage;"DEG C WAS = ";Period;" s
seconds"
1890 PRINT "THE CORRECTED WAVESPEED AT TAVERAGE =";Taverage;"DEG C WAS ";Wave;"
m/s"
2000 PRINT "ROOM TEMP SPECIMEN THICKNESS = ";Thickness;" m, MEASURED AT 74 DEGR
EES F "
2010 PRINT "ROOM TEMP SPECIMEN THICKNESS = ";Nominal;" in"
2020 REM RESTART DATA ACQUISITION TO MAKE ANOTHER READING
2030 OUTPUT 707;"RUN"
2040 REM
2050 REM STORE INFORMATION ON DISK
2060 REM
2070 PRINT "DO YOU WANT TO SAVE THIS DATA POINT TO A DISK ? "
2080 R$=""
2090 INPUT "PRESS <enter> TO SAVE      PRESS <X> TO ABORT SAVE",R$
2100 IF R$="X" OR R$="x" THEN
2110     I=I-3
2120     GOTO 2260
2130     END IF
2140 INPUT "NAME THE DATA FILE...( < 8 chars, or RETURN for same name)",File$
2150 Dpoint(I)=Nominal
2160 Dpoint(I+1)=Wave
2170 Dpoint(I+2)=Taverage
2180 Entry=(I+2)/3
2190 REM
2200 F$=File$&"":,703,1"
2210 CALL Save_rvect(Dpoint(*),F$)
2220 REM
2230 PRINT "THIS DATASET IS ENTRY #";Entry;
2240 INPUT "PRESS RETURN TO MAKE ANOTHER MEASUREMENT",R$
2250 REM RESTART MEASUREMENT PROGRAM
2260 NEXT I
2270 END

```

Figure 34. Wave Speed Determination Program, Contact Test .

This Program is entitled "Conpred." It directs the Hewlett Packard data acquisition system, via interactive communications with the operator, to control the Hewlett Packard oscilloscope and Hewlett Packard digital voltmeter to obtain data necessary to compute specimen thickness.

```

10  REM  PROGRAM "CONPRED"FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM  THIS PROGRAM WRITTEN BY ROBB E. LARSON
40  REM  MECHANICAL ENGINEERING DEPARTMENT
50  REM
60  REM  CONTAINS PORTIONS OF PROGRAMS
70  REM  ORIGINALLY WRITTEN BY BARBARA H. BAXTER
80  REM
90  REM  FOR USE IN THICKNESS PREDICTION WITH THE CONTACT TRANSDUCER
100 REM  INSTRUMENT AND THE HP3497A DATA ACQUISITION SYSTEM
110 REM
120 REM  THIS PROGRAM DETERMINES THE WAVE VELOCITY AND PREDICTS
130 REM  THE THICKNESS OF A CYLINDRICAL 304 STAINLESS STEEL SPECIMEN.
140 REM  THE PROGRAM IS DESIGNED FOR USE OVER A RANGE OF TEMPERATURES.
150 REM  DATA FILES ARE CREATED FOR EASE IN PROCESSING DATA.
160 REM
170 REM  THIS PROGRAM REQUIRES TWO TYPE "E" THERMOCOUPLES. TWO
180 REM  TEMPERATURE MEASUREMENTS WILL BE RECORDED BY THE HP DATA
190 REM  ACQUISITION SYSTEM/300. PLACE THE T-COUPLE ACQ LIBRARY CARD
200 REM  IN SLOT 1 OF THE 3497A CONTROL UNIT. CONNECT CHANNEL 37 TYPE
210 REM  "E" THERMOCOUPLE TO THE INSIDE SURFACE OF THE TEST SPECIMEN
220 REM  (Tin). CONNECT CHANNEL 38 TYPE "E" THERMOCOUPLE TO THE
230 REM  OUTSIDE SURFACE OF THE TEST SPECIMEN (Tout).
240 REM
250 REM  VARIABLE LIST
260 REM
270 REM Loop1 : time interval in which the FIRST voltage peak occurs
280 REM Loop2 : time interval in which the second voltage peak occurs
290 REM Vtm$ : string variable called in VTIME function
300 REM Volt : numerical value of Vtm$
310 REM Voltpeak : maximum voltage variable for comparison of voltage
320 REM Tdl$ : string variable called in TDELTA function
330 REM Period : numerical value of Tdl$
340 REM Wave : calculated wavespeed of stainless steel specimen
350 REM Nominal : nominal wall thickness calculated by calibration
360 REM Info(*) : variable array to store data point collection
370 REM File$ : file name to save data on disk
380 REM F$ : file string used in function call SAVE_rvect
390 REM Runnum : run number
400 REM Channel : thermocouple channel number

```

Figure 35. Thickness Measurement Program, Contact Test.

```

410 REM Voltage1 : voltage for measuring TC temp at active junction
420 REM Vref : reference voltage for TC
430 REM Tref : reference temperature for TC
440 REM Tin(*) : inside temperature array, deg. C.
450 REM Tout(*) : outside temperature array, deg. C.
460 REM Tavef(*) : average temperature (degrees F)
470 REM Tavec(*) : average temperature (degrees C)
480 REM Alpha : thermal expansion coefficient
490 REM Hthick : heated thickness, inches; calculated using alpha
500 REM Refthick : predicted specimen thickness in inches, corrected to
510 REM reference temperature using alpha
520 REM Thickerr : difference between predicted thickness and
530 REM actual measured specimen thickness, corrected to 48.5 C.
540 REM Refthickm: predicted specimen thickness, meters; corrected to 48.5 C.
550 REM Mhthick : heated thickness, meters
560 REM C : dataset counter
570 REM Wavet : correlated wavespeed, m/s
580 REM Ewavet : correlated wavespeed, in/s
590 REM Tinf(*) : inside temp array, deg. F
600 REM Toutf(*) : outside temp array, deg. F
610 REM Begin : approximate location of first voltage peak
620 REM finish : approximate location of second voltage peak
630 REM Tpeak1 : time at actual first voltage peak
640 REM Tpeak2 : time at actual second voltage peak
650 REM Hthick2 : predicted thickness from delta time at high temperature
660 REM BEGIN PROGRAM
670 REM
680 CLEAR SCREEN
690 OPTION BASE 1
700 DIM Info(150)
710 DIM Files(8)
720 DIM F$(14)
730 DIM Tin(25)
740 DIM Tout(25)
750 DIM Tavef(25)
760 DIM Tinf(25)
770 DIM Toutf(25)
780 DIM Tavec(25)
790 DIM Wave(25)
800 DIM Ewave(25)
810 CALL Sys_init("P")
820 REM RESET THE OSCILLOSCOPE TO ITS DEFAULT PARAMETERS
830 CLEAR 707
840 OUTPUT 707; "*RST"
850 OUTPUT 707; ":DISP:CONNECT ON"
860 OUTPUT 707; ":CHANNEL1:RANGE .80"
870 OUTPUT 707; ":CHANNEL1:OFFSET 0.00"
880 OUTPUT 707; ":WAVEFORM:RECORD FULL"
890 REM THE TIME RANGE VALUE IS 10 TIMES THE TIME PER DIVISION
900 OUTPUT 707; ":TIMEBASE:RANGE 2000 NS"

```

Figure 35. Thickness Measurement Program, Contact Test.

```

910  OUTPUT 707;":TIMEBASE:REFERENCE CENTER"
920  OUTPUT 707;":TIMEBASE:DELAY 4.01 US"
930  OUTPUT 707;":TRIG:SOURCE CHAN2"
940  OUTPUT 707;":TRIGGER:LEVEL 3.5"
950  OUTPUT 707;":DISPLAY:CONNECT ON"
960  OUTPUT 707;":DISPLAY:TMARKER ON"
970  OUTPUT 707;":ACQUIRE:TYPE AVERAGE;COUNT 64"
980  REM
990  PRINTER IS 1
1000 CLEAR SCREEN
1010 PRINT USING "5/"
1020 R$=""
1030 PRINT "IF YOU WANT TO MAKE A CALIBRATION RUN, PRESS <RETURN>"
1040 PRINT "IF YOU WANT TO ENTER THE NOMINAL THICKNESS, PRESS <N>"
1050 INPUT R$
1060 IF R$="N" OR R$="n" THEN
1070     CLEAR SCREEN
1080     INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
1090     GOTO 3530
1100 END IF
1110 PRINT
1120 FOR I=1 TO 150 STEP 6
1130 C=(I+5)/6
1140 PRINT "DATA ACQUISITION SYSTEM IS TAKING TEMPERATURE MEASUREMENTS"
1150 CALL Dcvs(39,U3)
1160 CALL Dcvs(38,U2)
1170 CALL Dcvs(37,U1)
1180 Tref=10*U3
1190 Tin(C)=FNThmc(U1,"E",Tref)
1200 Tout(C)=FNThmc(U2,"E",Tref)
1210 Tavec(C)=(Tin(C)+Tout(C))/2
1220 Tinf(C)=Tin(C)*1.8+32
1230 Toutf(C)=Tout(C)*1.8+32
1240 Tavef(C)=Tavec(C)*1.8+32
1250 PRINT " INSIDE  WALL TEMPERATURE = ";Tin(C);" Degrees C  ";Tinf(C);" Degr
ees F"
1260 PRINT " OUTSIDE WALL TEMPERATURE = ";Tout(C);" Degrees C  ";Toutf(C);" De
grees F"
1270 REM CALCULATE WAVE VELOCITY AS A FUNCTION OF AVERAGE TEMPERATURE
1280 REM
1290 REM Wavespeed correlation from 6/23/92
1300 REM
1310 Wavet=-2.66E-7*(Tavec(C)^3)+2.69E-4*(Tavec(C)^2)-.537*Tavec(C)+5806
1320 REM
1330 Ewavet=(Wavet/.0254)
1340 PRINT " AVERAGE WALL TEMPERATURE = ";Tavec(C);" Degrees C  ";Tavef(C);" D
egrees F"
1350 PRINT "Wavespeed used to establish specimen thickness is";Ewavet,"in/sec"
1360 PRINT "                               or ";Wavet,"m/s"
1370 R$=""
1380 INPUT "PRESS <X> TO MEASURE TEMPERATURES AGAIN <RETURN> TO CONTINUE",R$
1390 IF R$="X" OR R$="x" THEN
1400     CLEAR SCREEN

```

Figure 35. Thickness Measurement Program, Contact Test.

```

1410   GOTO 1140
1420 ELSE
1430   CLEAR SCREEN
1440   END IF
1450 PRINT USING "10/"
1460 PRINT "PRESS RETURN IF ALL OSCILLOSCOPE SETTINGS ARE APPROPRIATE"
1470 INPUT "MAKE ADJUSTMENTS IF NECESSARY THEN PRESS RETURN TO CONTINUE",R$
1480 CLEAR SCREEN
1490 PRINT "PRESS <local> THEN <delta t/V markers> ON THE OSCILLOSCOPE PANEL TO
"
1500 PRINT "USE THE TIME MARKERS TO FIND THE RANGE OF THE PEAKS OF INTEREST"
1510 INPUT "ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED ",
Begin
1520 INPUT "ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED "
,Finish
1530 REM
1540 CLEAR SCREEN
1550 PRINT "ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF"
1560 PRINT
1570 PRINT "      ";Begin-.008;" AND " ";Begin+.008;" microseconds"
1580 REM
1590 PRINT USING "5/"
1600 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1610 PRINT
1620 PRINT "      ";Finish-.008;" AND " ";Finish+.008;" microseconds"
1630 REM TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE
1640 OUTPUT 707;";STOP"
1650 REM SEARCH WAVEFORM FOR MAXIMUM VOLTAGE PEAKS
1660 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1670 REM
1680 REM THE RANGE OF Loop1 IS THE TIME INTERVAL (in micro seconds)
1690 REM AT WHICH THE FIRST VOLTAGE PEAK OCCURS
1700 LET Voltpeak=0
1710 LET Volt=0
1720 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1730   REM MEASURE THE VOLTAGE AT THE TIME Loop1
1740   OUTPUT 707;";MEASURE:VTIME? "&VAL$(Loop1)&" US"
1750   ENTER 707;Vtm$
1760   LET Volt=VAL(Vtm$)
1770   IF Volt>Voltpeak THEN
1780     Voltpeak=Volt
1790     Tpeak1=Loop1
1800   ELSE
1810     END IF
1820 NEXT Loop1
1830 REM SET START MARKER AT Tpeak (THE TIME AT THE FIRST VOLTAGE PEAK)
1840 OUTPUT 707;";MEAS:TSTART "&VAL$(Tpeak1)&" US"
1850 REM THE RANGE OF Loop2 IS THE TIME INTERVAL (in micro seconds)
1860 REM AT WHICH THE SECOND VOLTAGE PEAK OCCURS
1870 LET Voltpeak=0
1880 LET Volt=0
1890 FOR Loop2=Finish-.008 TO Finish+.008 STEP .0005
1900   REM MEASURE THE VOLTAGE AT THE TIME Loop2

```

Figure 35. Thickness Measurement Program, Contact Test.

```

1910     OUTPUT 707;":MEASURE:VTIME? "&VAL$(Loop2)&" US"
1920     ENTER 707;Vtm$
1930     LET Volt=VAL(Vtm$)
1940     IF Volt>=Voltpeak THEN
1950         Voltpeak=Volt
1960         Tpeak2=Loop2
1970     ELSE
1980         END IF
1990     NEXT Loop2
2000     REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
2010     OUTPUT 707;":MEAS:TSTOP "&VAL$(Tpeak2)&" US"
2020     REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
2030     OUTPUT 707;":MEASURE:TDELTA?"
2040     ENTER 707;Td1$
2050     Period=VAL(Td1$)
2060     CLEAR SCREEN
2070     PRINT USING "5/"
2080     PRINT "THE TIME PERIOD MEASURED WAS   =   ";Period;" seconds"
2090     PRINT "THE WAVESPEED CALCULATED WAS   =   ";Wavet;" m/s"
2100     REM
2110     REM CALCULATE THE THICKNESS FROM THE MEASURED PERIOD
2120     REM ESTABLISH NOMINAL THICKNESS FOR CALIBRATION RUN
2130     IF I=1 THEN
2140         Nominal=Wavet*Period/2
2150         PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
.0254;" in"
2160         R$=""
2170         INPUT "PRESS RETURN TO CONTINUE MAKING MEASUREMENTS",R$
2180     ELSE
2190         PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = ";Nominal;" m";Nominal/
.0254;" in"
2200         R$=""
2210         INPUT "PRESS <N> IF NOMINAL THICKNESS IS INCORRECT, PRESS <RETURN> TO C
ONTINUE",R$
2220         IF (R$="N" OR R$="n") THEN
2230             INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
2240         ELSE
2250             END IF
2260         INPUT "PRESS <T> TO MEASURE TIME INTERVAL AGAIN, PRESS <RETURN> TO CONT
INUE",R$
2270         IF (R$="T" OR R$="t") THEN
2280             CLEAR SCREEN
2290             GOTO 1480
2300         ELSE
2310             END IF
2320         END IF
2330     IF I=1 THEN
2340         CLEAR SCREEN
2350         GOTO 3530
2360     ELSE
2370         END IF
2380     REM
2390     REM CALCULATE THERMAL EXPANSION
2400     Alpha=.000000000833*Tavef(C)+.0000094165

```

Figure 35. Thickness Measurement Program, Contact Test.

```

2410 Hthick=(Nominal/.0254)*(1+Alpha*(Tavef(C)-48.5))
2420 Mhthick=Hthick*.0254
2430 REM
2440 REM WAVESPEED CALCULATION IS IN m/s
2450 CLEAR SCREEN
2460 REM CALCULATE SPECIMEN THICKNESS AT AVERAGE TEMPERATURE
2470 Hthick2=Ewavel*Period/2
2480 REM CALCULATE SPECIMEN THICKNESS AT REFERENCE TEMPERATURE OF 48.5 F
2490 Refthick=Hthick2/(Alpha*(Tavef(C)-48.5)+1)
2500 Thickerr=Refthick-(Nominal/.0254)
2510 PRINT "THE TIME PERIOD MEASURED AT ";Tavef(C); F = ";Period;" seconds"
2520 PRINT "THE CALCULATED WAVESPEED WAS           = ";Wavel;" m/s"
2530 PRINT
2540 PRINT
2550 PRINT "THE CORRECTED NOMINAL THICKNESS AT ";Tavef(C); F = ";Hthick;" in"
2560 PRINT "      (using alpha)                                ";Mhthick;" m"
2570 PRINT
2580 PRINT "THE CALCULATED HEATED THICKNESS AT ";Tavef(C); F = ";Hthick2;" in"
2590 PRINT "      (using V vs T curve)                        ";Hthick2*.0254;" m"
2600 PRINT
2610 PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F  : "
2620 PRINT "SPECIMEN THICKNESS           Nominal = ";Nominal/.0254
2630 PRINT "      (inches)                 Predicted = ";Refthick
2640 Refthickm=Refthick*.0254
2650 PRINT "SPECIMEN THICKNESS           Nominal = ";Nominal
2660 PRINT "      (METERS)                 Predicted = ";Refthickm
2670 REM
2680 PRINT
2690 PRINT "Measurement error, corrected to 48.5 degrees C =";Thickerr,"INCH"
2700 R$=""
2710 INPUT "PRESS <P> TO PRINT DATA <RETURN> TO CONTINUE",R$
2720 IF (R$="P" OR R$="p") THEN
2730 REM *****
2740 REM *           OUTPUT INFORMATION
2750 REM *****
2760 PRINTER IS 701
2770 PRINT USING "20A,35A";";";"SPECIMEN THICKNESS PREDICTION DATA"
2780 PRINT "
2790 PRINT
2800 PRINT
2810 PRINT "OPERATOR: Larson, Robb E. "
2820 PRINT "MONTANA STATE UNIVERSITY"
2830 PRINT "DEPARTMENT OF MECHANICAL ENGINEERING"
2840 PRINT "CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFPRED'"
2850 PRINT
2860 PRINT "          ***** RUN NUMBER ";C-1;" *****"
2870 PRINT
2880 PRINT "          304 STAINLESS STEEL SPECIMEN"
2890 PRINT "          AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) "
2900 PRINT

```

Figure 35. Thickness Measurement Program, Contact Test.

```

2910 PRINT "WAVE VELOCITY CORRELATION"
2920 PRINT "V = -2.66E-7*T^3 +2.69E-4*T^2-.537*T+5806"
2930 PRINT
2940 PRINT
2950 PRINT "THE TIME PERIOD MEASURED AT ";Tavef(C);" F = ";Period;" seconds"
2960 PRINT "THE CALCULATED WAVESPEED WAS           = ";Wavet;" m/s"
2970 PRINT
2980 PRINT
2990 PRINT USING "38A,4D.4D";"SPECIMEN TEMPERATURE outside surface=";Toutf(C)
);" F"
3000 PRINT USING "38A,3D.3D";"SPECIMEN TEMPERATURE inside surface =" ;Tinf(C)
;" F"
3010 PRINT USING "30A, 3D.3D";"AVERAGE SPECIMEN TEMPERATURE =" ;Tavef(C);" F"
3020 PRINT
3030 PRINT
3040 PRINT "THE CORRECTED NOMINAL THICKNESS AT ";Tavef(C);" F = ";Hthick;" in"
3050 PRINT "      (using alpha)                      ";Mhthick;" m"
3060 PRINT
3070 PRINT "THE CALCULATED HEATED THICKNESS AT ";Tavef(C);" F = ";Hthick2;" in"
3080 PRINT "      (using V vs T curve)                ";Hthick2*.0254;
" m"
3090 PRINT
3100 PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F  : "
3110 PRINT "SPECIMEN THICKNESS           Nominal = ";Nominal
3120 PRINT "      (METERS)                   Predicted = ";Refthickm
3130 PRINT "SPECIMEN THICKNESS           Nominal = ";Nominal/.0254
3140 PRINT "      (INCHES)                   Predicted = ";Refthick
3150 PRINT
3160 PRINT
3170 PRINT
3180 PRINT "MEASUREMENT ERROR (corrected to 48.5 degrees C.) =";Thickerr,"INCH"
3190 PRINT
3200 PRINT "PRINTER IS 1"
3210 PRINT "END IF"
3220 REM RESTART DATA ACQUISITION TO MAKE ANOTHER READING
3230 OUTPUT 707;" :RUN"
3240 REM*****
3250 REM STORE INFORMATION ON DISK
3260 REM*****
3270 REM
3280 PRINT "DO YOU WANT TO SAVE THIS DATA POINT TO A DISK ? "
3290 R$=""
3300 INPUT "PRESS <enter> TO SAVE           PRESS <X> TO ABORT SAVE",R$
3310 IF R$="X" OR R$="x" THEN
3320     I=I-6
3330     CLEAR SCREEN
3340     GOTO 3530
3350 ELSE
3360     END IF
3370 INPUT "NAME THE DATA FILE...(8 chs max, RETURN for previous; DRIVE 703,1)"
,File$
3380 Runnum=C
3390 Info(I)=Nominal
3400 Info(I+1)=Refthick

```

Figure 35. Thickness Measurement Program, Contact Test.

```
3410 Info(I+2)=Taved(C)
3420 Info(I+3)=Hthick
3430 Info(I+4)=Hthick2
3440 Info(I+5)=Thickerr
3450 PRINT "RUN NUMBER ";Runnum-1
3460 F$=File$&": ,703,1"
3470 CALL Save_Invect(Info(*),F$)
3480 REM
3490 CLEAR SCREEN
3500 PRINT "DATA SET NUMBER";Runnum-1;"OF 25 ALLOWABLE SETS WAS JUST SAVED"
3510 INPUT "PRESS RETURN TO MAKE ANOTHER MEASUREMENT",R$
3520 REM RESTART MEASUREMENT PROGRAM
3530 NEXT I
3540 END
```

Figure 35. Thickness Measurement Program, Contact Test.

This Program is entitled "C1trans." It accesses wave speed versus temperature data files which have been saved to disk, and then sends the accessed data stream through the Hewlett Packard computer serial port to an IBM compatible computer for graphing and data reduction.

```

10  REM PROGRAM NAME IS "C1TRANS" AND IS INTENDED TO BE USED FOR
20  REM DATA TRANSFER FOLLOWING WAVESPEED CALIBRATION DATA TO
30  REM CREATE WAVESPEED VS. TEMPERATURE CURVE.
40  REM
50  REM THIS PROGRAM TRANSFERS EDAT FILES FROM HP9000 340 TO AN
60  REM IBM COMPATIBLE MACHINE
70  REM
80  REM BE SURE THAT BEFORE RUNNING THIS PROGRAM, THE IBM IS READY
90  REM TO ACCEPT THE FILE. CONFIGURE THE IBM TO ACCEPT DATA WITH
100 REM PROGRAM SMARTCOM.EXEC, AND SELECT HP340 AS DEVICE TYPE.
110 REM
120 REM THIS PROGRAM WRITTEN BY ROBB E. LARSON
130 REM DEPARTMENT OF MECHANICAL ENGINEERING
140 REM MONTANA STATE UNIVERSITY
150 REM LAST EDITED 10/15/92
160 REM
170 REM BASED UPON A PROGRAM ORIGINALLY CREATED BY
180 REM CARL FEHRES
190 REM MONTANA STATE UNIVERSITY
200 REM DEPARTMENT OF MECHANICAL ENGINEERING
210 REM JUNE 1991
220 I
230 CALL Sys_init("P")
240 REM
250 REM OPTION TO SET THE ARRAY TO START AT 0 INSTEAD OF 1
260 REM
270 OPTION BASE 1
280 REAL Vnumber
290 INTEGER Vtype
300 DIM F$(20)
310 DISP "INPUT FILE NAME AND ADDRESS TO BE TRANSFERED":
320 INPUT F$
330 REM
340 REM DIMENSIONING THE VARIABLES
350 REM THIS CALL COMMAND WILL FIND OUT THE SIZE OF THE FILE TO BE TRANSFERED
360 REM
370 CALL Vect_info(F$,Vtype,Vnumber)
380 Vnumb=Vnumber
390 PRINT Vnumb
400 ALLOCATE REAL Vd(1:Vnumb)

```

Figure 36. Wavespeed Data Transfer Program.

```
410 DISP " "  
420 REM  
430 REM ASSIGNING THE OUTPUT DEVICE TO SERIAL PORT  
440 REM  
450 ASSIGN @Serial TO 16  
460 REM  
470 REM RETRIEVING THE ARRAY FROM IT'S BDAT FORM  
480 REM  
490 CALL Get_rarray(F$,Vd(*))  
500 DISP "NOW TRANSFERING THE FILE.... PLEASE WAIT"  
510 K=Vnumb/3  
520 FOR J=0 TO K-1  
530 REM OUTPUTING THE DATA POINT TO THE SERIAL PORT  
540 M=Vd(J*3+3)  
550 O=Vd(J*3+2)  
560 OUTPUT 16;M;" ";O  
570 NEXT J  
580 DISP "FILE TRANSFER IS NOW COMPLETE"  
590 END
```

Figure 36. Wavespeed Data Transfer Program .

This Program is entitled "Cyltrans." It accesses specimen thickness versus temperature data files which have been saved to disk, and then sends the accessed data stream through the Hewlett Packard computer serial port to an IBM compatible computer for graphing and data reduction.

```

10  REM  PROGRAM "CYLTRANS" FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM  FOR DATA TRANSFER FOLLOWING THICKNESS PREDICTION TESTS, TO
40  REM  CREATE THICKNESS VS. TEMPERATURE CURVES.
50  REM
60  REM  THIS PROGRAM TRANSFERS BDAT FILES FROM HP9000 340 TO AN
70  REM  IBM COMPATIBLE MACHINE
80  REM
90  REM  BE SURE THAT BEFORE RUNNING THIS PROGRAM, THE IBM IS READY
100 REM  TO ACCEPT THE FILE. CONFIGURE THE IBM TO ACCEPT DATA WITH
110 REM  PROGRAM SMARTCOM.EXEC, AND SELECT HP340 AS DEVICE TYPE.
120 REM
130 REM  THIS PROGRAM WRITTEN BY ROBB E. LARSON
140 REM  DEPARTMENT OF MECHANICAL ENGINEERING
150 REM  MONTANA STATE UNIVERSITY
160 REM
170 REM  BASED UPON A PROGRAM ORIGINALLY CREATED BY
180 REM  CARL FEHRES
190 REM  MONTANA STATE UNIVERSITY
200 REM  DEPARTMENT OF MECHANICAL ENGINEERING
210 REM  JUNE 1991
220 !
230 CALL Sys_init("P")
240 REM
250 REM  OPTION TO SET THE ARRAY TO START AT 0 INSTEAD OF 1
260 REM
270 OPTION BASE 0
280 REAL Vnumber
290 INTEGER Vtype
300 DIM F$(20)
310 DISP "INPUT FILE NAME AND ADDRESS TO BE TRANSFERED";
320 INPUT F$
330 REM
340 REM  DIMENSIONING THE VARIABLES
350 REM  THIS CALL COMMAND WILL FIND OUT THE SIZE OF THE FILE TO BE TRANSFERED
360 REM
370 CALL Vect_info(F$,Vtype,Vnumber)
380 Vnumb=Vnumber
390 PRINT Vnumber
400 ALLOCATE REAL Vd(1:Vnumb)

```

Figure 37. Thickness Data Transfer Program.

```
410 DISP " "
420 REM
430 REM ASSIGNING THE OUTPUT DEVICE TO SERIAL PORT
440 REM
450 ASSIGN @Serial TO 16
460 REM
470 REM RETRIEVING THE ARRAY FROM IT'S BDAT FORM
480 REM
490 CALL Get_rarray(F$,Vd(*))
500 DISP "NOW TRANSFERING THE FILE.... PLEASE WAIT"
510 K=Vnumb/6
520 FOR J=0 TO K-1
530 REM OUTPUTING THE DATA POINT TO THE SERIAL PORT
540 M=Vd(J*6+2)
550 O=Vd(J*6+3)
560 OUTPUT 16;O;" ";M
570 NEXT J
580 DISP "FILE TRANSFER IS NOW COMPLETE"
590 END
```

Figure 37. Thickness Data Transfer Program .

This Program is entitled "Errtrans." It accesses specimen thickness prediction error versus temperature data files which have been saved to disk, and then sends the accessed data stream through the Hewlett Packard computer serial port to an IBM compatible computer for graphing and data reduction.

```

10  REM  PROGRAM "ERRTRANS" FOR H.P. DATA ACQUISITION SYSTEM
20  REM
30  REM  FOR DATA TRANSFER FOLLOWING THICKNESS PREDICTION TESTS, TO
40  REM  CREATE THICKNESS MEASUREMENT ERROR VS. TEMPERATURE CURVE.
50  REM
60  REM  THIS PROGRAM TRANSFERS BDAT FILES FROM HP9000 340 TO AN
70  REM  IBM COMPATIBLE MACHINE
80  REM
90  REM  BE SURE THAT BEFORE RUNNING THIS PROGRAM, THE IBM IS READY
100 REM  TO ACCEPT THE FILE. CONFIGURE THE IBM TO ACCEPT DATA WITH
110 REM  PROGRAM SMARTCOM.EXEC, AND SELECT HP340 AS DEVICE TYPE.
120 REM
130 REM  THIS PROGRAM WRITTEN BY ROBB E. LARSON
140 REM  DEPARTMENT OF MECHANICAL ENGINEERING
150 REM  MONTANA STATE UNIVERSITY
160 REM
170 REM  BASED UPON A PROGRAM ORIGINALLY CREATED BY
180 REM  CARL FEHRES
190 REM  MONTANA STATE UNIVERSITY
200 REM  DEPARTMENT OF MECHANICAL ENGINEERING
210 REM  JUNE 1991
220 !
230 CALL Sys_init("P")
240 REM
250 REM  OPTION TO SET THE ARRAY TO START AT 0 INSTEAD OF 1
260 REM
270 OPTION BASE 0
280 REAL Vnumber
290 INTEGER Vtype
300 DIM F$(20)
310 DISP "INPUT FILE NAME AND ADDRESS TO BE TRANSFERED",
320 INPUT F$
330 REM
340 REM  DIMENSIONING THE VARIABLES
350 REM  THIS CALL COMMAND WILL FIND OUT THE SIZE OF THE FILE TO BE TRANSFERED
360 REM
370 CALL Vect_info(F$,Vtype,Vnumber)
380 Vnumb=Vnumber
390 PRINT Vnumber
400 ALLOCATE REAL Vd(1:Vnumb)

```

Figure 38. Error Data Transfer Program .

```

410 DISP " "
420 REM
430 REM ASSIGNING THE OUTPUT DEVICE TO SERIAL PORT
440 REM
450 ASSIGN @Serial TO 16
460 REM
470 REM RETRIEVING THE ARRAY FROM IT'S BDAT FORM
480 REM
490 CALL Get_array(Fs,Vd(*))
500 DISP "NOW TRANSFERING THE FILE.... PLEASE WAIT"
510 K=Vnumb/6
520 FOR J=0 TO K-1
530 REM OUTPUTING THE DATA POINT TO THE SERIAL PORT
540 M=Vd(J*6+6)
550 O=Vd(J*6+3)
560 OUTPUT 16:O;" ";M
570 NEXT J
580 DISP "FILE TRANSFER IS NOW COMPLETE"
590 END

```

Figure 38. Error Data Transfer Program.

APPENDIX B

SAMPLE DATA RUNS

This listing gives a sample of the Hewlett Packard computer screen display for each data point taken during one of the thickness prediction data runs, using the noncontact transducer device in the cylindrical test specimen. Specimen nominal thickness for this listing was 4.226 mm. Test temperature range was from 9.0 to 270.6 °C.

```

                                SPECIMEN THICKNESS PREDICTION DATA

OPERATOR:  Larson, Robb E.      RUN NUMBER 1
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

    NOMINAL SPECIMEN THICKNESS    = 0.1664 in
    *PREDICTED SPECIMEN THICKNESS = 0.1664 in

    WAVE VELOCITY CORRELATION
    U = -2.93E-6*T^3 +.00256*T^2-.974*T+5859

AT RUN 1  CONDITIONS:
    SPECIMEN THICKNESS (nominal) =      0.16636 in
                                      4.2254 mm
    (U vs T curve) =      0.16636 in
                                      4.2254 mm

THICKNESS PREDICTION MEASUREMENT ERROR = 7.31474470939E-7 inch

    TIME PERIOD OF ECHO PULSES 1.4445 us
    SPECIMEN WAVE VELOCITY = 19194.09ft/s
                              5850.36 m/s

-----RUN 1 CONDITIONS -----

SPECIMEN TEMPERATURE outside surface= 48.319 F
                                      9.066 C
SPECIMEN TEMPERATURE inside surface = 48.289 F
                                      9.049 C
AVERAGE SPECIMEN TEMPERATURE = 48.303 F
                              9.058 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 2
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1661 in

WAVE VELOCITY CORRELATION
 $V = -2.93E-6 \cdot T^3 + .00256 \cdot T^2 - .974 \cdot T + 5859$

AT RUN 2 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16636 in
4.2254 mm
(V vs T curve) = 0.16613 in
4.2196 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000229701264665 inch

TIME PERIOD OF ECHO PULSES 1.4425 us
SPECIMEN WAVE VELOCITY = 19220.71 ft/s
5858.47 m/s

-----RUN 2 CONDITIONS -----

SPECIMEN TEMPERATURE outside surface = 48.337 F
9.078 C
SPECIMEN TEMPERATURE inside surface = 48.283 F
9.046 C
AVERAGE SPECIMEN TEMPERATURE = 48.310 F
9.061 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 3
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1554 in
*PREDICTED SPECIMEN THICKNESS = 0.1602 in

WAVE VELOCITY CORRELATION
 $V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$

AT RUN 3 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16654 in
4.2302 mm
(U vs T curve) = 0.16639 in
4.2264 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000150434879654 inch

TIME PERIOD OF ECHO PULSES 1.4575 us
SPECIMEN WAVE VELOCITY = 19044.30ft/s
5804.70 m/s

-----RUN 3 CONDITIONS -----

```
SPECIMEN TEMPERATURE outside surface= 187.986 F
                                         86.659 C
SPECIMEN TEMPERATURE inside surface = 144.111 F
                                         62.284 C
AVERAGE SPECIMEN TEMPERATURE =166.049 F
                               74.472 C
```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 4
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 49.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1663 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5959$$

AT RUN 4 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16655 in
4.2303 mm
(V vs T curve) = 0.16646 in
4.2282 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -8.59668753625E-5 inch

TIME PERIOD OF ECHO PULSES 1.4585 μ s
SPECIMEN WAVE VELOCITY = 19032.01 ft/s
5800.96 m/s

-----RUN 4 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 192.007 F
                                         88.893 C
SPECIMEN TEMPERATURE inside surface = 148.525 F
                                         64.735 C
AVERAGE SPECIMEN TEMPERATURE =170.266 F
                               76.815 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 5
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1662 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00250 * T^2 - .974 * T + 5859$$

AT RUN 5 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16665 in
4.2328 mm
(U vs T curve) = 0.16649 in
4.2288 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000158025471253 inch

TIME PERIOD OF ECHO PULSES 1.4635 μ s
SPECIMEN WAVE VELOCITY = 18977.95ft/s
5784.48 m/s

-----RUN 5 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 277.578 F
                                           136.432 C
SPECIMEN TEMPERATURE inside surface = 182.091 F
                                           83.384 C
AVERAGE SPECIMEN TEMPERATURE =229.834 F
                               109.908 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 6
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1662 in

WAVE VELOCITY CORRELATION

$$U = -2.93E-6 * T^3 + .00250 * T^2 - .974 * T + 5859$$

AT RUN 5 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.18673 in
4.2348 mm
(U vs T curve) = 0.18657 in
4.2308 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000158532645789 inch

TIME PERIOD OF ECHO PULSES 1.4675 us
SPECIMEN WAVE VELOCITY = 18935.32ft/s
5771.49 m/s

-----RUN 6 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 355.275 F
                                         179.597 C
SPECIMEN TEMPERATURE inside surface = 202.680 F
                                         94.822 C
AVERAGE SPECIMEN TEMPERATURE =278.977 F
                               137.209 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 7
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1662 in

WAVE VELOCITY CORRELATION
 $V = -2.93E-8 \cdot T^3 + .00256 \cdot T^2 - .974 \cdot T + 5859$

AT RUN 7 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16688 in
4.2388 mm
(V vs T curve) = 0.16668 in
4.2337 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00019744533877 inch

TIME PERIOD OF ECHO PULSES 1.4735 us
SPECIMEN WAVE VELOCITY = 18875.71 ft/s
5753.32 m/s

-----RUN 7 CONDITIONS -----

SPECIMEN TEMPERATURE outside surface= 523.594 F
273.109 C
SPECIMEN TEMPERATURE inside surface = 221.828 F
105.460 C
AVERAGE SPECIMEN TEMPERATURE = 372.711 F
189.284 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 8
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1564 in
*PREDICTED SPECIMEN THICKNESS = 0.1562 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 8 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16692 in
4.2397 mm
(U vs T curve) = 0.16679 in
4.2366 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000122867303784 inch

TIME PERIOD OF ECHO PULSES 1.4755 μ s
SPECIMEN WAVE VELOCITY = 18854.41 ft/s
5746.82 m/s

-----RUN 8 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 542.061 F
                                         283.367 C
SPECIMEN TEMPERATURE inside surface = 248.904 F
                                         120.502 C
AVERAGE SPECIMEN TEMPERATURE =395.482 F
                               201.935 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 9
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1657 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 9 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16704 in
4.2428 mm
(U vs T curve) = 0.16637 in
4.2258 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00066500804881 inch

TIME PERIOD OF ECHO PULSES 1.4745 μ s
SPECIMEN WAVE VELOCITY = 18880.69ft/s
5754.84 m/s

-----RUN 9 CONDITIONS -----

```
SPECIMEN TEMPERATURE outside surface= 638.944 F
                                           337.191 C
SPECIMEN TEMPERATURE inside surface = 294.240 F
                                           145.689 C
AVERAGE SPECIMEN TEMPERATURE =466.592 F
                               241.440 C
```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 10
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1659 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 10 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16710 in
4.2443 mm
(V vs T curve) = 0.16668 in
4.2336 mm

THICKNESS PREDICTION MEASUREMENT ERROR = $-.000420946751997$ inch

TIME PERIOD OF ECHO PULSES 1.4785 us
SPECIMEN WAVE VELOCITY = 18836.63ft/s
5741.41 m/s

-----RUN 10 CONDITIONS -----

```
SPECIMEN TEMPERATURE outside surface= 692.299 F
                                           366.933 C
SPECIMEN TEMPERATURE inside surface = 314.406 F
                                           156.892 C
AVERAGE SPECIMEN TEMPERATURE =503.352 F
                               261.852 C
```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 11
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1564 in
*PREDICTED SPECIMEN THICKNESS = 0.1565 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 11 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16713 in
4.2450 mm
(U vs T curve) = 0.16729 in
4.2483 mm

THICKNESS PREDICTION MEASUREMENT ERROR = .000166084704132 inch

TIME PERIOD OF ECHO PULSES 1.4845 μ s
SPECIMEN WAVE VELOCITY = 18763.51 ft/s
5719.12 m/s

-----RUN 11 CONDITIONS -----

```
SPECIMEN TEMPERATURE outside surface= 714.781 F
                                         379.323 C
SPECIMEN TEMPERATURE inside surface = 323.458 F
                                         161.921 C
AVERAGE SPECIMEN TEMPERATURE =519.120 F
                               270.622 C
```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 13
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1649 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 13 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16695 in
4.2406 mm
(U vs T curve) = 0.16545 in
4.2025 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00149344350257 inch

TIME PERIOD OF ECHO PULSES 1.4645 μ s
SPECIMEN WAVE VELOCITY = 19000.01 ft/s
5791.20 m/s

-----RUN 13 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 581.538 F
                                           305.299 C
SPECIMEN TEMPERATURE inside surface = 251.256 F
                                           121.809 C
AVERAGE SPECIMEN TEMPERATURE =418.397 F
                               213.554 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 14
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1655 in

WAVE VELOCITY CORRELATION

$$U = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 14 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.16694 in
4.2404 mm
(V vs T curve) = 0.16604 in
4.2174 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000900573060464 inch

TIME PERIOD OF ECHO PULSES 1.4695 us
SPECIMEN WAVE VELOCITY = 18934.44ft/s
5771.22 m/s

-----RUN 14 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 576.826 F
                                           302.681 C
SPECIMEN TEMPERATURE inside surface = 246.283 F
                                           119.046 C
AVERAGE SPECIMEN TEMPERATURE =411.554 F
                               210.853 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 15
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1653 in

WAVE VELOCITY CORRELATION
 $V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$

AT RUN 15 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16682 in
4.2372 mm
(U vs T curve) = 0.16574 in
4.2089 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00107304257529 inch

TIME PERIOD OF ECHO PULSES 1.4635 μ s
SPECIMEN WAVE VELOCITY = 18997.93ft/s
5790.57 m/s

-----RUN 15 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 478.236 F
                                         247.909 C
SPECIMEN TEMPERATURE inside surface = 195.654 F
                                         90.919 C
AVERAGE SPECIMEN TEMPERATURE =336.945 F
                               169.414 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 16
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1652 in

WAVE VELOCITY CORRELATION

$$V = -2.53E-8 * T^3 + .00256 * T^2 - .374 * T + 5959$$

AT RUN 15 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.16674 in
4.2352 mm
(V vs T curve) = 0.16560 in
4.2063 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00113446561769 inch

TIME PERIOD OF ECHO PULSES 1.4595 μ s
SPECIMEN WAVE VELOCITY = 19040.55 ft/s
5803.59 m/s

-----RUN 16 CONDITIONS -----

SPECIMEN TEMPERATURE outside surface= 410.845 F
210.470 C
SPECIMEN TEMPERATURE inside surface = 163.589 F
73.105 C

AVERAGE SPECIMEN TEMPERATURE =287.217 F
141.788 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

RUN NUMBER 18

```
SPECIMEN TEMPERATURE outside surface= 149.097 F
                                         65.054 C
SPECIMEN TEMPERATURE inside surface = 104.934 F
                                         40.519 C
AVERAGE SPECIMEN TEMPERATURE =127.016 F
                               52.787 C
```

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 19
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1667 in

WAVE VELOCITY CORRELATION
 $V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$

AT RUN 19 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16636 in
4.2254 mm
(U vs T curve) = 0.16669 in
4.2340 mm

THICKNESS PREDICTION MEASUREMENT ERROR = .000337212722811 inch

TIME PERIOD OF ECHO PULSES 1.4475 μ s
SPECIMEN WAVE VELOCITY = 19154.41 ft/s
5838.27 m/s

-----RUN 19 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface = 49.152 F
                                           9.529 C
SPECIMEN TEMPERATURE inside surface = 48.564 F
                                           9.202 C
AVERAGE SPECIMEN TEMPERATURE = 48.858 F
                               9.365 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. RUN NUMBER 20
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :

NOMINAL SPECIMEN THICKNESS = 0.1664 in
*PREDICTED SPECIMEN THICKNESS = 0.1669 in

WAVE VELOCITY CORRELATION

$$V = -2.93E-6 * T^3 + .00256 * T^2 - .974 * T + 5859$$

AT RUN 20 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.16636 in
4.2254 mm
(V vs T curve) = 0.16693 in
4.2400 mm

THICKNESS PREDICTION MEASUREMENT ERROR = .0005732884525 inch

TIME PERIOD OF ECHO PULSES 1.4495 μ s
SPECIMEN WAVE VELOCITY = 19127.92 ft/s
5830.19 m/s

-----RUN 20 CONDITIONS -----

```

SPECIMEN TEMPERATURE outside surface= 48.690 F
                                           9.272 C
SPECIMEN TEMPERATURE inside surface = 48.319 F
                                           9.066 C
AVERAGE SPECIMEN TEMPERATURE = 48.504 F
                               9.169 C

```

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.

This listing gives a sample of the Hewlett Packard computer screen display for each data point taken during one of the thickness prediction data runs, using the contact transducer device in the cylindrical test specimen. Specimen nominal thickness for this listing was 5.479 mm. Test temperature range was from 9.36 to 652.61 °C.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
MONTANA STATE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING
CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFPRED'

***** RUN NUMBER 1 *****

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 48.8642 F = 1.888E-6 seconds
THE CALCULATED WAVESPEED WAS = 5800.98224057 m/s

SPECIMEN TEMPERATURE outside surface = 48.1378 F
SPECIMEN TEMPERATURE inside surface = 48.591 F
AVERAGE SPECIMEN TEMPERATURE = 48.864 F

THE CORRECTED NOMINAL THICKNESS AT 48.8642 F = .215710877716 in
(using alpha) .00547905629399 m

THE CALCULATED HEATED THICKNESS AT 48.8642 F = .215710124851 in
(using V vs T curve) .00547903717122 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
SPECIMEN THICKNESS Nominal = .00547903742247
(METERS) Predicted = .00547901829976
SPECIMEN THICKNESS Nominal = .215710134743
(INCHES) Predicted = .21570938188

MEASUREMENT ERROR corrected to 48.5 degrees = -7.52862540865E-7 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 2 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION

$$V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$$

THE TIME PERIOD MEASURED AT 47.4359 F = 1.889E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5801.4145708 m/s

SPECIMEN TEMPERATURE outside surface = 47.4890 F
 SPECIMEN TEMPERATURE inside surface = 47.383 F
 AVERAGE SPECIMEN TEMPERATURE = 47.436 F

THE CORRECTED NOMINAL THICKNESS AT 47.4359 F = .215707964236 in
 (using alpha) .0054789822916 m

THE CALCULATED HEATED THICKNESS AT 47.4359 F = .215725829217 in
 (using V vs T curve) .00547943606212 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00547949119755
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .215727999904

MEASUREMENT ERROR corrected to 48.5 degrees = 1.78651606862E-5 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 3 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 173.7905 F = 1.917E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5765.23832261 m/s

SPECIMEN TEMPERATURE outside surface = 186.5552 F
 SPECIMEN TEMPERATURE inside surface = 161.026 F
 AVERAGE SPECIMEN TEMPERATURE = 173.791 F

THE CORRECTED NOMINAL THICKNESS AT 173.7905 F = .215968541675 in
 (using alpha) .00548560095855 m

THE CALCULATED HEATED THICKNESS AT 173.7905 F = .217558304418 in
 (using V vs T curve) .00552598093222 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00551936908139
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .21729799533

MEASUREMENT ERROR corrected to 48.5 degrees = .00158786058733 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 4 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION

$$V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$$

THE TIME PERIOD MEASURED AT 194.4491 F = 1.927E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5759.53148484 m/s

SPECIMEN TEMPERATURE outside surface = 205.5470 F
 SPECIMEN TEMPERATURE inside surface = 193.351 F
 AVERAGE SPECIMEN TEMPERATURE = 194.449 F

THE CORRECTED NOMINAL THICKNESS AT 194.4491 F = .216011691033 in
 (using alpha) .00548669695223 m

THE CALCULATED HEATED THICKNESS AT 194.4491 F = .21847671597 in
 (using V vs T curve) .00554930858565 m

AT A REFERENCE TEMPERATURE OF 48.5 F :

SPECIMEN THICKNESS	Nominal = .00547903742247
(METERS)	Predicted = .00554156164889
SPECIMEN THICKNESS	Nominal = .215710134743
(INCHES)	Predicted = .21817171846

MEASUREMENT ERROR corrected to 48.5 degrees = .00246158371758 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 5 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 373.7471 F = 1.94E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5711.9215424 m/s

SPECIMEN TEMPERATURE outside surface = 420.5714 F
 SPECIMEN TEMPERATURE inside surface = 326.923 F
 AVERAGE SPECIMEN TEMPERATURE = 373.747 F

THE CORRECTED NOMINAL THICKNESS AT 373.7471 F = .216392630593 in
 (using alpha) .00549637281705 m

THE CALCULATED HEATED THICKNESS AT 373.7471 F = .218132436856 in
 (using V vs T curve) .00554056389613 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .0055230891242
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .217444453709

MEASUREMENT ERROR corrected to 48.5 degrees = .00173431896593 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFRED'

***** RUN NUMBER 5 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 49.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.68E-7 \cdot T^3 + 2.86E-4 \cdot T^2 - .517 \cdot T + 5309$

THE TIME PERIOD MEASURED AT 491.7542 F = 1.95555E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5621.95692845 m/s

SPECIMEN TEMPERATURE outside surface = 947.3448 F
 SPECIMEN TEMPERATURE inside surface = 438.494 F
 AVERAGE SPECIMEN TEMPERATURE = 491.754 F

THE CORRECTED NOMINAL THICKNESS AT 491.7542 F = .218649854615 in
 (using alpha) .00553230122721 m

THE CALCULATED HEATED THICKNESS AT 491.7542 F = .218721783032 in
 (using V vs T curve) .00555553328502 m

AT A REFERENCE TEMPERATURE OF 49.5 F :
 SPECIMEN THICKNESS Nominal = .30547903742247
 (METERS) Predicted = .30553144124081
 SPECIMEN THICKNESS Nominal = .219713134743
 (INCHES) Predicted = .217773277197

MEASUREMENT ERROR corrected to 49.5 degrees = 1.00206314245452 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 7 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 595.8815 F = 1.9505E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5655.99644431 m/s

SPECIMEN TEMPERATURE outside surface = 648.3470 F
 SPECIMEN TEMPERATURE inside surface = 543.416 F
 AVERAGE SPECIMEN TEMPERATURE = 595.882 F

THE CORRECTED NOMINAL THICKNESS AT 595.8815 F = .216880604091 in
 (using alpha) .00550876734392 m

THE CALCULATED HEATED THICKNESS AT 595.8815 F = .218279154116 in
 (using V vs T curve) .00554429051454 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00551436888031
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .21710113702

MEASUREMENT ERROR corrected to 48.5 degrees = .00139100227738 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA ---

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRD'

***** RUN NUMBER 8 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 589.1207 F = 1.971E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5657.67481365 m/s

SPECIMEN TEMPERATURE outside surface= 640.7042 F
 SPECIMEN TEMPERATURE inside surface = 537.537 F
 AVERAGE SPECIMEN TEMPERATURE = 589.121 F

THE CORRECTED NOMINAL THICKNESS AT 589.1207 F = .21686549067 in
 (using alpha) .00550838346302 m

THE CALCULATED HEATED THICKNESS AT 589.1207 F = .219513327808 in
 (using V vs T curve) .00557563852885 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00554593418538
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .218343865566

MEASUREMENT ERROR corrected to 48.5 degrees = .00263373082329 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Lanson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 9 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5805$

THE TIME PERIOD MEASURED AT 596.7258 F = 1.971E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5658.26945242 m/s

SPECIMEN TEMPERATURE outside surface = 638.4886 F
 SPECIMEN TEMPERATURE inside surface = 536.963 F
 AVERAGE SPECIMEN TEMPERATURE = 586.726 F

THE CORRECTED NOMINAL THICKNESS AT 596.7258 F = .216660140934 in
 (using alpha) .00550824757973 m

THE CALCULATED HEATED THICKNESS AT 596.7258 F = .219536400976 in
 (using V vs T curve) .00557622456478 m

AT A REFERENCE TEMPERATURE OF 48.5 F :

SPECIMEN THICKNESS	Nominal = .00547903742247
(METERS)	Predicted = .00554665394645
SPECIMEN THICKNESS	Nominal = .215710134743
(INCHES)	Predicted = .218372202616

MEASUREMENT ERROR corrected to 48.5 degrees = .00266206797337 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 10 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 717.2402 F = 1.969E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5625.87910352 m/s

SPECIMEN TEMPERATURE outside surface = 777.8552 F
 SPECIMEN TEMPERATURE inside surface = 656.625 F
 AVERAGE SPECIMEN TEMPERATURE = 717.240 F

THE CORRECTED NOMINAL THICKNESS AT 717.2402 F = .217154689072 in
 (using alpha) .00551572910244 m

THE CALCULATED HEATED THICKNESS AT 717.2402 F = .218058188087 in
 (using V vs T curve) .00553867797742 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00550183363716
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .21660762351

MEASUREMENT ERROR corrected to 48.5 degrees = .000897488767389 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFPRED'

***** RUN NUMBER 11 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 770.099 F = 1.989E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5612.69113261 m/s

SPECIMEN TEMPERATURE outside surface = 635.3472 F
 SPECIMEN TEMPERATURE inside surface = 704.851 F
 AVERAGE SPECIMEN TEMPERATURE = 770.099 F

THE CORRECTED NOMINAL THICKNESS AT 770.099 F = .217275723806 in
 (using alpha) .00551890338467 m

THE CALCULATED HEATED THICKNESS AT 770.099 F = .219756745338 in
 (using V vs T curve) .00558182133158 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .005541601291
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .218173279173

MEASUREMENT ERROR corrected to 48.5 degrees = .00245314443034 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 12 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.15 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5606$

THE TIME PERIOD MEASURED AT 833.9792 F = 1.985E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5596.61562624 m/s

SPECIMEN TEMPERATURE outside surface = 904.7840 F
 SPECIMEN TEMPERATURE inside surface = 763.174 F
 AVERAGE SPECIMEN TEMPERATURE = 833.979 F

THE CORRECTED NOMINAL THICKNESS AT 833.9792 F = .217423335039 in
 (using alpha) .00552255270999 m

THE CALCULATED HEATED THICKNESS AT 833.9792 F = .218686653899 in
 (using V vs T curve) .00555464100904 m

AT A REFERENCE TEMPERATURE OF 48.5 F :

SPECIMEN THICKNESS	Nominal = .00547903742247
(METERS)	Predicted = .00551087287983
SPECIMEN THICKNESS	Nominal = .215710134743
(INCHES)	Predicted = .216963499206

MEASUREMENT ERROR corrected to 48.5 degrees = .00125336446287 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 13 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 921.1874 F = 1.996E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5574.30363923 m/s

SPECIMEN TEMPERATURE outside surface= 1015.7630 F
 SPECIMEN TEMPERATURE inside surface = 826.612 F
 AVERAGE SPECIMEN TEMPERATURE = 921.187 F

THE CORRECTED NOMINAL THICKNESS AT 921.1874 F = .217627219047 in
 (using alpha) .00552773136378 m

THE CALCULATED HEATED THICKNESS AT 921.1874 F = .219021851652 in
 (using V vs T curve) .00556315503195 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00551414904255
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .21709248199

MEASUREMENT ERROR corrected to 48.5 degrees = .0013823472472 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFRED'

***** RUN NUMBER 14 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION

$$V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$$

THE TIME PERIOD MEASURED AT 1076.5445 F = 2.0095E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5532.98253458 m/s

SPECIMEN TEMPERATURE outside surface= 1216.6556 F
 SPECIMEN TEMPERATURE inside surface = 936.433 F
 AVERAGE SPECIMEN TEMPERATURE = 1076.544 F

THE CORRECTED NOMINAL THICKNESS AT 1076.5445 F = .217997199685 in
 (using alpha) .00553712867199 m

THE CALCULATED HEATED THICKNESS AT 1076.5445 F = .218868669355 in
 (using V vs T curve) .00555926420162 m

AT A REFERENCE TEMPERATURE OF 48.5 F :

SPECIMEN THICKNESS	Nominal =	.00547903742247
(METERS)	Predicted =	.00550094052463
SPECIMEN THICKNESS	Nominal =	.215710134743
(INCHES)	Predicted =	.2165724616

MEASUREMENT ERROR corrected to 48.5 degrees = .000862326856668 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA ---

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 15 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 1120.8425 F = 2.0135E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5520.71538493 m/s

SPECIMEN TEMPERATURE outside surface= 1265.2376 F
 SPECIMEN TEMPERATURE inside surface = 976.447 F
 AVERAGE SPECIMEN TEMPERATURE = 1120.842 F

THE CORRECTED NOMINAL THICKNESS AT 1120.8425 F = .218104283923 in
 (using alpha) .00553984881164 m

THE CALCULATED HEATED THICKNESS AT 1120.8425 F = .218818118653 in
 (using V vs T curve) .00555798021378 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00549696979468
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .216416133649

MEASUREMENT ERROR corrected to 48.5 degrees = .000705998905942 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFPRED'

***** RUN NUMBER 16 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 1206.698 F = 2.0055E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5496.16171674 m/s

SPECIMEN TEMPERATURE outside surface= 1399.4204 F
 SPECIMEN TEMPERATURE inside surface = 1013.976 F
 AVERAGE SPECIMEN TEMPERATURE =1206.698 F

THE CORRECTED NOMINAL THICKNESS AT 1206.698 F = .21831383551 in
 (using alpha) .00554517142196 m

THE CALCULATED HEATED THICKNESS AT 1206.698 F = .216980166002 in
 (using V vs T curve) .00551129621646 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00544556622663
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .214392371127

MEASUREMENT ERROR corrected to 48.5 degrees = -.00131776361577 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA ---

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 17 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 973.9706 F = 2.0055E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5560.52525168 m/s

SPECIMEN TEMPERATURE outside surface= 1098.4928 F
 SPECIMEN TEMPERATURE inside surface = 849.448 F
 AVERAGE SPECIMEN TEMPERATURE = 973.971 F

THE CORRECTED NOMINAL THICKNESS AT 973.9706 F = .217751948602 in
 (using alpha) .0055308994945 m

THE CALCULATED HEATED THICKNESS AT 973.9706 F = .219520342367 in
 (using V vs T curve) .00557581669612 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00552353344501
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .217461946654

MEASUREMENT ERROR corrected to 48.5 degrees = .00175181191128 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONFPRED'

***** RUN NUMBER 18 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 50.5211 F = 1.881E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5800.50272878 m/s

SPECIMEN TEMPERATURE outside surface= 51.0692 F
 SPECIMEN TEMPERATURE inside surface = 49.973 F
 AVERAGE SPECIMEN TEMPERATURE = 50.521 F

THE CORRECTED NOMINAL THICKNESS AT 50.5211 F = .215732131241 in
 (using alpha) .00547959613393 m

THE CALCULATED HEATED THICKNESS AT 50.5211 F = .214778457339 in
 (using V vs T curve) .00545537281642 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547949138349
 (METERS) Predicted = .00545526852944
 SPECIMEN THICKNESS Nominal = .215728007224
 (INCHES) Predicted = .214774351553

MEASUREMENT ERROR corrected to 48.5 degrees = -.000953655671308 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA ---

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 19 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 678.5654 F = 1.961E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5635.48794494 m/s

SPECIMEN TEMPERATURE outside surface= 763.4912 F
 SPECIMEN TEMPERATURE inside surface = 593.640 F
 AVERAGE SPECIMEN TEMPERATURE = 678.565 F

THE CORRECTED NOMINAL THICKNESS AT 678.5654 F = .217066768599 in
 (using alpha) .00551349592241 m

THE CALCULATED HEATED THICKNESS AT 678.5654 F = .217543146851 in
 (using V vs T curve) .00552559593001 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00549106180689
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .216183535704

MEASUREMENT ERROR corrected to 48.5 degrees = .000473400961397 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 20 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 456.0872 F = 1.939E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5690.93383762 m/s

SPECIMEN TEMPERATURE outside surface = 523.0364 F
 SPECIMEN TEMPERATURE inside surface = 389.138 F
 AVERAGE SPECIMEN TEMPERATURE = 456.087 F

THE CORRECTED NOMINAL THICKNESS AT 456.0872 F = .216571442803 in
 (using alpha) .0055009146472 m

THE CALCULATED HEATED THICKNESS AT 456.0872 F = .217218911637 in
 (using V vs T curve) .00551736035558 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .005495417726
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .216355028583

MEASUREMENT ERROR corrected to 48.5 degrees = .00064469383991 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 21 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 303.5876 F = 1.927E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5730.18657305 m/s

SPECIMEN TEMPERATURE outside surface = 354.7886 F
 SPECIMEN TEMPERATURE inside surface = 252.387 F
 AVERAGE SPECIMEN TEMPERATURE = 303.588 F

THE CORRECTED NOMINAL THICKNESS AT 303.5876 F = .216242192656 in
 (using alpha) .00549255169345 m

THE CALCULATED HEATED THICKNESS AT 303.5876 F = .217363573352 in
 (using V vs T curve) .00552103476314 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00550745041035
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .216828756313

MEASUREMENT ERROR corrected to 48.5 degrees = .00111862157016 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 22 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.66E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 178.1069 F = 1.921E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5764.0415305 m/s

SPECIMEN TEMPERATURE outside surface = 192.3530 F
 SPECIMEN TEMPERATURE inside surface = 163.861 F
 AVERAGE SPECIMEN TEMPERATURE = 178.107 F

THE CORRECTED NOMINAL THICKNESS AT 178.1069 F = .215977544611 in
 (using alpha) .00548582963311 m

THE CALCULATED HEATED THICKNESS AT 178.1069 F = .217967003545 in
 (using V vs T curve) .00553636189004 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .00552950711353
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .217697130454

MEASUREMENT ERROR corrected to 48.5 degrees = .00198699571102 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.
 MONTANA STATE UNIVERSITY
 DEPARTMENT OF MECHANICAL ENGINEERING
 CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** RUN NUMBER 23 *****

304 STAINLESS STEEL SPECIMEN
 AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)

WAVE VELOCITY CORRELATION
 $V = -2.69E-7 \cdot T^3 + 2.69E-4 \cdot T^2 - .537 \cdot T + 5806$

THE TIME PERIOD MEASURED AT 47.6465 F = 1.887E-6 seconds
 THE CALCULATED WAVESPEED WAS = 5801.35227831 m/s

SPECIMEN TEMPERATURE outside surface = 47.7950 F
 SPECIMEN TEMPERATURE inside surface = 47.498 F
 AVERAGE SPECIMEN TEMPERATURE = 47.646 F

THE CORRECTED NOMINAL THICKNESS AT 47.6465 F = .215708393777 in
 (using alpha) .00547899320184 m

THE CALCULATED HEATED THICKNESS AT 47.6465 F = .215495113173 in
 (using V vs T curve) .00547357587459 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
 SPECIMEN THICKNESS Nominal = .00547903742247
 (METERS) Predicted = .0054736200514
 SPECIMEN THICKNESS Nominal = .215710134743
 (INCHES) Predicted = .215496852417

MEASUREMENT ERROR corrected to 48.5 degrees = -.000213282325681 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.

APPENDIX C

DATA TRANSFER PROCEDURE

The following procedure documents the series of steps used during this research to transfer raw data, as recorded by the Hewlett Packard computer and Hewlett Packard data acquisition system, to an IBM compatible computer. Future researchers may have to modify this procedure for any different equipment used.

1. Attach cable from Hewlett Packard 9000 series computer RS232 serial port (ref: S/N 9837_ 2515A00537) to the IBM compatible computer communications port, "com1." (ref: Zenith Data Systems, S/N 625CE1883.)

2. Load the controlling data transfer program, corresponding to the data to be transferred, into the Hewlett Packard computer. (e.g., 'C1trans', ref: appendix A.)

3. Load program "Smartcom Exec" into the IBM compatible computer. ("Smartcom Exec", copyright 1990 & 1991, version 2.0A, by Hayes Microcomputer Products, Inc. Reference: License no. 93-00297.)

4. Use the curser in the IBM compatible screen to select the "on-line" menu within program "Smartcom Exec." Then select "H.P. Series 340" from the "phone book entries" listed.

5. Choose "Down load from H.P. Series 340 [D]," and type the name of the data file into which you wish to deposit incoming data. (e.g., "TEST1.DAT".)

6. "Run" the program on the Hewlett Packard computer: Enter the filename per the prompt displayed on the Hewlett Packard screen. Include the path, and note that the Hewlett Packard machine is case sensitive. (e.g., "TEST1:,707,0" versus "test1:,707,0" .) Do NOT yet key in 'enter.'

7. Key in 'Return' on the IBM compatible machine FIRST, then immediately (within 15 seconds) key in 'enter' on the Hewlett Packard machine. If the transfer has been made successfully, the data string will appear on the IBM compatible screen, per the format delineated in the program run on the Hewlett Packard machine.

8. Repeat for new data sets and/or programs. Data may now be utilized in IBM compatible graphing or data processing programs.

APPENDIX D

TRANSDUCER SPECIFICATIONS



221 Crescent St Waltham MA 02154
Tel: 800-225-8330, 617-899-2740
Fax: 617-899-1552

TRANSDUCER DESCRIPTION

PART NO.: V203 FREQUENCY: 10.0 MHz
SERIAL NO.: 149704 ELEMENT SIZE: .125" DIA.
DESIGNATION: CONTACT

TEST INSTRUMENTATION

PULSER/RECEIVER: PANAMETRICS 5052 UA: #1
DIGITAL OSCILLOSCOPE: LECROY 9400-V2.06FT #1
COMPUTER PROGRAM: VER 1.4 SETUP: DWG. #5979
CABLE: RG-174/U LENGTH: 4 FT.

TEST CONDITIONS

PULSER ENERGY: 1
PULSER DAMPING: 50 ohm
RECEIVER SETTING: 40 dB GAIN / 42 dB ATTENUATION
TARGET: BACK WALL OF .22" POLYSTYRENE

MEASUREMENTS PER ASTM E1065

PEAK FREQUENCY ---- 10.8 MHz WAVEFORM DURATION:
CENTER FREQUENCY -- 10.6 MHz @ -14dB LEVEL -- .118 us
UPPER FREQ @ -6dB -- 15.2 MHz @ -20dB LEVEL -- .158 us
LOWER FREQ @ -6dB -- 6.00 MHz @ -40dB LEVEL -- .305 us
@ -6dB BANDWIDTH --- 86.8 % FOCAL LENGTH ----

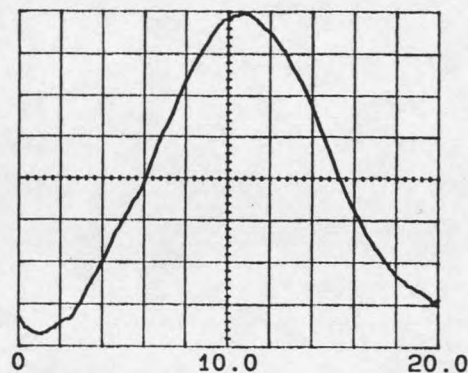
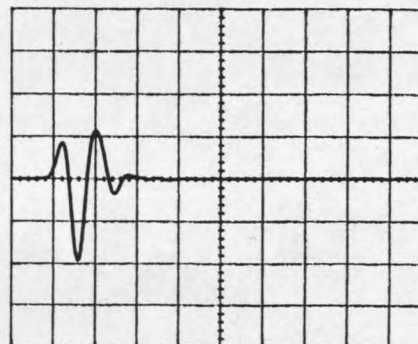
COMMENTS:

TECHNICIAN: (1) *Karen Mohr* DATE: 02-11-91

TRANSDUCER CERTIFICATION

WAVEFORM

VERTICAL SENSITIVITY: 200 mv/div
HORIZONTAL RESOLUTION: .10 us/div



SPECTRUM
SCALE FORMAT: LINEAR (MHZ)

Shown below is the calibration documentation for the contact transducer,
Panametrics part number V203-RM.

Figure 41. Contact Transducer Specifications.



PANAMETRICS

221 CRESCENT STREET WALTHAM, MA 02254
(617) 899-2719/1-800-225-8130
TELEX: 6817337/1 AX: 6178991552

TRANSDUCER DESCRIPTION

P/N V311 FREQ: 10.0MHZ DIAM: .500"
S/N133199 FOCUSED IMMERISION
DESIGN FOCAL LENGTH: 2.000" PTF

TEST INSTRUMENTATION

PANAMETRICS 5052 UA: #3
ENERGY SETTING: 1
PULSER DAMPING: 50ohms
RECEIVER ATTENUATION: 30dB
CABLE: RG-58/U LENGTH: 1FT.

LECROY9400-V2.06FT DIGITAL OSCILLOSCOPE: #1

TEST CONDITIONS

ECHO FROM FRONT SURFACE OF .13" BALL-STEEL
WATER PATH: 2.138" FOCUSED AT: 2.138"
COMPUTER PROGRAM: VER. 1.2 SETUP: DWG. #5978

ASTM E1065 MEASUREMENTS

PEAK FREQUENCY	-----	10.8MHZ	WAVEFORM DURATION:
CENTER FREQUENCY	----	10.1MHZ	@-14dB LEVEL .210usec
UPPER FREQUENCY @-6dB		13.2MHZ	@-20dB LEVEL .263usec
LOWER FREQUENCY @-6dB		6.90MHZ	@-40dB LEVEL .443usec
BANDWIDTH	-----	62.7%	

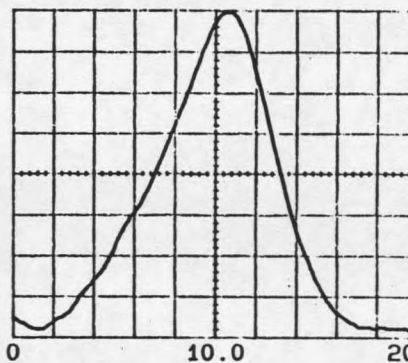
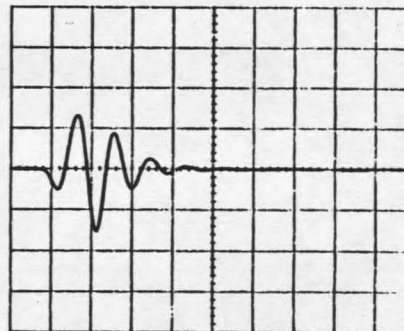
COMMENTS:

TECHNICIAN: (3)

DATE: 01-11-90

WAVEFORM

VERTICAL SENSITIVITY: 200mv/div
HORIZONTAL SENSITIVITY: .10us/div



SPECTRUM
SCALE FORMAT: LINEAR (MHZ)

Shown below is the calibration documentation for the noncontact transducer,
Panametrics part number V311.

Figure 42. Noncontact Transducer Specifications.

APPENDIX E

TORCH HEATING TIP INSTRUCTIONS

The text of the manufacturer's instructions for use of the Smith Welding Equipment, Inc. torch heating tip is shown below:

ST630 HEATING TIP Instruction Sheet

Use with Natural Gas and Oxygen

The ST630 can be used with Natural Gas and oxygen at a wide range of pressure settings. The injector design of the tip provides fine performance and large volumes of heat at fuel gas pressure settings from 3 ounces per square inch (5 inches water pressure) to 10 lbs. per sq. in.

TIP NO.	FUEL GAS	GAS PRES.	O2 PRES.	GAS CONS.	O2 CONS.
ST630	Natural gas	3 ounces to 10 psi	30 PSI	107*	190*

*Flows based on 3 oz. natural gas pressure at 30 PSI oxygen pressure, with 50 ft. 3/8" I.D. hose.

LIGHTING AND ADJUSTMENT

A. When fuel gas supply pressure is less than 1 PSI:

1. Open torch fuel valve approx. one turn and light.
2. Open torch oxygen valve to neutral flame setting.
3. Open torch fuel valve wide open, at least 3 full turns.
4. Open torch oxygen valve to desired flame setting.

B. When fuel gas supply pressure is 1 PSI and over:

1. Open torch fuel valve approx. 1/8 turn and light.
2. Continue opening fuel valve until flame starts to leave the tip end.
3. Open torch oxygen valve to neutral flame setting.
4. Continue opening the fuel and oxygen valves alternately until the desired flame setting is reached.

FLASHBACK: Heating tips will flashback if starved or excessively overheated. If flashback occurs, shut off OXYGEN FIRST--and FAST

Flashback is the result of one or more of the following conditions:

1. Insufficient gas supply.
2. Insufficient regulator capacity
3. Restrictions from too many hose fittings.
4. Starved flame setting

The National Board of Fire Underwriters requires a hydraulic back pressure valve to be used when the gas pressure is 1 lb. or less. A line type regulator should be used on line installations when supply pressure is over 1 pound.

IMPORTANT: Head nut may loosen if tip is starved or overheated. If flame appears around head nut, then retighten head nut.

APPENDIX F

OREGON STATE UNIVERSITY HIGH TEMPERATURE FLUIDIZED BED SPECIFICATIONS

The specifications for the Oregon State University High Temperature Fluidized Bed test facility are as follows:

Cross sectional area of the bed:	2 ft x 1 ft (0.61 m x .30 m.).
Height of the primary test section:	4 ft (1.22 m)
Cross sectional area of the bed disengaging zone:	2 ft x 2 ft (0.61 m x 0.61 m)
Height of the disengaging zone:	4 ft (1.22 m)
Method of heating the bed:	Propane combustion to preheat fluidizing gas stream
Design operating temperature:	1600 F. (871 C.)
Maximum superficial velocity:	15 ft/sec (4.57 m/s)
Distributor plate design:	Perforated 316 SST plate with 7/32" dia. holes on 3/4" centers
Compressor design:	Positive displacement rotary blower
Entrained solids collection:	Cyclone separator equipped with a collection bucket. No continuous recycling of solids.

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