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

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

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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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Date 12/18/92

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TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS-continued

LIST OF FIGURES

LIST OF FIGURES-continued

LIST OF FIGURES-continued

FIGURE PAGE

NOMENCLATURE

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

NOMENCLATURE-continued

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

ABSTRACT

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

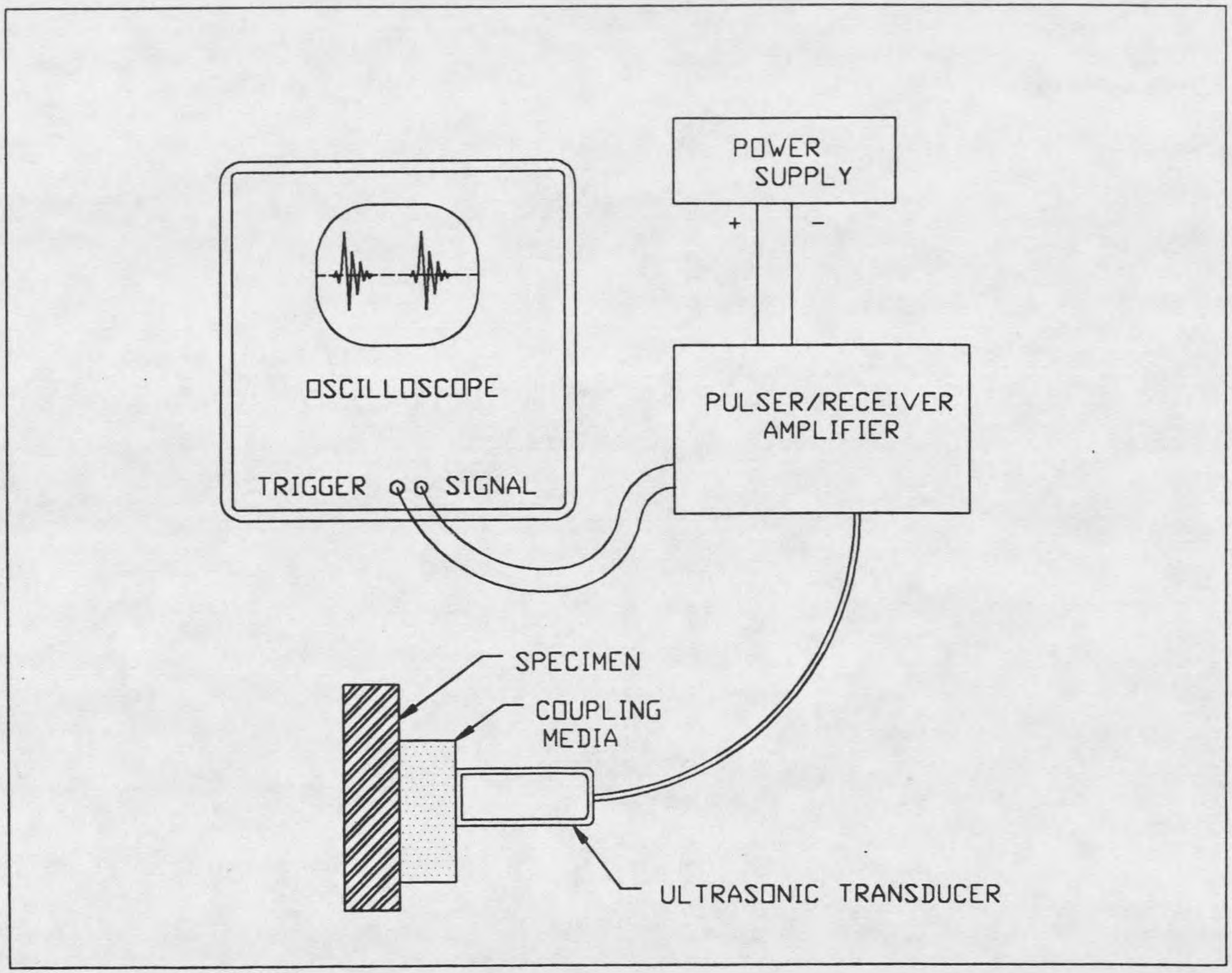

Figure 1. Typical Ultrasonic Dimensional Inspection Apparatus.

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

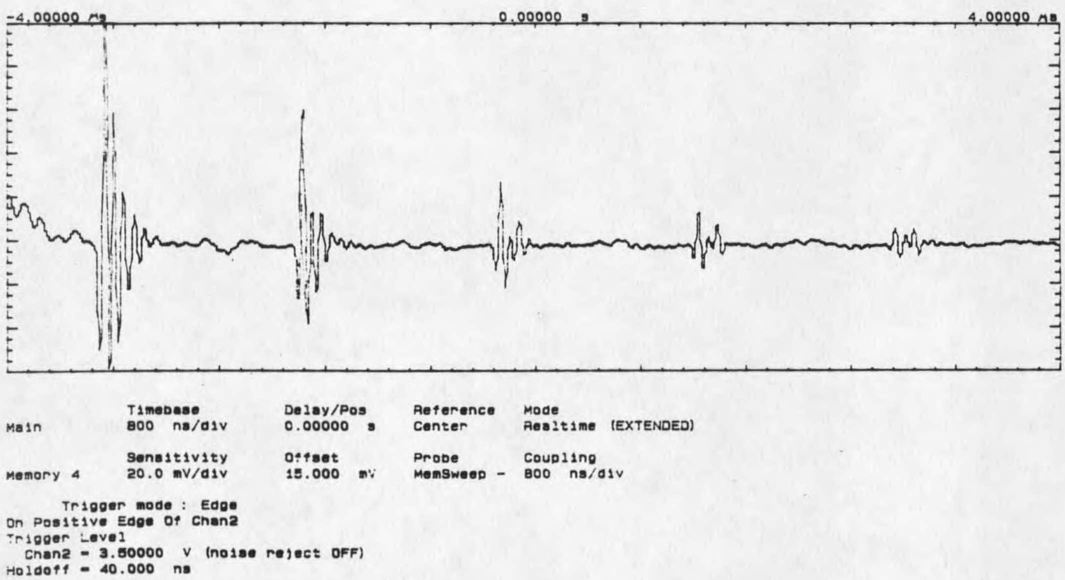

Figure 2. Sample Oscilloscope Waveform.

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

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

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

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

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

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

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

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

CHAPTER 2

DATA ACQUISITION SYSTEM

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

The system consisted of the following components:

1. A Hewlett Packard HP9836 computer with dual 5.25 inch floppy disk drives.
2. A Hewlett Packard HP3497A Data Acquisition Control Unit.
3. A Hewlett Packard HP3456A Digital Voltmeter. [Accuracy (0 - 0.1 volt range) +/- (.0022 % +24 counts), 6 decimal places carried, integrated over 10 power line cycles. Input resistance >10^{10} ohms.]
4. Two Hewlett Packard HP9121 dual 3.5 inch floppy disk drive units.
5. A Hewlett Packard HP9153C hard disk drive.
6. A Hewlett Packard HP54502A Digitizing Oscilloscope. [400 MHz bandwidth, risetime 3.5 nanoseconds, dual 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.

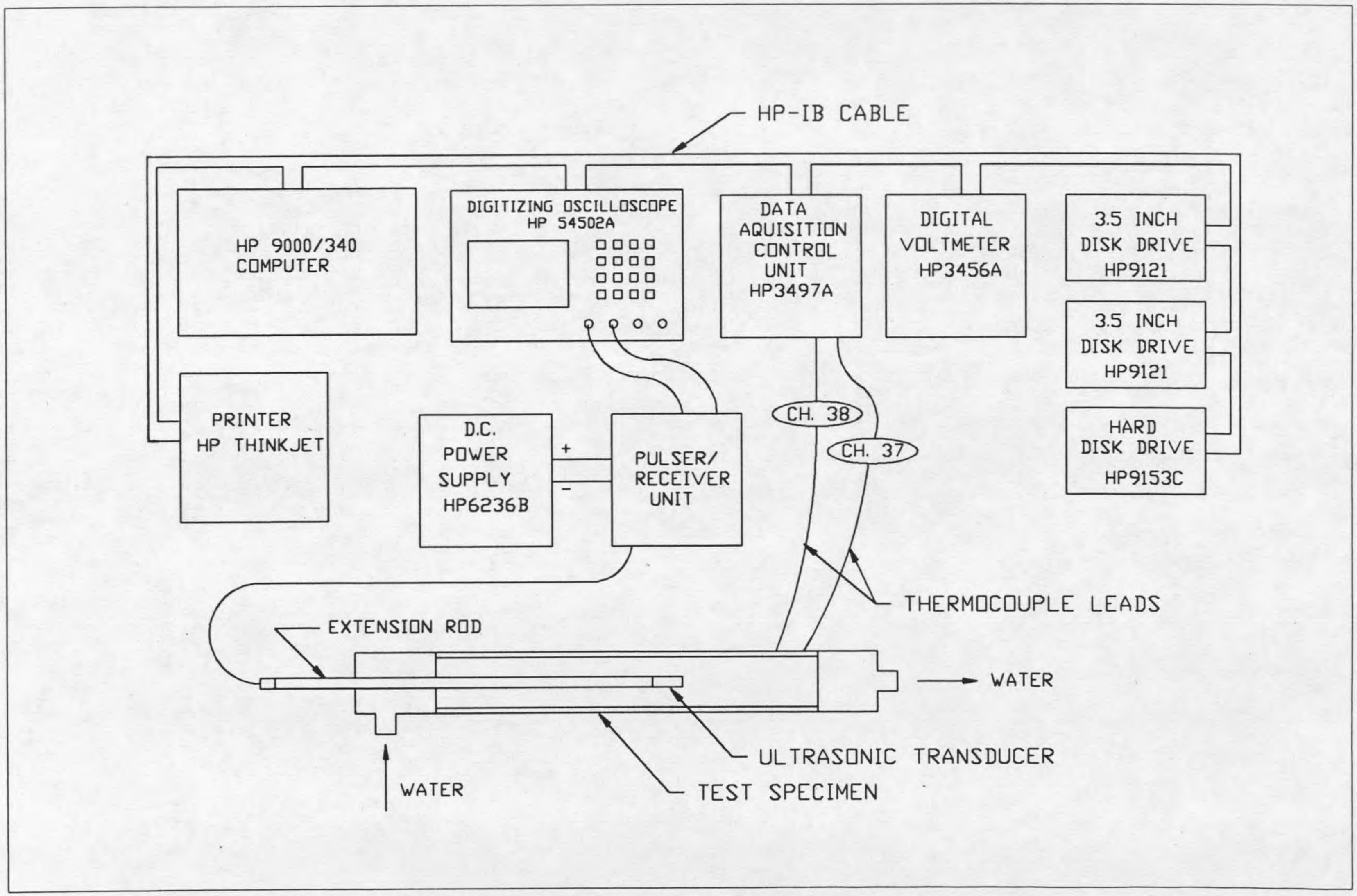

Figure 3. Data Acquisition System Apparatus.

CHAPTER 3

PLANAR TESTING , NONCONTACT TRANSDUCER

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

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

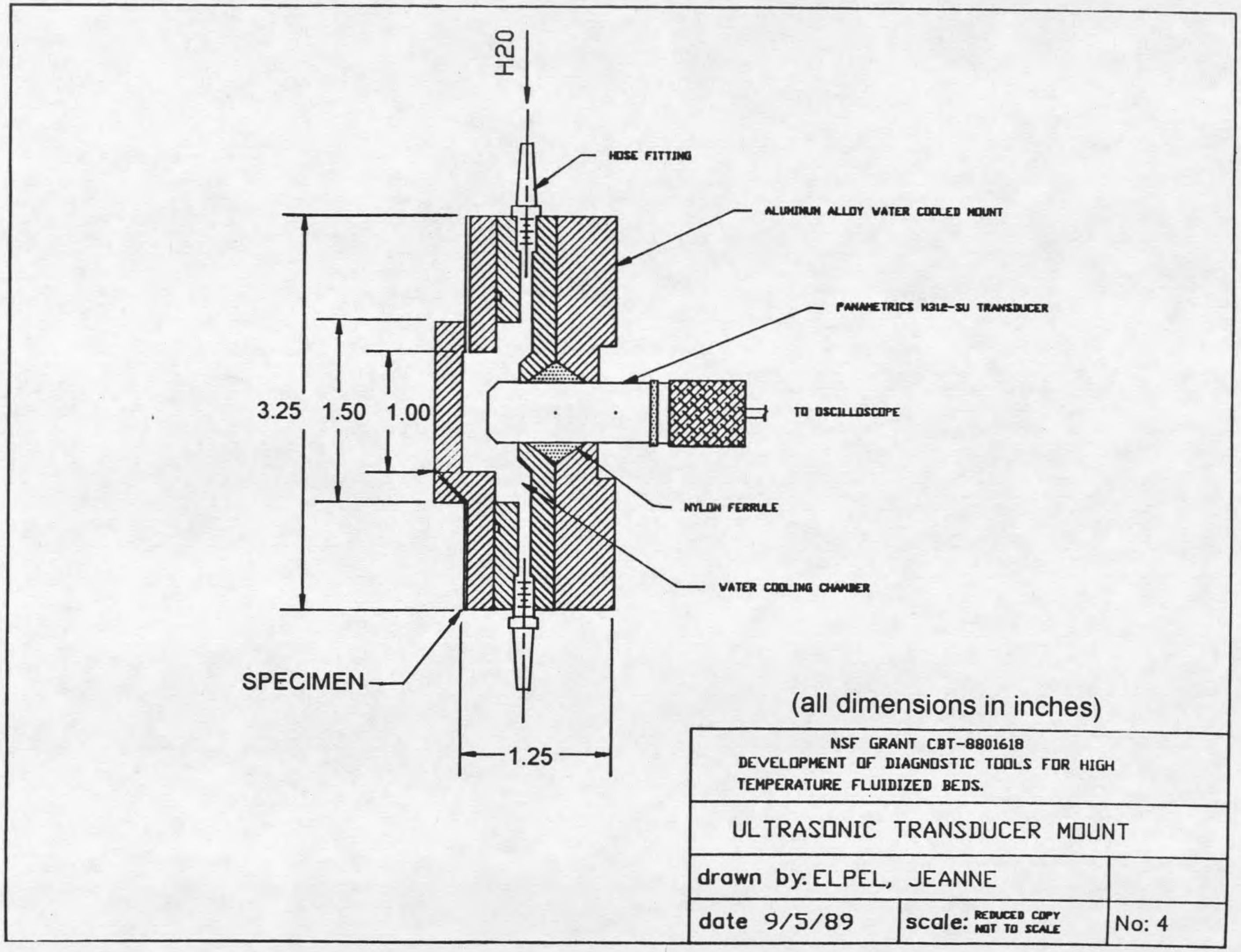

Figure 4. Noncontact Planar Test Apparatus.

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;

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

The three wave velocities were then averaged to establish the wave velocity of 316 stainless steel at ambient conditions (15.5 ^{o}C). Test specimens of three thicknesses were then tested over a range of elevated temperatures, from 16 ^{o}C to 260 ^{o}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;

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

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.