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.
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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December 1992
APPROVAL
of a thesis submitted by
Robb Edward Larson

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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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>x</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. DATA ACQUISITION SYSTEM</td>
<td>8</td>
</tr>
<tr>
<td>3. PLANAR TESTING, NONCONTACT TRANSDUCER</td>
<td>11</td>
</tr>
<tr>
<td>4. CYLINDRICAL TEST SPECIMEN DESIGN</td>
<td>19</td>
</tr>
<tr>
<td>5. CYLINDRICAL TESTING, NONCONTACT TRANSDUCER</td>
<td>26</td>
</tr>
<tr>
<td>Wave Speed Determination</td>
<td>26</td>
</tr>
<tr>
<td>Thickness Measurement</td>
<td>34</td>
</tr>
<tr>
<td>6. PLANAR TESTING, CONTACT TRANSDUCER</td>
<td>42</td>
</tr>
<tr>
<td>7. CYLINDRICAL TESTING, CONTACT TRANSDUCER</td>
<td>48</td>
</tr>
<tr>
<td>8. SUMMARY and CONCLUSIONS</td>
<td>57</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>62</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>64</td>
</tr>
<tr>
<td>Appendix A - Computer Programs</td>
<td>65</td>
</tr>
<tr>
<td>Wave Speed Determination Program, Noncontact Test</td>
<td>66</td>
</tr>
<tr>
<td>Thickness Measurement Program, Noncontact Test</td>
<td>72</td>
</tr>
<tr>
<td>Wave Speed Determination Program, Contact Test</td>
<td>80</td>
</tr>
<tr>
<td>Thickness Measurement Program, Contact Test</td>
<td>85</td>
</tr>
<tr>
<td>Wave Speed Data Transfer Program</td>
<td>93</td>
</tr>
<tr>
<td>Thickness Data Transfer Program</td>
<td>95</td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
<td>----</td>
</tr>
<tr>
<td>Error Data Transfer Program</td>
<td>97</td>
</tr>
<tr>
<td>Appendix B - Sample Data Runs.</td>
<td>99</td>
</tr>
<tr>
<td>Sample Thickness Measurement Data Run, Noncontact Transducer</td>
<td>100</td>
</tr>
<tr>
<td>Sample Thickness Measurement Data Run, Contact Transducer</td>
<td>120</td>
</tr>
<tr>
<td>Appendix C - Data Transfer Procedure</td>
<td>143</td>
</tr>
<tr>
<td>Appendix D - Transducer Specifications</td>
<td>145</td>
</tr>
<tr>
<td>Appendix E - Torch Heating Tip Instructions</td>
<td>148</td>
</tr>
<tr>
<td>Appendix F - Oregon State University High Temperature</td>
<td></td>
</tr>
<tr>
<td>Fluidized Bed Specifications</td>
<td>150</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Typical Ultrasonic Dimensional Inspection Apparatus</td>
<td>4</td>
</tr>
<tr>
<td>2. Sample Oscilloscope Waveform</td>
<td>5</td>
</tr>
<tr>
<td>3. Data Acquisition System Apparatus</td>
<td>10</td>
</tr>
<tr>
<td>4. Noncontact Planar Test Apparatus</td>
<td>12</td>
</tr>
<tr>
<td>5. Planar Specimen Wave Speed Correlation</td>
<td>14</td>
</tr>
<tr>
<td>6. Planar Test Specimen Design</td>
<td>15</td>
</tr>
<tr>
<td>7. Thickness Measurements for Planar Specimens</td>
<td>16</td>
</tr>
<tr>
<td>8. Thickness Measurements for Planar Specimens</td>
<td>17</td>
</tr>
<tr>
<td>9. Measurement Error versus Temperature for Planar Specimens</td>
<td>18</td>
</tr>
<tr>
<td>10. Thermal Expansion Relationships for Stainless Steel</td>
<td>20</td>
</tr>
<tr>
<td>11. Cylindrical Test Specimen Design</td>
<td>22</td>
</tr>
<tr>
<td>12. Cylindrical Test Specimen Design</td>
<td>23</td>
</tr>
<tr>
<td>13. Cylindrical Test Specimen Design</td>
<td>24</td>
</tr>
<tr>
<td>14. Cylindrical Test Specimen Design</td>
<td>25</td>
</tr>
<tr>
<td>15. Noncontact Cylindrical Test Apparatus</td>
<td>27</td>
</tr>
<tr>
<td>16. Wave Speed Calibration Test Specimen</td>
<td>29</td>
</tr>
<tr>
<td>17. Wave Speed versus Temperature for 304 Stainless Steel</td>
<td>33</td>
</tr>
<tr>
<td>18. Typical Oscilloscope Waveform</td>
<td>35</td>
</tr>
</tbody>
</table>
LIST OF FIGURES-continued

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>19. Measured Wall Thickness versus Average Specimen Temperature</td>
<td>38</td>
</tr>
<tr>
<td>20. Measured Wall Thickness versus Average Specimen Temperature</td>
<td>39</td>
</tr>
<tr>
<td>21. Measurement Error versus Temperature, Cylindrical Tests</td>
<td>40</td>
</tr>
<tr>
<td>22. Measurement Error versus Temperature, Cylindrical Tests</td>
<td>41</td>
</tr>
<tr>
<td>23. Experimental Contact Transducer Extension Tips</td>
<td>45</td>
</tr>
<tr>
<td>24. Planar Test Apparatus, Contact Transducer</td>
<td>46</td>
</tr>
<tr>
<td>25. Cylindrical Test Apparatus, Contact Transducer</td>
<td>49</td>
</tr>
<tr>
<td>26. Wave Speed versus Temperature for 304 Stainless Steel</td>
<td>52</td>
</tr>
<tr>
<td>27. Measured Wall Thickness versus Average Specimen Temperature</td>
<td>53</td>
</tr>
<tr>
<td>28. Measured Wall Thickness versus Average Specimen Temperature</td>
<td>54</td>
</tr>
<tr>
<td>29. Measurement Error versus Temperature, Cylindrical Tests</td>
<td>55</td>
</tr>
<tr>
<td>30. Measurement Error versus Temperature, Cylindrical Tests</td>
<td>56</td>
</tr>
<tr>
<td>31. Contact Transducer Alignment Fixture</td>
<td>59</td>
</tr>
<tr>
<td>32. Wave Speed Determination Program, Noncontact Test</td>
<td>66</td>
</tr>
<tr>
<td>33. Thickness Measurement Program, Noncontact Test</td>
<td>72</td>
</tr>
<tr>
<td>34. Wave Speed Determination Program, Contact Test</td>
<td>80</td>
</tr>
<tr>
<td>35. Thickness Measurement Program, Contact Test</td>
<td>85</td>
</tr>
<tr>
<td>36. Wave Speed Data Transfer Program</td>
<td>93</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES - continued

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>37. Thickness Data Transfer Program</td>
<td>95</td>
</tr>
<tr>
<td>38. Error Data Transfer Program</td>
<td>97</td>
</tr>
<tr>
<td>39. Sample Thickness Measurement Data Run, Noncontact Transducer</td>
<td>100</td>
</tr>
<tr>
<td>40. Sample Thickness Measurement Data Run, Contact Transducer</td>
<td>120</td>
</tr>
<tr>
<td>41. Contact Transducer Specifications</td>
<td>146</td>
</tr>
<tr>
<td>42. Noncontact Transducer Specifications</td>
<td>147</td>
</tr>
</tbody>
</table>
NOMENCLATURE

α  thermal expansion coefficient, in/in/°F

°C  degrees Centigrade

CRT  cathode ray tube

dc  direct current

E  thickness measurement error

°F  degrees Farenheight

HP-IB  Hewlett Packard Interface Bus

in  inch

kHz  kilohertz, i.e. $10^3$ cycles per second

L  length, m

La  specimen thickness at ambient temperature, m

La,i  specimen thickness at ambient temperature, in

Lh  elevated temperature specimen thickness, m

Lp,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.
- **Tave**: average specimen temperature, °C.
- **Tave,F**: average specimen temperature, °F.
- **Ta**: ambient temperature, °C.
- **Ta,F**: ambient temperature, °F.
- **Tin**: temperature measured at inside surface of specimen, °C.
- **Tref**: reference temperature, 9.16 °C. (48.5 °F.)
- **Tout**: temperature measured at outside surface of specimen, °C.
- **V**: sonic wave velocity, m/s
- **Va**: ambient temperature wave velocity, m/s
- **V.D.C.**: volts, direct current
- **Vh**: elevated temperature wave velocity, m/s
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 discreet 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.

![Sample Oscilloscope Waveform](image)

**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;

\[ L = \frac{V \times P}{2} \]

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) +/-(.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.
6. A Hewlett Packard HP54502A Digitizing Oscilloscope. [400 MHz bandwidth, risetime 3.5 nanoseconds, dual curser accuracy (dc) +/- 2% of scale +.032 x volts/division, time base reference accuracy 0.01%, repetitive delta time accuracy +/-(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.
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
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;

\[ V_a = 2 \times \frac{L_a}{P} \]  

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;

\[ E = L_{p,ref} - L_{ref} \]  

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.
WAVE VELOCITY CHARACTERISTICS
THREE 316 S.S. SPECIMENS
10–185°C \( V = -0.614792T + 5828.19 \)
185–260°C \( V = -0.46359T + 5814.05 \)
BY: BARBARA BAXTER

---

**Figure 5.** Planar Specimen Wave Speed Correlation.
HOLES ON 2.50 DIA CIRCLE.

SECTION A-A

TYPE J THERMOCOUPLE LOCATIONS

RECTANGULAR GROOVE, DEPTH 0.04, WIDTH 0.09 TYP. 2 PL.

(all dimensions in inches)

NOTE: THREE SPECIMEN THICKNESSES, 0.200 in. 0.179 in. 0.152 in.

drawn by: ELPEL, JEANNE

date 8/29/89 scale: REDUCED COPY NOT TO SCALE

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.
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 "Ta".

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:

\[ V_a = \frac{2 \times L_a}{P} \]  

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.

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;

\[ T_{ave} = \frac{(T_{in} + T_{out})}{2} \]
This temperature, "Tave", was checked to verify that it was within 1 °C. of that used as "Ta" 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;

\[
L_a = V_a \times \frac{P}{2}
\]

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 \( \alpha \), 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) \( \alpha = 8.33 \times 10^{-10} \times T_{a,F} + 9.41165 \times 10^{-6} \)

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

(8) \( L_h = L_{a,i} \times 0.0254 \times \left[ 1 + \alpha \times (T_{ave,F} - T_{a,F}) \right] \)

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

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.

Polynomial curvefit for data:
\[ y = -2.93E-6x^3 + 0.00256x^2 - 0.974x + 5859. \text{ var:} 150, \text{ max dev:} 27.4 \]
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.](image)

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;

\[
V_a = -2.93 \times 10^{-6} \times T_{ave}^3 + .00255 \times T_{ave}^2 - .974 \times T_{ave} + 5859
\]

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;

\[
L_a = V_a \times \frac{P}{2}
\]
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 curve fit equation;

\[
V_h = -2.93 \times 10^{-6} \times T_{ave}^3 + 0.00255 \times T_{ave}^2 - 0.974 \times T_{ave} + 5859
\]

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;

\[
L_h = V_h \times \frac{P}{2}
\]
This elevated temperature thickness was normalized to a reference thickness at a reference temperature of 9.16 °C. (48.5 °F.) using the \( \alpha \) value calculated as follows;

\[
(14) \quad L_{\text{ref}} = L_h \times 0.0254 / \left( \alpha \times (T_{\text{ave,F}} - 48.5) + 1 \right)
\]

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;

\[
(15) \quad E = L_{p,\text{ref}} - L_{\text{ref}}
\]

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.
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 non-contact 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:

\[ V_h = -2.66 \times 10^{-7} \times T_{ave}^3 + 2.69 \times 10^{-4} \times T_{ave}^2 - 0.537 \times T_{ave} + 5806 \]  

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.
Polynomial curvefit for data:

$$ y = +3.15E-7x^1 + 5.50, \text{ var:} 8.81E-4, \text{ max dev:} 0.0574 $$

![Graph of Measured Wall Thickness versus Average Specimen Temperature.](image)

**Figure 27.** Measured Wall Thickness versus Average Specimen Temperature.
Polynomial curvefit for data:

\[ y = -1.27 \times 10^{-4}x^4 + 4.27, \text{ var: } 0.00214, \text{ max dev: } 0.0862 \]

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.
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.

![Contact Transducer Alignment Fixture](image)

**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.
REFERENCES CITED
REFERENCES CITED


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.

Figure 32. Wave Speed Determination Program, Noncontact Test.
Figure 32. Wave Speed Determination Program, Noncontact Test.
Figure 32. Wave Speed Determination Program, Noncontact Test.
69

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; micro seconds”
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; micro seconds”
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$)
1640 IF Volt>Voltpeak THEN
1650 Voltpeak=Volt
1660 Tpeak1=Loop1
1670 ELSE
1680 END IF
1690 NEXT Loop1
1700 REM SET START MARKER AT Tpeak (THE TIME AT THE FIRST VOLTAGE PEAK)
1710 OUTPUT 707;”MEAS:START ”&VAL$(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$)
1810 IF Volt>Voltpeak THEN
1820 Voltpeak=Volt
1830 Tpeak2=Loop2
1840 ELSE
1850 END IF
1860 NEXT Loop2
1870 REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
1880 OUTPUT 707;”MEAS:STOP ”&VAL$(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.
Figure 32. Wave Speed Determination Program, Noncontact Test.
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.

Figure 33. Thickness Measurement Program, Noncontact Test.
73

REM Tpeak : time at which Voltpk occurs
REM TdS : string variable called in TDelta function
REM Period : numerical value of TdS
REM Wave : calculated wavespeed of stainless steel specimen
REM Nominal : nominal wall thickness calculated by calibration
REM Info(*) : variable array to store data point collection
REM File# : file name to save data on disk
REM FS : file string used in function call SAVE_rvect
REM Runnum : run number
REM Channel : thermocouple channel number
REM Voltage : voltage for measuring TC temp at active junction
REM Uref : reference voltage for TC
REM Tref : reference temperature for TC
REM Tin(*) : inside temperature array
REM Tout(*) : outside temperature array
REM Tavef(*) : average temperature (degrees F)
REM Tavec(*) : average temperature (degrees C)
REM Alpha : thermal expansion coefficient
REM Hthick : heated thickness, inches
REM Refthick : predicted specimen thickness in inches
REM Thickerr : difference between predicted thickness and actual measured specimen thickness, corrected to 48.5 C.
REM Refthickm : predicted specimen thickness in meters
REM Uavef(*) : wave velocity (ft/s)
REM Uavec(*) : wave velocity (m/s)
REM Mhthick : heated thickness, meters
REM BEGIN PROGRAM
REM
REM CLEAR SCREEN
O P T I O N B A S E 1
DIM Info(150)
DIM FileS(15)
DIM FS(14)
DIM Tin(25)
DIM Tout(25)
DIM Tavef(25)
DIM Tavec(25)
DIM Tinf(25)
DIM Toutf(25)
DIM Wave(25)
DIM Uave(25)
CALL Sys_init("P")
REM RESET THE OSCILLOSCOPE TO ITS DEFAULT PARAMETERS
CLEAR 707;
"RST"
OUTPUT 707;":DISP:CONNECT ON"
OUTPUT 707;":CHANNEL1:RANGE .32"
OUTPUT 707;":CHANNEL1:OFFSET .025"
OUTPUT 707;":WAVEFORM:RECORD FULL"
REM THE TIME RANGE VALUE IS 10 TIMES THE TIME PER DIVISION

Figure 33. Thickness Measurement Program, Noncontact Test.
CLEAR SCREEN
PRINT USING "5/"
RS=""
PRINT "IF YOU WANT TO MAKE A CALIBRATION RUN, PRESS <RETURN>"
PRINT "IF YOU WANT TO ENTER THE NOMINAL THICKNESS, PRESS <N>"
INPUT RS
IF RS="N" OR RS="n" THEN
CLEAR SCREEN
INPUT "ENTER NOMINAL THICKNESS in meters", Nominal
GOTO 3480
END IF
PRINT
FOR I=1 TO 150 STEP 6
C=(I+5)/6
PRINT "DATA ACQUISITION SYSTEM IS TAKING TEMPERATURE MEASUREMENTS"
CALL Dcvst39(V3>)
CALL Dcvst38(V2>)
CALL Dcvst37(V1>)
Tref=10*V3
Tin(C)=FNThmc(V1,"E",Tref)
Tave(C)=(Tin(C)+Tout(C))/2
Tinf(C)=Tin(C)*1.8+32
Toutf(C)=Tout(C)*1.8+32
PRINT "INSIDE WALL TEMPERATURE = "; Tin(C);" Degrees C  "; Tinf(C);" Degrees F"
PRINT "OUTSIDE WALL TEMPERATURE = "; Tout(C);" Degrees C  "; Toutf(C);" Degrees F"
REM CALCULATE WAVE VELOCITY AS A FUNCTION OF AVERAGE TEMPERATURE
REM Wavespeed correlation from 6/23/92
Wavet=-2.33E-9*(Tave(C)**3)+.00256*(Tave(C)**2)-.974*Tave(C)+5859
Ewavet=(Wavet/6254)
PRINT "AVGAE WALL TEMPERATURE = "; Tave(C);" Degrees C  "; Ewavet;" in/sec"
PRINT "Wavespeed used to establish specimen thickness is "; Ewavet;" m/sec" OR "Wavet;" m/s"
INPUT Rs="" OR Rs=""X" THEN
clear screen
Figure 33. Thickness Measurement Program, Noncontact Test.
75

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$;
1480 CLEAR SCREEN
1490 PRINT "PRESS <local> THEN <delta t/V markers> ON THE OSCILLOSCOPE PANEL TO"
1500 PRINT "USE THE TIME MARKERS TO FIND THE RANGE OF THE PEAKS OF INTEREST"
1510 INPUT "ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED ",Begin;
1520 INPUT "ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED ",Finish;
1530 REM
1540 CLEAR SCREEN
1550 PRINT "ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF"
1560 PRINT "  " &Begin-.008;  AND " &Begin+.008;  microseconds"
1570 REM
1580 PRINT USING "5/"
1590 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1600 PRINT "  " &Finish-.008;  AND " &Finish+.008;  microseconds"
1610 REM TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE
1620 OUTPUT 707: "STOP"
1630 REM SEARCH WAVEFORM FOR MAXIMUM VOLTAGE PEAKS
1640 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1650 REM
1660 REM THE RANGE OF Loop1 IS THE TIME INTERVAL (in microseconds)
1670 REM AT WHICH THE FIRST VOLTAGE PEAK OCCURS
1680 LET Voltpeak=0
1690 LET Volt=0
1700 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1710 LET Volt=0
1720 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1730 REM MEASURE THE VOLTAGE AT THE TIME Loop1
1740 OUTPUT 707: "MEASURE:TIME?" &VAL$(Loop1) &" US"
1750 LET Volt=VAL(Vtm$)
1760 IF Volt>Voltp then
1770 Voltp=Volt
1780 Tpeak1=Loop1
1790 ELSE END IF
1800 NEXT Loop1
1810 END IF
1820 NEXT Loop1
1830 REM SET START MARKER AT Tpeak (THE TIME AT THE FIRST VOLTAGE PEAK)
1840 OUTPUT 707: "MEAS:ISTART " &VAL$(Tpeak1) &" US"
1850 REM THE RANGE OF Loop2 IS THE TIME INTERVAL (in microseconds)
1860 REM AT WHICH THE SECOND VOLTAGE PEAK OCCURS
1870 LET Voltp=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.
```plaintext
1910  OUT PUT '707i':'MEASURE:TIME? "&VAL$(Loop2)&" US"
1920  ENTER '707i':tm8
1930  LET Volt=VAL(Utm$)
1940  IF Volt>Volteek THEN
1950    Volteek=Volt
1960  Teeek2=Loop2'
1970  ELSE
1980  END IF
1990  NEXT Loop2
2000  REM SET STOP MARKER AT Tpeek (THE TIME AT THE SECOND VOLTAGE PEAK)
2010  OUTPUT '707i':'MEAS:STOP "&VAL$(Tpeek2)&" US"
2020  REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
2030  OUTPUT '707i':'MEASURE:IDELTA?'
2040  ENTER '707i':Tdelta
2050  Period=VAL(Tdelta)
2060  CLEAR SCREEN
2070  PRINT USING "5/"
2080  PRINT 'THE TIME PERIOD MEASURED WAS = "(Period)" seconds'
2090  PRINT 'THE WAVESPEED CALCULATED WAS = "Wavet" m/s'
2100  REM
2110  REM CALCULATE THE THICKNESS FROM THE MEASURED PERIOD
2120  REM ESTABLISH NOMINAL THICKNESS FOR CALIBRATION RUN
2130  IF I=I THEN
2140    Nominal=Wavet*Period/2
2150  PRINT 'THE NOMINAL ROOM TEMPERATURE THICKNESS = "(Nominal)" m';Nominal/ .02544;" in"
2160  R$=""
2170  INPUT "PRESS RETURN TO CONTINUE MAKING MEASUREMENTS",R$
2180  ELSE
2190  PRINT 'THE NOMINAL ROOM TEMPERATURE THICKNESS = "(Nominal)" m';Nominal/ .02544;" in"
2200  R$=""
2210  INPUT "PRESS <N> IF NOMINAL THICKNESS IS INCORRECT, PRESS <RETURN> TO CONT"
2220  IF (R$="N" OR R$="n") THEN
2230    INPUT "ENTER NOMINAL THICKNESS in meters",Nominal
2240  ELSE
2250  END IF
2260  INPUT "PRESS <T> TO MEASURE TIME INTERVAL AGAIN, PRESS <RETURN> TO CONT"
2270  IF (R$="T" OR R$="t") THEN
2280    CLEAR SCREEN
2290  GOTO 1480
2300  ELSE
2310  END IF
2320  END IF
2330  IF I=I THEN
2340    CLEAR SCREEN
2350  GOTO 3480
2360  ELSE
2370  END IF
2380  END IF
2350  REM CALCULATE THERMAL EXPANSION
2400  Alpha=0.0000000833*Tavef(C)+0.000054255
```

Figure 33. Thickness Measurement Program, Noncontact Test.
REM WAVESPEED CALCULATION IS IN m/s
2450 Wave(C)=2*Mthick/Period
2460 Wave(C)=2*(Hthick/12)/Period

CLEAR SCREEN

REM CALCULATE SPECIMEN THICKNESS AT AVERAGE TEMPERATURE
2480 Hthick2=Ewave2*Period/2

REM CALCULATE SPECIMEN THICKNESS AT REFERENCE TEMPERATURE OF 48.5 F
2490 Refthick=Hthick2/(Alpha+Uavef(C)-48.5) +1

REM CALCULATE SPECIMEN THICKNESS AT REFERENCE TEMPERATURE OF 48.5 F
2500 Thickerr=Refthick-Nominal/.0254

PRINT "THE TIME PERIOD MEASURED AT "Uavef(C);" F = "Period," seconds"
2520 PRINT "THE HEATED WAVESPEED MEASURED WAS = "Wavet/" m/s"
2530 PRINT "THE CALCULATED WAVESPEED WAS = "Wavet/m/s"
2540 PRINT

REM PRINT "THE CORRECTED NOMINAL THICKNESS AT "Uavef(C);" F = "Hthick;" in"
2560 PRINT "(using alpha) "Mthick; m"
2570 PRINT 'THE CALCULATED HEATED THICKNESS AT "Uavef(C);" F = "Hthick2;" in"
2580 PRINT "(using V vs T curve) "Hthick2/.0254; "m"

PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F :"
2590 PRINT "SPECIMEN THICKNESS Nominal = "Nominal/.0254
2600 PRINT "(inches) Predicted = "Refthick
2610 PRINT "SPECIMEN THICKNESS Nominal = "Nominal
2620 PRINT "(METERS) Predicted = "Refthickm

REM PRINT "Measurement error, corrected to 48.5 degrees C = "Thickerr," INCH"
2630 REM

REM * OUTPUT INFORMATION
2640 REM  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

PRINT USING "20A.35A"; "SPECIMEN THICKNESS PREDICTION DATA"
2650 PRINT "OPERATOR: Larson, Robb E. RUN NUMBER",C-I
2660 PRINT "MONTANA STATE UNIVERSITY"
2670 PRINT "304 STAINLESS STEEL SPECIMEN"
2680 PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C) :"
2690 PRINT "NOMINAL SPECIMEN THICKNESS = "Nominal/.0254; "in"
2700 PRINT "PREDICTED SPECIMEN THICKNESS = "Refthick"ki in"

Figure 33. Thickness Measurement Program, Noncontact Test.
PRINT "WAVE VELOCITY CORRELATION"
PRINT "V = -2.83E-6*T^3 +.00256*T^2 - .974*T +5859"
PRINT "AT R = 1"
PRINT USING "5X,38A,2.5D,3A","SPECIMEN THICKNESS (nominal) = ""hthick; " in"
PRINT USING "43A,D,4D",""hthick*25.4; " mm"
PRINT USING "58X,18A,2.5D,3A","(V vs T curve) = ""hthick2; " in"
PRINT USING "43A,D,4D",""hthick2*25.4; " mm"
PRINT "THICKNESS PREDICTION MEASUREMENT ERROR = ""thicker; " inch"
PRINT USING "5X,27A,D,4D,3A","TIME PERIOD OF ECHO PULSES = ""Period*100"
PRINT USING "5X,25A,7D,2D,4A","SPECIMEN WAVE VELOCITY = ""Ewave(C); " ft/s"
PRINT USING "32A,4D,2D",""Wave(C); m/s"
PRINT
PRINT USING "13A,3D,19A","-----RUN C-1----- CONDITIONS -----"
PRINT USING "36A,3D,3D","SPECIMEN TEMPERATURE outside surface = ""Tout(C); F"
PRINT USING "38A,3D,3D",""Tout(C); C"
PRINT USING "36A,3D,3D","SPECIMEN TEMPERATURE inside surface = ""Tinf(C); F"
PRINT USING "38A,3D,3D",""Tinf(C); C"
PRINT USING "36A,3D,3D","AVERAGE SPECIMEN TEMPERATURE = ""Tavef(C); F"
PRINT USING "38A,3D,3D",""Tavef(C); C"
PRINTER IS 1
END IF
REM RESTART DATA ACQUISITION TO MAKE ANOTHER READING
OUTPUT 707,"RUN"
REM STORE INFORMATION ON DISK
REM "DO YOU WANT TO SAVE THIS DATA POINT TO A DISK ? "
INPUT "PRESS <enter> TO SAVE PRESS <X> TO ABORT SAVE",R$
IF R$="x" THEN
I=I-6
CLEAR SCREEN
GOTO 3480
ELSE
END IF
INPUT "NAME THE DATA FILE...(8 chs max, RETURN for previous; DRIVE 703,1)", File$
Runnum=C
Info(I)=Nominal
Info(I+1)=Refthick
Info(I+2)=Tavef(C)
Info(I+3)=Hthick
Info(I+4)=Hthick2
Info(I+5)=Thicker
PRINT "RUN NUMBER ";Runnum-1

Figure 33. Thickness Measurement Program, Noncontact Test.
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.

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 UTIME function
520 REM Volt : numerical value of Vtm$
530 REM Voltpeak : 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 ++++++++++++++++++++++++++++++++++++++++T+=?+++++++++++++++++++++++T-+-+-+++++++
660 REM
670 CLEAR SCREEN
680 REM
690 OPTION BASE 1
700 DIM Dpoint(75)
710 DIM File$(14)
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 8.0000 US"
860 OUTPUT 707;":TRIG:SOURCE CHAN1"
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.
510 REM 8
520 FOR I=1 TO 74 STEP 3
530 PRINTER IS 701
540 CALL Sys_init(“F”)  
550 CALL Dcvsi39(V4)  
560 CALL Dcvsi36(V1)  
570 CALL Dcvsi37(V2)  
580 CALL Dcvsi38(V3)  
590 TR=1
600 Ttrans=FNThmc(V1,“J”,Tr)
610 Tinside=FNThmc(V2,“E”,Tr)
620 Toutside=FNThmc(V3,“E”,Tr)
630 Taverage=.5*(Tinside+Toutside)  
640 REM PRINT TEMPERATURES
650 REM  
660 PRINT “---------------------------------------------------------------”  
670 PRINT “TRANSUCER BACKSHELL TEMP IS “,Ttrans,” DEGREES C”  
680 PRINT “OUTSIDE WALL TEMP=” ,Toutside,” DEG C”  
690 PRINT “AVERAGE WALL TEMP=” ,Taverage,” DEG C”  
700 PRINT “INSIDE WALL TEMP=” ,Tinside,” DEG C”  
710 PRINTER IS 1
720 REM
730 PRINT “---------------------------------------------------------------”  
740 PRINT “TRANSUCER BACKSHELL TEMP IS “,Ttrans,” DEGREES C”  
750 PRINT “OUTSIDE WALL TEMP=” ,Toutside,” DEG C”  
760 PRINT “AVERAGE WALL TEMP=” ,Taverage,” DEG C”  
770 PRINT “INSIDE WALL TEMP=” ,Tinside,” DEG C”  
780 REM
790 PRINT “PRESS RETURN IF ALL OSCILLOSCOPE SETTINGS ARE APPROPRIATE”  
800 INPUT “MAKE ADJUSTMENTS IF NECESSARY THEN PRESS RETURN TO CONTINUE” ,RS
810 CLEAR SCREEN
820 PRINT “PRESS <local> THEN <delta t/V markers> ON THE SCOPE PANEL TO”  
830 PRINT “USE THE TIME MARKERS TO FIND THE RANGE OF THE FIRST VOLTAGE PEAK”  
840 INPUT “ENTER THE TIME (in microseconds) WHERE THE FIRST PEAK IS LOCATED” ,Here
850 INPUT “ENTER THE TIME (in microseconds) WHERE THE SECOND PEAK IS LOCATED” ,There
860 REM
870 PRINT USING “10/”  
880 PRINT “ATTEMPTING TO FIND THE FIRST VOLTAGE PEAK BETWEEN THE RANGE OF”  
890 PRINT “ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF”  
900 PRINT  
910 PRINT USING “10/”  
920 PRINT “TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE”  
930 OUTPUT 707,”STOP”  
940 REM MEASURE THE TIME AT WHICH THE FIRST PEAK OCCURS
950 FOR Lp1=Here-.006 TO Here+.006 STEP .0002
960 REM MEASURE THE VOLTAGE AT THE TIME Lp1
970 OUTPUT 707,”MEASURE|VTIME? “,VAL$|Lp1|&” US”

Figure 34. Wave Speed Determination Program, Contact Test.
Figure 34. Wave Speed Determination Program, Contact Test.
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.

Figure 35. Thickness Measurement Program, Contact Test.
Figure 35. Thickness Measurement Program, Contact Test.
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/U 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 "  " Begin-,.008;  AND  "Begin+,008; microseconds"
1570 REM
1580 PRINT USING "$/"
1590 PRINT "ATTEMPTING TO FIND THE SECOND VOLTAGE PEAK BETWEEN THE RANGE OF"
1600 PRINT "  Finish-.008;  AND  ;Finish+,008; microseconds"
1610 REM
1620 PRINT "TEMPORARILY STOP DATA ACQUISITION SO MEASUREMENTS CAN BE MADE"
1630 OUTPUT 707;:"STOP"
1640 REM SEARCH WAVEFORM FOR MAXIMUM VOLTAGE PEAKS
1650 REM LOOP ALGORITHM TO MEASURE VOLTAGES AND COMPARE VALUES
1660 REM
1670 REM
1680 REM THE RANGE OF Loop1 IS THE TIME INTERVAL (in microseconds)
1690 REM AT WHICH THE FIRST VOLTAGE PEAK OCCURS
1700 LET Voltpeak=0
1710 LET Volt=0
1720 FOR Loop1=Begin-.008 TO Begin+.008 STEP .0005
1730 REM MEASURE THE VOLTAGE AT THE TIME Loop1
1740 OUTPUT 707;:"MEASURE =  VTIME? "&VAL$(Loop1)&" US"
1750 ENTER 707;Vtm$
1760 LET Volt=VAL(Vtm$
1770 IF Volt=Voltpeak THEN
1780 Voltpeak=Volt
1790 TpeakI=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 microseconds)
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.
89

1510 OUTPUT 707;"MEASURE:VTIME? &VAL$(Loop2)&" US"
1520 ENTER 707;Vtn$
1530 LET Volt=VAL$(Vtn$)
1540 IF Volt>Voltpk THEN
1550 Voltpk=Volt
1560 Tpk2=Loop2
1570 ELSE
1580 END IF
1590 NEXT Loop2
2000 REM SET STOP MARKER AT Tpeak (THE TIME AT THE SECOND VOLTAGE PEAK)
2010 OUTPUT 707;"MEAS:STOP &VAL$(Tpeak2)&" US"
2020 REM MEASURE THE TIME INTERVAL BETWEEN START AND STOP MARKERS
2030 OUTPUT 707;"MEASURE:TDELTA?"
2040 ENTER 707;Tdl$
2050 Period=VAL$(Tdl$)
2060 CLEAR SCREEN
2070 PRINT USING "$/
2080 PRINT "THE TIME PERIOD MEASURED W A S  = " ,Period;" seconds"
2090 PRINT "THE WAVESPEED CALCULATED W A S  = " ,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/0.0254; " in"
2160 RS=""
2170 INPUT "PRESS RETURN TO CONTINUE MAKING MEASUREMENTS",RS
2180 ELSE
2190 PRINT "THE NOMINAL ROOM TEMPERATURE THICKNESS = " ,Nominal; " m" ,Nominal/0.0254; " in"
2200 RS=""
2210 INPUT "PRESS <N> IF NOMINAL THICKNESS IS INCORRECT, PRESS <RETURN> TO CONTINUE",RS
2220 IF (RS="N" OR RS="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 CONTINUE",RS
2270 IF (RS="T" OR RS="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=0.0000000000833+Tevef(C)+0.0000094165

Figure 35. Thickness Measurement Program, Contact Test.
REM WAVE SPEED CALCULATION IS IN m/s
CLEAR SCREEN
REM CALCULATE SPECIMEN THICKNESS AT AVERAGE TEMPERATURE
Hthick = Ewavet + Period/2
REM CALCULATE SPECIMEN THICKNESS AT REFERENCE TEMPERATURE OF 48.5 F
Refthick = Hthick2/(Alpha * (Tavef(C) - 48.5) + 1)
Thickerr = Refthick - (Nominal / .0254)
PRINT "THE TIME PERIOD MEASURED AT " Tavef(C) " F = " Periods " seconds"
PRINT "THE CALCULATED WAVE SPEED WAS " Wave " m/s"
PRINT
PRINT
PRINT "THE CORRECTED NOMINAL THICKNESS AT " Tavef(C) " F = " Hthick " in"
PRINT " (using alpha)"
PRINT "Mhthick " m"
PRINT
PRINT "THE CALCULATED HEATED THICKNESS AT " Tavef(C) " F = " Hthick2 " in"
PRINT " (using V vs T curve)"
PRINT "Hthick2 " in"
PRINT "Nominal/.0254"

PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F:
PRINT "SPECIMEN THICKNESS Nominal = "Nominal/.0254
PRINT "inches"
PRINT Predicted = "Refthick"
PRINT "METERS"
PRINT Predicted = "Refthickm"
REM
REM "Measurement error, corrected to 48.5 degrees C = "Thickerr, " INCH"
REM
REM "PRESS <P> TO PRINT DATA (RETURN) TO CONTINUE", R$&"=
REM * OUTPUT INFORMATION*
PRINT "OPERATOR: Larson, Robb E."
PRINT "MONTANA STATE UNIVERSITY"
PRINT "DEPARTMENT OF MECHANICAL ENGINEERING"
PRINT "CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: CONPRED"
PRINT "RUN NUMBER" C-I" "
PRINT "304 STAINLESS STEEL SPECIMEN"
PRINT "AT A REFERENCE TEMPERATURE OF 48.5 F (9.16 C)"
PRINT

Figure 35. Thickness Measurement Program, Contact Test.
91

PRINT "WAVE VELOCITY CORRELATION"
PRINT "V = -2.66E-7*T^3 + 2.66E-4*T^2 - .537*T + 5800" 
PRINT 
PRINT "THE TIME PERIOD MEASURED AT Tavef(C) = Period; seconds"
PRINT "THE CALCULATED WAVESPEED WAS = Wave;' m/s"
PRINT 
PRINT USING "38A.4D.4D"; "SPECIMEN TEMPERATURE outside surface = Toutf(C) ; F" 
PRINT USING "38A.3D.3D"; "SPECIMEN TEMPERATURE inside surface = Tinf(C) ; F"
PRINT USING "38A.3D.3D"; "AVERAGE SPECIMEN TEMPERATURE = Tavef(C) ; F"
PRINT 
PRINT "THE CORRECTED NOMINAL THICKNESS AT Tavef(C) ; F = Hthick1; in" 
PRINT " (using alpha) " Hthick1; m" 
PRINT 
PRINT "THE CALCULATED HEATED THICKNESS AT Tavef(C) ; F = Hthick2; in" 
PRINT " (using V vs T curve) " Hthick2* .0254; " m"
PRINT 
PRINT "MEASUREMENT ERROR (corrected to 48.5 degrees C.) = Thickerr; INCH"

Figure 35. Thickness Measurement Program, Contact Test.
Figure 35. Thickness Measurement Program, Contact Test.

3410 Info(I+2)=Tavec('C)
3420 Info(I+3)=Hnick
3430 Info(I+4)=Hthick1
3440 Info(I+5)=Thickerr
3450 PRINT "FUN NUMBER";Runnum-1
3460 Fl=File$".703.1"
3470 CALL Save_rect(Info(*),Fl)
3480 REM
3490 CLEAR SCREEN
3500 PRINT "DATA SET NUMBER";Runnum-1;"OF 25 ALLOWABLE SETS WAS JUST SAVED"
3510 INPUT "PRESS RETURN TO MAKE ANOTHER MEASUREMENT",R$
3520 REM RESTART MEASUREMENT PROGRAM
3530 NEXT I
3540 END
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 WAVE SPEED CALIBRATIONS TO
30 REM CREATE WAVE SPEED VS. TEMPERATURE CURVE.
40 REM
50 REM THIS PROGRAM TRANSFER DATA FILES FROM HP5000 540 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.EXE, AND SELECT HP540 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 ORINIGALLY CREATED BY
180 REM CHARLES FERRES
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 VnumDtr
290 INTEGER Vtype
300 DIM F#(20)
310 DISC "INPUT FILE " AND ADDRESS TO BE TRANSFERED:
320 INPUT F#
330 REM
340 REM DIMENSIONING THE VARIABLES
350 CALL Vect_info(F#,Vtype,Vnumb)
360 Vnumb+Vnumb
370 CALL Print Vnumb
380 PRINT Vnumb
390 REM
400 ALLOCATE REAL var1(1:Vnumb)

Figure 36. Wavespeed Data Transfer Program.
```
94

410 DISP "  
420 REM
430 REM ASSIGNING THE OUTPUT DEVICE TO SERIAL PORT
440 REM
450 ASSIGN GSerial TO I B
460 REM
470 REM RETRIEVING THE ARRAY FROM ITS BOAT FORM
480 REM
490 CALL Get_array(F$,Vd(\n))
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.

Figure 37. Thickness Data Transfer Program.
96

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(F$,%d[*])
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;0;" " ;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.

```plaintext
10 REM PROGRAM "ERRTRANS" FOR H.P. DATA ACQUISITION SYSTEM
20 REM FOR DATA TRANSFER FOLLOWING THICKNESS PREDICTION TESTS, TO
30 REM CREATE THICKNESS MEASUREMENT ERROR VS. TEMPERATURE CURVE.
40 REM THIS PROGRAM TRANSFERS DATA FILES FROM HP9000 340 TO AN IBM
50 REM IBM COMPATIBLE MACHINE
60 REM BE SURE THAT BEFORE RUNNING THIS PROGRAM, THE IBM IS READY
70 REM TO ACCEPT THE FILE. CONFIGURE THE IBM TO ACCEPT DATA WITH
80 REM PROGRAM SMARTCOM.EXEC, AND SELECT HP340 AS DEVICE TYPE.
90 REM THIS PROGRAM WRITTEN BY ROBB E. LARSON
100 REM DEPARTMENT OF MECHANICAL ENGINEERING
110 REM MONTANA STATE UNIVERSITY
120 REM BASED UPON A PROGRAM ORIGINALLY CREATED BY
130 REM CARL FEHRES
140 REM MONTANA STATE UNIVERSITY
150 REM DEPARTMENT OF MECHANICAL ENGINEERING
160 REM JUNE 1981
170 CALL Sys_init("P")
180 REM OPTION TO SET THE ARRAY TO START AT 0 INSTEAD OF 1
190 REM OPTION BASE 0
200 REAL Vnumber
210 INTEGER Vtype
220 DIM Fs(200)
230 DISP "INPUT FILE NAME AND ADDRESS TO BE TRANSFERRED;"
240 INPUT Fs
250 REM DIMENSIONING THE VARIABLES
260 REM THIS CALL COMMAND WILL FIND OUT THE SIZE OF THE FILE TO BE TRANSFERRED
270 CALL Vect_info(Fs,Vtype,Vnumber)
280 Vnumb=Vnumber
290 PRINT Vnumb
300 REM 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 REM ASSIGN @Serial TO 16
460 REM
470 REM RETRIEving THE ARRAY FROM IT'S BOAT FORM
480 REM
490 CALL Get_array(F$,$ Va(♦ ))
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 16:01: " iM
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.  
**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**

\[ V = -2.93E^{-6}T^3 + 0.00256T^2 - 0.974T + 5.959 \]

**AT RUN 1 CONDITIONS:**

**SPECIMEN THICKNESS (nominal)** = 0.16636 in  
**SPECIMEN THICKNESS (V vs T curve)** = 0.16636 in  
**TIME PERIOD OF ECHO PULSES** = 1.4445 us  
**SPECIMEN WAVE VELOCITY** = 19194.05 ft/s  
**THICKNESS PREDICTION MEASUREMENT ERROR** = 7.3147470333E-7 inch

**SPECIMEN TEMPERATURE outside surface** = 48.319 F  
**SPECIMEN TEMPERATURE inside surface** = 48.288 F  
**AVERAGE SPECIMEN TEMPERATURE** = 48.303 F

---

**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
\[ V = -2.93E-6 \times T^3 + 6.02E-3 \times T^2 - 9.34 \times T + 5859 \]

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 = -0.00229701264665 inch

TIME PERIOD OF ECHO PULSES 1.4425 us
SPECIMEN WAVE VELOCITY = 5859.47 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 = 49.310 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 (9.15 C) :

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

WAVE VELOCITY CORRELATION
V = -2.93E-6*T^3 + .0025E*T^2 -.974*T+5859

AT RUN 3 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16664 in
4.2302 mm

(V 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 = 15044.30 ft/s
5884.70 m/s

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

SPECIMEN TEMPERATURE outside surface = 187.986 F
96.659 C
SPECIMEN TEMPERATURE inside surface = 144.111 F
62.264 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 48.5 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 + 7.02E-7*T^2 - .74*T + 5859

AT RUN 4 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.1655 in
4.2303 mm
(V vs T curve) = 0.1654 in
4.2262 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -8.596687536255E-5 inch

TIME PERIOD OF ECHO PULSES 1.4565 us
SPECIMEN WAVE VELOCITY = 19032.01 ft/s
5800.96 m/s

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

SPECIMEN TEMPERATURE outside surface = 192.007 F
88.833 C
SPECIMEN TEMPERATURE inside surface = 148.525 F
64.736 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 40.5 F (9.16 C):

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

WAVE VELOCITY CORRELATION
\[ V = -2.83E-6 \cdot T^{-3} + 0.0256 \cdot T^{-2} - 0.974 \cdot T + 5859 \]

AT RUN 5 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16655 in
(V vs T curve) = 0.16649 in

THICKNESS PREDICTION MEASUREMENT ERROR = -.000158025471253 inch

TIME PERIOD OF ECHO PULSES 1.4635 us
SPECIMEN WAVE VELOCITY = 18977.95 ft/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

\[ V = -2.93E-6 \times T^3 + .00256 \times T^2 - .974 \times T + 5859 \]

AT RUN 6 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.16673 in
                                    4.2348 mm
(U vs T curve) = 0.16657 in
                    4.2308 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.000158532645789 inch

TIME PERIOD OF ECHO PULSES 1.4675 \( \mu \)s
SPECIMEN WAVE VELOCITY = 18935.32 ft/s
                        5771.49 m/s

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

SPECIMEN TEMPERATURE outside surface = 355.275 F
                                      179.597 C
SPECIMEN TEMPERATURE inside surface = 202.660 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-6*T^3 + .00256*T^2 -.974*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
273.108 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.
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 = 0.1664 in
PREDICTED SPECIMEN THICKNESS = 0.1662 in

WAVE VELOCITY CORRELATION

\[ V = -2.93 \times 10^{-5} T^3 + 0.00256 T^2 - 0.974 T + 5859 \]

AT RUN 8 CONDITIONS:

SPECIMEN THICKNESS (nominal) = 0.16692 in

\[ (V \text{ vs } T \text{ curve}) = 0.16678 \text{ in} \]

THICKNESS PREDICTION MEASUREMENT ERROR = -.00122867303784 inch

TIME PERIOD OF ECHO PULSES 1.4755 us
SPECIMEN WAVE VELOCITY = 18854.41 ft/s

\[ 5746.82 \text{ m/s} \]

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

SPECIMEN TEMPERATURE outside surface = 542.061 F

\[ 283.357 \text{ C} \]

SPECIMEN TEMPERATURE inside surface = 248.904 F

\[ 120.502 \text{ C} \]

AVERAGE SPECIMEN TEMPERATURE = 355.462 F

\[ 201.835 \text{ C} \]

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
\[ V = -2.93E^{-6}T^3 + 0.00256T^2 - 0.374T + 6269 \]

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 = -0.006650804881 inch

TIME PERIOD OF ECHO PULSES 1.4745 us
SPECIMEN WAVE VELOCITY = 18880.69 ft/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 = 466.582 F 241.440 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.
OPERATOR: Larson, Robb E. RUN NUMBER 10
MONTANA STATE UNIVERSITY

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

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

WAVE VELOCITY CORRELATION
V = -2.37E-8 * T^3 + .00256 * T^2 - .974 * T + 5.659

AT RUN 10 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16710 in
(specimen) = 0.16668 in

THICKNESS PREDICTION MEASUREMENT ERROR = -0.000420945751997 inch

TIME PERIOD OF ECHO PULSES 1.4785 us
SPECIMEN WAVE VELOCITY = 18836.52 ft/s
5741.41 m/s

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

SPECIMEN TEMPERATURE outside surface = 692.29 F
366.833 C
SPECIMEN TEMPERATURE inside surface = 314.406 F
156.892 C
AVERAGE SPECIMEN TEMPERATURE = 503.352 F
261.862 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.
OPERATOR: Larson, Robb E. RUN NUMBER 11
MONTANA STATE UNIVERSITY

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (9.18 C):

NOMINAL SPECIMEN THICKNESS = 0.1664 in
PREDICTED SPECIMEN THICKNESS = 0.1665 in

WAVE VELOCITY CORRELATION
\[ V = -2.93E-6 \cdot T^3 + 0.00255 \cdot T^2 - 0.974 \cdot T + 5859 \]

AT RUN 11 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16713 in
SPECIMEN THICKNESS (V vs T curve) = 0.16729 in

THICKNESS PREDICTION MEASUREMENT ERROR = .000166084704132 inch

TIME PERIOD OF ECHO PULSES 1.4845 us
SPECIMEN WAVE VELOCITY = 18753.51 ft/s
5718.12 m/s

---- RUN 11 CONDITIONS ----

SPECIMEN TEMPERATURE outside surface = 714.761 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.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larsen, Robb E.
MONTANA STATE UNIVERSITY

324 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
\[ V = -2.93E-5 \times T^3 + 0.0255 \times T^2 - 0.974 \times T + 5859 \]

AT RUN 12 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16707 in
4.2436 mm
(V vs T curve) = 0.16641 in
4.2258 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -0.000650640854298 inch

TIME PERIOD OF ECHO PULSES 1.4755 us
SPECIMEN WAVE VELOCITY = 18871.49 ft/s
5752.03 m/s

-----RUN 12 CONDITIONS-----

SPECIMEN TEMPERATURE outside surface = 680.711 F
360.395 C
SPECIMEN TEMPERATURE inside surface = 290.124 F
143.402 C
AVERAGE SPECIMEN TEMPERATURE = 465.417 F
251.898 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E. 
MONTANA STATE UNIVERSITY

RUN NUMBER 13

304 STAINLESS STEEL SPECIMEN
AT A REFERENCE TEMPERATURE OF 48.5 F (8.65 C):

NOMINAL SPECIMEN THICKNESS = 0.1654 in
PREDICTED SPECIMEN THICKNESS = 0.1649 in

WAVE VELOCITY CORRELATION
\[ V = -2.93 \times 10^{-6} T^3 + 0.00258 T^2 - 0.974 T + 5859 \]

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

THICKNESS PREDICTION MEASUREMENT ERROR = -0.00149344350257 inch

TIME PERIOD OF ECHO PULSES 1.4645 us
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 = 416.397 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
\[ V = -2.93 \times 10^{-5} T^3 + 0.00256 T^2 - 0.074 T + 58.59 \]

AT RUN 14 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16694 in
4.2404 mm
\( (V \text{ vs } T \text{ curve}) = 0.16604 \text{ in} \)
4.2174 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -0.000980573050464 inch

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

-----RUN 14 CONDITIONS-----
SPECIMEN TEMPERATURE outside surface = 576.826 F
302.681 C
SPECIMEN TEMPERATURE inside surface = 246.263 F
119.046 C
AVERAGE SPECIMEN TEMPERATURE = 411.554 F
210.863 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.
OPERATOR: Larson, Robb E. 
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 = -2.33E-6*T^3 + .00256*T^2 -.974*T +5859

AT RUN 15 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16682 in 4.2372 mm
(V vs T curve) = 0.16574 in 4.2099 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.00107304257525 inch

TIME PERIOD OF ECHO PULSES 1.4635 us
SPECIMEN WAVE VELOCITY = 16997.93 ft/s
5790.57 m/s

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

SPECIMEN TEMPERATURE outside surface 478.236 F 247.509 C
SPECIMEN TEMPERATURE inside surface = 195.654 F 90.519 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 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 = 0.1652 in

WAVE VELOCITY CORRELATION

\[ V = -2.35E-6 * T^3 + .00256 * T^2 - .374 * T + 5359 \]

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 = -.0011345561769 inch

TIME PERIOD OF ECHO PULSES 1.4595 us
SPECIMEN WAVE VELOCITY = 19040.55 ft/s
5803.58 m/s

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

SPECIMEN TEMPERATURE outside surface = 410.846 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.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.  RUN NUMBER 17
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
$$V = -2.93E-6 \times T^3 + .00256 \times T^2 - .974 \times T + 5659$$

AT RUN 17 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16675 in
4.2354 mm
(V vs T curve) = 0.16567 in
4.2081 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -.001074677736 inch

TIME PERIOD OF ECHO PULSES 1.4605 us
SPECIMEN WAVE VELOCITY = 19028.81 ft/s
5793.88 m/s

---------RUN 17 CONDITIONS--------

SPECIMEN TEMPERATURE outside surface = 424.114 F
217.841 C
SPECIMEN TEMPERATURE inside surface = 163.153 F
72.863 C
AVERAGE SPECIMEN TEMPERATURE = 253.634 F
145.352 C

Figure 39. Sample Thickness Measurement Data Run, Noncontact Transducer.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larson, Robb E.  RUN NUMBER 18
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 = 0.1660 in

WAVE VELOCITY CORRELATION
\[ V = -2.93E-6 \times T^3 + 0.0255 \times T^2 - 1.974 \times T + 5059 \]

AT RUN 18 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16648 in 4.2286 mm
(V vs T curve) = 0.16613 in 4.2197 mm

THICKNESS PREDICTION MEASUREMENT ERROR = -0.000348948475133 inch

TIME PERIOD OF ECHO PULSES 1.4515 us
SPECIMEN WAVE VELOCITY = 19115.85 ft/s 5825.51 m/s

-------RUN 18 CONDITIONS -------

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

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

\[ V = -2.63E-6 T^3 + 0.0256 T^2 - 0.974 T + 5853 \]

AT RUN 19 CONDITIONS:

  SPECIMEN THICKNESS (nominal) = 0.16636 in 4.2254 mm
  (V vs T curve) = 0.16669 in 4.2240 mm

THICKNESS PREDICTION MEASUREMENT ERROR = .000337212722811 inch

TIME PERIOD OF ECHO PULSES 1.4475 us
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 = 48.584 F 9.202 C
AVERAGE SPECIMEN TEMPERATURE = 48.858 F 9.366 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 + .33255*T^2 - .974*T + 5659

AT RUN 20 CONDITIONS:
SPECIMEN THICKNESS (nominal) = 0.16635 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 us
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: 'CONPRED'

**** 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*T’3 +2.66E-4*T’2-.537*T+5805

THE TIME PERIOD MEASURED AT 48.6642 F = 1.889E-6 seconds
THE CALCULATED WAVESPEED WAS = 5800.9824057 m/s

SPECIMEN TEMPERATURE outside surface = 48.1378 F
SPECIMEN TEMPERATURE inside surface = 48.591 F
AVERAGE SPECIMEN TEMPERATURE = 48.854 F

THE CORRECTED NOMINAL THICKNESS AT 48.6642 F = .21570877716 in
(using alpha) = .0054790529359 m

THE CALCULATED HEATED THICKNESS AT 48.6642 F = .215710124651 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 TRANSUDER THICKNESS PREDICTION PROGRAM: 'CONFRED'

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

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

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

THE TIME PERIOD MEASURED AT 47.4359 F = \( 1.889E-5 \) seconds
THE CALCULATED WAVESPEED WAS \( 5001.4145708 \) m/s

SPECIMEN TEMPERATURE outside surface = 47.4890 F
SPECIMEN TEMPERATURE inside surface = 47.383 F
AVERAGE SPECIMEN TEMPERATURE = 47.435 F

THE CORRECTED NOMINAL THICKNESS AT 47.4359 F = \( .215707384236 \) in
(using alpha) \( .0054783622016 \) m

THE CALCULATED HEATED THICKNESS AT 47.4359 F = \( .215725829217 \) in
(using \( V vs T \) curve) \( .00547843605212 \) m

AT A REFERENCE TEMPERATURE OF 48.5 F :
SPECIMEN THICKNESS
(METERS) Nominal = \( .005478503742247 \)
(Predicted = \( .00547845119755 \)
SPECIMEN THICKNESS
(INCHES) Nominal = \( .215710134743 \)
(Predicted = \( .215727899904 \)

MEASUREMENT ERROR corrected to 48.5 degrees = \( 1.7651606862E-5 \) 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: 'CONPREO'

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

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

WAVE VELOCITY CORRELATION
\[
V = -2.66E-7 + 2.69E-4 T + 2.577 T + 5606
\]

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) = .00548580095855 m

THE CALCULATED HEATED THICKNESS AT 173.7905 F = .217558304418 in
(using \( V \) vs \( T \) curve) = .00552588093222 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
SPECIMEN THICKNESS (METERS)
Nominal = .00547903742247
Predicted = .00551936608139

SPECIMEN THICKNESS (INCHES)
Nominal = .215710134743
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
\[ V = -2.66E-7T^3 + 2.89E-4T^2 - .537T + 5806 \]

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 = 183.351 F
AVERAGE SPECIMEN TEMPERATURE = 194.449 F

THE CORRECTED NOMINAL THICKNESS AT 194.4491 F = \( .00548669695223 \) m

THE CALCULATED HEATED THICKNESS AT 194.4491 F = \( .00554930858565 \) 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 = \( .00246156371758 \) 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: 'CONPREO'

***** 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*T^3 +2.69E-4*T^2-.537*T+6606

THE TIME PERIOD MEASURED AT 373.7471 F = 1.59E-6 seconds
THE CALCULATED WAVESPEED WAS = 5711.9215424 m/s

SPECIMEN TEMPERATURE outside surface= 420.5714 F
SPECIMEN TEMPERATURE inside surface = 328.523 F
AVERAGE SPECIMEN TEMPERATURE = 373.747 F

THE CORRECTED NOMINAL THICKNESS AT 373.7471 F = .216392630583 in
(using alpha) = .00545637281706 m

THE CALCULATED HEATED THICKNESS AT 372.7471 F = .218324368856 in
(using V vs T curve) = .00554056368613 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
SPECIMEN THICKNESS
(METERS) Nominal = .00547903742247
(Predicted = .00552330891242
SPECIMEN THICKNESS
(INCHES) Nominal = .215710134743
(Predicted = .217444453709

MEASUREMENT ERROR corrected to 48.5 degrees = .00173431896583 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 9 ***

0.4 STAINLESS STEEL SPECIMEN

AT A REFERENCE TEMPERATURE OF 48.5 F (9.2 C)

LAMEL VELOCITY CORRELATION

\[ v = -2.65 \times 10^{-7} T - 2.65 \times 10^{-4} T^2 - 0.077 T + 0.035 \]

THE TIME PERIOD MEASURED AT 481.754 F = 1.999996-8 seconds
THE CALCULATED WAVE SPEED \( w \) = 5021.99999945 m/s

SPECIMEN TEMPERATURE outside surface = 547.2448 F
SPECIMEN TEMPERATURE inside surface = 426.454 F
CALCULATED SPECIMEN TEMPERATURE = 481.754 F

THE CORRECTED NOMINAL THICKNESS AT 481.754 F = .218646654815 in
(using alpha) \( .0055325012341 \times \)

THE CALCULATED HEATED THICKNESS AT 481.754 F = .218721783032 in
(using V vs T curve) \( .00553253326902 \times \)

AT A REFERENCE TEMPERATURE OF 48.5 F:

SPECIMEN THICKNESS (METERS) Nominal = .2054793742247
Predicted = .20553144124081

SPECIMEN THICKNESS (INCHES) Nominal = .21570134743
Predicted = .217773277187

MEASUREMENT ERROR corrected to 48.5 degrees = .0000243426452 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: 'CONPREO'

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

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

WAVE VELOCITY CORRELATION
\[ V = -2.66E-7 \times T^3 + 2.69E-4 \times T^2 - 537 \times T + 5606 \]

THE TIME PERIOD MEASURED AT 595.8815 F = 1.3605E-6 seconds
THE CALCULATED WAVE SPEED 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 = .216880604051 in
(using alpha) = .00550976763432 m

THE CALCULATED HEATED THICKNESS AT 595.8815 F = .218278154116 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 (INCHES) Nominal = .215710134743
Predicted = .21710113702

MEASUREMENT ERROR corrected to 48.5 degrees = .00139100227738 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.
OPERATOR: Larson, Robb E.
MONTANA STATE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING
CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPRED'

***** 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*T^3 +2.68E-4*T^2-.537*T+5686

THE TIME PERIOD MEASURED AT 589.1207 F = 1.971E-6 seconds
THE CALCULATED WAVESPEED WAS = 5657.67491365 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 = .21666549057 in
(using alpha) .00550636346302 m

THE CALCULATED HEATED THICKNESS AT 589.1207 F = .215513327908 in
(using V vs T curve) .005567663652685 m

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS Nominal = .00547903742247
(METERS) Predicted = .0055459346538
SPECIMEN THICKNESS Nominal = .215710124743
(INCHES) Predicted = .218343865566

MEASUREMENT ERROR corrected to 48.5 degrees = .00263373062329 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 9 *****

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

WAVE VELOCITY CORRELATION
\[ v = -2.66E-7 \times T^3 + 2.69E-4 \times T^2 - 537 \times T + 5806 \]

THE TIME PERIOD MEASURED AT 586.7256 F = 1.971E-6 seconds
THE CALCULATED WAVESPEED WAS = 5658.26945242 m/s

SPECIMEN TEMPERATURE outside surface = 538.4886 F
SPECIMEN TEMPERATURE inside surface = 536.983 F
AVERAGE SPECIMEN TEMPERATURE = 586.725 F

THE CORRECTED NOMINAL THICKNESS AT 586.7256 F = .218536400376 in
(using V vs T curve)
THE CALCULATED HEATED THICKNESS AT 586.7256 F = .215710134743 in
(using V vs T curve)

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS Nominal = .00547903742247 m
(METERS) Predicted = .00554655394845 m
SPECIMEN THICKNESS (INCHES) Nominal = .215710134743
 Predicted = .218536400376

MEASUREMENT ERROR corrected to 48.5 degrees = .00266205797377 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*T^3 + 2.69E-4*T^2 - .537*T + 5806

THE TIME PERIOD MEASURED AT 717.2402 F = 1.968E-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) .00553667877742 m

AT A REFERENCE TEMPERATURE OF 48.5 F :
SPECIMEN THICKNESS Nominal = .00547803742247
(METERS) Predicted = .00550183363716
SPECIMEN THICKNESS Nominal = .215710134743
(INCHES) Predicted = .21660762351

MEASUREMENT ERROR corrected to 48.5 degrees = .000897488767369 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 11 ******

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

WAVE VELOCITY CORRELATION
\[ V = -2.66E-7 \times T^{3} + 2.69E-4 \times T^{2} - 537 \times T + 5806 \]

THE TIME PERIOD MEASURED AT 770.099 F = 1.389E-6 seconds
THE CALCULATED WAVESPEED WAS = 5612.69122381 m/s

SPECIMEN TEMPERATURE outside surface = 535.3472 F
SPECIMEN TEMPERATURE inside surface = 704.651 F
AVERAGE SPECIMEN TEMPERATURE = 770.099 F

THE CORRECTED NOMINAL THICKNESS AT 770.099 F = .217275723606 in
(using alpha) .00551860338467 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 = .21570134743 Inches
Predicted = .218172278173

MEASUREMENT ERROR corrected to 48.5 degrees = .0024531444244 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Larsen, 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 (9.16 C)

WAVE VELOCITY CORRELATION
V = -2.66E-7*T^3 +2.89E-4*T^2-.537*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 = .21742335839 in
(using alpha)
= .00592255270999 m

THE CALCULATED HEATED THICKNESS AT 833.9792 F = .218666653899 in
(using V vs T curve)
= .005955464100904 m

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS Nominal = .00547903742247
(METERS) Predicted = .0055107287983
SPECIMEN THICKNESS Nominal = .215710134743
(INCHES) Predicted = .216963499206

MEASUREMENT ERROR corrected to 48.5 degrees = .0012533646287 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*T^3 + 2.69E-4*T^2 - .537*T + 5806

THE TIME PERIOD MEASURED AT 921.1874 F = 1.99E-6 seconds
THE CALCULATED WAVESPEED WAS = 5574.3033923 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) = .00552773136373 m

THE CALCULATED HEATED THICKNESS AT 921.1874 F = .219021851652 in
(using V vs T curve) = .00555315503195 m

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
$V = -2.66E-7 + 2.89E-4 + 2.537 - 5806$

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 = .217957199685 in
(using alpha) = .00553712867199 m

THE CALCULATED HEATED THICKNESS AT 1076.5445 F = .218866669355 in
(using V vs T curve) = .0055926420162 m

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS (METERS) Nominal = .00547903742247
Predicted = .00550054052463
SPECIMEN THICKNESS (INCHES) Nominal = .215710134743
Predicted = .2165724616

MEASUREMENT ERROR corrected to 48.5 degrees = .00086232686668 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 = -2.65E-7*T^3 + 2.65E-4*T^2 - .537*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 = 1255.2376 F
SPECIMEN TEMPERATURE inside surface = 975.447 F
AVERAGE SPECIMEN TEMPERATURE = 1120.842 F

THE CORRECTED NOMINAL THICKNESS AT 1120.8425 F
(using alpha) = .218104283923 in
(using V vs T curve) = .218816118653 in

THE CALCULATED HEATED THICKNESS AT 1120.8425 F
(using V vs T curve) = .218816118653 in

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS (METERS) Nominal = .00547903742247
Predicted = .00549699679468
SPECIMEN THICKNESS (INCHES) Nominal = .215710124743
Predicted = .216416133649

MEASUREMENT ERROR corrected to 48.5 degrees = .00070598905942 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.
SPECIMEN THICKNESS PREDICTION DATA

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

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

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

WAVE VELOCITY CORRELATION
\[ V = -2.66E-7T^3 + 2.59E-4T^2 - 6.537T + 5806 \]

THE TIME PERIOD MEASURED AT 1206.698 F = 2.0055E-6 seconds
THE CALCULATED WAVESPEED WAS = 5496.18171574 m/s

SPECIMEN TEMPERATURE outside surface = 1399.4204 F
SPECIMEN TEMPERATURE inside surface = 1013.976 F
AVERAGE SPECIMEN TEMPERATURE = 1205.698 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
(METERS) Nominal = .00547903742247
Predicted = .00544556622663
SPECIMEN THICKNESS
(INCHES) Nominal = .215710134743
Predicted = .214332371127

MEASUREMENT ERROR corrected to 48.5 degrees = -.00131775631577 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
\[ V = -2.66 \times 10^{-7} T^3 + 2.68 \times 10^{-4} T^2 - 0.597 T + 5806 \]

THE TIME PERIOD MEASURED AT 973.9705 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 973.9705 F = \( .21751948602 \) in
\( .0055308994945 \) m

THE CALCULATED HEATED THICKNESS AT 973.9705 F = \( .219520342367 \) in
\( .00555081669612 \) m

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

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

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

WAVE VELOCITY CORRELATION
\[ V = -2.66E-7 \times T^3 + 2.69E-4 \times T^2 - 0.537 \times T + 5806 \]

THE TIME PERIOD MEASURED AT 50.5211 F = 1.681E-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) = .00547958613353 m

THE CALCULATED HEATED THICKNESS AT 50.5211 F = .214776457338 in
(using V vs T curve) = .00545527261642 m

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS
(METERS) Nominal = .00547949138349
(PREDICTED) = .00545526852944
SPECIMEN THICKNESS
(INCHES) Nominal = .215728007224
(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*T^3 + 2.69E-4*T^2 - .537*T + 5806

THE TIME PERIOD MEASURED AT 98.554 F = 1.961E-5 seconds
THE CALCULATED WAVESPEED WAS = 5635.48794494 m/s

SPECIMEN TEMPERATURE outside surface = 763.4912 F
SPECIMEN TEMPERATURE inside surface = 583.640 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 = .217543146651 in
(using V vs T curve) = .00552555593001 m

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS (METERS) Nominal = .00547903742247
      Predicted = .00548106180669
SPECIMEN THICKNESS (INCHES) Nominal = .215710134743
      Predicted = .215183555704

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 46.5 F (9.16°C)

WAVE VELOCITY CORRELATION
\[ V = -2.66 \times 10^{-7} T^3 + 2.68 \times 10^{-4} T^2 - 0.537 T + 5806 \]

THE TIME PERIOD MEASURED AT 456.0872 F = 1.593E-6 seconds
THE CALCULATED WAVESPEED WAS = 5690.93363762 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 = .005456417726
SPECIMEN THICKNESS Nominal = .215710134743
(INCHES) Predicted = .216355028583

MEASUREMENT ERROR corrected to 48.5 degrees = .006448938391 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.
SPECIMEN THICKNESS PREDICTION DATA

OPERATOR: Lerson, 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
\[ v = -2.66E-7 \cdot T^3 + 2.58E-4 \cdot T^2 - 0.537 \cdot T + 5.806 \]

THE TIME PERIOD MEASURED AT 303.5876 F = 1.927E-6 seconds
THE CALCULATED WAVESPEED WAS = 5730.16657325 m/s

SPECIMEN TEMPERATURE outside surface = 354.7866 F
SPECIMEN TEMPERATURE inside surface = 252.387 F
AVERAGE SPECIMEN TEMPERATURE = 303.588 F

THE CORRECTED NOMINAL THICKNESS AT 303.5876 F = .218242192656 in
(using alpha) = .00549255168345 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 = .005555745041035
SPECIMEN THICKNESS  Nominal = .216570134743
(INCHES)  Predicted = .216628756313

MEASUREMENT ERROR corrected to 48.5 degrees = .0011862157016 INCH

Figure 40. Sample Thickness Measurement Data Run, Contact Transducer.
OPERATOR: Larson, Robb E.
MONTANA STATE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING
CONTACT TRANSDUCER THICKNESS PREDICTION PROGRAM: 'CONPREP'

**** RUN NUMBER 22 ****

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

WAVE VELOCITY CORRELATION
\[ v = -2.66E^{-7}T^{-3} + 2.69E^{-4}T^{-2} - .537T + 5806 \]

THE TIME PERIOD MEASURED AT 178.1069 F = 1.521E-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 (using alpha)
\[ .215977544611 \text{ in} \]
\[ .0054729563311 \text{ m} \]

THE CALCULATED HEATED THICKNESS AT 178.1069 F (using V vs T curve)
\[ .217967003545 \text{ in} \]
\[ .00553635188004 \text{ m} \]

AT A REFERENCE TEMPERATURE OF 48.5 F:
SPECIMEN THICKNESS (METERS) Nominal = .0054729563311
Predicted = .00553635188004

SPECIMEN THICKNESS (INCHES) Nominal = .215977544611
Predicted = .217967003545

MEASUREMENT ERROR corrected to 48.5 degrees = .00198599571102 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 = -2.68E-7*T^3 + 2.68E-4*T^2 - .537*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 = 0.215705393777 in
(using alpha)

THE CORRECTED HEATED THICKNESS AT 47.6465 F = 0.215395113173 in
(using V vs T curve)

MEASUREMENT ERROR corrected to 48.5 degrees = -0.000213262325681 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.)


4. Use the cursor 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
Figure 41. Contact Transducer Specifications.
PANAMETRICS

TRANSDUCER DESCRIPTION

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

TEST INSTRUMENTATION

PANAMETRICS 5052 UA: #3
ENERGY SETTING: 1
PULSER DAMPING: 500ohms
RECEIVER ATTENUATION: 0dB
CABLE: RG-58/U LENGTH: 1FT.

LECGRO9400- V2.06T  DIGITAL OSCILLOSCOPE: #1

TEST CONDITIONS

ECHO FROM FRONT SURFACE OF .13" BALL-STEEL
WATER PATH: 2.130"  FOCUSED AT: 2.138"

COMPUTER PROGRAM: VER. 1.2 SETUP: DWG. #6978

ASTM E1065 MEASUREMENTS

PEAK FREQUENCY ------- 10.8MHZ  WAVEFORM DURATION:
CENTER FREQUENCY ------- 10.1MHZ  0-14dB LEVEL .210us/sec
UPPER FREQUENCY 0-6dB  13.2MHZ  0-20dB LEVEL .263us/sec
LOWER FREQUENCY 0-6dB  6.90MHZ  0-40dB LEVEL .443us/sec
BANDWIDTH ---------- 62.7%

 COMMENTS:

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.

<table>
<thead>
<tr>
<th>TIP NO.</th>
<th>FUEL GAS</th>
<th>GAS PRES.</th>
<th>O2 PRES.</th>
<th>GAS CONS.</th>
<th>O2 CONS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST630</td>
<td>Natural gas</td>
<td>3 ounces</td>
<td>30 PSI</td>
<td>107*</td>
<td>190*</td>
</tr>
</tbody>
</table>

*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:

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