
**Pacific Northwest
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**Development of a Density Sensor
for In-Line Real-Time Process Control
and Monitoring of Slurries during
Radioactive Waste Retrieval and
Transport Operations at DOE Sites**

J. A. Bamberger
M. S. Greenwood

November 2001



Prepared for the U.S. Department of Energy
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Richland, Washington 99352

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Summary

This report describes development of a density sensor (densimeter) for in-line real-time process control and monitoring of slurries during radioactive waste retrieval and transport operations at US Department of Energy (DOE) sites. At these sites millions of gallons of radioactive liquid and sludge wastes must be retrieved from underground storage tanks and transported via underground pipelines for treatment or disposal. A major concern during the transfer operations is plugging of the transfer lines. Blocked transfer lines could significantly escalate the remediation costs both in terms of pipeline replacement costs and costs of maintenance of inactive facilities and operating personnel. The density sensor can be used for real-time process monitoring that could be used to detect conditions that could lead to degraded transport and line plugging. The three main factors that contribute to transfer line plugging are: 1) settling of solid particles during transfer, 2) crystallization of the waste, and 3) gelation of the waste. Depending on the mechanism, plugging or its onset may result in a change in the density or particle size distribution of the slurry. In addition, the onset of pipeline plugging may also lead to an increase in the pressure drop in the transfer lines. The densimeter presents numerous benefits over grab sampling of the waste followed by off-line analysis. Benefits include: early detection and prevention of pipeline plugging events, real-time process data of the density through the transfer process, reduction or elimination of grab sampling and off-line analysis, and reduced radiation exposure for workers

The density sensor, shown in Figure 1, was developed based on the need to provide a small, robust instrument that could be retrofitted into existing pump pit manifolds and transfer lines. The probe uses ultrasonic signal reflection at the fluid-pipe wall interface to quantify density in situ in real time. The sensor is mounted in the wall of the pipe between two connecting flanges. This instrument was selected for monitoring radioactive waste transport based on several characteristic features: the sensing surface is non-intrusive and does not disrupt the slurry flow (the sensor is located flush with the pipeline wall); instrument performance is not affected by slight amounts of entrained air that could be present during waste retrieval and transfer; nor is it affected by electromagnetic noise from nearby pumps and other equipment; and the instrument is compact (the sensor is located on the perimeter of the pipe wall).

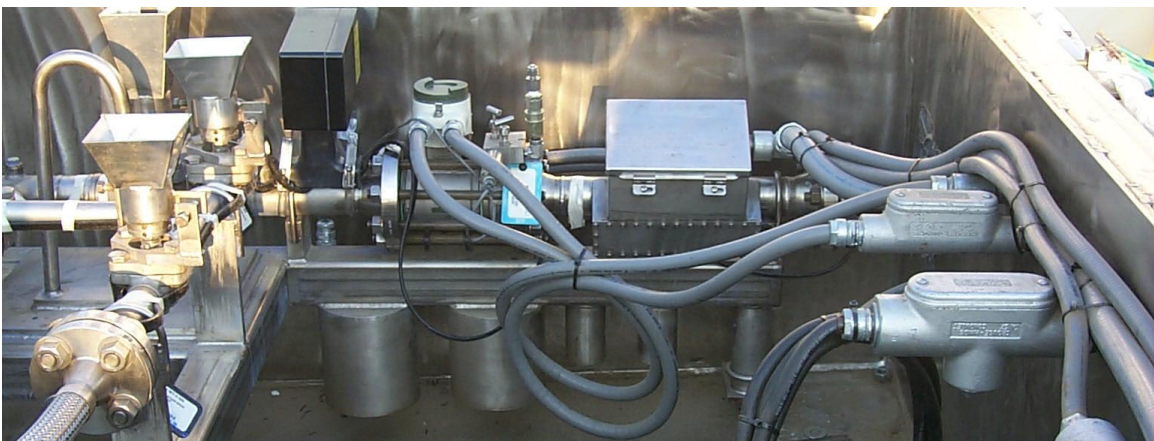


Figure 1 Density sensor installed at Hanford in the SY-101 site in the pump pit (after installation the densimeter was covered with blanket insulation)

During probe development for deployment in a radioactive waste stream, components were tested for chemical and radiation resistance and the spool piece (flanged insert containing the sensor) was pressure tested in accordance with ASME Process Piping Code B31.3. In addition, because the probe is installed in a transfer line associated with a tank filled with waste with the potential to generate flammable gas, the design was reviewed by the Hanford Site Flammable Gas Equipment Advisory Board to evaluate probe installation and use in an area requiring compliance with Ignition Source Control Set 2. The board ruled that the density sensor components are not formally approved for use in a Class I, Division 2, Group B atmosphere; however, the components are normally non-sparking and provide equivalent safety.

The density sensor performance was evaluated in both vertical (at Oak Ridge National Laboratory) and horizontal (at Pacific Northwest National Laboratory and at Hanford) orientations. In most cases, prediction of density was within $\pm 2\%$ when compared with reference grab samples.

Deployment and Demonstration

The density sensor has been deployed as a component in the modified process manifold that is installed in the prefabricated pump pit at Hanford tank SY-101 site. In FY-2001 after completion of densimeter installation and connection of cabling, the probe operation in air was verified. In FY-2002, the density sensor performance will be evaluated during transfers of both water and waste through the pipeline.

Next Generation Through-Wall Density Sensor

The density sensor design installed in FY-2001 at Tank SY-101 is based on the original densimeter concept proposed in FY-1996 and evaluated at ORNL in FY-1997. Upgrades to the SY-101 densimeter include the ability to operate over an increased pressure range (based on design of a new spool piece) and an enhanced calibration scheme that incorporates the effects of temperature into the methodology.

In a separate project an approach has been demonstrated to develop an ultrasonic sensor that: 1) can be attached permanently to a pipeline wall, possibly as a spool piece inserted into the line or 2) can clamp onto an existing pipeline wall and be movable to another location. Also, an analysis method has been developed to make the measurement self-calibrating. This investigation has shown the path forward to develop clamp-on sensors for measurement of fluid and slurry density. This method is especially attractive for applications such as Hanford where radioactive fluids are routinely transported because the sensors could be applied to existing equipment without the need to penetrate the pipe pressure boundary or to open the system to install new equipment.

Contents

Acknowledgments	iii
Summary	v
1.0 Introduction.....	1.1
1.1 Pipeline Transport at DOE Sites Historical Background	1.1
1.2 Density Sensor Development Chronology	1.2
1.2.1 CMST – Funded Initial Sensor Development	1.2
1.2.2 TDI – Funded Initial Deployment Development for Hanford	1.2
1.2.3 ASTD Project Included Density Sensor in Review.....	1.3
1.2.4 SLRRP – Incorporated Densimeter into a Deployment at SY-101	1.3
1.3 Density Sensor Configurations Evaluated for Deployment	1.4
1.4 Densimeter Applications	1.5
2.0 Conclusions and Recommendations	2.1
2.1 Conclusions	2.1
2.1.1 Deployment and Demonstration.....	2.2
2.1.2 Next Generation Through-Wall Density Sensor	2.2
2.2 Recommendations	2.3
3.0 Density Sensor Theory of Operation.....	3.1
3.1 Density Sensor Theory	3.1
3.1.1 Measuring the Reflection Coefficient	3.2
3.1.2 Reflection and Transmission Coefficients	3.2
3.1.3 Determining the Density of a Liquid Using 0 and 60 Degree Angles of Incidence.....	3.3
3.2 Enhancements Applied to Signal Analysis.....	3.5
4.0 Density Sensor Spool Piece and Hardware Configurations	4.1
4.1 Density Sensor Designed for Tests at ORNL.....	4.1
4.2 Initial Hanford Density Sensor Deployment Configuration for C-106 Pump Pit.....	4.2
4.3 Density Sensor for SY-101 Transfer Line.....	4.4
4.3.1 Pressure Containment Design	4.4
4.3.2 SY-101 Density Sensor Transducer Configuration.....	4.6
4.3.3 Component Testing	4.8
4.4 Computer Controlled Data Acquisition System	4.9
4.5 Densimeter-Computer Connections	4.12
5.0 Density Sensor Pipeline Evaluations	5.1
5.1 Densimeter Evaluation at ORNL.....	5.1
5.2 Densimeter Demonstration in the Instrument Validation Facility.....	5.4
5.3 Tests at 305 Building in Modified Process Manifold.....	5.6
5.4 Density Sensor Performance	5.10
6.0 Density Sensor Calibration	6.1
6.1 Approach for Sensor Calibration.....	6.1
6.2 Experimental Reflection Coefficients for use in Regression Analysis.....	6.4

6.2.1	Velocity measurements in liquids/slurry	6.4
6.2.2	Calculation of reflection coefficients	6.4
6.3	Regression analysis for reflection coefficients	6.6
6.4	Regression Analysis for Density Values	6.8
6.5	Determination of the Density	6.13
6.5.1	Using data for three angles	6.13
6.5.2	Procedure for Densities Less Than 1050 kg/m ³	6.14
6.5.3	Statistical Analysis	6.14
7.0	Computer Control System Operating Instructions	7.1
7.1	Directory Structure	7.1
7.2	Input File	7.1
7.3	Output Files	7.3
7.3.1	Adjusted Voltage	7.3
7.4	System Setup	7.10
7.4.1	Measurement of Pulser Voltage	7.10
7.4.2	Measurement using Water	7.10
7.4.3	Setting Amplifier Gains	7.13
7.4.4	Adjustment to System and/or Changes to Input File	7.16
8.0	Density Sensor Deployment at SY-101 Site	8.1
8.1	Installation	8.1
8.1.1	Equipment in the DACS Trailer	8.3
8.2	Density Sensor Operational Check	8.4
9.0	Density Sensor Improvements – Through-Wall Sensor	9.1
9.1	Approach to Through-Wall Measurement of Density	9.1
9.2	Clamp-on Sensor Applications	9.4
10.0	Economic Advantages of Slurry Monitoring	10.1
10.1	Densimeter Cost Estimate	10.1
10.1.1	Cost of Initial Deployments	10.1
10.1.2	Estimates of Cost of Future Deployments	10.2
10.2	Impacts of Plugged Pipelines	10.3
11.0	References	11.1
12.0	Appendix Densimeter Prints	12.1
13.0	Distribution	13.1

Figures

Figure 1 Density sensor installed at Hanford in the SY-101 site in the pump pit.....	v
Figure 2.1 Density sensor installed at Hanford in the SY-101 site in the pump pit before and after installation of blanket insulation.....	2.2
Figure 3.1 Schematic diagram of wedge design.	3.1
Figure 3.2 Definition of terminology used in equations of reflection and transmission coefficients.	3.3
Figure 3.3 Graph showing the reflection and transmission coefficient for a Rexolite™ wedge in contact with water.	3.5
Figure 4.1 ORNL densimeter spool piece.....	4.1
Figure 4.3 Proposed transfer configuration from Tank C-106 to Tank AY-102.	4.3
Figure 4.4 Densimeter configuration for deployment in the 10-cm (4-in.) transfer line from Tank C-106 to Tank AY-102.....	4.4
Figure 4.5 Density sensor spool piece	4.5
Figure 4.6 Density sensor components showing spool piece (8, 10) wedges (3 – 60 degree, 4 – 47 degree), and electrical connection box (9, 23).....	4.6
Figure 4.7 View showing transducers and wedges positioned on spool piece	4.7
Figure 4.8 Transducer wedges with transducers and connectors installed	4.7
Figure 4.9 View inside transducer housing after pressure test showing labels, connectors and O-ring seal	4.8
Figure 4.10 View inside the spool piece showing the transducer wedge and pipe-wall interface	4.8
Figure 4.11 Rexolite blocks (A through H) exposed to increasing doses of radiation.	4.9
Figure 4.12 Density sensor control system architecture	4.10
Figure 4.13 Density electronics board components	4.11
Figure 4.14 Toneburst signal appearing on the computer monitor.	4.12
Figure 4.15 Cable connections between densimeter and computer controller.....	4.13
Figure 4.16 Labeled lemo and thermocouple connectors	4.13
Figure 4.17 Densimeter cables and computer connections during pipeline tests at 336 building	4.14
Figure 5.1 Vertical installation of densimeter during ORNL pipe loop tests	5.1
Figure 5.2 Configuration of the instrument validation facility pipe loop	5.5
Figure 5.3 Modified process manifold test configuration.....	5.8
Figure 5.4 Densimeter 1 (left) and densimeter 2 (right) installed in the modified process manifold	5.9
Figure 5.5 Data acquisition computers for the two density sensors.....	5.9
Figure 5.6 Comparison between densimeter and reference densities	5.10

Figure 6.1	Plots of bottle sample density and temperature for probes 1 (top) and 2(bottom)	6.2
Figure 6.2	Velocity of sound in sugar water as a function of temperature	6.5
Figure 6.3	Velocity of sound in kaolin clay slurries in sugar water as a function of temperature	6.5
Figure 6.4	Probe 1 variation of reflection coefficient with voltage	6.9
Figure 6.5	Probe 2 variation of reflection coefficient with voltage	6.10
Figure 6.6	Probe 1 variation of density with voltage	6.11
Figure 6.7	Variation of density with voltage	6.12
Figure 6.8	Density and percent error for Probes 1 and 2	6.15
Figure 8.1	Densimeter location in the prefabricated pump pit (upper right corner – penetrating wall)	8.1
Figure 8.2	Densimeter installed in the MPM inside the PPP	8.2
Figure 8.3	Densimeter after installation of blanket insulation	8.2
Figure 8.4	Densimeter cable field connections in PPP (left) and junction box (right)	8.3
Figure 8.5	Densimeter cables inside panel in DACS trailer	8.3
Figure 8.6	Density sensor connector locations on panel in DACS trailer	8.4
Figure 8.7	Wave form for longitudinal wave transducer pair BC in air	8.5
Figure 8.8	Wave form for longitudinal wave transducer pair DE in air	8.5
Figure 8.9	Wave form for longitudinal wave transducer FF in air	8.6
Figure 8.10	Wave form for longitudinal wave transducer GG in air	8.6
Figure 8.11	Wave form for shear wave transducer AA in air	8.7
Figure 8.12	Evaluation of pulser voltage obtained in DACS trailer	8.7
Figure 9.1	Clamp-on sensor applied to 2-in. Schedule 40 pipe	9.2

Tables

Table 1.1	Details of the highly hazardous radioactive waste stored at the DOE sites	1.1
Table 1.2	Density sensor configurations evaluated for deployment	1.5
Table 4.1	Slurry transport parameters for transfer from Tank C-106 to AY-102	4.3
Table 4.2	Density sensor design and operational criteria	4.5
Table 4.3	Transducer dimensions for Probes 1 and 2	4.7
Table 5.1	Density sensor data obtained during the instrument evaluation at ORNL	5.2
Table 5.2	Range of fluid properties evaluated during pipe loop tests	5.5
Table 5.3	Test sequence and range of operating parameters	5.6
Table 5.4	Comparison between densimeter and reference densities obtained during pipe loop tests	5.7
Table 6.1	Calculation of the experimental reflection coefficients for Probes 1 and 2	6.6
Table 6.2	Coefficients for probes 1 and 2	6.7
Table 6.3	Percent error in reflection coefficients based on Equation 6.5 compared to experimental values	6.8
Table 6.4	Percent error in density based on Equation 6.6 compared to the bottle sample density	6.8
Table 6.5	Voltage, reflection coefficient, and density data for probes 1 and 2	6.13
Table 6.6	Statistical analysis for final values of density	6.16
Table 6.7	Comparison of density values with bottle sample density	6.16
Table 7.1	Information about output files datasum1.dat or datasum2.dat	7.4
Table 7.2	Amplifier gain calibrations for computer 1 and computer 2	7.5
Table 7.3	Example of file calc2.dat	7.6
Table 7.4	Example of output file	7.8
Table 7.5	Example of water data for probe 1	7.11
Table 7.6	Example of water data for probe 2	7.12
Table 7.7	Gain settings for probes 1 and 2	7.13
Table 7.8	Example of voltage variation with temperature for Probe 1	7.14
Table 7.9	Example of voltage variation with temperature for Probe 2	7.15
Table 8.1	Output from auto test of densimeter with probes in contact with air	8.8
Table 9.1	Data obtained with the 0.64-cm- (0.25-in.-) thick stainless steel plate	9.3
Table 9.2	Data obtained with the 0.38-cm- (0.15-in.-) thick stainless steel plate	9.3
Table 10.1	Cost of densimeter for SY-101 deployment	10.2
Table 10.2	Estimated cost of future density sensor deployments	10.3

Symbols

ASTD	Accelerated Site Technology Deployment project
$b_{0,x}$ to $b_{8,x}$	coefficients in polynomial expansion where x denotes a transducer pair
c	speed of sound
c_L	longitudinal speed of sound
c_T	transverse (shear) speed of sound
CMST	Characterization, Monitoring, and Sensor Technology
CP	Crosscutting Program
D_{LL}	transmitted longitudinal wave
DACS	data acquisition and control system
DOE	Department of Energy
DST	double-shell tank
EM	US Department of Energy Environmental and Waste Management (EM)
G	solids quantities
GAAT	Gunite and Associated Tanks
GUI	graphical user interface
H	solid quantities
HTI	Hanford Tanks Initiative
INEEL	Idaho National Environmental and Engineering Laboratory
J	solid and liquid quantities
LDRD	Laboratory directed research and development
MPM	modified process manifold
N	sum of solid and liquid quantities
ORNL	Oak Ridge National Laboratory
ORP	Hanford Site Office of River
PC	personal computer
PNNL	Pacific Northwest National Laboratory
PPP	prefabricated pump pit
RC_{liq}	reflection coefficient in liquid
RC_T	theoretical value of reflection coefficient at a given angle
RC_{water}	reflection coefficient in water
RC_X	experimental value of the reflection coefficient at a given angle
RC_Z	experimental value for the perpendicular reflection
RF	radio frequency
R_{LL}	reflection coefficient for reflected longitudinal wave
R_{LLX}	reflection coefficient at a non-zero angle
R_{TL}	reflection coefficient for reflected shear wave
SLRRP	SY-101 Surface Level Rise Remediation Project
SST	single-shell tank
SW	sugar water
T	temperature
TDI	Slurry Monitoring Technology Deployment Initiative
TFA	Tanks Focus Area
TOF	time of flight

UDMS	ultrasonic density measurement system
UT	ultrasound
V_{liq}	voltage in liquid
V_{water}	voltage in water
V_x	voltage at 0 dB amplifier gain
Z_{liq}	acoustic impedance of liquid
Z_{solid}	acoustic impedance of solid

Greek Symbols

α	angle
α_L	angle of longitudinal wave
α_T	angle of transverse wave
μ	viscosity
ρ	density of liquid
ρ_s	density of solid
σ	standard deviation

1.0 Introduction

Staff at Pacific Northwest National Laboratory (PNNL) are developing ultrasonic sensing systems to monitor radioactive waste rheological and other physical properties during transport (Greenwood, Skorpik and Bamberger, 1997 and 1999), to detect stratification and onset of sedimentation (Fort et al. 1993), and to measure particle size and concentration (Bamberger, Kytomaa, and Greenwood 1998) of slurries during processing. The technologies are also being applied in various industries to characterize pulp fiber composition, characterize physical changes during refining, track development of hydrates during oil production and transport, and visualize fluid processes in real-time (Bamberger, Bond, and Greenwood 1999 and Bamberger, Greenwood Bond 1999).

The development of a density sensor for deployment at DOE sites to measure fluid and slurry density has been in progress for several years and is covered by several US Patents (Greenwood 2000a, b, Greenwood and Harris 1999, Greenwood and Lail 1998). The need for real-time process monitoring and control during pipeline transport and fluid mixing at DOE sites is evident. Background information that supports this is presented in Section 1.1. A review of the background of the densimeter development is presented in Section 1.2 and 1.3. Potential densimeter applications are summarized in Section 1.4.

1.1 Pipeline Transport at DOE Sites Historical Background

The U. S. Department of Energy (DOE) is responsible for eventual disposal of millions of gallons of radioactive liquid and sludge wastes which are stored in the underground storage tanks at Hanford and other DOE sites (Table 1.1). Remediation plans for most of the hazardous radioactive waste stored in underground storage tanks at several of the DOE sites include: 1) retrieval operations to remove the wastes from storage tanks and 2) transport and staging operations to transfer the wastes to treatment or storage facilities. Retrieval operations involve mixing solid and liquid wastes to create slurries that can be transported to specified locations.

Table 1.1 Details of the highly hazardous radioactive waste stored at the DOE sites

Site	Number of Tanks	Waste Volume		Radioactivity	
		m ³	M gal	P Bq (10 ¹⁵ Bq)	M Curies
Hanford	177	204,000	54	7400	200
INEEL	11	5,300	1.4	18	0.5 in tanks
Oak Ridge	40	1630	0.43	1.7	0.047
Savannah River	49	132,000	35	16000	420
West Valley	3	180	0.047	22	0.6

Currently at Hanford all wastes transfers between tanks and tank farms occur via pipeline. The possibility of pipeline plugging remains a significant issue regarding timely delivery of the feed to meet DOE remediation milestones. Also, blockage of transfer lines could significantly escalate the remediation costs both in terms of pipeline replacement costs and costs of maintenance of inactive facilities and operating personnel.

Plugging of underground slurry transfer pipelines is not uncommon. Cross-site transfer lines between 200 East and 200 West Areas of the Hanford Site have existed for about forty years. Plugging of the cross-site transfer lines has occurred several times throughout the history of the Hanford site. In many cases, the plugs were successfully removed by high-pressure flushing. However, some transfer lines could not be unplugged and to date, of the six transfer lines that have been built four are permanently plugged.

At Hanford, the tank waste must be staged to provide the required composition feed in the correct sequence to the vitrification plant. This can lead to multiple transfers of the slurry before it is treated at the vitrification facility. For instance, sludge in the 200W area Single Shell Tanks (SSTs) must be first transferred to the Double Shell Tank (DST) SY farm. This waste must be resuspended and mixed and then transferred cross-site to either the AN or AP tank farm. The waste may then again be resuspended and mixed and transferred to the AY farm before it is eventually sent to the vitrification facility. The numerous blending and transfers before the waste is finally sent to the vitrification plant increase the probability of a pipeline plugging event occurrence.

The three main factors that contribute to transfer line plugging are: 1) settling of solids particles during transfer, 2) crystallization of the waste, and 3) gelation of the waste. Depending on the mechanism, plugging or its onset may result in a change in the particle size distribution or the density of the slurry. In addition, the onset of pipeline plugging may also lead to an increase in the pressure drop in the transfer lines. Therefore, monitoring the particle size distribution and density of the slurry and the pressure drop in the transfer lines represent several of the methods for the early detection and prevention of pipeline plugging.

1.2 Density Sensor Development Chronology

Density sensor development has been funded since 1996.

1.2.1 CMST – Funded Initial Sensor Development

Density sensor development for pipeline deployment was initially funded in 1996 by the US Department of Energy Environmental and Waste Management (EM) 50 through the Characterization, Monitoring, and Sensor Technology (CMST) Crosscutting Program (CP). The sensing approach was selected as a novel technique with promise for characterizing slurry density. The sensor is unique because the measurement is made at the slurry-probe interface enabling measurement of very dense, highly attenuative slurries. In 1997, the initial densimeter configuration was installed in a pipe spool piece and its performance was evaluated during tests at Oak Ridge National Laboratory (Hylton et al. 1998).

1.2.2 TDI – Funded Initial Deployment Development for Hanford

Also, in 1997, the densimeter was included as a part of the Slurry Monitoring Technology Deployment Initiative (TDI) proposal to evaluate instrumentation for characterizing slurry properties during pipeline transport. This proposal was selected for funding, and in 1998, work was initiated to develop a densimeter design in a 10.2 cm (4 in.) pipeline for monitoring slurry properties during waste

transfer from Tank C-106 to Tank AY-102. In late 1998, the Hanford Site priorities changed and the date for deployment and probe evaluation in the Tank C-106 transfer line became uncertain. Therefore, a new deployment location was sought.

1.2.3 ASTD Project Included Density Sensor in Review

Additional evaluation of density sensor performance occurred as a part of the Accelerated Site Technology Deployment (ASTD) project that was funded to reduce the likelihood of pipeline blockage during waste-transfer operations by evaluating instrumentation. The ASTD project, with collaboration from Waste Retrieval Sluicing System Project, Hanford SY-101 Surface Level Rise Remediation Project (SLRRP) and Hanford Tanks Initiative (HTI), evaluated three online slurry monitoring devices for use at the Hanford and ORNL sites. These instruments included: 1) the Lasentec M600 Particle Size Analyzer developed by Laser Sensor Technology, Inc., Redmond, Washington, 2) the Red Valve Pressure sensor manufactured by Red Valve Company, Inc., Pittsburgh, Pennsylvania, and 3) the ultrasonic densimeter developed at the Pacific Northwest National Laboratory (PNNL).

The Hanford Tanks Initiative was the original Hanford Site customer for the slurry monitoring technology. The HTI planned to remove a hard heel from single-shell tank (SST) 241-C-106 with a vehicular deployed retrieval system, and transfer the waste to double-shell tank 241-AY-102. Due to Hanford budget constraints, the HTI project was delayed. Some portions of HTI have been picked up by the project that will retrieve waste from SST 241-C-104 and transfer the waste to 241-AY-101. The slurry monitoring technology from the ASTD study may be deployed during this transfer. The project to sluice waste from 241-C-106 to 241-AY-102 successfully demonstrated the Red Valve Pressure sensors. Oak Ridge National Laboratory successfully demonstrated the Lasentec particle size measurement technology during clean out of the Gunitite and Associated Tanks (GAAT). The Hanford SY-101 Surface Level Rise Remediation Project will demonstrate the densimeter. The results of this densimeter demonstration will be published after the completion of this transfer.

The ASTD review (Bontha et al. 2000) showed that slurry monitors present numerous benefits over the baseline instrumentation plan that calls for grab sampling of the waste followed by off-line analysis. Benefits include:

- Early detection and prevention of pipeline plugging events
- Real-time data of the particle size distribution, density, and pressure drop through the transfer process
- Reduction or elimination of grab sampling and off line analysis
- Reduced radiation exposure for workers.

1.2.4 SLRRP – Incorporated Densimeter into a Deployment at SY-101

In May 1999, the SY-101 Surface Level Rise Remediation Project (SLRRP) and the Tanks Focus Area (TFA) developed a Memorandum of Understanding to permit redirecting an ongoing project to develop and demonstrate an in-line slurry monitoring instrument to measure waste density during planned pipeline waste transfer operations between SY-101 and SY-102. The Ultrasonic Density Measurement System (UDMS) being developed by Pacific Northwest National Laboratory was selected after SLRRP concluded that this technology offered a significant size advantage that would enable it to be installed in

the limited available space. TFA and SLRRP agreed under the terms of a Memorandum of Understanding to attempt to complete the design, fabrication and demonstration of this developmental technology on a very aggressive schedule in an effort to have it available for use by the project. Development and deployment of a density measurement capability was not required for execution of the SY-101 SLRRP transfers, but was being pursued as a desirable enhancement to the baseline transfer system capabilities. UDMS data would be used to analyze various aspects of the transfer process and diagnose potential difficulties, but would not be used in “real-time” to control transfer operations. The anticipated primary use of the data provided by the UDMS is to make possible an accurate mass balance during and after the transfer process.

PNNL has fabricated two UDMS in-line sensor spool pieces for SLRRP transfer line, the second providing a backup unit. A data acquisition system has also been developed. Following completion of bench-top testing of the sensors, PNNL installed both units in a pipe-loop test facility in the Hanford 336 Building and conducted testing of the sensor to provide data for calibration of the system. A series of tests using a sugar-water solution and sugar-water-kaolin solution were completed and a demonstration was provided to PNNL, TFA, and SLRRP project staff on December 10, 2000. A real-time response was observed to changes in density as sugar was added to the batch tank feeding the pipe loop. As expected, the system measured an initial spike in density and then leveled off as the sugar mixed thoroughly as it was pumped around the pipe loop.

In FY-2000, the densimeter was installed in the 241-SY-101 modified process manifold. To support deployment the densimeter performance was evaluated in a test of the manifold component operation in the Fluor Hanford Engineering Laboratory in the 305 building. In FY-2001, this manifold was installed at SY-101 in the prefabricated pump pit. In FY-2002, the densimeter performance will be evaluated during planned line flushes with water and during waste transfers. This demonstration will complete an outstanding TFA key deliverable from 1999 for demonstration of the unit under radioactive waste transfer conditions. Data and calibrations from this demonstration will be reviewed with TFA and SLRRP staff.

Based on the sensor process monitoring evaluations at Oak Ridge, PNNL and tests at Fluor Hanford, the densimeter is expected to meet requirements for measuring slurry density during slurry transfer operations at Hanford and other DOE sites.

1.3 Density Sensor Configurations Evaluated for Deployment

Based on these projects, three density sensor designs have been completed and two density sensor spool pieces have been designed, constructed, calibrated, and tested for deployment as shown in Table 1.2. The initial densimeter model was evaluated at PNNL and at tests in a pipeline at Oak Ridge National Laboratory (ORNL). A second densimeter was developed for deployment at Hanford and was tested at PNNL and at Hanford prior to installation in FY-2001 in a pipeline at the Hanford site.

Table 1.2 Density sensor configurations evaluated for deployment

Site	Pipe Diameter		Design Pressure		Installed	Operated	Planned Operation
	cm	in.	MPa (g)	psig			
ORNL	5.1	2	0.5	67	FY-1997	FY-1997	Test completed
Hanford C-106	10.2	4	2.1	310	No	No	Not scheduled
Hanford SY-101	5.1	2	2.8	400	FY-2001	No	FY-2002

1.4 Densimeter Applications

The in-line density sensor was developed initially for monitoring retrieval operations from radioactive waste storage tanks at the Hanford Site in eastern Washington (Greenwood and Lail 1998, Greenwood, Skorpik, and Bamberger 1998). The sensor can be used to measure density in a pipeline for process control in many process industries including the petrochemical industry, in the production of chemical reagents, in food processing, in the production of paper, and in the production of textiles. If an array of sensors is placed around the perimeter of a horizontal pipe, the sensor at the top can be used to detect presence of air bubbles or partially fully pipe flow; the sensor along the side can be used to detect the bulk density, and the sensor along the bottom of the pipe can be used to detect the onset of sedimentation or stratified flow. The sensor can also be placed in a vessel for the determination of the density of the contents, and several sensors at different elevations and radial locations in the vessel can be used to determine the homogeneity of the vessel contents. In addition to the density, the sensor measures the speed of sound in a liquid or slurry, which is of interest for materials characterization, and also measures the response to a shear wave, which can provide information about the viscosity of the fluid.

2.0 Conclusions and Recommendations

This report describes development of a density sensor (densimeter) for in-line real-time process control and monitoring of slurries during radioactive waste retrieval and transport operations at US Department of Energy (DOE) sites. At these sites millions of gallons of radioactive liquid and sludge wastes must be retrieved from underground storage tanks and transported via underground pipelines for treatment or disposal. A major concern during the transfer operations is plugging of the transfer lines. Blocked transfer lines could significantly escalate the remediation costs both in terms of pipeline replacement costs and costs of maintenance of inactive facilities and operating personnel. The density sensor can be used for real-time process monitoring that could be used to detect conditions that could lead to degraded transport and line plugging. The three main factors that contribute to transfer line plugging are: 1) settling of solid particles during transfer, 2) crystallization of the waste, and 3) gelation of the waste. Depending on the mechanism, plugging or its onset may result in a change in the density or particle size distribution of the slurry. In addition, the onset of pipeline plugging may also lead to an increase in the pressure drop in the transfer lines. The densimeter presents numerous benefits over grab sampling of the waste followed by off-line analysis. Benefits include: early detection and prevention of pipeline plugging events, real-time process data of the density through the transfer process, reduction or elimination of grab sampling and off-line analysis, and reduced radiation exposure for workers.

2.1 Conclusions

The density sensor, shown in Figure 2.1, was developed based on the need to provide a small, robust instrument that could be retrofitted into existing pump pit manifolds and transfer lines. The probe uses ultrasonic signal reflection at the fluid-pipe wall interface to quantify density in situ in real time. The sensor is mounted in the wall of the pipe spool piece. This instrument was selected for monitoring radioactive waste transport based on several characteristic features: the sensing surface is non-intrusive and does not disrupt the slurry flow (the sensor is located flush with the pipeline wall); instrument performance is not affected by slight amounts of entrained air that could be present during waste retrieval and transfer; nor is it affected by electromagnetic noise from nearby pumps and other equipment; and the instrument is compact (the sensor is located on the perimeter of the pipe wall).

During probe development for deployment in a radioactive waste stream, components were tested for chemical and radiation resistance and the spool piece was pressure tested in accordance with ASME Process Piping Code B31.3. In addition, because the probe is installed in a transfer line associated with a tank filled with waste with the potential to generate flammable gas, the design was reviewed by the Hanford Site Flammable Gas Equipment Advisory Board to evaluate probe installation and use in an area requiring compliance with Ignition Source Control Set 2. The board ruled that the density sensor components are not formally approved for use in a Class I, Division 2, Group B atmosphere; however, the components are normally non-sparking and provide equivalent safety.

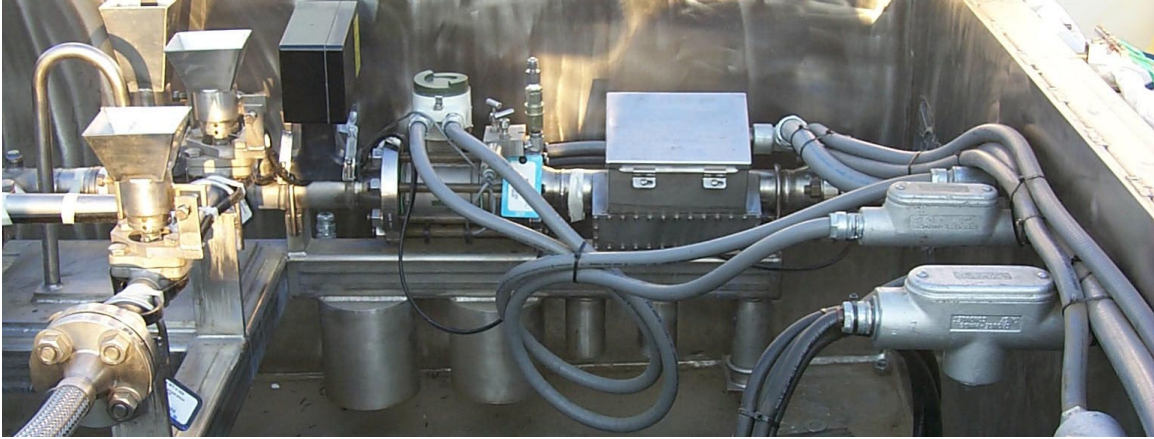


Figure 2.1 Density sensor installed at Hanford in the SY-101 site in the pump pit before and after installation of blanket insulation

2.1.1 Deployment and Demonstration

The density sensor has been deployed as a component in the modified process manifold that is installed in the prefabricated pump pit at Hanford tank SY-101 site. In FY-2001 after completion of densimeter installation and connection of cabling, the probe operation in air was verified. In FY-2002, the density sensor performance will be evaluated during transfers of both water and waste through the pipeline.

2.1.2 Next Generation Through-Wall Density Sensor

The density sensor design installed in FY-2001 at Tank SY-101 is based on the original densimeter concept proposed in FY-1996 and evaluated at ORNL in FY-1997. Upgrades to the SY-101 densimeter include the ability to operate over an increased pressure range (based on design of a new spool piece) and an enhanced calibration scheme that incorporates the effects of temperature into the methodology. Also, an approach has been demonstrated to develop an ultrasonic sensor that: 1) can be attached permanently to a pipeline wall, possibly as a spool piece inserted into the line, or 2) can clamp onto an existing pipeline wall and be movable to another location. An analysis method has been developed to make the

measurement self-calibrating. This investigation has shown the path forward to develop clamp-on sensors for measurement of fluid and slurry density. This method is especially attractive for applications such as Hanford where radioactive fluids are routinely transported because the sensors could be applied to existing equipment without the need to penetrate the pipe pressure boundary or to open the system to install new equipment.

2.2 Recommendations

The goal of the density sensor development is to provide a useful real-time measurement of slurry density throughout all of operations of radioactive waste transport at US Department of Energy Sites. As a step in attaining this goal, the densimeter has been developed and installed at the SY-101 Site. The following anticipated activities would permit evaluation of densimeter performance in a radioactive waste environment and provide valuable information regarding future deployments.

- Evaluate the performance of the density sensor during transport of water (such as precedes or follows each transport)
- Evaluate the performance of the density sensor during transport of a range of radioactive waste slurries
- Evaluate the performance of the density sensor during transport of partially full lines
- Evaluate the long-term sensor performance to detect any trends that could be attributed to changes induced by contact with the waste chemicals or radioactivity.

To support rapid sensor deployment several aspects of additional development are recommended:

- Develop a density sensor that 1) can be attached permanently to a pipeline wall without penetrating the pipe pressure boundary, possibly as a spool piece inserted into the line or 2) can clamp onto an existing pipeline wall and be movable to another location.
- Ensure that the sensor is self-calibrating. An analysis method has been developed to make the measurement self-calibrating which is a very important feature, because with a clamp-on sensor signal strength is sensitive to the pressure with which the transducer is coupled to the pipe.
- Develop the densimeter control system to permit wireless data transmission between the deployment site and the data acquisition site.

These additional features will make the densimeter much easier and less costly to deploy and reduce the radiation dose to workers by eliminating the need to penetrate piping that had transported radioactive waste, and by eliminating the need to install a significant amount of wiring in the potentially contaminated areas between the sensor and the data acquisition site.

3.0 Density Sensor Theory of Operation

The density sensor theory of operation was developed based on an elegant yet simple single-wedge transducer configuration in contact with the fluid or slurry to be interrogated. This approach is described below.

3.1 Density Sensor Theory

The ultrasonic density sensor, shown schematically in Figure 3.1, consists of longitudinal (B, C, D, E, and F) and shear wave (A) transducers mounted upon a plastic wedge. Rexolite^{tm(a)} was selected for the wedge based on its acoustic properties coupled with the ability to operate in a high pH solution and resist radiation damage. Analysis of the signals reflected from the wedge-fluid interface is used to determine the fluid properties of density (ρ), speed of sound (c), and viscosity (μ). The transducers have a center frequency of 2.25 MHz. Transducers F and A operate in the pulse-echo mode; when ultrasound from transducer F strikes the wedge-liquid interface, part of it is reflected back toward F and the rest is transmitted into the fluid. Transducer pairs B-C and D-E operate in the pitch-catch mode; when ultrasound from transducer B (or D) strikes the interface, some of it is reflected toward transducer C (or E), some mode converts to a shear wave in the wedge, and part is transmitted into the liquid. The reflection coefficient, which describes the amount of ultrasound reflected to the receive transducer, is dependent upon the densities and sound speeds in the liquid and the wedge material. To measure the reflection coefficient compare the voltage on the receiver transducer with the wedge immersed in fluid to the voltage obtained with the wedge immersed in a reference liquid, usually water. The density is obtained by measuring the reflection coefficient at two angles of incidence and then solving for the density of the liquid and speed of sound in the liquid, based upon previously determined properties of the wedge material.

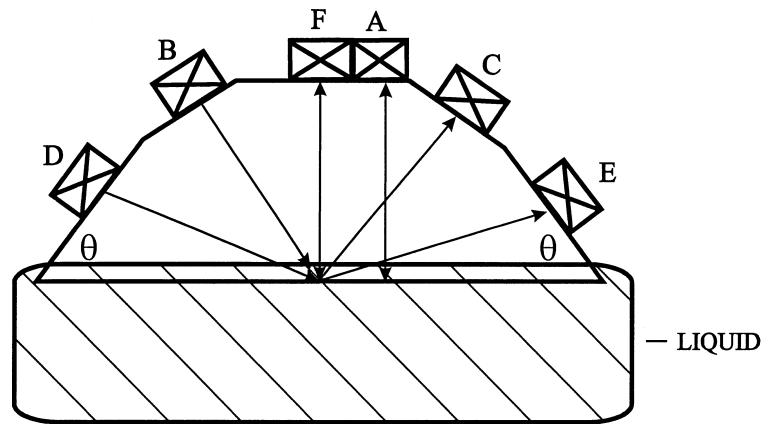


Figure 3.1 Schematic diagram of wedge design.

^a C-LEC Plastics, Inc. 215-708-7731

3.1.1 Measuring the Reflection Coefficient

The measurement is accomplished by sending an ultrasonic toneburst signal to the send transducer and measuring the amplitude of the signal obtained by the receive transducer. In order to determine the reflection coefficient (RC_{liq}), the amplitude of the received signal with the base of the wedge immersed in fluid is compared with that with the base immersed in water (RC_{water}), or any other reference liquid or air. The voltage of the received signal is directly proportional to the pressure and to the reflection coefficient; therefore, the following relationship is obtained:

$$RC_{liq} / RC_{water} = V_{liq} / V_{water} \quad (3.1)$$

where V_{liq} and V_{water} refer to the voltage amplitude of the toneburst. This equation is rearranged as follows:

$$RC_{liq} = RC_{water}(V_{liq}/V_{water}) \quad (3.2)$$

The reflection coefficient for water (RC_{water}) can be determined theoretically because the speeds of sound and densities of the wedge material and water are known. Therefore, the reflection coefficient for the liquid can be obtained from voltage measurements and the calculated reflection coefficient for water, for a given angle of incidence.

3.1.2 Reflection and Transmission Coefficients

When ultrasound traveling in a solid strikes the liquid interface perpendicularly, the reflection coefficient is given by

$$RC = (Z_{liq} - Z_{solid}) / (Z_{liq} + Z_{solid}) \quad (3.3)$$

where the acoustic impedance of the liquid (Z_{liq}) is the product of the density of the liquid (ρ) and the speed of sound in the liquid (c), and the acoustic impedance of the solid (Z_{solid}) is the product of the density of the solid (ρ_s) and the longitudinal speed of sound (c_L). When Z_{liq} is less than Z_{solid} , the reflection coefficient has a negative value. This means that the longitudinal wave undergoes a 180 deg phase change upon reflection.

The reflection and transmission coefficients for the acoustic pressure are given by Krautkramer and Krautkramer (1983) using the notation shown in Figure 3.2. Since the relationship for the reflected longitudinal reflection coefficient is used so often, the notation is simplified as follows:

$$G = (c_T / c_L)^2 \sin 2\alpha_L \sin 2\alpha_T \quad (3.4)$$

$$H = \cos^2 2\alpha_T \quad (3.5)$$

$$J = \rho c \cos \alpha_L / \rho_s c_L \cos \alpha \quad (3.6)$$

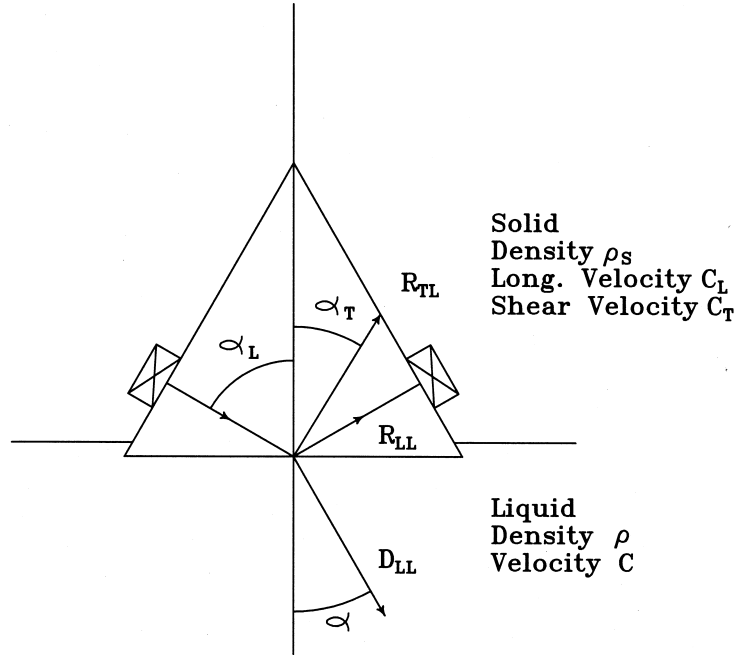


Figure 3.2 Definition of terminology used in equations of reflection and transmission coefficients.

The reflection coefficient for the reflected longitudinal wave (R_{LL}) is given by

$$R_{LL} = (1/N) (G - H + J) \quad (3.7)$$

where

$$N = G + H + J \quad (3.8)$$

The terms G and H involve only quantities concerning the solid, while J contains those of the liquid and solid. This division makes the reverse problem--using reflection coefficients to determine the density of the liquid and its speed of sound--quite simple. When α_L is equal to zero, then α and α_T are also zero and Equation 3.7 and Equation 3.8 reduce to Equation 3.3. The reflection coefficients for the reflected shear wave (R_{TL}) and the transmitted longitudinal wave, (D_{LL}) are given as follows:

$$R_{TL} = (2/N) (c_T/c_L)^2 \sin 2\alpha_L \cos 2\alpha_T \quad (3.9)$$

$$D_{LL} = (2/N) (\rho c \cos \alpha_L \cos 2\alpha_T) / (\rho_s c_L \cos \alpha) \quad (3.10)$$

3.1.3 Determining the Density of a Liquid Using 0 and 60 Degree Angles of Incidence

In order to determine the density of a liquid and the speed of sound in a liquid, the reflection coefficient at two angles must be determined experimentally. This approach is first described for the condition when one angle of incidence must be 0 deg. The non-zero angle was chosen to be 60 deg.

Denote RC_Z as the experimental value for the perpendicular reflection coefficient and R_{LLX} , as that at a non-zero angle. The density and velocities for the wedge are known. Solving Equation 3.7 for J yields

$$J = -G + H(1 + R_{LL})/(1 - R_{LL}) \quad (3.11)$$

Since all terms on the right are known, J can be determined. Solving Equation 3.3 for the acoustic impedance of the liquid Z_{liq} we find

$$Z_{liq} = Z_{solid} (1 + RC_Z)/(1 - RC_Z) \quad (3.12)$$

When Z_{liq} is substituted into the definition of J in Equation 3.6, the only unknown in the resulting equation is $\cos \alpha$, which is given by

$$\cos \alpha = Z_{liq} \cos \alpha_L / J \rho_s c_L \quad (3.13)$$

The angle α can be determined because all terms on the right side are known. The speed of sound (c) in the liquid can be found from Snell's law at the interface now that angle α is known.

$$c = c_L (\sin \alpha / \sin \alpha_L) \quad (3.14)$$

The density of the liquid can be obtained because the acoustic impedance (Z_{liq}) and the speed of sound (c) are known.

$$\rho = Z_{liq} / c \quad (3.15)$$

Equation 3.13 is an important step in the inverse problem. The question is, how much does $\cos \alpha$ change when the density of the liquid changes slightly? If c is less than c_L , then from Equation 3.14 angle α will be less than angle α_L . The cosine of an angle changes most rapidly at a larger angle. Therefore, the sensitivity of Equation 3.13 increases as angle α , and likewise α_L , increases. This is one reason why angle α was chosen to be 60 deg. In Figure 3.1, the central ray from transducer D makes an angle of 60 deg with the normal to the surface.

In Figure 3.3 the reflection coefficient for ultrasound striking a Rexolitetm-water interface is plotted versus the incident angle. At both 0 deg and 60 deg the slope of the curve is zero. Therefore, the reflection coefficient for rays deviating only slightly from these angles does not change. This characteristic makes it very advantageous to use these two angles for the determination of the density. Another important feature is that the reflection coefficient for water at 38 deg is zero. This means that a small change in the density of the liquid will give a large *percentage* change in the reflection coefficient for incident angles near this cross-over point. This feature can be used to detect small changes in the density of a liquid.

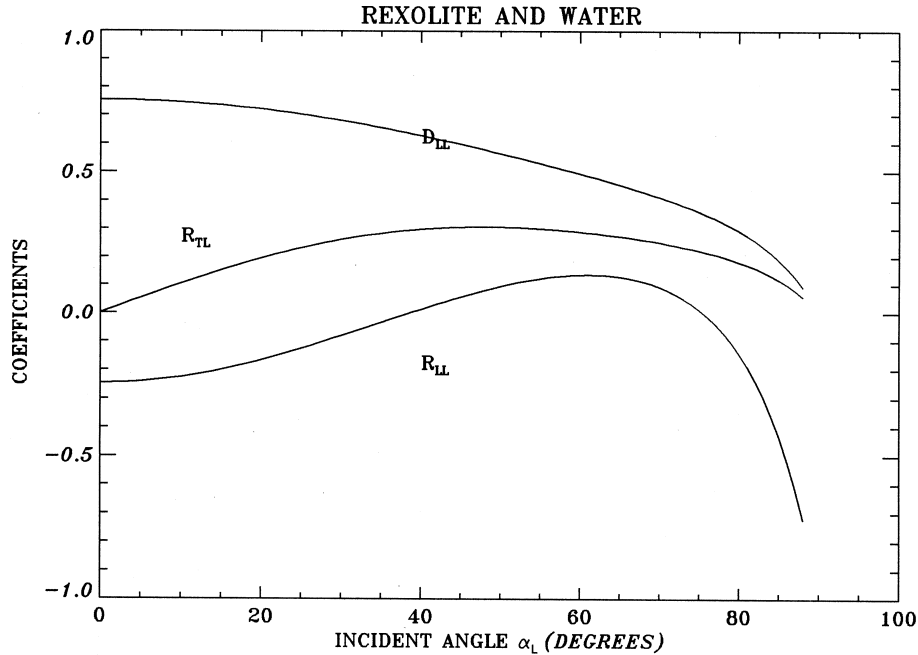


Figure 3.3 Graph showing the reflection and transmission coefficient for a Rexolite™ wedge in contact with water.

3.2 Enhancements Applied to Signal Analysis

The calibration of the sensor is essential to ensure its high performance. To enhance sensor performance over an elevated temperature range the calibration data was analyzed to develop a model that is a function of sensor voltage and temperature. To do this we incorporated an expression of the reflection coefficient as a polynomial expansion in terms of voltage and temperature. This procedure was implemented for the data taken with the densimeter installed in the modified process manifold which was tested in the 305 Bldg. A regression analysis, with a least squares fitting procedure, was carried out for several thousand data points. The model chosen is as follows:

$$\begin{aligned}
 RC_{liq_x} = & b0_x + b1_x T + b2_x T^2 + b3_x V_x + b4_x V_x^2 + b5_x TV_x + b6_x TV_x^2 \\
 & + b7_x T^2 V_x + b8_x T^2 V_x^2
 \end{aligned}
 \tag{3.17}$$

This represents three equations, where x is a shorthand for any one of the three transducer pairs: BC, DE, or FF. V_x (at 0 dB amplifier gain) and T have been measured, but in order to determine the constants in the polynomial expansion, values of RC_{liq_x} are needed. This method for determining the constants provided a robust method for predicting the reflection coefficients and density. The application is described in Section 5.

4.0 Density Sensor Spool Piece and Hardware Configurations

Three density sensor spool piece designs have been developed for Oak Ridge pipe loop tests, for C-106 transfer monitoring, and for SY-101 transfer monitoring. From these designs, two densimeter spool pieces have been constructed, calibrated, and tested for deployment. The first densimeter model, described in Section 4.1, was evaluated at PNNL and during tests in a pipeline at Oak Ridge National Laboratory (ORNL). The second densimeter spool piece, described in Section 4.3, was developed for deployment at Hanford and was tested at PNNL and at Hanford prior to installation in a pipeline at the Hanford site.

4.1 Density Sensor Designed for Tests at ORNL

The transducer wedge in the densimeter spool piece evaluated during tests at ORNL is based on the transducer wedge design shown in Figure 3.1. Figure 4.1 shows the 5.1-cm-diameter, 30.5-cm-long, Schedule 40 stainless steel spool piece design. Figure 4.2 shows photographs of two early models of the density sensor, an immersion probe and the pipeline spool piece evaluated during tests at ORNL. Figure 4.2a shows the tank sensor (Model I), and Figure 4.2b shows a close-up of its probe, which has dimensions of 9.6 cm x 3.5 cm x 5.6 cm. The Rexolite^(tm) wedge is placed within the stainless steel case and the angles of incidence are 0 deg, 40 deg, and 60 deg. Thermocouples are placed in the wedge very near the base of the wedge and at the top of the wedge in order to determine temperature uniformity of the wedge. A thermocouple in contact with the fluid also measures its temperature. The transducer and thermocouple connections pass through the tube of Model I to the top connector box, where connections to the computer are made. Figure 4.2c shows the pipeline model of the probe (Model II), in which the base of the wedge is aligned with a cutout section in the wall of the pipe to produce a non-invasive pipeline sensor. The wedge design is very similar to that in Model I, except that the angles of incidence are 0 deg, 42 deg, and 60 deg. Three thermocouples also measure the temperature at two locations in the wedge and the temperature of the liquid. In both models, the transducers operate at a frequency of 2.25 MHz.

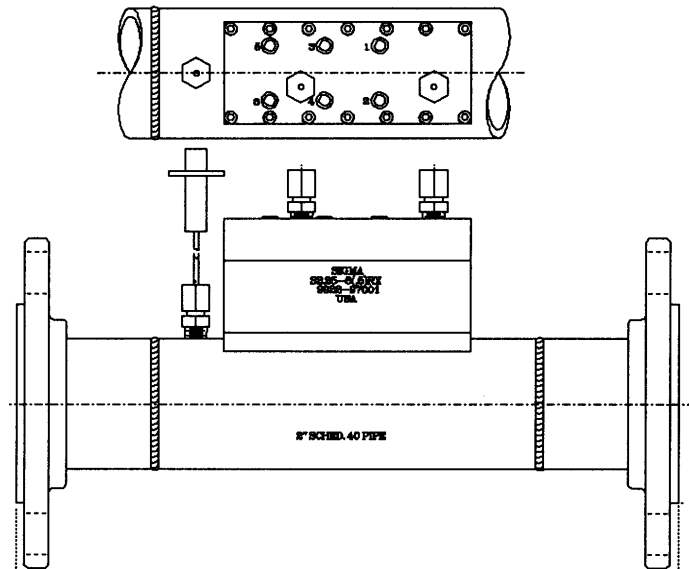


Figure 4.1 ORNL densimeter spool piece

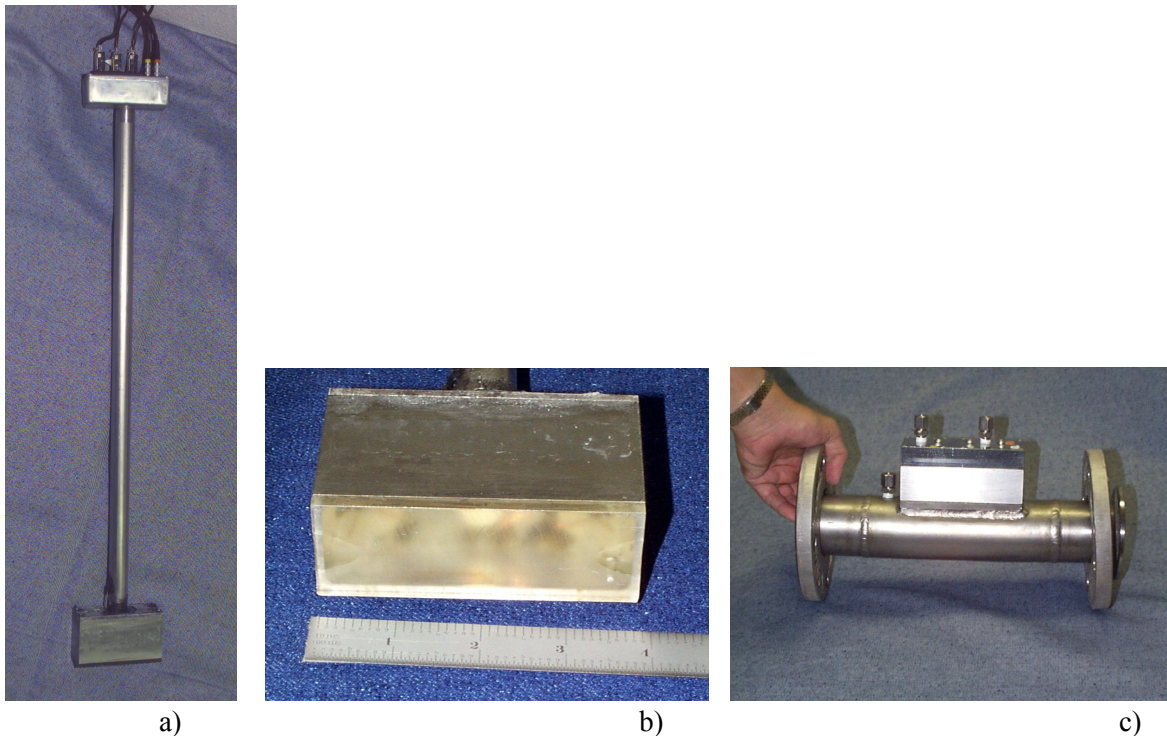


Figure 4.2 Photographs of the Model I tank sensor in a) with a close-up of the base in b) and the Model II pipeline sensor in c).

4.2 Initial Hanford Density Sensor Deployment Configuration for C-106 Pump Pit

To support the Hanford Tanks Initiative, the densimeter was selected for installation in the pump pit at the beginning of the transfer line between Tank C-106 and Tank AY-102, shown in Figure 4.3. The densimeter was to be used to measure the density of the slurry transferred between the two tanks.

Process parameters defining this transfer are listed in Table 4.1. A design for a sensor spool piece was developed to meet these operating conditions. The spool piece, shown schematically in Figure 4.4, was designed to be constructed from 4-in. Schedule 40, ASTM 312, Grade 304L stainless pipe using 4-in. Class 300 lb ASTM A182 F304L weld-neck flanges with raised face. The overall length (flange-face to flange-face) was 42.2 cm (16-5/8 in.). After the spool-piece design was complete but prior to probe construction, the project direction changed to support densimeter deployment in the Tank SY-101 5 cm (2-in.) transfer line, instead of the Tank 106-C 10 cm (4-in.) transfer line.

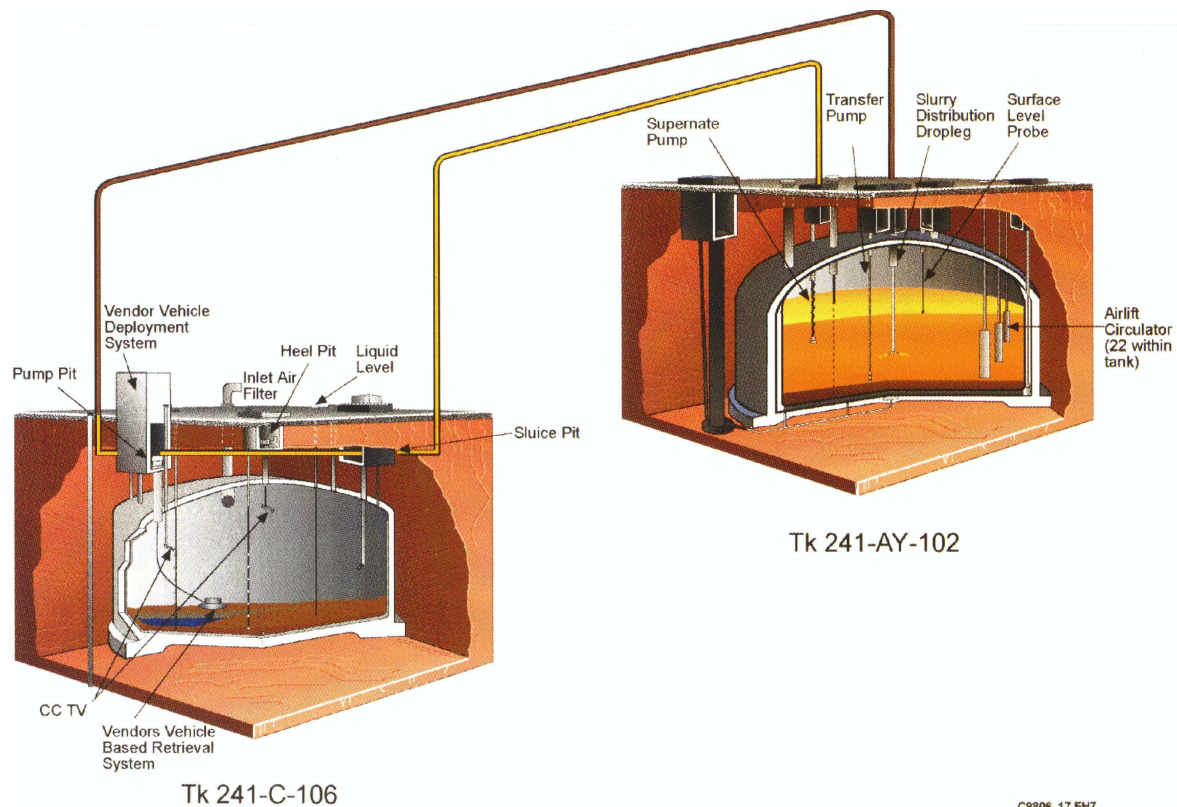


Figure 4.3 Proposed transfer configuration from Tank C-106 to Tank AY-102.

Table 4.1 Slurry transport parameters for transfer from Tank C-106 to AY-102.

Parameter	Parameter Range		Nominal
Flow rate	1136 – 1818 L/min	250 – 400 gpm	1591 L/min (350 gpm)
Temperature	4.4 – 48.9 C	40 – 120 F	23.9 C (75 F)
Operating Pressure	0.956 - 2.14 MPa gauge	140 – 310 psig	1.14 MPa gauge (165 psig)
Viscosity	4 – 100 cP		15 cP
Specific gravity	1 – 1.2		1.15
Percent solids	0 - 30 wt%		10 wt%
Particle size	<<1 – 3175 μm^{a}		50 μm sludge 500 μm hardpan
Radiation	60 R/hr inside pipe 40 R/hr outside pipe 0.5 R/hr 3.04 m (10 ft) away from pipe ^b		100 R/hr in pipeline

a The maximum particle size that can pass through the system is 0.64 cm (1/4 in.)

b Calculated using the ISOSHL D code (Engel et al. 1966)

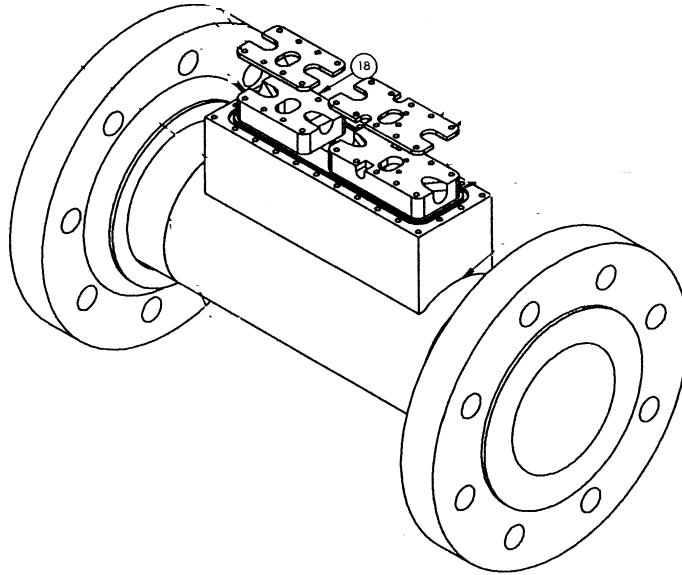


Figure 4.4 Densimeter configuration for deployment in the 10-cm (4-in.) transfer line from Tank C-106 to Tank AY-102.

4.3 Density Sensor for SY-101 Transfer Line

Specifications for density sensor deployment in the SY-101 transfer line were developed in conjunction with the SY-101 team. The specifications were based on information provided in the report HNF-3885 *Functional Requirements and Technical Criteria for the 241-SY-101 RAPID Mitigation System* (Erhart 1999). These criteria are listed in Table 4.2. In addition, because the probe would be installed in a transfer line associated with a tank filled with waste with the potential to generate flammable gas, the design was reviewed by the Hanford Site Flammable Gas Equipment Advisory Board to evaluate probe installation and use in an area requiring compliance with Ignition Source Control Set 2. The board ruled^a that the densimeter components are not formally approved for use in a Class I, Division 2, Group B atmosphere; however, the components are normally non-sparking and provide equivalent safety.

4.3.1 Pressure Containment Design

To meet the design pressure requirement of 2.76 MPa (g) (400 psig) and the pressure test requirement of 4.14 MPa (g) (600 psig), the probe (shown in Figure 4.5) was designed using Schedule 80 stainless steel pipe and 300-lb-class flanges. To achieve a pressure boundary between the transducer wedge and the steel housing, two O-ring seals were incorporated into the probe design. These transducer wedges differ from the design shown in Figure 3.1. To accommodate the O-ring seals and still maintain a small profile wedge, the transducers were located on two separate wedges installed in series, as shown in Figure 4.6. Prints for the densimeter design are provided in the Appendix. After the transducers, O-rings, and cover

^a Flammable Gas Equipment Advisory Board Interpretation/Recommendation Report, FGEAB-99-003, Rev. 0, April 20, 1999.

plates (shown on Figure 4.6) were installed, the probe assembly was pressure tested. The pressure test was conducted in accordance with ASME Process Piping Code Section B31.3.

Table 4.2 Density sensor design and operational criteria

Parameter	SY-101 Design Criteria	Density Probe
Specific gravity	1.0 to 1.7	Tested over range from 980 to 1800 kg/m ³
Waste maximum temperature	54 C (130 F)	Components good to 100 C (212 F), calibrated over range from 20 C to 60 C (68 F to 140 F)
Diluted waste temperature	43 C to 54 C (110 to 130 F)	Probe operates over this range
Working pressure	2.59 MPa (g) (230 psig)	Designed to operate at this pressure
Design pressure		2.76 MPa (g) (400 psig)
Remote readout	In DACS trailer	Provide display for density (kg/m ³)
ASTM 312 304L	For piping	For piping ASTM A240 304L for pipe saddle
ASME B31.3 Pressure test	At 1.5 x design pressure	4.14 MPa (g) (1.5 x 400 psig = 600 psig)
Spool piece length flange-face to flange-face	Specified by Tony Benegas ^a	48.3 cm (19 in.)
pH	No range specified	Rexolite tm good to pH 14; confirmed by lab tests.
Radiation level	No range specified	100 rad/hr in pipeline; tested to 1x10 ⁶ R total exposure; Rexolite tm good to 1x10 ¹⁰ rad



Figure 4.5 Density sensor spool piece

^a Email Communication. From: Benegas, Tony R, Sent: Friday, May 21, 1999 5:33 PM. To: Powell, William J (Bill); Bamberger, Judith A, Cc: Holmes, Carl W; Buchanan, Joseph R; Merriman, Raymond E; Wilk, Jerome L (Jerry); Erhart, Michael F; Hanson, Carl E; Benegas, Tony R. Subject:RE: Densimeter orientation in pipeline.

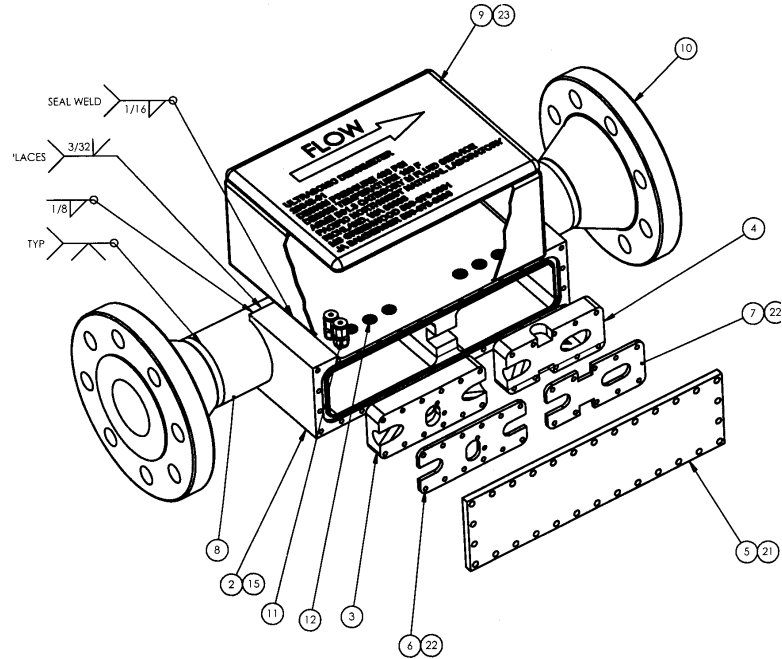


Figure 4.6 Density sensor components showing spool piece (8, 10) wedges (3 – 60 degree, 4 – 47 degree), and electrical connection box (9, 23).

4.3.2 SY-101 Density Sensor Transducer Configuration

Angles of 0, 47, and 60 degrees were selected for transducer orientation. The 60 degree wedge houses longitudinal wave transducer F (operating in pulse-echo mode) and transducer pair D-E (operating in pitch-catch mode). The 47-degree wedge houses shear wave transducer A and longitudinal wave transducer G (operating in pulse-echo mode) and transducer pair B-C (operating in pitch-catch mode). The transducer locations are shown in Figure 4.7. In this design an additional transducer G was incorporated into the system. This transducer, whose location is visible on the side of the 47 degree wedge shown in Figure 4.6, is oriented to measure the reflected signal at an air-wedge interface and provides a real-time reference not affected by the fluid. In this probe the wedge-liquid interface is in the near field of the transducers in order to make the wedge small and still use 1.27 cm diameter PZT7A transducers. This is a change from the original model evaluated at ORNL, in which the wedge-liquid interface was in the far field. Dimensions for the transducers and distance to the base of the wedge are listed in Table 4.3. Two thermocouples were installed in the wedges, one near the base of the wedge and another near the top of the wedge to monitor the temperature and gradients throughout the wedge.

The wedges, shown in Figure 4.8 with the transducers mounted, are installed in the spool piece in Figure 4.9. The longitudinal wave transducers are tuned with a 12.0 microhenry inductor and the shear wave transducer is tuned with a 0.33 microhenry inductor. In the direction of flow, the wedges are machined flush to match the diameter of the pipe and tapered toward the area where the ultrasonic beam is reflected, which is flat. To incorporate transducer A (the shear wave transducer) at the downstream end of the 47 degree wedge, this interface was not machined, thus providing a flat surface for beam reflection, shown in Figure 4.10.

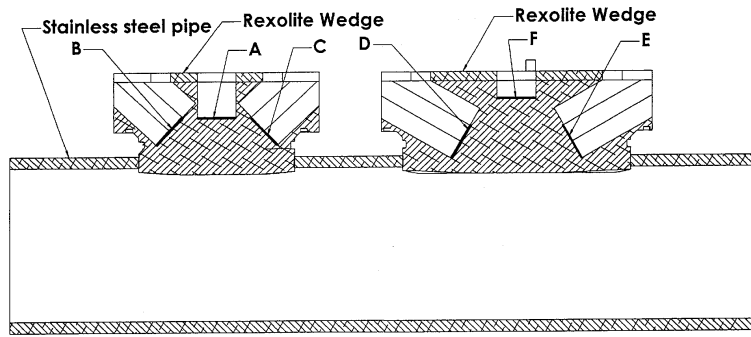


Figure 4.7 View showing transducers and wedges positioned on spool piece

Table 4.3 Transducer dimensions for Probes 1 and 2

Location	Probe 1				Probe 2			
	Distance		Diameter		Distance		Diameter	
	cm	in.	cm	in.	cm	in.	cm	in.
A	0.48	0.19	1.27	0.50	0.64	0.25	1.27	0.50
B	1.81	0.71	1.27	0.50	2.16	0.85	1.27	0.50
C	1.67	0.66	1.27	0.50	2.16	0.85	1.27	0.50
D	2.03	0.80	1.27	0.50	2.16	0.85	1.27	0.50
E	2.03	0.80	1.27	0.50	2.16	0.85	1.27	0.50
F	2.74	1.08	1.07	0.42	2.74	1.08	1.07	0.42
G	2.54	1.00	1.27	0.50	2.54	1.00	1.27	0.50



Figure 4.8 Transducer wedges with transducers and connectors installed

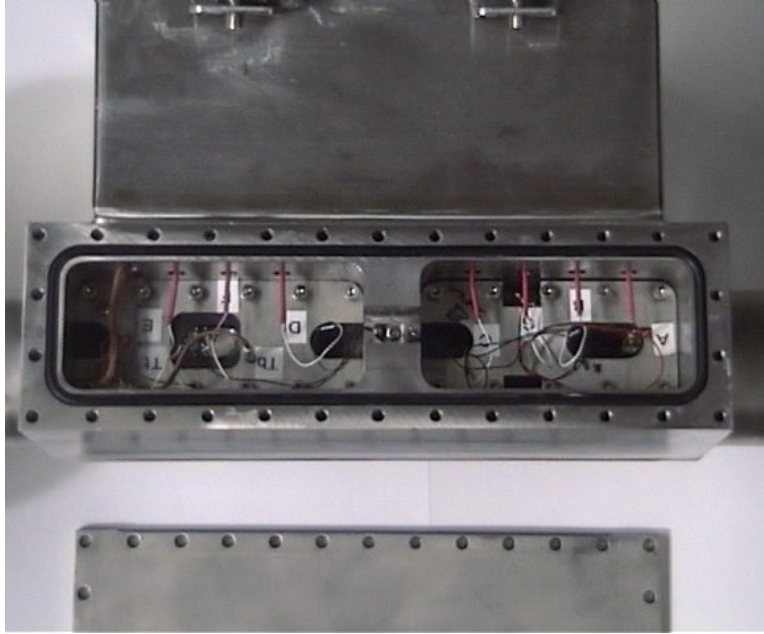


Figure 4.9 View inside transducer housing after pressure test showing labels, connectors and O-ring seal

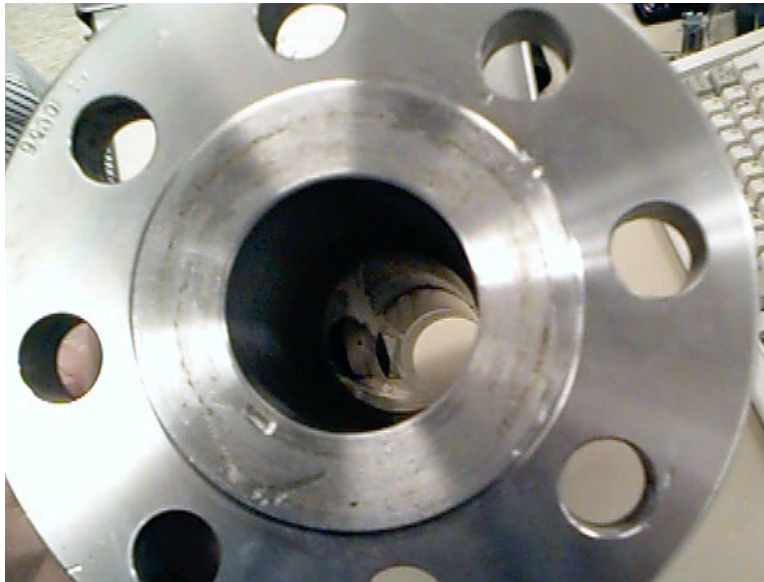


Figure 4.10 View inside the spool piece showing the transducer wedge and pipe-wall interface

4.3.3 Component Testing

The densimeter will be installed in a pipeline that will intermittently transport radioactive waste slurries. Therefore, materials for the probe, specifically the Rexolite™ wedge and O-ring seals, were selected based on their resistance to radiation and resistance to high pH. In addition samples of Rexolite™ and the O-rings were tested in a gamma radiation field and in a chemical waste simulant. The probe wedge in contact with the slurry was selected to operate up to pH 14. To evaluate the ability of the

Rexolite™ block to withstand high pH, it was exposed to pH 13 and pH 14 continuously for 2 weeks. Measurements made after exposure was complete showed no visible changes to the Rexolite™, no change in size of block and no change in speed of sound. The pH specified for probe operation will range from pH 12 to 13. No degradation or changes were observed in the O-rings.

To evaluate resistance to radiation, the probe wedge, transducers, O-rings, and epoxies were exposed to radiation in a gamma pit. The Rexolite™ exposures were for one to eight hours at an exposure rate of 1.25×10^5 R/hr for a total exposure of 5×10^5 R. This is equivalent to a pipeline exposure of 100 R/hr for 2 to 14 months. The blocks, shown in Figure 4.11, exhibited some color change with increasing exposure but no significant degradation was observed. The O-ring exposures were up to 300×10^5 R.

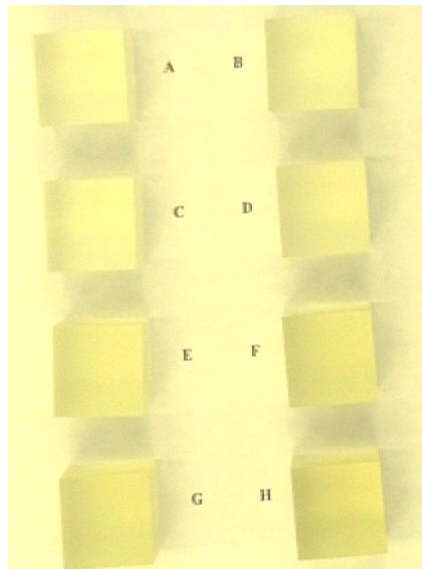


Figure 4.11 Rexolite blocks (A through H) exposed to increasing doses of radiation.

4.4 Computer Controlled Data Acquisition System

The densimeter is operated and controlled by a personal computer with a single ultrasonic (UT) data acquisition card that is a custom Pacific Northwest National Laboratory (PNNL) design. This control architecture is shown in Figure 4.12. It contains an ultrasonic pulser, receiver, a high-speed, high-resolution digitizer, and a multiplexer. The board, shown schematically in Figure 4.13, typically would replace two commercially available cards, but in addition, it offers overall improved performance required for the precision of the measurements. A full-sized printed circuit card using miniature surface-mounted electronic components allows components to be placed on both sides of the board. All design and circuit board layouts were done at PNNL in addition to populating the board with the components. The board is controlled with PNNL custom software that an operator uses via a graphical user interface (GUI). All raw and processed data are displayed in real time and can be archived on hard disk.

The pulser generates an RF (radio frequency) sinusoidal toneburst with the center frequency and number of cycles set by the operator. The center frequency was 2.25 MHz and the number of cycles in the toneburst ranged from 10 to 15. The ultrasonic receiver provides a gain ranging from 0 to 40 dB that

is set by the operator or automatically by using the automatic gain control feature. The digitizer has 12 bits of resolution (1 part in 4096) with a sampling rate up to 40 MHz. The maximum sampling rate of 40 MHz means that a sample is obtained every 25 nanoseconds. The custom-written software consists of five modules: 1) instrument setup, 2) data acquisition and display, 3) parameter measurement, 4) data storage, and 5) density determination. The software, written in “C,” operates on a DOS-based platform on a personal computer (PC).

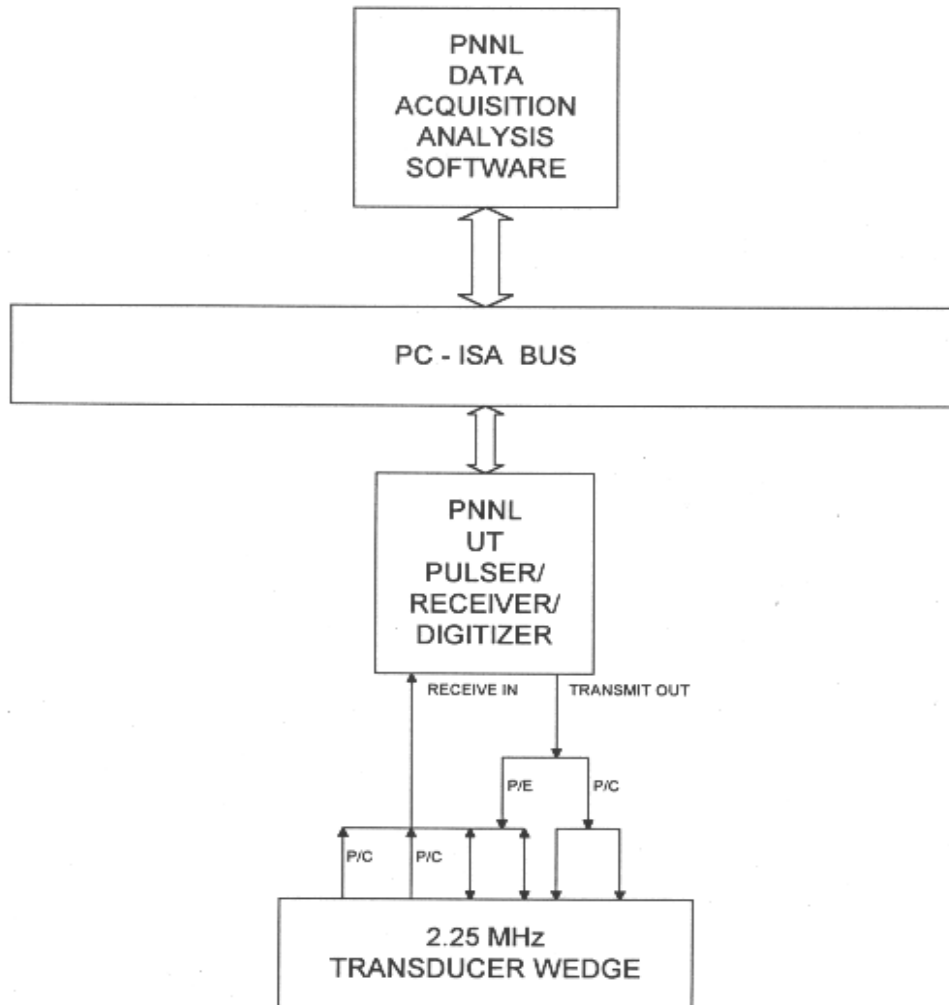


Figure 4.12 Density sensor control system architecture

Averaging is used to factor out random noise. The system finds the peak amplitude and the time of flight for each raw signal, averages the value of each one for the chosen number of signals, and calculates the standard deviation. The maximum and minimum values of the peak are also determined.

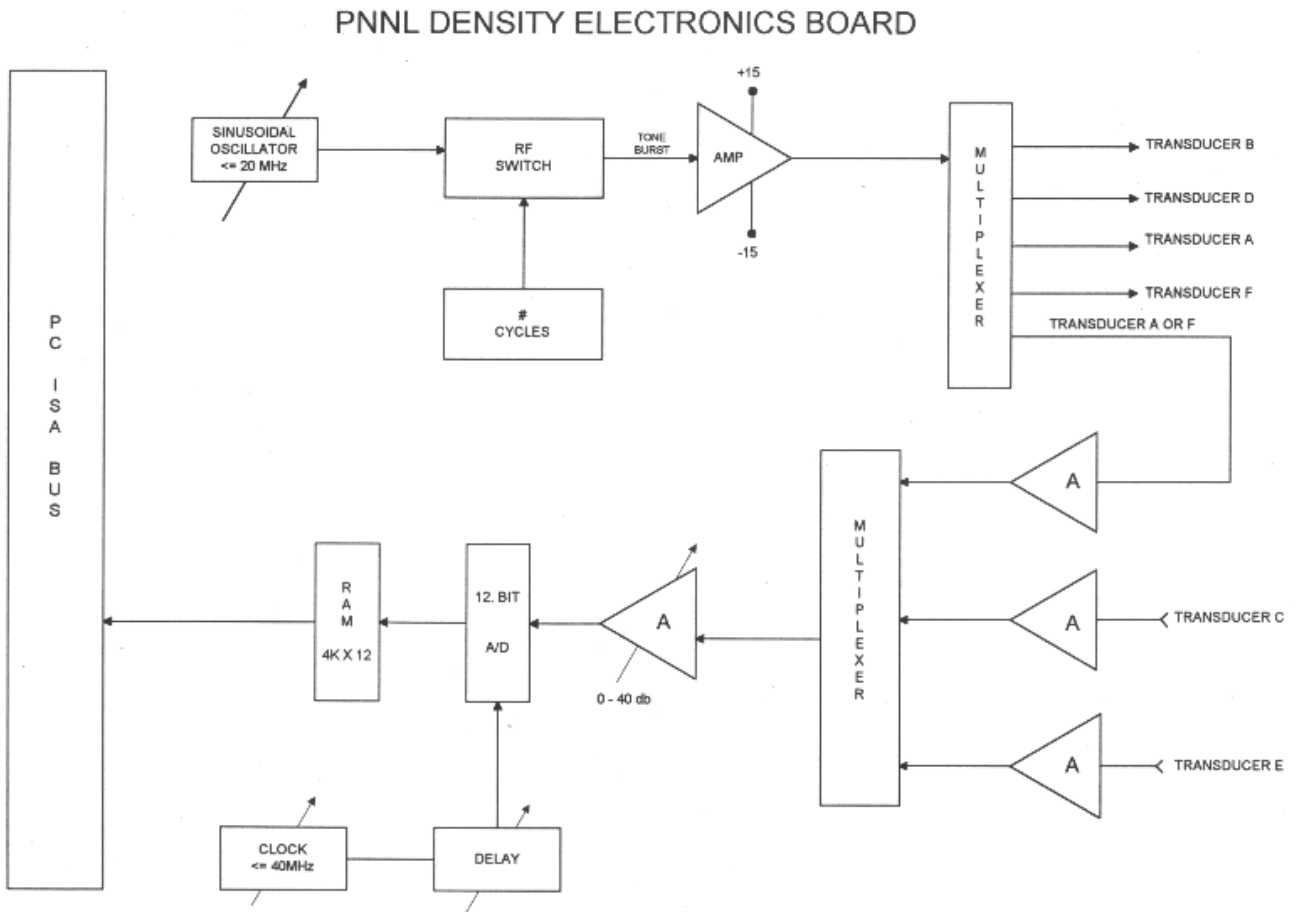


Figure 4.13 Density electronics board components

Instrument setup consists of setting parameters for the pulser (frequency and number of cycles), receiver (gain), and digitizer (sample rate and sample delay) either manually or by invoking the automatic gain control feature. Figure 4.14 shows the receive signal and gates displayed on the computer monitor. The operator sets the software gates: a time-of-flight gate (labeled “TOF” in Figure 4.14) with a defined start time but no end, and an amplitude measurement gate beginning with G1 and ending with G2. A threshold for the TOF gate is shown in Figure 4.14 by a dotted line slightly above the time axis. The peak amplitude is found by examining the peak-to-peak amplitude within the amplitude measurement gate and selecting the largest value. The time of flight is the time for the signal to travel from the send transducer to the receive transducer. It is found by first locating the time point after the TOF gate where the waveform first exceeds the set threshold. Next, the software finds the preceding zero-voltage crossover point, which becomes the resulting time of flight.

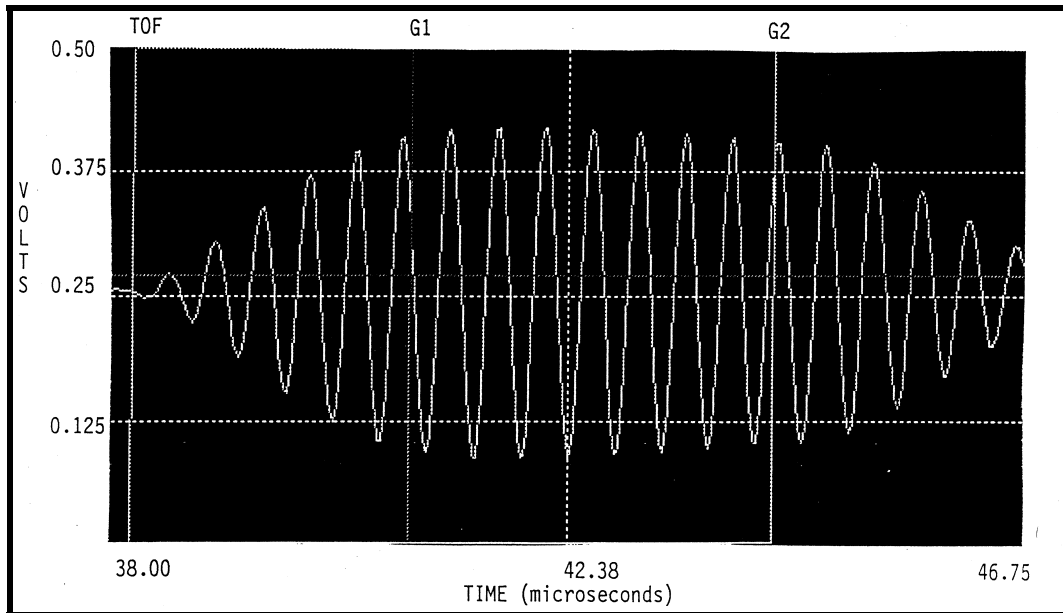


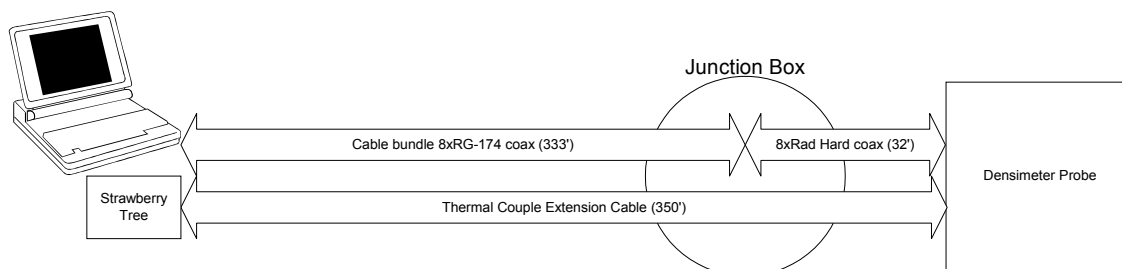
Figure 4.14 Tone burst signal appearing on the computer monitor.

4.5 Densimeter-Computer Connections

A schematic diagram of the densimeter system layout and components is shown in Figure 4.15. The three parts include the densimeter, connecting cables, and computer control system. The cable distance between the densimeter and the computer in the field is 107 m (350 ft) in length. Cables are routed from the computer to a junction box where they are connected with radiation-hardened cables that are connected to the densimeter. The cable connections inside the densimeter electrical box are shown in Figure 4.16. Connections between the densimeter and the computer controller during the probe tests in 336 building are shown in Figure 4.17.

Densimeter System Layout

Dimensions: 11.75"Wx11.5"Hx11.25"D
Lunch Box Style Portable PC (33lbs.)
110VAC



Connectors:

1. Lemo female on end of standard coax at Junction Box.
2. Lemo male on end of standard coax at computer.
3. Lemo male on both ends of Rad Hard coax.
4. Standard Thermal couple connector on end of Thermal couple extension cable at Densimeter Probe.
5. Thermal couple extension cable goes into terminal strip at computer.

Figure 4.15 Cable connections between densimeter and computer controller



Figure 4.16 Labeled lemo and thermocouple connectors

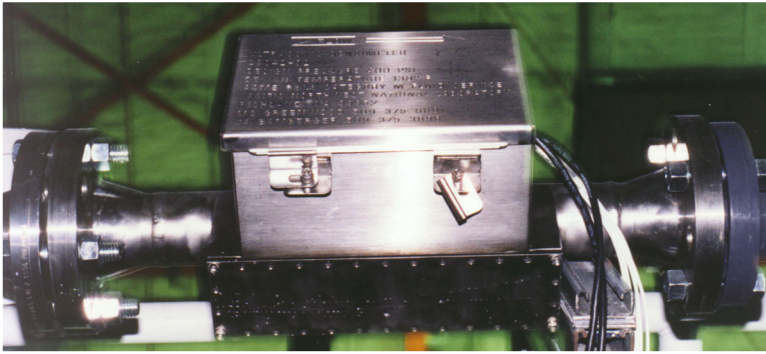


Figure 4.17 Densimeter cables and computer connections during pipeline tests at 336 building

5.0 Density Sensor Pipeline Evaluations

The densimeter probes have been tested in pipelines at Oak Ridge, PNNL, and at Hanford. Pertinent observations from these tests are described.

5.1 Densimeter Evaluation at ORNL

In FY-1997 the performance of densimeter models, I and II shown in Figure 4.2, were evaluated during comparative testing of slurry monitors at Oak Ridge National Laboratory (Hylton et al. 1998). During these tests, the densimeter was installed vertically in the pipe loop as shown in Figure 5.1. Flow was vertically upward through the densimeter. This is the only evaluation of the densimeter performance in the vertical orientation. Subsequent tests and the installation at Hanford have the densimeter installed in a horizontal orientation.

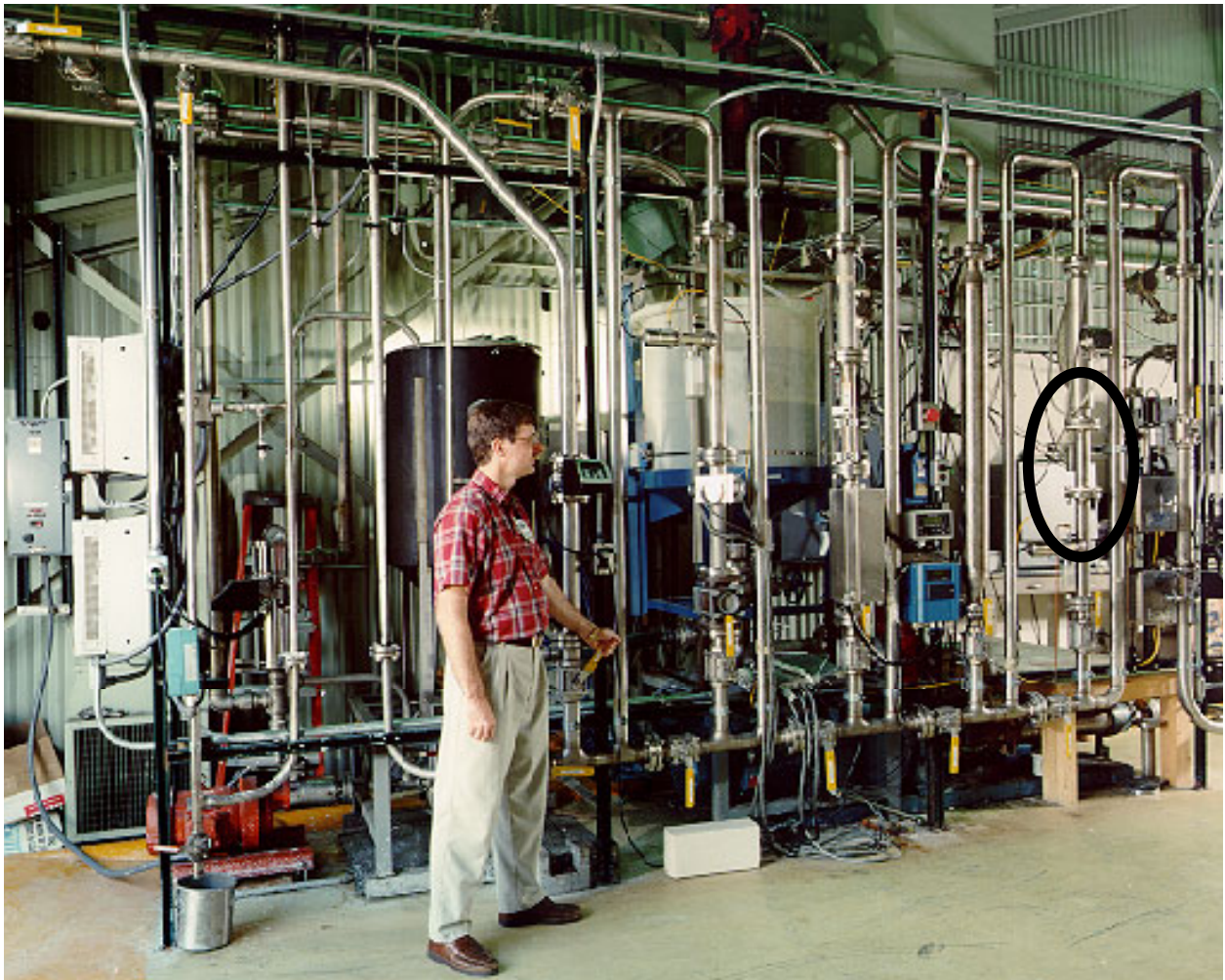


Figure 5.1 Vertical installation of densimeter during ORNL pipe loop tests

The extensive performance evaluation at ORNL evaluated effects of seven parameters: flow rate, air entrainment, density, viscosity, concentration, particle size, and temperature. The simulants started with water, followed by sugar water (to increase density and viscosity) and then switched to slurries to add effects of increased density, solids concentration, and particle size. The slurries were composed of up to three types of particulate:

- kaolin clay (feldspar EPK Kaolin) with a particle size distribution ranged that to ~90 μm and a mean diameter of ~20 μm
- sand (Quikrete Play Sand). 75% of the particles ranged between 250 and 500 μm and 95% of the particles ranged between 125 and 500 μm
- Chert gravel (Rogers Group) with a particle size between 1000 and 4000 μm .

The slurries were mixed with water or with 50 wt% sugar water. The eight flow rates evaluated ranged from 0.06 m/s to 2.7 m/s (0.2 ft/s to 9 ft/s) and tests were conducted at two temperatures 25 C and 50 C. To evaluate the effects of air entrainment, several tests at fluid velocities of 1.5 m/s (5 ft/s) were infused with an air volumetric flow rate of either 1.57×10^{-4} or 3.11×10^{-4} m^3/s (0.33 or 0.66 ft^3/min) that corresponded to 5 and 10 vol % air. The test design was both a crossed (factorial) and a hierarchical (nested) design. Slurry temperature, slurry flow rate, and induced air flow rate represent the same factor levels for each slurry matrix and matrix composition. The nested factor levels of the matrix concentration depend upon the slurry matrix type. The water matrix was used to check both the test loop and the functionality of the slurry monitoring instruments and to compare conditions at the beginning of the evaluation with those at the end of the evaluation.

Each test lasted ~ 20 to 30 min at each test condition. Each run contains 40 cases, measurements taken every 30 s for 20 min. A value of the density was determined for each case and the Sensor Average Density is the density of these values. Comparison between the probe measurements and bottle samples obtained during tests at ORNL for a series of the matrix are shown in Table 5.1. Evaluation of the data showed that:

- The density measurements are not affected by the slurry flow rate through the pipeline
- The density measurements are not affected by entrained air

Table 5.1 Density sensor data obtained during the instrument evaluation at ORNL

Slurry	Nominal Conditions					Reference Density Average (g/cm^3)	Sensor Density Average (g/cm^3)
	Temp	Fluid Flow Rate		Air Flow Rate			
	(deg C)	(m/s)	(ft/s)	(m^3/s) $\times 10^{-4}$	(cfm)		
Water	50	1.5	5	1.57	0.33	1.2797	1.2290
	50	1.5	5	3.11	0.66	1.2797	1.2776

30% Kaolin in Water	50	0.91	3	0	0	1.1918	1.1702
	50	0.30	1	0	0	1.1967	1.1717
	50	2.7	9	0	0	1.1936	1.2233
	50	1.5	5	1.57	0.33	1.1936	1.1730
20% Kaolin in Water	50	2.1	7	0	0	1.1241	1.1887
	50	0.12	0.4	0	0	1.1339	1.1550
	50	0.91	0.3	0	0	1.1344	1.1331
	50	1.5	5	3.11	0.66	1.1292	1.1610
15% Kaolin in Water	50	2.1	7	0	0	1.3201	1.2873
	50	0.91	3	0	0	1.3229	1.3160
	50	0.30	1	0	0	1.3243	1.3209
	50	0.24	0.8	0	0	1.3244	1.3170
	50	1.5	5	1.57	0.33	1.3220	1.3102
8.5% Kaolin in Sugar Water	50	2.7	9	0	0	1.2782	1.3747
	50	2.1	7	0	0	1.2792	1.2633
	50	0.91	3	0	0	1.2808	1.2995
	50	1.5	5	1.57	0.33	1.2797	1.2290
	50	1.5	5	3.11	0.66	1.2797	1.2776
30% Kaolin, Sand in Sugar Water	50	0.91	3	0	0	1.4203	1.2725
	50	0.30	1	0	0	1.4132	1.2533
	50	0.49	1.6	0	0	1.4268	1.2550
	50	1.5	5	1.57	0.33	1.4224	1.2856
20% Kaolin, Sand in Sugar Water	50	0.91	3	0	0	1.3680	1.2818
	50	0.30	1	0	0	1.3478	1.2798
	50	0.18	0.6	0	0	1.3525	1.2833
	50	0.27	0.9	0	0	1.3568	1.2965
	50	1.5	5	1.57	0.33	1.3717	1.2606
10% Kaolin, Sand, Gravel in Sugar Water	50	1.5	5	0	0	1.3043	1.3446
	50	0.30	1	0	0	1.2757	1.3312
	50	0.18	0.6	0	0	1.2787	1.3056
	50	0.12	0.4	0	0	1.2777	1.3778
	50	1.5	5	1.57	0.33	1.2933	1.3257
20% Kaolin, Sand, Gravel in Sugar Water	50	1.5	5	0	0	1.3640	1.3103
	50	2.1	7	0	0	1.3617	1.2874
	50	1.5	5	1.57	0.33	1.3640	1.3207

The results of the ORNL pipeline demonstration showed the promise of an instrument such as the densimeter. The small size of the densimeter and its tolerance to entrained air, as demonstrated during the qualification tests at ORNL, make it extremely useful for deployment in existing locations and conditions where air may be entrained in the pipeline. The developers also noted that the ultrasonic densimeter:

- Can interrogate extremely dense slurries and settled solids layers because the ultrasonic signal does not need to penetrate the slurry to evaluate the slurry density.
- Has a simple compact design allowing deployment in short pipe spool pieces ≤ 30 cm (12 in.) long, or in vessels by insertion of a single sensor probe into the fluid, or by attaching the probe to the vessel wall.
- Is not affected by electromagnetic noise and can be located in harsh environments such as pump pits or other areas crowded with machinery.

Based on the results of these qualification tests, the densimeter was selected for demonstration at the Hanford Site as a part of the Hanford Tanks Initiative (HTI).

5.2 Densimeter Demonstration in the Instrument Validation Facility

To support HTI deployment, the densimeter performance was evaluated during two sets of non-radioactive transport tests using waste simulants. During the first tests, the densimeter operation was evaluated during tests in the PNNL Instrument Validation facility (Bontha et al. 2000, Reynolds et al 1996). The purpose of the tests was to evaluate densimeter performance over a range of operating conditions simulating transport of water, viscous liquids, and slurry. At the completion of these tests, the decision was made to install the densimeter into a replacement process manifold that would eventually be deployed at the Hanford Site. After the densimeter was installed and the manifold assembly was pressured tested, a similar series of performance evaluation tests were conducted, this time to evaluate the performance of the densimeter in the piping configuration in which it would eventually be deployed. This section describes the results of these two sets of performance evaluations.

In 1999, the performance characteristics of two densimeters were evaluated during pipe loop tests in the Instrument Validation Facility at PNNL, shown in Figure 5.2. Pump process variables and slurry properties were measured during the tests. The densities of slurry samples were periodically measured using a pycnometer. Samples were taken through ports S-3 on the upstream leg of the pipe loop and S-4 on the down stream leg of the pipe loop; the samples were measured immediately in the laboratory and the measurements were obtained at essentially the same temperature as the slurry circulating in the pipe loop. The average of these values was used to specify the density of the flowing slurry. The test matrix was designed to evaluate the density of water, the density of fluids with densities greater than water, and densities of a range of slurries. The test matrix was set up to be conducted sequentially with three fluids: water, sugar water, and kaolin clay in a sugar water suspension. The range of densities and wt% of the fluids evaluated during the tests are summarized in Table 5.2 (Bamberger and Greenwood 2000).

Table 5.2 Range of fluid properties evaluated during pipe loop tests

Fluid	Density Range	Wt% Range	Quantity Of Component
Water	988 - 994 kg/m ³	0	503 kg (1109 lbm)
Sugar water	1005 - 1108 kg/m ³	4.3 - 27.7 wt% sugar in water	22.7 - 193 kg (50 - 425 lbm)
Kaolin clay in sugar water	1130 - 1459 kg/m ³	3.2 - 41.8 wt% kaolin in sugar water	22.7 - 498 kg (50 - 1100 lbm)

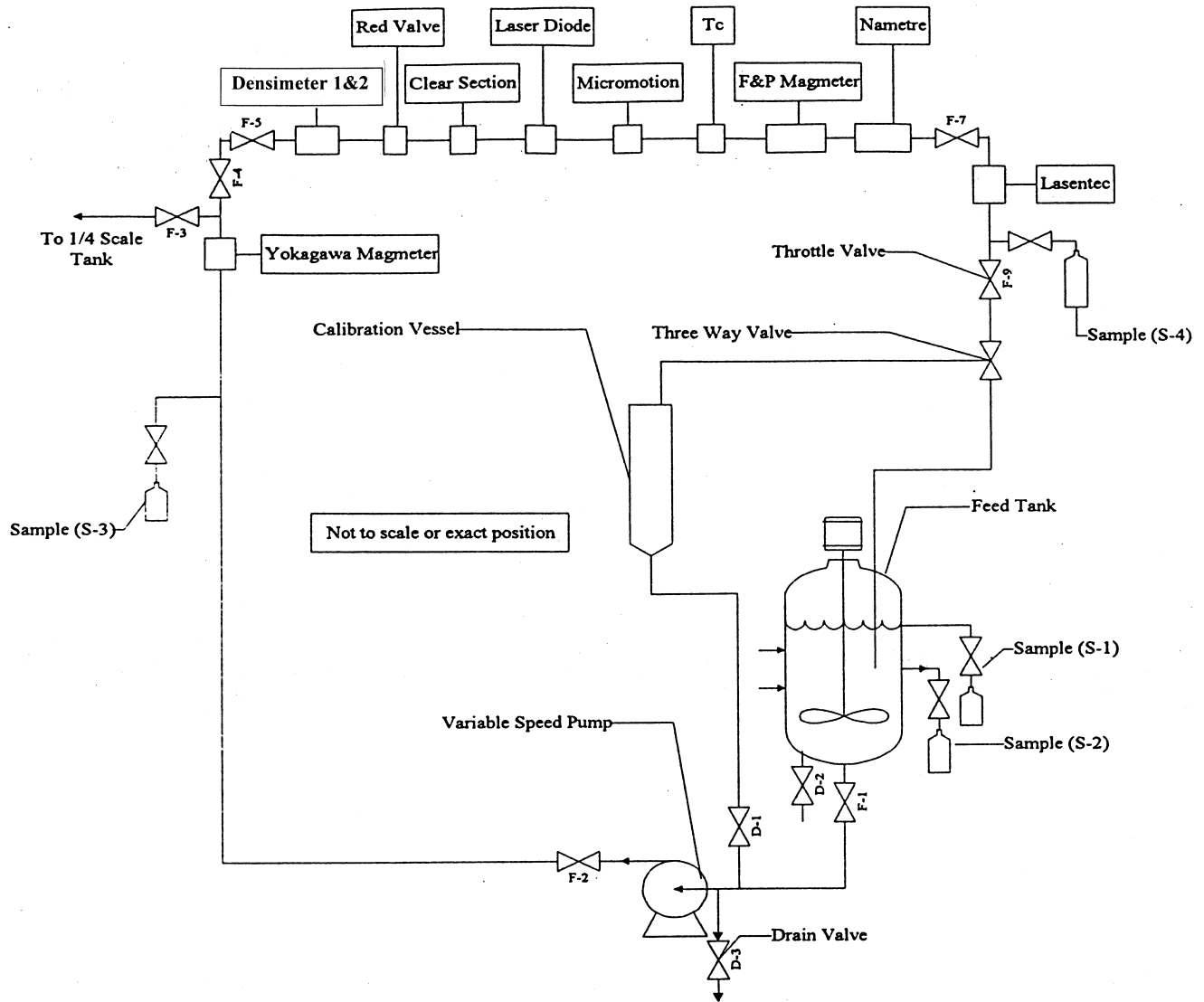


Figure 5.2 Configuration of the instrument validation facility pipe loop

After the loop was filled with water, the water was pumped continuously through the loop until a steady state temperature was achieved. Density data, grab samples and process data were taken during this transient. After steady state temperature was achieved, the loop was operated continuously to obtain long term operating data. An overview of this sequence is provided in Table 5.3.

Table 5.3 Test sequence and range of operating parameters

Fluid	Water	Sugar Water	Kaolin in Sugar Water
Duration	20 hr	24 hr	5 hr
Temperature range	50.8 – 53.8 C	48.4 – 50.0 C	54.7 – 57.8 C
Flow rate range	0.33 m ³ /min (87 gpm)	0.32-0.33 m ³ /min (86 – 87 gpm)	0.26 – 0.33 m ³ /min (68 – 86 gpm)

Densimeter transducer received voltages and probe temperatures were recorded continuously throughout the tests. Comparisons between the pipe loop test data and the calibration data obtained in the laboratory over a range of temperatures showed a discrepancy between the two. After much analysis and measurement of other parameters, this discrepancy was tracked to slight but observable changes in the input voltage. The data was analyzed to further understand the effects of the difference in the input voltage levels for the two locations. From this data, densities were calculated. Data obtained from probe 1 was analyzed based on data from the 0, 47, and 60 degree sensors. These calculated densities were compared with the densities obtained from the grab samples and the results are summarized in Table 5.4. Agreements are good, usually within +/- 2%.

5.3 Tests at 305 Building in Modified Process Manifold

Performance testing of the densimeter was carried out in the 305 Building, Fluor Hanford, Inc. Engineering Laboratory during September and October 2001 (Witwer 1999 and Witwer et al. 2001). The densimeter was installed in the process (pump outlet) manifold, which will be installed in the 241-SY-101 Prefabricated Pump Pit (PPP). The process manifold had previously undergone minor modification, including installation of the densimeter, followed by acceptance pressure testing, prior to the performance testing documented here. The manifold was connected in line with a pump and a slurry-mixing tank as shown in Figure 5.3. The densimeter computer controllers are visible to the right of the manifold.

The tests were conducted using the two densimeters, shown in Figure 5.4. Densimeter 1 (installed to the left) will be included in the manifold when it is installed at the site. Densimeter 2 (installed to the right downstream from densimeter 1) is installed in the manifold so that both sensors can be evaluated simultaneously during the tests. Densimeter 2 will be removed after testing and will not be installed at the site. Both densimeters were included in the system when it was pressure tested at 4.13 MPa (g) (600 psig). To ensure that the densimeter sensor is in contact with the slurry, the densimeters were installed with the transducer wedge oriented at the 3 o'clock position or lower when observed from the upstream end. The data acquisition computers are shown in Figure 5.5.

Table 5.4 Comparison between densimeter and reference densities obtained during pipe loop tests

Fluid	Density By Weight (kg/m ³)	Probe 1	
		Density (kg/m ³)	Error (%)
Sugar Water	1005	994	-1.1
	1020	992	-2.7
	1032	1017	-1.5
	1048	1035	-1.2
	1061	1068	0.7
	1073	1085	1.1
	1085	1090	0.5
	1096	1109	1.2
	1100	1114	1.3
	1100	1153	4.8
Kaolin in Sugar Water	1130	1167	3.3
	1165	1196	2.7
	1199	1231	2.7
	1226	1247	1.7
	1269	1272	0.2
	1325	1363	2.9
	1384	1395	0.8
	1425	1424	-0.1
	1425	1417	-0.6
	1455	1422	-2.3

This performance evaluation was conducted using the same procedure and sequence as the pipe loop tests. A series of water, sugar water, and kaolin clay in sugar water simulants were pumped through the manifold. The densimeters were operated continuously during these tests as the fluid density was incrementally increased through addition of sugar and then kaolin clay. Testing with simulants ranging in density from approximately 1,000 to 1,400 kg/m³ was proposed, but testing was terminated prior to completion of the proposed test matrix because of pump seal failures, combined with schedule constraints. Testing was terminated after obtaining data from a simulant with a density of 1241 kg/m³. At the completion of the tests, Densimeter 29042-1 remained installed in the process manifold and Densimeter 29042-2 was removed from the process manifold.



Figure 5.3 Modified process manifold test configuration

The average (mean) density data and standard deviation in the data obtained at each density is compared with a grab sample density, listed in Table 5.4. A grab sample involved obtaining a thoroughly mixed sample of the slurry out of the mixing tank of the same mix as recorded by the densitometer(s). A pycnometer was used to provide a precisely measured volume, which was then measured on a calibrated balance to determine the sample density. The percent error between the mean and bottle sample density is also shown. These deviations ranged from 0 to 1.5% for probe 1 and slightly higher for probe 2.

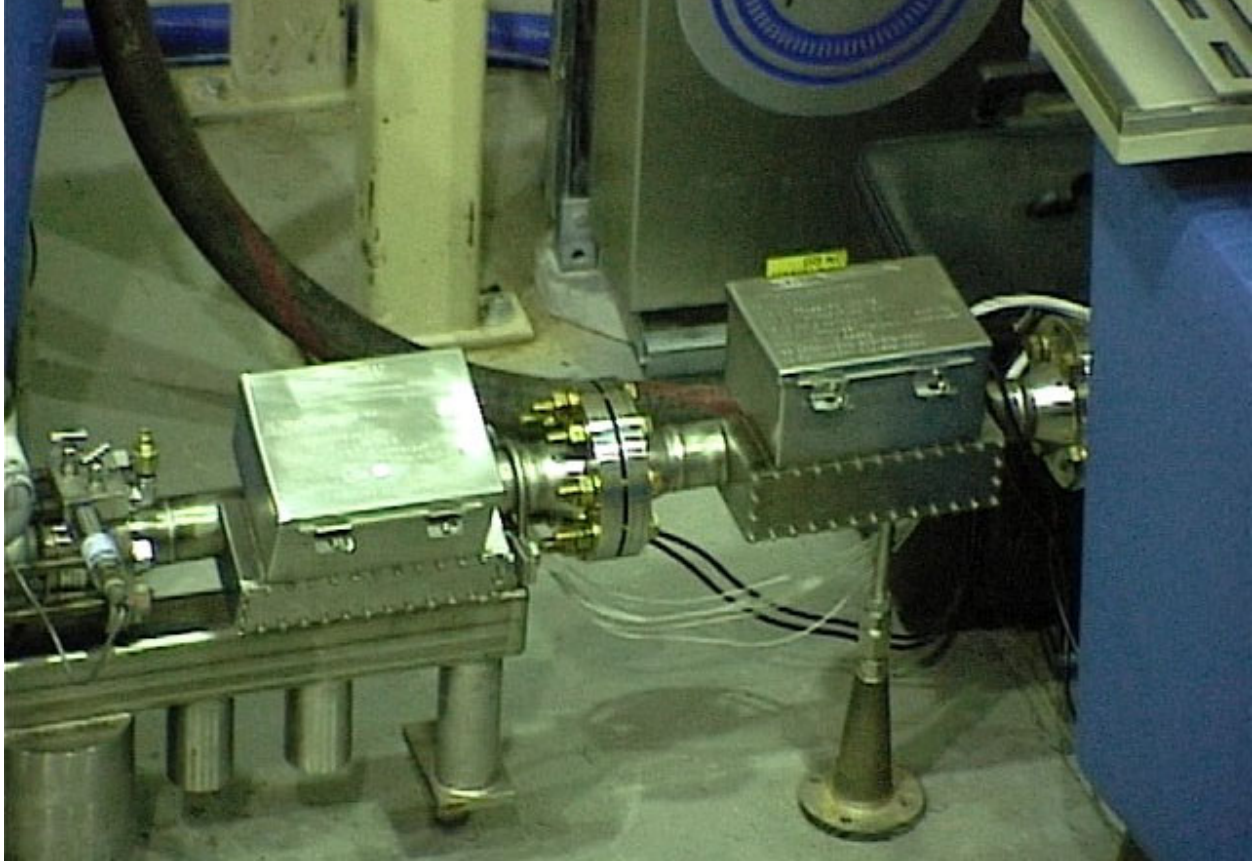


Figure 5.4 Densimeter 1 (left) and densimeter 2 (right) installed in the modified process manifold

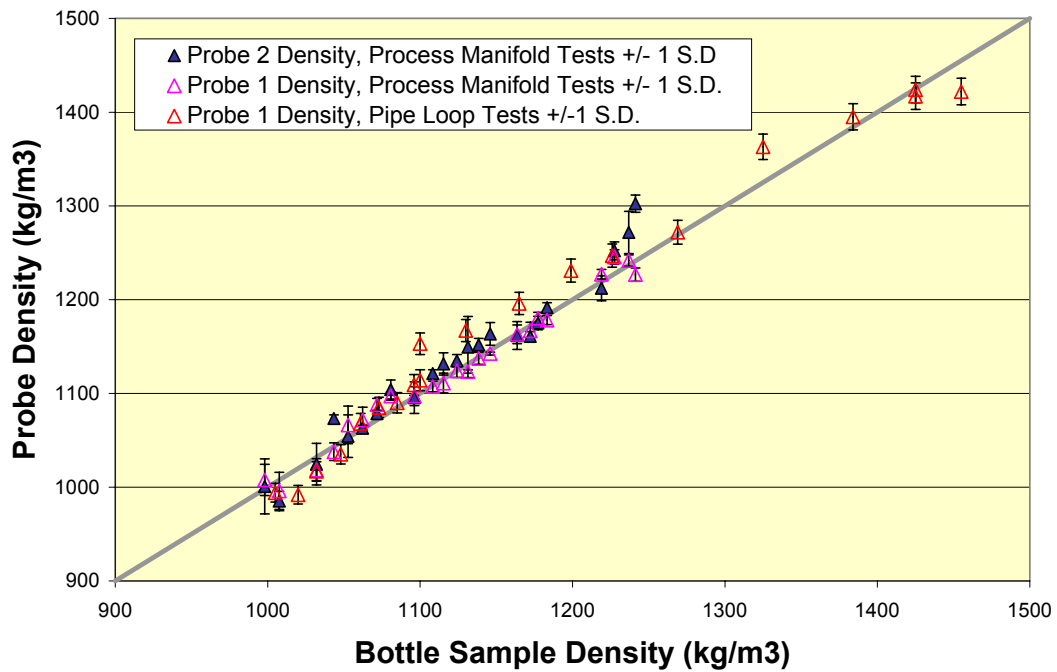


Figure 5.5 Data acquisition computers for the two density sensors.

5.4 Density Sensor Performance

The densimeter performance has been evaluated over the range of operating conditions proposed for deployment (Bamberger et al. 2001). During two sets of process tests, densities ranged from water up to slurries with bulk densities of 1455 kg/m^3 . These two data sets are compared in Figure 5.6. Over the range tested, most deviations between the measured and the reference densities are within $\pm 2\%$.

Figure 5.6 Comparison between densimeter and reference densities



6.0 Density Sensor Calibration

In the fall of 2000, tests of the density sensor were conducted in a pipeline using non-radioactive simulant slurries. This was the last test before the sensor was installed at the SY-101 site. The data presented here are the results of these tests.

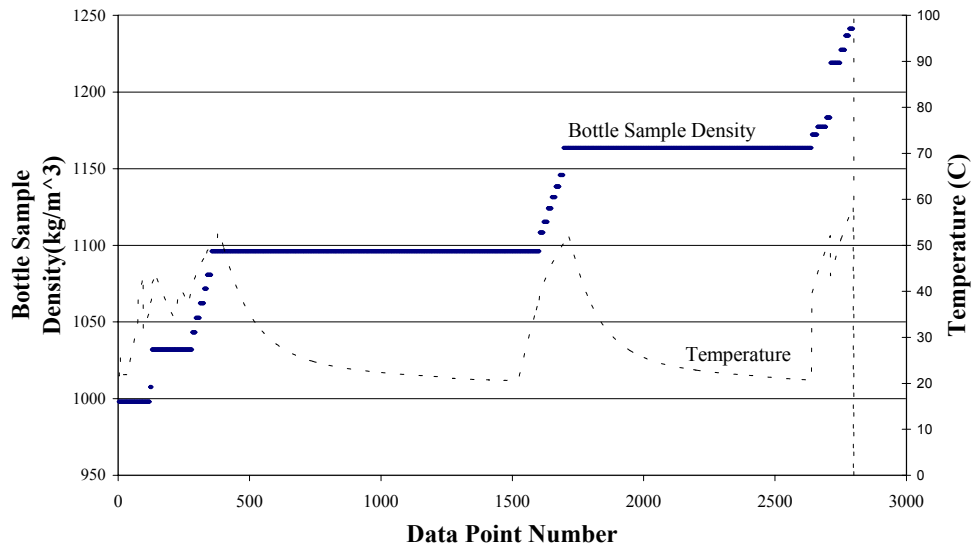
Two probes, designated Probe 1 and Probe 2, were constructed and both were calibrated during the tests. The probes were installed in the modified process manifold (MPM) and placed in a pipe loop assembly at the Fluor Hanford Inc. Engineering Laboratory. After completion of the tests, Probe 1 remained installed in the process manifold and Probe 2 was removed and remains a spare. The test began with water. Subsequently sugar was added to the tank to increase the density. The action of the pump caused the temperature of the liquid to rise, and there was no other source of heat. When the density of the sugar water solution reached a weight percentage of about 50%, kaolin clay was added to increase the density. We had hoped to add more kaolin, but, because of pump seal failures, data could not be obtained at a higher density with the existing pump. During the testing the voltage measurements for V_{BC} , V_{DE} , V_{FF} , and V_{AA} were obtained for water, 18 sugar water solutions ranging in density from 1008 kg/m^3 to 1219 kg/m^3 , and the sugar-water-kaolin slurries ranging in density from 1227 kg/m^3 to 1241 kg/m^3 . Measurements of the temperature were also obtained. For each liquid or slurry concentration, a grab sample was obtained from the tank and its density measured by weighing using a pycnometer. These are referred to as bottle sample density measurements.

From this large set of data, 2796 data points for Probe 1 and 3828 data points for Probe 2 were selected for analysis. This data set included times when the slurry was well mixed. Figure 6.1a and b show plots of the bottle sample density and the temperature at the base of the wedge. Two sets of data were obtained over a large range of temperature, when the pump was turned off overnight, and the sugar water solution cooled down. These are shown in Figure 6.1.

6.1 Approach for Sensor Calibration

The calibration of the sensor is obviously an important step to ensure its high performance. Initially, the probes were calibrated referenced to water, as had been done for the original model. However, subsequent tests on the second-generation sensor showed that with this approach the density was determined correctly at room temperature, but not at higher temperatures. This observation is quite puzzling because one can ask: Why should room temperature be “special?” However, philosophical questions aside, the voltages on the receive transducers operated in an expected manner. When the density of the liquid increased, the voltage on transducers BC and DE increased, while the voltage on FF decreased. Therefore, the voltages were indeed supplying information about the density, but to extract the information a more complicated interpretation and calibration were needed.

Bottle Sample Density and Temperature vs Data Point Number, Probe 1



Bottle Sample Density vs Data Point Number, Probe 2

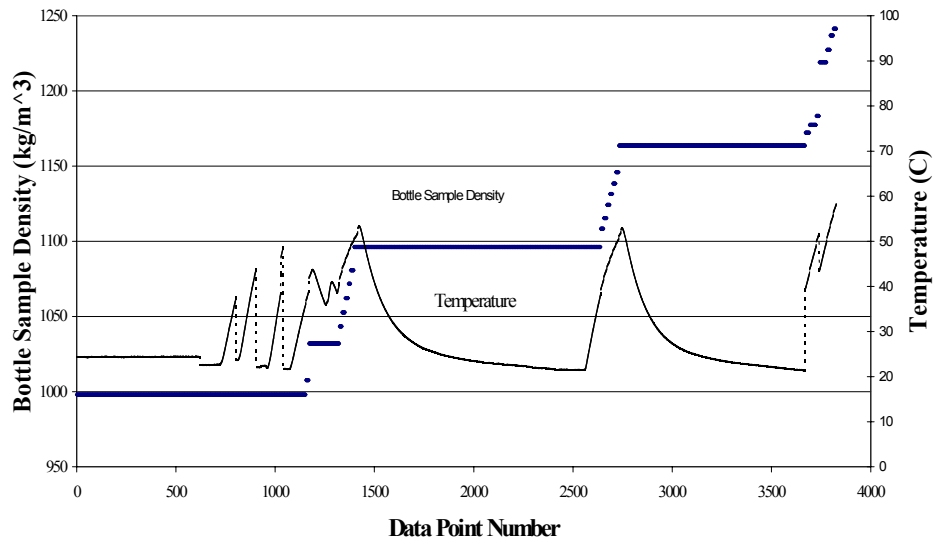


Figure 6.1 Plots of bottle sample density and temperature for probes 1 (top) and 2 (bottom)

The density is obtained by measuring the voltages on two receive transducers. The calibration is needed to relate the voltage measurement to the determination of the reflection coefficient. In turn, the reflection coefficient depends upon the density of the liquid or slurry and the speed of sound in it. Therefore, the determination of two reflection coefficients permits the determination of the density of the liquid and speed of sound.

The objective was to obtain the reflection coefficient as a polynomial expansion in terms of the voltage and temperature. A regression analysis, with a least squares fitting procedure, was carried out for several thousand data points. That is,

$$RC_x = f_x(V_x, T) \quad (6.1)$$

This represents three equations, where x is a shorthand for any one of the three transducer pairs: BC, DE, or FF. V_x and T have been measured, but in order to determine the constants in the polynomial expansion, values of RC_x are needed. The method for determining the reflection coefficients is described in Section 6.2 and the results of the regression analysis are presented in Section 6.3.

Two reflection coefficients are needed to determine the density and speed of sound in a liquid, as stated above. However, data were obtained for three angles. The procedure for analyzing results using three angles is described in Section 6.5.1.

The tests of the sensor were carried out for liquid/slurry having a density ranging from 998 kg/m³ up to 1241 kg/m³. It is well known that, even though Equation 6.1 is valid within this density range, it may not be valid *outside* of this range, especially where there are terms quadratic in V_x and T . For this reason, we considered a polynomial expansion in terms of the density of the liquid (ρ) in terms of the voltage (V_x) and temperature (T):

$$\rho_x = g_x(V_x, T) \quad (6.2)$$

Since all of these quantities were measured during the tests, a regression analysis was carried out to determine the constants for the polynomial expansion. However, a restriction was placed on the expansion: It must be linear in V_x , but was quadratic in terms of the temperature T . For density values outside the range of the tests, Equation 6.2 will be used to determine the density.

The expansion for the density, given in Equation 6.2, is very important for another reason. This relationship can be used to predict density (at a somewhat reduced accuracy) using as few as one of the three transducers. This is a back up position that can be employed if one or more of the transducers cease to operate. Suppose that during the transfer of radioactive waste one of the transducers fails. The transducer FF is a particularly important one, as we shall see. If that occurs, then the density measurements will not be possible, using only reflection coefficients. Two probes are available and were calibrated. Even so, during the transfer it may not be possible to replace Probe 1 with Probe 2. The regression analysis in terms of density in Equation 6.2 provides a means of obtaining information about the density. Therefore, of the three transducers, *one* operational transducer can provide information about the density. Two operational transducers (even if FF has failed) will provide an average value of the density. However, this procedure may not be as accurate as using the two-reflection-coefficient method for the following reasons. The voltage measured by the transducer is dependent upon both the density of the liquid *and* the velocity of sound in the liquid. The data obtained during the tests were for sugar water, primarily. Therefore, the voltage measurement is dependent upon the speed of sound in *sugar water*. A slurry having the same density as the sugar water can have a slightly different speed of sound. Therefore, the accuracy of the density expansion will depend upon the similarity of the speed of sound for that slurry to that for the sugar water. It is expected that this will result in a small error, at least for the smaller

values of the density. Even though the accuracy is not as great, it will show a trend in the density data and can also provide information to prevent pipeline plugging. Somewhat reduced accuracy is surely far preferable to not obtaining any measurements.

6.2 Experimental Reflection Coefficients for use in Regression Analysis

The equations for the reflection coefficients are given in Equations 3.3 through 3.8. These equations show that the reflection coefficients are dependent upon the following parameters:

- α incident angle
- c_L longitudinal velocity in wedge
- c_T shear velocity in wedge
- ρ_s density of wedge
- c longitudinal velocity in liquid
- ρ density of liquid

Thus, if these six quantities are known the reflection coefficient can be calculated. The density of the wedge material Rexolite is 1049 kg/m^3 , the longitudinal speed c_L is 2337 m/s , and the shear speed c_T is 1157 m/s . The longitudinal and shear velocities in Rexolite as a function of temperature were measured over the temperature range from temperature from 15.5 C to 82.2 C and the results are given by:

$$c_L = -0.0064202 T^2 - 1.5906566 T + 2374.3089 \quad (6.3)$$

$$c_T = -0.00316062 T^2 - 0.6816773 T + 1173.4053 \quad (6.4)$$

The velocity of sound in water as a function of temperature was obtained from the equation given by Povey et al. (1997). The bottle sample density is used for the density of the liquid. In order to determine the reflection coefficient, it is necessary to determine the longitudinal velocity in the sugar water and sugar-water-kaolin slurry.

6.2.1 Velocity measurements in liquids/slurry

To measure the velocity, a bracket containing two transducers, separated by several cm, was placed in the solution, which was heated. By measuring the time of flight and the temperature, the velocity as a function of temperature was obtained. This procedure was followed for sugar water solutions having a density of 1038 kg/m^3 (10% sugar by weight [10% SW]), 1121 kg/m^3 (30% SW), and 1230 kg/m^3 (50% SW). Figure 6.2 shows the velocity as a function of temperature for these three solutions. Figure 6.3 shows the data obtained for a sample of the sugar-water-kaolin slurry used in the test. Linear interpolation was used to find the velocity for a specific temperature and density.

6.2.2 Calculation of reflection coefficients

The reflection coefficients for BC, DE, and FF were calculated for the 2796 data points for Probe 1 and the 3828 data points for Probe 2. The last three columns of Table 6.1 show the results of the calculation of the reflection coefficients for six data points for Probe 1 and six, for Probe 2. These are the so-called experimental reflection coefficients.

Velocity of Water and Sugar Water

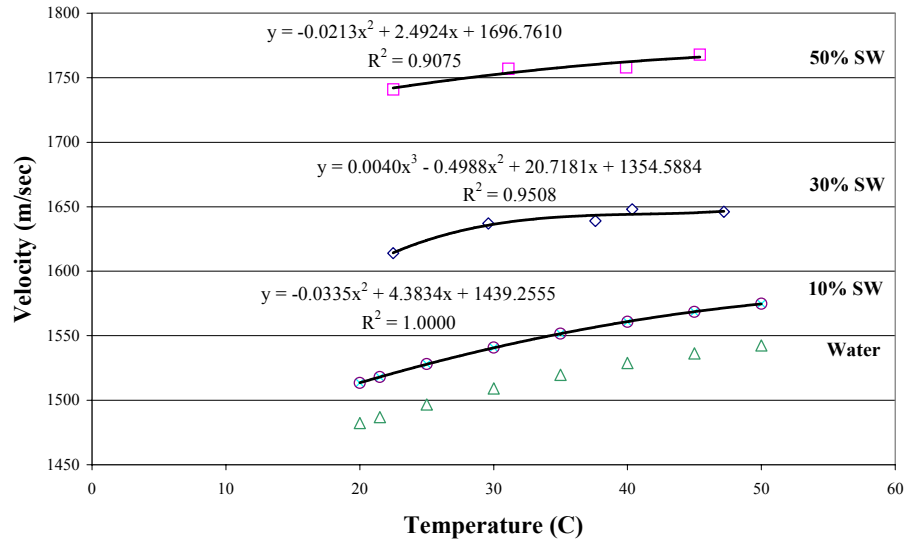


Figure 6.2 Velocity of sound in sugar water as a function of temperature

Kaolin Clay Slurries in Sugar Water from Tests in Modified Process Manifold in 305 Building

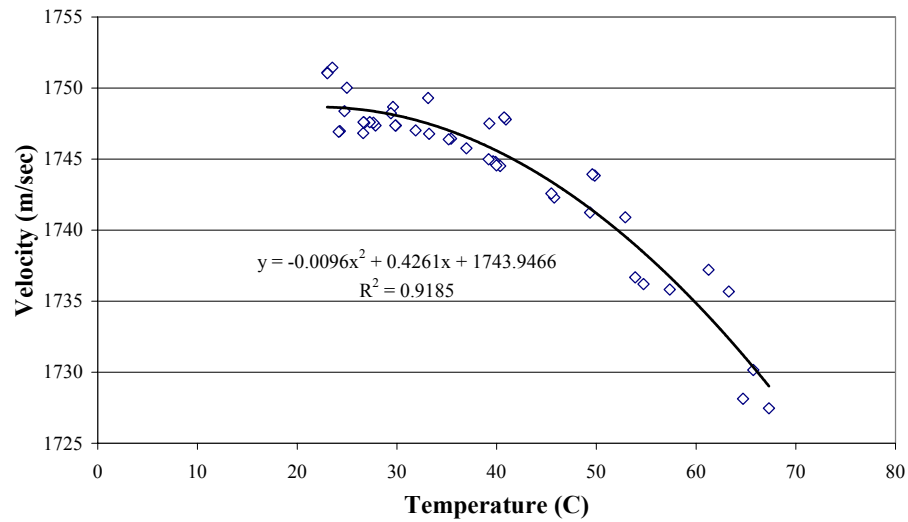


Figure 6.3 Velocity of sound in kaolin clay slurries in sugar water as a function of temperature

Table 6.1 Calculation of the experimental reflection coefficients for Probes 1 and 2

Probe	Data Pt. Number	Bottle Density	BaseTemp	Vadj BC	Vadj DE	Vadj FF	RC BCexp	RC DEexp	RC FFexp
		(kg/m ³)	(C)	(volts)	(volts)	(volts)			
1	17	998	21.9	0.01562	0.03618	0.08081	0.07477	0.13811	-0.24540
1	212	1032	35.7	0.02087	0.03367	0.06653	0.11338	0.17746	-0.20498
1	325	1072	47.5	0.02329	0.03188	0.05259	0.15127	0.21624	-0.16512
1	383	1096	52.8	0.02375	0.03075	0.04526	0.17033	0.23568	-0.14469
1	1896	1164	29.3	0.03532	0.05118	0.04069	0.19721	0.26038	-0.10941
1	2786	1241	57.6	0.03441	0.03847	0.01597	0.25679	0.32281	-0.04786
2	10	998	24.3	0.00873	0.01167	0.04752	0.07809	0.14164	-0.24233
2	1350	1053	45.3	0.01179	0.01286	0.03289	0.13695	0.20181	-0.18079
2	2816	1164	41.3	0.01790	0.01815	0.02075	0.20729	0.27184	-0.10111
2	3764	1219	47.5	0.01979	0.01884	0.01200	0.24528	0.31095	-0.06019
2	3801	1237	54.4	0.01911	0.01731	0.00969	0.25398	0.31983	-0.05067
2	3812	1241	56.4	0.01857	0.01650	0.00924	0.25626	0.32217	-0.04824

6.3 Regression analysis for reflection coefficients

A regression analysis was carried out using the following model equation:

$$\begin{aligned}
 RC_{liq_x} = & b0_x + b1_x T + b2_x T^2 + b3_x * V_x + b4_x * V_x^2 + b5_x TV_x + b6_x TV_x^2 \\
 & + b7_x T^2 V_x + b8_x T^2 V_x^2
 \end{aligned}
 \tag{6.5}$$

where x is a shorthand notation for BC, DE, or FF. T is the temperature and V_x is the voltage at 0 dB amplifier gain. A regression analysis was carried out for each transducer to determine the nine coefficients in Equation 6.5. The input data is similar to that shown in Table 6.1. Table 6.2 lists the values of the coefficients for Probe 1 and Probe 2.

The question is, of course: How well can nine constants fit several thousand data points? For all of the data points, the value of RC_{liqDE}, say, was calculated using the temperature and value of V_{DE}. The absolute value of the error between RC_{liqDE} and RC_{expDE} was calculated. The average value of the error and the standard deviation were obtained. Similar calculations were carried out for RC_{liqBC} and RC_{liqDE}. Table 6.3 shows the error in the reflection coefficient RC_{liq_x} for Probe 1 and Probe 2. The errors seem quite reasonable. The errors for Probe 1 are smaller than those for Probe 2.

Figures 6.4 and 6.5 show the variation in the reflection coefficients as a function of the voltage, when a given constant temperature is substituted into Equation 6.5 for the three transducer pairs for Probes 1 and 2 respectively.

Table 6.2 Coefficients for probes 1 and 2

	Polynomial Expansion Coefficients for			
	Reflection Coefficients		Density	
	Probe 1	Probe 2	Probe 1	Probe 2
b0BC	0.00007	1.4880E-01	1.0173E+03	9.8551E+02
b1BC	0.00000	-9.7451E-03	-8.8795E+00	-7.4660E+00
b2BC	0.00000	1.1371E-04	1.0743E-01	8.4090E-02
b3BC	0.00001	-9.9982E+00	4.2031E+03	1.2636E+04
b4BC	0.06041	6.3885E+02		
b5BC	0.00019	1.1441E+00	2.0258E+02	1.6022E+02
b6BC	-0.00147	-1.1050E-02	-1.5914E+00	-1.0932E-01
b7BC	0.00000	-3.5075E+01		
b8BC	-0.00004	3.5836E-01		
b0DE	-0.00006	-2.9235E-01	9.3123E+02	9.6796E+02
b1DE	0.00001	2.3529E-02	-1.4845E+01	-1.1992E+01
b2DE	0.00000	-4.0835E-04	2.2695E-01	1.5126E-01
b3DE	0.00767	5.7966E+01	1.4286E+03	1.2240E+04
b4DE	-0.10433	-1.6926E+03		
b5DE	-0.00046	-3.7408E+00	3.8101E+02	3.4706E+02
b6DE	0.01047	6.6076E-02	-3.9290E+00	-1.5643E+00
b7DE	0.00001	1.3453E+02		
b8DE	-0.00023	-2.2738E+00		
b0FF	-0.00071	2.3837E-01	1.4069E+03	1.4120E+03
b1FF	0.00001	-1.2809E-02	-2.7904E+00	-2.1761E+00
b2FF	0.00000	1.5567E-04	1.8491E-02	6.4875E-03
b3FF	-0.00546	-1.9777E+01	-3.6296E+03	-6.0740E+03
b4FF	-0.05269	2.5103E+02		
b5FF	0.00034	9.0394E-01	-3.1991E+01	-8.0462E+01
b6FF	-0.01540	-1.1709E-02	2.3620E-01	6.3480E-01
b7FF	-0.00002	-1.5795E+01		
b8FF	0.00033	1.9714E-01		

Table 6.3 Percent error in reflection coefficients based on Equation 6.5 compared to experimental values

	% error^a for RClqBC	% error for RClqDE	% error for RClqFF
Probe 1	1.00 ± 1.08	0.73 ± 0.70	1.10 ± 1.63
Probe 2	1.38 ± 1.46	1.04 ± 0.96	1.28 ± 1.60
(a)	For all of the data points used in the analysis, the average value of the percent error and the standard deviation of the percent error are shown.		

6.4 Regression Analysis for Density Values

A regression analysis was carried out for the density using the following model equations:

$$\rho_x = b0_x + b1_x T + b2_x T^2 + b3_x V_x + b5_x T V_x + b6_x T^2 V_x \quad (6.6)$$

where $x = BC, DE, \text{ or } FF$, as before. V_x is the voltage on the appropriate transducer, T is the temperature, and ρ_x is the bottle sample density. The expansion is quadratic in terms of the temperature, but is linear in terms of V_x . (Note that the coefficients in Equation 6.6 have a different definition than in Equation 6.5) Table 6.2 lists the six coefficients for Probe 1 and Probe 2 for each value of x .

For all of the data points in the analysis, the measured temperature and voltage were substituted into Equation 6.6 in order to predict the value of the density. Table 6.1 shows the temperature, voltage, and bottle density for six data points for Probe 1 and Probe 2. Table 6.4 compares the value of density (ρ) predicted from Equation 6.6 with the bottle sample density. The average value of the error and the standard deviation of the error are shown. These results show that Equation 6.6 is an excellent representation of the data.

Table 6.4 Percent error in density based on Equation 6.6 compared to the bottle sample density

	% error^a for Density for BC	% error for Density for DE	% error for Density for FF
Probe 1	0.26 ± 0.30	0.25 ± 0.29	0.28 ± 0.30
Probe 2	0.26 ± 0.27	0.34 ± 0.29	0.33 ± 0.28
(a)	The average value and standard deviation for the percent error are shown for all of the data points used in the analysis		

Figures 6.6 and 6.7 show the variation in the density as a function of the voltage for Probes 1 and 2 respectively, when a given constant temperature is substituted into Equation 6.6.

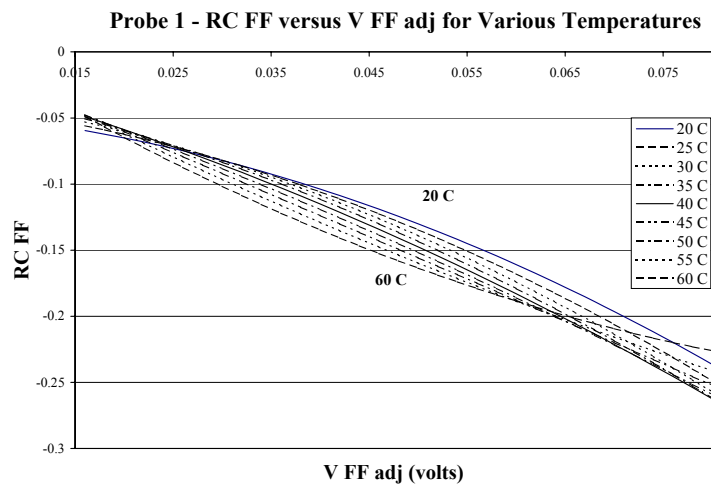
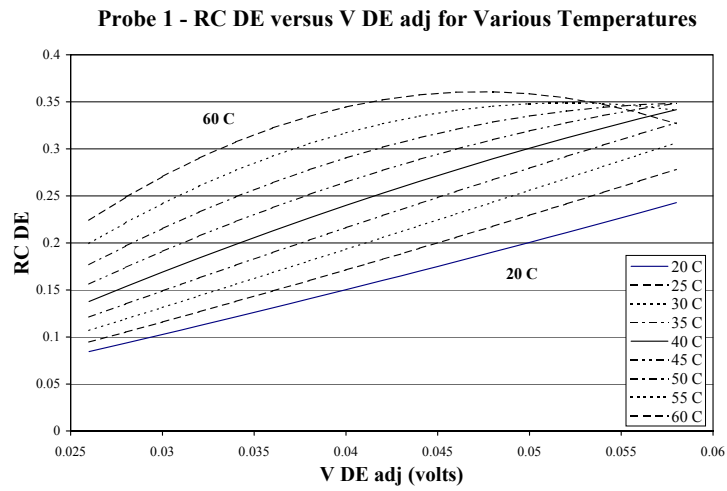
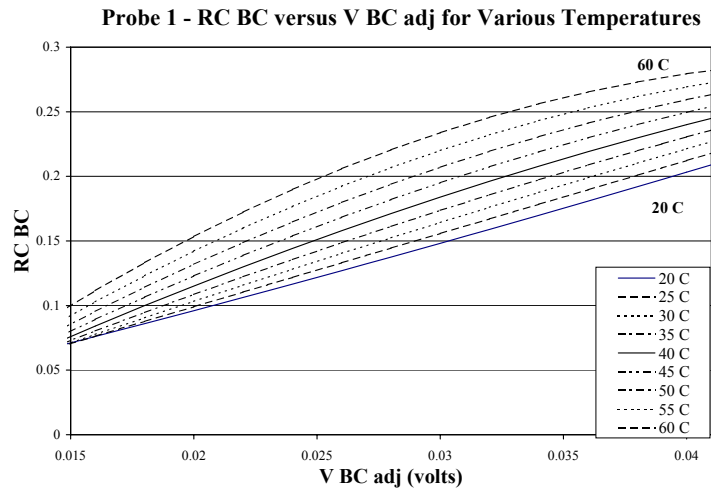


Figure 6.4 Probe 1 variation of reflection coefficient with voltage

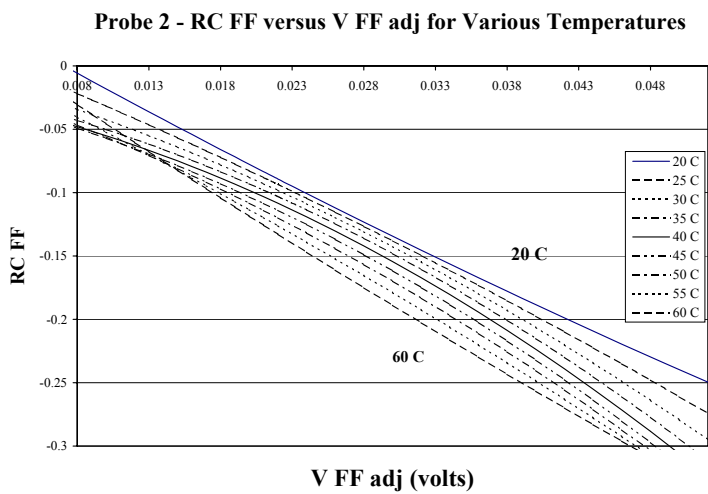
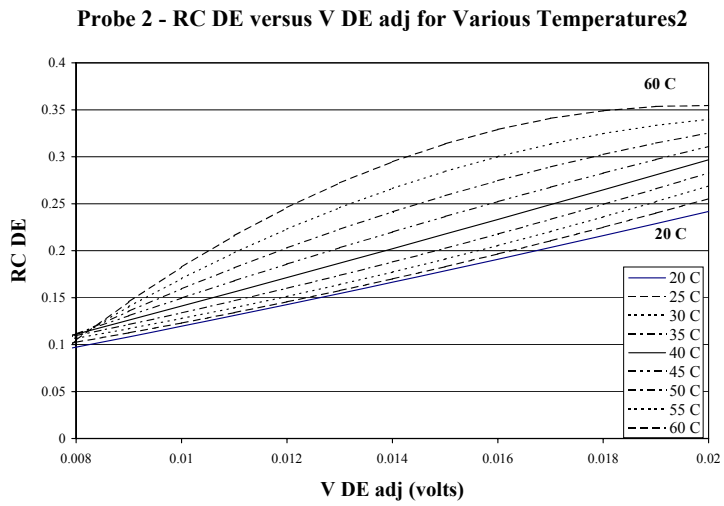
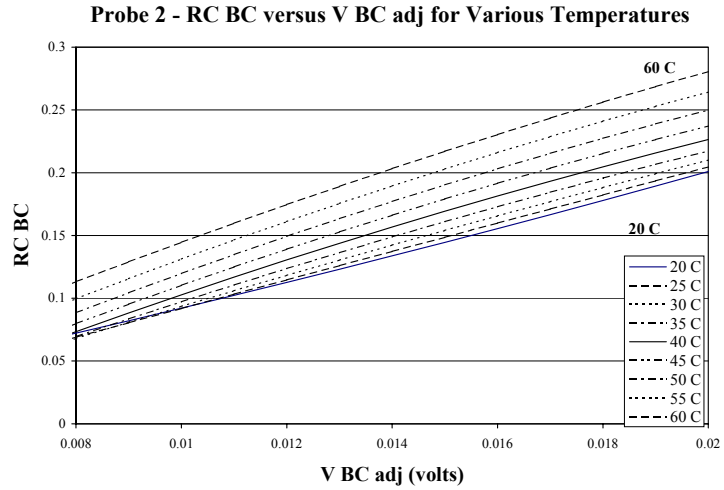
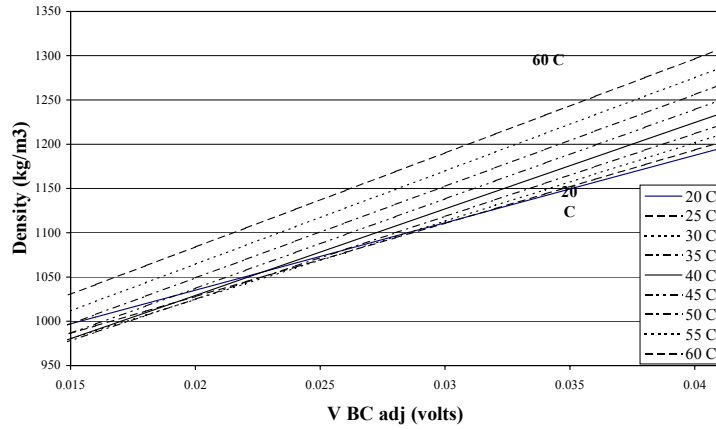
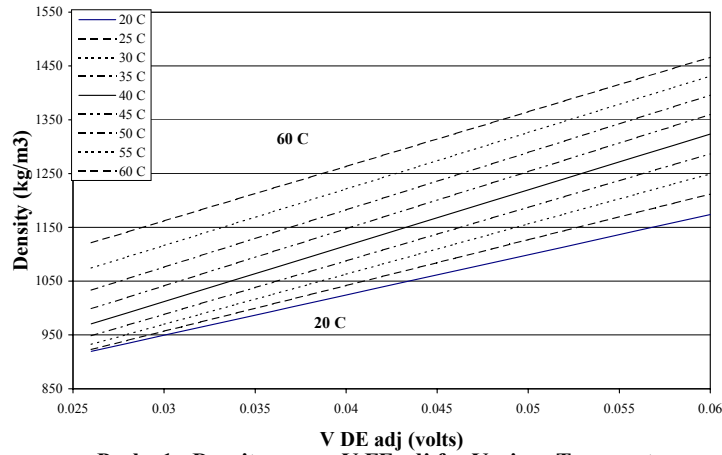


Figure 6.5 Probe 2 variation of reflection coefficient with voltage

Probe 1- Density versus V BC adj for Various Temperatures



Probe 1 - Density versus V DE adj for Various Temperatures



Probe 1 - Density versus V FF adj for Various Temperatures

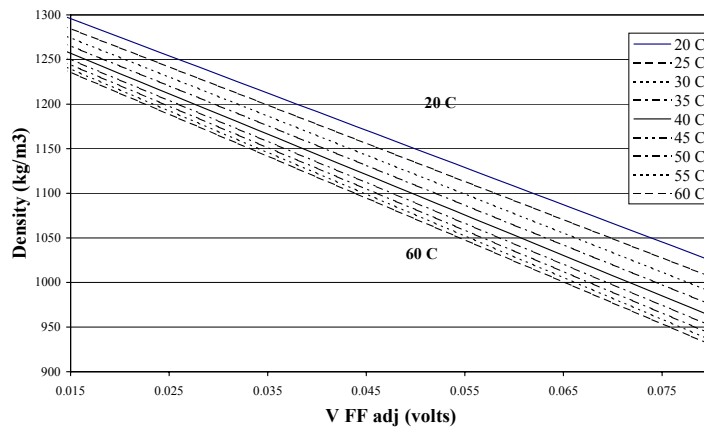
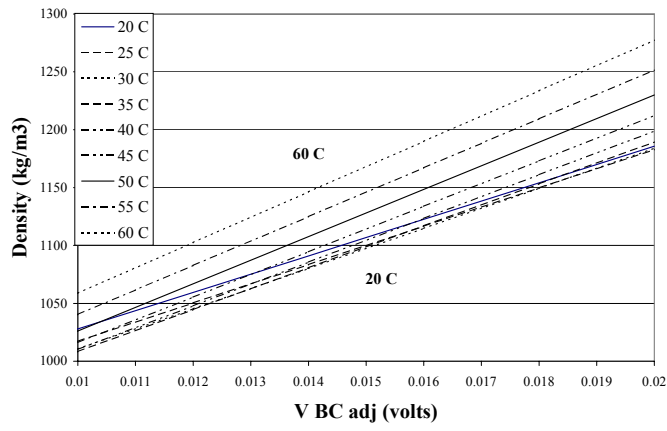
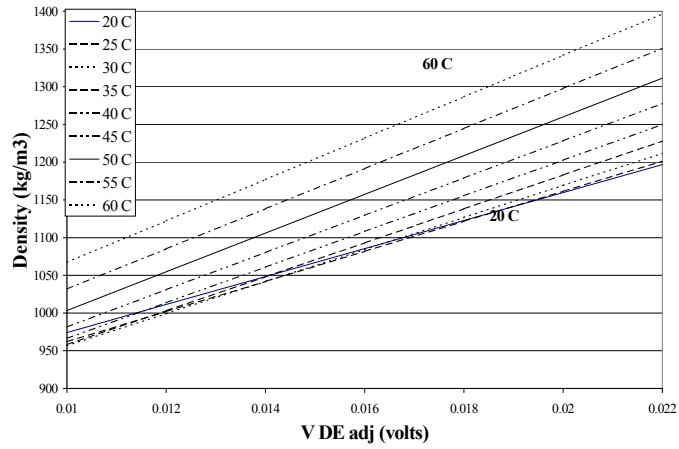


Figure 6.6 Probe 1 variation of density with voltage

Probe 2 - Density versus V BC adj for Various Temperatures



Probe 2 - Density versus V DE adj for Various Temperatures



Probe 2 - Density versus V FF adj for Various Temperatures

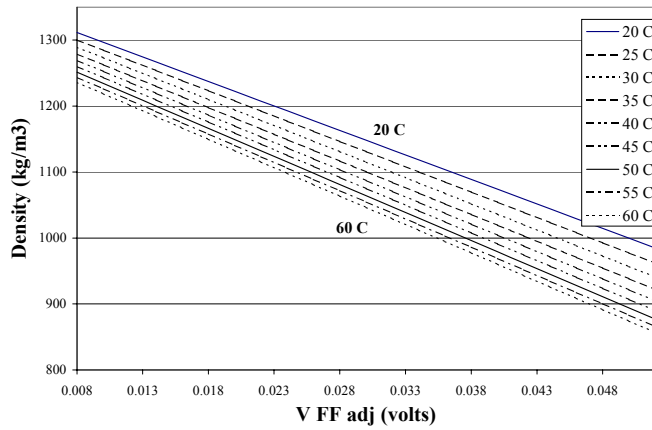


Figure 6.7 Variation of density with voltage

6.5 Determination of the Density

Table 6.5 shows data for Probe 1 and Probe 2. The values RC_{liqBC} , RC_{liqDE} , and RC_{liqFF} were calculated using Equation 6.5. These values can be compared with the experimental reflection coefficients RC_{BCexp} , RC_{DEexp} , and RC_{FFexp} that are given in Table 6.1. The agreement is very good. When the values of two reflection coefficients are known, the density of the liquid and speed of sound in the liquid can be determined. A simple procedure for this calculation is given in Equations 3.11 through 3.15. The table shows the density (density 0-60) obtained using values of RC_{liqDE} , and RC_{liqFF} . Similarly, it shows the density (density 0-47) obtained using values of RC_{liqBC} and RC_{liqFF} . Although Equations 16 through 23 (Greenwood, Skorpik, Bamberger, Harris 1999) illustrate the procedure to obtain the density and speed of sound when one angle is *not* 0° , the density obtained using RC_{liqBC} and RC_{liqDE} is not given. The reason is that the error in the value is larger, because there is only a 13 deg difference between these two angles.

Table 6.5 Voltage, reflection coefficient, and density data for probes 1 and 2

Probe	Data Pt. Number	Bottle Density	Base Temp	Vadj BC	Vadj DE	Vadj FF	RClq BC	RClq DE	RClq FF	Density 0-60	Density 0-47	Density 0-47-60
		(kg/m ³)	(C)	(volts)	(volts)	(volts)				(kg/m ³)	(kg/m ³)	(kg/m ³)
1	17	998	21.9	0.0156	0.0362	0.0808	0.0740	0.1384	-0.2450	999	1010	999
1	212	1032	35.7	0.0209	0.0337	0.0665	0.1155	0.1771	-0.2049	1031	1015	1031
1	325	1072	47.5	0.0233	0.0319	0.0526	0.1538	0.2189	-0.1622	1075	1076	1075
1	383	1096	52.8	0.0238	0.0307	0.0453	0.1693	0.2369	-0.1432	1099	1116	1105
1	1896	1164	29.3	0.0353	0.0512	0.0407	0.1937	0.2596	-0.1099	1164	1188	1172
1	2786	1241	57.6	0.0344	0.0385	0.0160	0.2518	0.3229	-0.0481	1247	1267	1253
2	10	998	24.3	0.0087	0.0117	0.0475	0.0774	0.1411	-0.2426	997	1002	997
2	1350	1053	45.3	0.0118	0.0129	0.0329	0.1366	0.2016	-0.1812	1051	1052	1052
2	2816	1164	41.3	0.0179	0.0181	0.0208	0.2062	0.2716	-0.1033	1152	1154	1153
2	3764	1219	47.5	0.0198	0.0188	0.0120	0.2411	0.3035	-0.0658	1221	1205	1216
2	3801	1237	54.4	0.0191	0.0173	0.0097	0.2523	0.3140	-0.0511	1262	1246	1256
2	3812	1241	56.4	0.0186	0.0165	0.0092	0.2519	0.3146	-0.0459	1292	1294	1293

6.5.1 Using data for three angles

Consider using the reflection coefficients RC_{liqDE} , and RC_{liqFF} to find the density and speed of sound in the liquid. Since all variables are now known, the reflection coefficient as a function of angle can be plotted (See Figure 3.3). While the reflection coefficients RC_{liqDE} and RC_{liqFF} will lie *exactly* on this curve, it is *not likely* that RC_{liqBC} will. Let us denote the value on the curve at 47 deg as RC_{tBC} . The difference between the theoretical curve and RC_{liqBC} is given by:

$$Dev47 = RC_{liqBC} - RC_{tBC} \quad (6.7)$$

The objective is to reduce the difference between RC_{liqBC} and the *final* theoretical curve by a factor of two:

$$\text{Devadj} = \text{Dev47} (\text{devcon}) \quad (6.8)$$

Where devcon is usually taken to be 0.5. The reflection coefficient at 60 deg is also adjusted. The following are the adjusted reflection coefficients:

$$\text{RC}_{\text{adjDE}} = \text{RC}_{\text{liqDE}} + \text{Devadj} \quad (6.9)$$

$$\text{RC}_{\text{adjBC}} = \text{RC}_{\text{liqBC}} + \text{Devadj} \quad (6.10)$$

The reflection coefficient for FF remains unchanged:

$$\text{RC}_{\text{adjFF}} = \text{RC}_{\text{liqFF}} \quad (6.11)$$

The final solution is obtained by using RC_{adjDE} and RC_{liqFF} to determine the value of the density and speed of sound. The values in the last column of Table 6.5, labeled density 0-47-60, were obtained in this manner, with one exception that will now be discussed. Data in Table 6.5 shows that the final value of the density is between that for density 0-60 and density 0-47, as would be expected.

6.5.2 Procedure for Densities Less Than 1050 kg/m³

The analysis of the data showed that for small values of the density, values less than about 1050 kg/m³, the regression analysis for the density is more accurate than using the two reflection coefficients, obtained from the regression analysis. Therefore, for this density region, the final value of the density is given by

$$\text{Density 0-47-60} = (\rho_{\text{BC}} + \rho_{\text{DE}})/2 \quad (6.12)$$

Where ρ_{BC} and ρ_{DE} are determined from Equation 6.6. ρ_{FF} was not included in the average because Table 6.4 shows that the error is slightly larger for it than the other values.

6.5.3 Statistical Analysis

Figure 6.8 shows the final value of the density, density 0-47-60, plotted versus the data point number and also the percent error relative to the bottle sample density.

One important question is whether the measurement of the density shows any bias. The quantity delta is defined as:

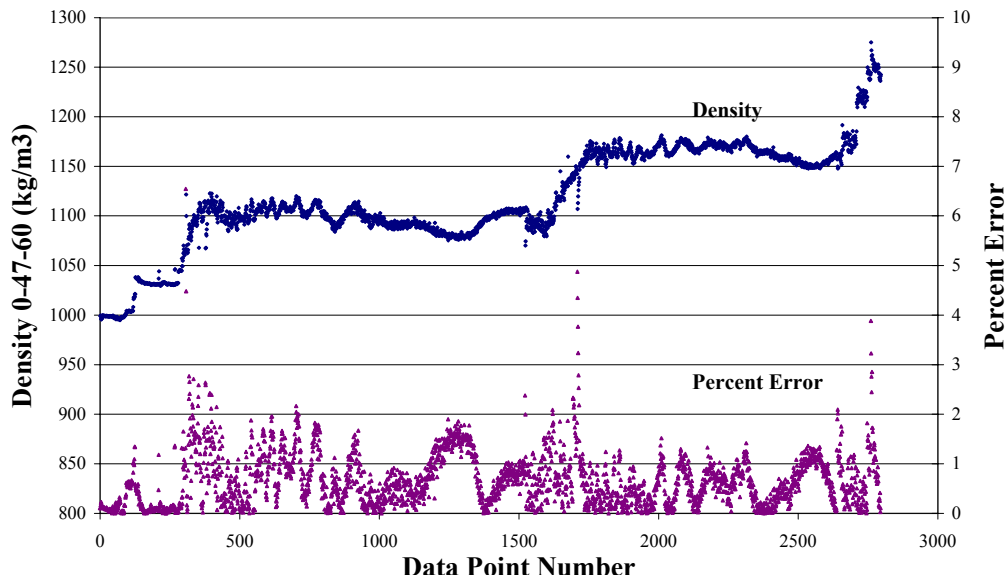
$$\text{Delta} = \text{density value} - \text{bottle sample density} \quad (6.13)$$

where delta can be positive or negative. The bias is defined as:

$$\text{Bias} = \text{average value of delta} \quad (6.14)$$

Table 6.6 shows the bias and the standard deviation of the value of delta. Data in Table 6.6 show that the bias values for both probes are very low. The conclusion is that the density sensor does not show a bias in its determination of the density. The standard deviation of the delta values is lower for Probe 1 than for Probe 2. Table 6.6 also shows the average value of the percent error relative to the bottle sample density for all of the data points. The standard deviation for the percent error is also shown. Table 6.7 shows the comparison of the average value of the density and its standard deviation with the bottle sample density. The percent error is obtained by comparing the average value of the density with the bottle sample density.

Density 0-47-60 vs Data Point Number, Probe 1



Density 0-47-60 vs Data Point Number, Probe 2

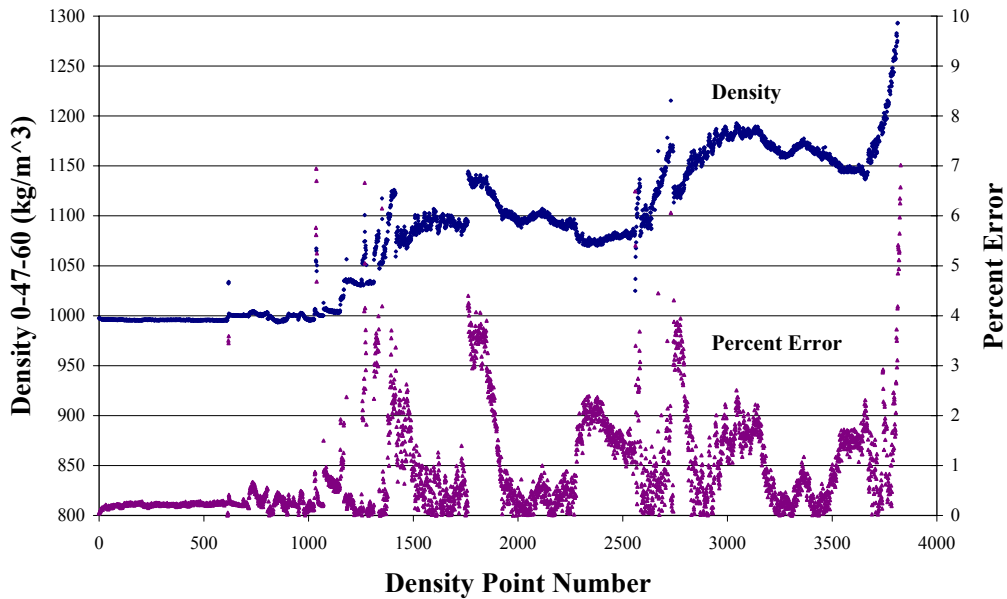


Figure 6.8 Density and percent error for Probes 1 and 2

Table 6.6 Statistical analysis for final values of density

	Bias	Standard Deviation	Average Percentage
	(kg/m³)	of Delta	
		(kg/m³)	Error
Probe 1	0.70	9.64	0.66 ± 0.55
Probe 2	0.59	15.00	0.90 ± 0.99

Table 6.7 Comparison of density values with bottle sample density

Bottle Sample Density	Probe 1			Probe 2		
	No. Data Points	Density	Percent	No. Data Points	Density	Percent
		(kg/m³)	(%)		(kg/m³)	(%)
998	119	999 ± 3	0.1	1155	998 ± 6	0.0
1008	7	1019 ± 2	1.1	15	1019 ± 3	1.2
1032	154	1032 ± 3	0.0	154	1039 ± 13	0.7
1043	13	1046 ± 18	0.2	13	1079 ± 3	3.4
1053	16	1067 ± 18	1.4	16	1059 ± 19	0.6
1062	16	1076 ± 10	1.3	16	1062 ± 5	0.0
1072	11	1089 ± 8	1.6	11	1077 ± 6	0.5
1081	17	1097 ± 4	1.5	17	1105 ± 8	2.2
1096	1249	1097 ± 10	0.1	1243	1095 ± 17	-0.1
1108	15	1097 ± 5	-1.0	15	1113 ± 5	0.4
1115	16	1104 ± 10	-1.0	16	1126 ± 11	1.0
1124	15	1119 ± 8	-0.5	15	1131 ± 6	0.6
1131	15	1124 ± 7	-0.7	14	1140 ± 5	0.7
1138	15	1133 ± 8	-0.4	15	1154 ± 9	1.4
1146	15	1138 ± 3	-0.7	15	1166 ± 15	1.8
1164	945	1164 ± 9	0.0	940	1163 ± 16	-0.1
1172	21	1160 ± 10	-1.0	21	1161 ± 5	-1.0
1177	34	1175 ± 6	-0.2	34	1170 ± 6	-0.7
1183	16	1177 ± 5	-0.6	15	1188 ± 3	0.4
1219	38	1219 ± 5	0.0	38	1206 ± 13	-1.1
1227	18	1249 ± 11	1.8	17	1243 ± 8	1.3
1237	15	1252 ± 4	1.2	16	1268 ± 9	2.5
1241	16	1245 ± 6	0.3	16	1309 ± 10	5.5

7.0 Computer Control System Operating Instructions

The object of this chapter is to describe the computer code and give information about the input files and output files. It will also describe how to determine if any settings need to be adjusted.

7.1 Directory Structure

The following are subdirectories of C:\work\cpgms\den00:

- WINDOWS
- DBASE
- LKUP
- MAKE
- MENU
- RUN
- SETUP
- START
- SYS
- TEMP
- UT
- AD
- DATA

The executable file, **main.exe**, is located in the MAKE subdirectory. The file in which the density is calculated from the measurements is called **density.c**, which is located in the RUN subdirectory.

The following are steps to running the program:

- Click on the “DOS Prompt Density” icon to get to C:\Windows
- Type “cd ..” to get the C:\
- Type **toden00**, which executes **toden00.bat** that takes you to C:\work\cpgms\den00
- Type **main**, which executes **main.bat** that starts the execution of **main.exe**. (Another alternative is to go to the MAKE subdirectory and type **main** to start the execution.)

It should not be necessary to recompile the program, but, if some changes are made, the following steps are used for recompiling:

- In the den00 directory, type “**touch setup\defines.h**” This ensures that all files are recompiled.
- In the den00 directory, type “**mk**” (which calls **mk.bat** and carries out the compilation).

7.2 Input File

The input file, **constnts.dat**, is located in the MAKE subdirectory and supplies parameters used by the program. This file is called in the code **density.c** in the function named **load_data**. The following parameters are read from the file, with one parameter per line on the file: **corrbc**, **corrde**, **corraa**, **corrff**,

addsubbc, addsubde, addsubaa, addsubff, necho, devcon, and ialtsol. The first ten parameters are entered as decimal values, and the last as an integer without a decimal point.

Before defining each of these parameters, we shall consider how one can make adjustments, if there has been some change in the transducer performance. Ideally, the voltage, obtained by each transducer pair BC, DE, AA, and FF when the liquid is water, is the same as that obtained from the calibration. For this ideal case, $\text{corrxx} = 1.0$ and $\text{addsubxx} = 0.0$, where xx is a shorthand for BC, DE, AA, and FF.

The voltage on a transducer depends upon the amplifier gain. The adjusted voltage V_{adjxx} is defined as the voltage adjusted to 0.0 dB amplifier gain and this is given on the output files as will be discussed shortly. The objective is to use corrxx and addsubxx and adjust the actual (or current value) V_{adjxx} so that it is equal to the desired value (i.e., the value obtained during calibration.)

$$\text{Desired value of } V_{\text{adjxx}} = (\text{corrxx}) V_{\text{adjxx}} + \text{addsubxx} \quad (7.1)$$

In order to calculate the viscosity of the liquid, using the voltage on AA, the echo number, necho, must be specified.

The parameter “devcon” is defined in Equation 6.8. A value of 0.5 means that the final theoretical curve passes midway between the reflection coefficients for 47 deg and 60 deg. A value of 0.0 means that the curve passes through the reflection coefficient at 60 deg. A value of 1.0 means that the curve passes through the reflection coefficient at 47 deg.

The parameter “ialtsol” is a parameter indicating an “alternate solution.” This parameter can have a value ranging from 0 to 6. The following specifies how to set this value:

- Ialtsol = 0 Ideal case and indicates no problems with any of the transducers.
- Ialtsol = 1 Indicates that transducer BC is not operational and that the density value is obtained without using this transducer.
- Ialtsol = 2 Indicates that transducer DE is not operational and that the density value is obtained without using this transducer.
- Ialtsol = 3 Indicates that transducer FF is not operational. The density is obtained using an average value of ρ_{BC} and ρ_{DE} obtained from Equation 6.6.
- Ialtsol = 4 Only transducer BC is operational. The density is obtained using ρ_{BC}
- Ialtsol = 5 Only transducer DE is operational. The density is obtained using ρ_{DE} from Equation 6.6.
- Ialtsol = 6 Only transducer FF is operational. The density is obtained using ρ_{FF} from Equation 6.6.

7.3 Output Files

There are five output files: `denvisc1.dat`, `rawdta1.dat`, `datasum1.dat`, `calc2.dat`, and another in the subdirectory `den00\data\sy101`. The first four files are located in the MAKE subdirectory.

The output file, `denvisc1.dat` for Probe 1 or `denvisc2.dat` for Probe 2, prints the values of the date, time, the final value of the density in kg/m^3 , the velocity of sound in m/sec, and the viscosity in centipoise. When the code is running, the data are APPENDED to this file. At some point, this file will become large. Therefore, **it is recommended to copy this file to another name and then delete `denvisc1.dat` at the start of a new run.**

The output file, `rawdta1.dat` (or `rawdta2.dat`) prints out information about the voltages and the amplifier gains on one line: date, time, VBC, VDE, VAA, VFF, VGG, gainBC, gainDE, gainAA, gainFF, gainGG. The amplifier gains are given in decibels (dB). As the data is obtained, it is *appended* to the existing file.

The output file `datasum1.dat` prints out 40 parameters on one line on the file. When the code is running, the data are APPENDED to this file. This output file can easily be viewed using Excel. Table 7.1 shows the headings for the 40 columns and also provides comments about those parameters whose definitions are not obvious. The parameter `irhoexp` was not defined in Table 7.1. In the code `density.c`, `irhoexp` is initially set equal to 0. This value can change under two conditions:

- If the `den0-60` is less than 1050 kg/m^3 , then the density is calculated using the regression analysis in terms of density, given by Equation 6.6. In this case, `irhoexp` is set equal to 1. A velocity of sound cannot be determined in this case and it is set equal to 999 m/sec, to serve as a flag.
- The regression analysis for the reflection coefficient is valid between density values of 998 kg/m^3 and 1241 kg/m^3 . Outside of this region the regression analysis in terms of *density* is used and `irhoexp` is set equal to 2.

It should be pointed out that the final value of the density and velocity of sound, given in the output file `denvisc1.dat`, are the values `den0-47-60` and `c0-47-60` when `irhoexp` is equal to 0. When `irhoexp` is equal to 1 or 2, the regression analysis in terms of density (Equation 6.6) is used and this value of the density becomes the so-called final value of the density.

7.3.1 Adjusted Voltage

We shall consider two types of voltages. The first is the voltage measured by the instrument with a certain amplifier gain. The second is the adjusted voltage that results by calculating the voltage at 0.0 dB amplifier gain (which means that there is no amplifier gain.) The relationship between them is given by:

$$\text{Adjusted voltage} = (\text{measured voltage}) \times 10^{-(\text{amplifier gain in dB}/20)} \quad (7.2)$$

Table 7.1 Information about output files datasum1.dat or datasum2.dat

Date	Time	Temp_Base	Temp_Top	VadjBC	VadjDE	VadjAA	VadjFF	VadjGG
		(C)	(C)	(volts)	(volts)	(volts)	(volts)	(volts)
vtref2BC	vtref2DE	vtref2AA	vtref2FF	vtref2G G	RClqBC	RClqDE	RClqAA	RClqFF
(volts)	(volts)	(volts)	(volts)	(volts)				
den0-60	c0-60	den0-47	c0-47	rhobc	rhode	rhoff	denrhoex	viscosity
(kg/m ³)	(m/sec)	(kg/m ³)	(m/sec)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(kg/m ³)	(cP)
den0-47-60	c0-47-60	necho	corrbc	corrde	corraa	corrff	addsubbc	addsubde
(kg/m ³)	(m/sec)							
addsubaa	addsubff	irhoexp	ialtsol					
Comments								
xx stands for BC, DE, AA, FF, and/or GG								
Vadjxx are the voltages adjusted to 0.0 dB amplifier gain.								
vtref2xx are the water reference voltages at 0.0 dB at a given temperature.								
RClqxx are the reflection coefficients calculated using the regression analysis, Equation 6.5.								
den0-60 and c0-60 are the density and velocity of sound obtained using 0 and 60 degree angles.								
den0-47 and c0-47 are the density and velocity of sound obtained using 0 and 47 degree angles.								
den0-47-60 and c0-47-60 values are obtained using 0, 47, and 60 degree angles.								
rhoxx (ρ_{xx}) are the density values obtained using the regression analysis for density, Equation 6.6.								
denrhoex is the average value of the applicable values of rhoxx								
If the regression analysis for density is not used, then rhoxx and denrhoex values will be 0.0.								

End of Table 7.1

The amplifier gain has also been calibrated and is usually not exactly an integer. Table 7.2 gives the values of the amplifier gains for each dB setting.

Table 7.2 Amplifier gain calibrations for computer 1 and computer 2

	Probe 1	Probe 2
dB Setting	Board #1	Board #2
1	0.82	0.98
2	1.72	1.82
3	2.92	2.86
4	3.94	3.67
5	4.88	4.62
6	5.87	5.84
7	6.72	6.82
8	7.77	7.81
9	8.82	8.61
10	9.88	9.86
11	11.14	11.12
12	12.02	12.21
13	12.85	13.21
14	13.97	14.25
15	15.03	15.09
16	16.27	16.11
17	17.23	17.14
18	18.1	18.23
19	19.11	19.43
20	20.03	20.27
21	21.04	20.83
22	22.28	21.82
23	23.21	22.88
24	24.23	24.15
25	25.11	25.17
26	26.05	26.02
27	27.26	26.98
28	28.28	27.89
29	29.2	28.92
30	30.21	30.16
31	30.87	31.02
32	31.96	32.02
33	32.93	32.84
34	33.91	33.74
35	34.78	34.89
36	35.32	35.88
37	35.69	36.75
38	35.91	37.51
39	35.97	37.92

40	36.02	38.13
Notes:		
1. High Voltage off.		
2. Board #1 0-40 dB window was shifted +1.8 dB to set the 0 dB point		

The file calc2.dat, shown in Table 7.3, is very useful when water is the liquid in the pipeline and you want to check the calibration of the density sensor. Usually, the data are listed in a line sequentially as BC, DE, AA, and FF. The voltages for the current liquid are shown in the line labeled “Voltages=”. The next line shows the adjusted voltages (“Adj volt:”) obtained using the exact gain settings (“gainadj:”). The next three lines show the same quantities for the reference fluid, which is water. Therefore, if the current fluid in the pipeline is water, then the values listed under “Adj volt:” should be the same as those listed under “Adj volt ref:” If they are not, then they can be corrected by using appropriate values of corrxx and addsubxx. This file gives information only about the last complete data set. That is, the next set of data writes over the preceding set and the data is obviously, *not appended* to the existing file. (The example shown of calc2.dat is not representative because this example is reading data from a file, with the pulser turned off. The adjusted voltages should be less than the voltages and they are not here.) It should also be noted that the adjusted voltage for the liquid and for reference (water) are also given in the file datasum1.dat, as explained above.

Table 7.3 Example of file calc2.dat

```

Incident angles: 47.00 60.00 0.00 0.00
Pipe,Base,Top,temp: 0.000 23.538 23.538 23.538
rhowdg,cl,ct: 1049.0000 2333.3119 1155.6093
rhref,ceref: 997.2740 1492.6879
Angles for reflected shear wave:
21.2363 25.3986 0.0000 0.0000
Angles for transmitted wave in liquid:
27.8960 33.6434 0.0000 0.0000
Correction factors for reference voltages:
0.9573 1.0483 1.0000 1.1592
Reflection coefficients for reference liquid:
0.076773 0.140281 -0.243639 -0.243639
Voltages: 0.407861 0.408826 0.176355 0.347546
Adj volt: 0.008904 0.012051 0.056675 0.049393
gainadj: 32.84 31.02 9.86 18.23
Ref Voltages: 0.008787 0.012084 0.116205 0.049010
Adj volt ref: 0.0088 0.0121 0.1162 0.0490
refgnadj: 0.00 0.00 0.00 0.00
ratlqrf: 1.058457 0.951340 0.487713 0.869419
Reflection coefficients for unknown liquid:
rcliq: 0.079605 0.144950 -0.118826 -0.251351
j :
rcliq: 0.079605 0.144950 -0.118826 -0.251351
corrxx: 0.957341 1.048276 1.000000 1.159195
addsub: 0.000000 0.000000 0.000000 0.000000
g, h, jexp: 0.164611 0.399510 0.370350
zwdg, zliq: 2447644.224509 1464357.351089

```



```

dum22: 0.807712
alplqrd, alplq: 0.630535 36.126977
cexpi: 1588.482683
Dnlqexpi: 921.859185
j : 1
  rcliq: 0.079605 0.144950 -0.118826 0.251351
  corrx: 0.957341 1.048276 1.000000 1.159195
addsub: 0.000000 0.000000 0.000000 0.000000
g, h, jexp: 0.164611 0.399510 0.370350
zwdg, zliq: 2447644.224509 4091188.701526
dum22: 2.256624
g, h, zwdg: 0.164611 0.399510 2447644.224509
Two possible solutions for density and speed from 0 and 60 deg:
Dnlqexpi: 921.8592 0.0000
cexpi: 1588.4827 0.0000
To determine which of two 0-60 densities is correct
If only one 0-60 solution, entries in following may be 0
g42, h42, zwdg: 0.000000 0.000000 2447644.224509
Two possible solutions for density and speed from 0 and 47 deg:
Dnz42: 0.0000 0.0000
cz42: 0.0000 0.0000
dfz42z60: 0.0000 0.0000
0 and 60 degree solution (2 angles):
Density in kg/m^3 = 921.8592
Speed of sound in m/sec = 1588.4827
Calculation using 0 and 47 degree RCs
g42, h42, zwdg: 0.165224 0.544056 2447644.224509
cz42: 1613.2939
Dnz42: 907.6817
adjustment for chi-squared fit, devcon = 0.500000
algebraic chi-squared:
dendev, cdev 917.012993 1596.877430
chisq 2.548573E-06
dev47, devcon, devadj 0.001919 0.500000 0.000960
dev[0], dev[1], dev[3] 0.001276 -0.000960 0.000000
chisq 2.548573E-06
density: 0.0000
speed: 0.0000
irhoexp, rhobc, rhode, rhoff, denrhoex 1 1001.9239 1004.9853
988.2171 1003.4546
necho = 5.00
Viscosity calculation now uses 0-60 density value(dnlqexp)
Viscosity in cP = 0.0000

```

End of Table 7.3

One type of output file is located in C:\work\cpgms\den00\data\sy101. When a loop test is selected to take the data, a subdirectory under sy101 is listed with a title involving the date and time. Under this subdirectory are listed the data files for each pass through the loop. This is the usual type of output. Table 7.4 shows an output file for one pass through the loop. The first five lines in the table give information about the transducer pairs: BC, DE, AA, FF, and GG. GG is a pulse-echo transducer with the wedge base in contact with air. It is not used in the calculation of the density. Below the table, the density, velocity, and viscosity values are displayed. These are the final values of the density and velocity and are the same as those that are recorded in denvisc1.dat. In the line where “Dnz42= “ is at the

beginning of the line, the first value is now the den0-60 and the second value is c0-60. It is a good check to compare the value of den0-60 with the final value of the density, given above. In the line for “Vtref2=”, the values are, sequentially, the water reference values for BC, DE, AA, and FF. The values in the bottom part of the file are the various settings used when one looks at the signal and sets up the data acquisition system.

Table 7.4 Example of output file

```

UT DENSITY DATA
Sensor ordering: B/C, D/E, A/A, F/F
      -tofs in usecs      -peaks in volts
avg tof      tof std      avg pk      pk std      max      min
16.817399   0.000663   0.386865   0.000712   0.394287  0.379395
19.137756   0.000565   0.354687   0.000398   0.358398  0.350586
0.000000    0.000000   0.337329   0.000734   0.346191  0.330811
25.910374   0.000594   0.314730   0.000195   0.317383  0.313232
23.750813   0.000466   0.374325   0.000357   0.378662  0.371582

Density(kg/m^3)=1065.0301  Velocity(m/sec)=1407.2456  Viscosity(cP)=32.8607

Date: 9/27/00  Time: 14:51

Pipe Temp-C=0.000
Base Temp-C=22.825
Top Temp-C=22.125

Probe ID=2  Gain ID=2  ISol=2  INoise=0
Dnlqexpi=1065.0301  0.0000  47.0000  60.000000
Dnz42=1098.7611  1381.2456  1065.0301  0.000000
Alphal=47.00  60.00  0.00  0.000000

Vtref2=0.016470  0.030347  0.233964  0.080141

Gnref2=0.000000  0.000000  0.000000  0.000000

AGC Flg(1=YES)=0

Lkup Cfg
  UT Gain db-BC.....27
    -DE.....20
    -AA.....4
    -FF.....12
    -GG.....8
  UT Freq Index.....3
  UT # TB Cycles-BC.....15
    -DE.....15
    -AA.....12
    -FF.....15
    -GG.....15
  UT # Data Set Avgs.....30
  UT TOF Gate Pt-BC.....618
    -DE.....688
    -AA.....1394

```

-FF.....	984
-GG.....	870
UT Gate1 Pt-BC.....	722
-DE.....	786
-AA.....	1440
-FF.....	1080
-GG.....	998
UT Gate2 Pt-BC.....	976
-DE.....	1036
-AA.....	1730
-FF.....	1280
-GG.....	1276
UT Threshold-BC.....	106
-DE.....	311
-AA.....	474
-FF.....	174
-GG.....	374
A/D Clk Index.....	7
A/D Start Pt-BC.....	580
-DE.....	670
-AA.....	1320
-FF.....	970
-GG.....	840
A/D # Sample Pts-BC.....	500
-DE	500
-AA	500
-FF	500
-GG	500
A/D Trig Dly Clk Index-BC.....	7
-DE.....	7
-AA.....	7
-FF.....	7
-GG.....	7
A/D Trig Dly Factor Index-BC..	0
-DE..	0
-AA..	0
-FF..	0
-GG..	0
A/D # Waveforms to Avg.....	15
A/D Bias-BC.....	2.50
-DE.....	2.50
-AA.....	2.50
-FF.....	2.50
-GG.....	2.50
Pk Flg(1=Pk,0=Pk-to-Pk)-BC.....	0
-DE.....	0
-AA.....	0
-FF.....	0
-GG.....	0

End of Table 7.4

7.4 System Setup

There are three steps in setting up the computer system and density sensor: 1) measure the pulser voltage, 2) with the probe full of water, compare voltages with the water reference values, and 3) make adjustments to system and/or changes to input file.

7.4.1 Measurement of Pulser Voltage

To carry out these measurements, an oscilloscope and a 17-foot cable are needed. The first step is to exit the code and turn off the high voltage.

At the end of the 17-foot cable, a small section of cable is usually attached using lemo connectors. This small section of cable has been modified so that, at one end, a 50 ohm resistor is connected between the ground and the hot wire in the center of the cable. A 10-to-1 probe is used by attaching the clip to the “hot” side of the resistor and the ground-connection clip to the “ground” side of the resistor. The 10-to-1 probe is input to Channel 1 of the oscilloscope, which has been set to AC 1 meg ohm. The other end of the 17-foot cable is inserted in the FF connector on the density-sensor board in the computer. The next step is to start the code, go to the FF display, and start it on the manual mode to get the voltage sent to the FF connector. The oscilloscope trigger is set to trigger on Ch 1. The voltage can now be determined using the oscilloscope reading.

For Probe 1 the oscilloscope reading should be 50.0 V peak-to-peak. For Probe 2, it should be 26.13 V peak-to-peak. These are the values that we used for the water calibration and also when the data were obtained in the tests in Bldg. 305. The voltages certainly should be very close to these values. However, the voltage output is somewhat dependent upon temperature, as we have observed and so it may be necessary to adjust the voltage. It is also helpful to wait about 10 minutes for the electronics to stabilize prior to taking the first measurement.

The pulser output voltage can be adjusted in the following manner. The back cover of the computer must be removed. The voltage is adjusted with a screw adjustment (very small) on the pulser board. The location of the pulser can be easily found, since it is near the heat radiator on the board.

The first step is to check the pulser setting and to adjust it to the values given above. The next step is to test with water.

7.4.2 Measurement using Water

When water is in the pipeline, you will want to assess as quickly as possible whether the voltages are those expected, based upon previous calibrations, and, in particular, with the calibration carried out at Bldg. 305. When the code is operating in the “loop” mode, the screen will display the voltages shown in the table at the top of Table 7.4. These voltages are affected by amplifier gains.

Tables 7.5 and 7.6 show the data obtained for water for Probe 1 and Probe 2. There are two sets of data. The first set is called the “water calibration.” Here, the adjusted voltages (defined as the voltage with no amplifier gain) are used. From the data at Bldg. 305 and previous water calibration data, a graph

of voltage versus temperature is plotted for each transducer pair (BC, DE, AA, and FF). A polynomial expansion is then obtained for the voltage as a function of temperature. From this expansion, the voltage as a function of temperature is obtained. The results are shown in Table 7.5 and 7.6 under the heading of water calibration.

Table 7.5 Example of water data for probe 1

Temp	Water	Water Cal					
C	VBC 305	BC water	VDE 305	DE water	VFF 305	FF water	AA water
	series eqn	cal	series eqn	cal	series eqn	cal	cal
20	0.015131	0.016100	0.036497	0.036904	0.086353	0.082498	0.320737
21	0.015440	0.016256	0.036174	0.036497	0.085410	0.081576	0.317355
22	0.015718	0.016403	0.035847	0.036089	0.084495	0.080691	0.313515
23	0.015965	0.016541	0.035516	0.035682	0.083608	0.079843	0.309240
24	0.016185	0.016670	0.035180	0.035275	0.082747	0.079033	0.304556
25	0.016378	0.016790	0.034838	0.034868	0.081912	0.078261	0.299486
26	0.016547	0.016901	0.034489	0.034461	0.081103	0.077526	0.294054
27	0.016691	0.017003	0.034134	0.034054	0.080318	0.076828	0.288286
28	0.016813	0.017096	0.033772	0.033647	0.079558	0.076168	0.282205
29	0.016913	0.017180	0.033402	0.033240	0.078822	0.075546	0.275835
30	0.016992	0.017255	0.033023	0.032833	0.078108	0.074961	0.269202
31	0.017052	0.017321	0.032636	0.032426	0.077417	0.074414	0.262328
32	0.017093	0.017378	0.032239	0.032018	0.076749	0.073904	0.255239
33	0.017115	0.017426	0.031832	0.031611	0.076102	0.073432	0.247959
34	0.017119	0.017465	0.031415	0.031204	0.075476	0.072997	0.240511
35	0.017106	0.017495	0.030986	0.030797	0.074870	0.072600	0.232921
36	0.017076	0.017516	0.030545	0.030390	0.074286	0.072240	0.225213
37	0.017030	0.017528	0.030092	0.029983	0.073721	0.071918	0.217411
38	0.016968	0.017531	0.029625	0.029576	0.073175	0.071633	0.209539
39	0.016891	0.017525	0.029145	0.029169	0.072649	0.071386	0.201621
40	0.016798	0.017510	0.028649	0.028762	0.072142	0.071176	0.193682
41	0.016690	0.017486	0.028138	0.028355	0.071654	0.071004	0.185747
42	0.016567	0.017453	0.027611	0.027947	0.071183	0.070021	0.177839
43	0.016430	0.017411	0.027066	0.027540	0.070731	0.069460	0.169983
44	0.016279	0.017360	0.026503	0.027133	0.070296	0.068894	0.162203
45	0.016113	0.017300	0.025921	0.026726	0.069879	0.068324	0.154523
46	0.015933	0.017231	0.025318	0.026319	0.069479	0.067750	0.146967
47	0.015739	0.017153	0.024693	0.025912	0.069095	0.067172	0.139561
48	0.015531	0.017066	0.024046	0.025505	0.068729	0.066590	0.132328
49	0.015309	0.016970	0.023374	0.025098	0.068379	0.066003	0.125293
50	0.015073	0.016865	0.022676	0.024691	0.068045	0.065412	0.118479
51	0.014822	0.016751	0.021950	0.024284	0.067727	0.064817	0.111912
52	0.014558	0.016628	0.021196	0.023876	0.067425	0.064218	0.105615

53	0.014279	0.016496	0.020410	0.023469	0.067139	0.063615	0.099613
54	0.013986	0.016355	0.019591	0.023062	0.066869	0.063007	0.093930
55	0.013679	0.016205	0.018737	0.022655	0.066614	0.062395	0.088590
56	0.013357	0.016046	0.017845	0.022248	0.066374	0.061779	0.083618
57	0.013020	0.015878	0.016913	0.021841	0.066149	0.061159	0.079038
58	0.012668	0.015701	0.015938	0.021434	0.065940	0.060535	0.074874
59	0.012301	0.015515	0.014916	0.021027	0.065745	0.059906	0.071151
60	0.011918	0.015320	0.013844	0.020620	0.065565	0.059273	0.067892

Table 7.6 Example of water data for probe 2

Temp	Water	Water cal					
C	VBC 305	BC water	VDE 305	DE water	VFF 305	FF water	AA water
	series eqn	cal	series eqn	cal	series eqn	cal	cal
20	0.008113	0.008494	0.011284	0.012052	0.050221	0.050950	0.136053
21	0.008286	0.008584	0.011422	0.012068	0.049600	0.050401	0.130265
22	0.008445	0.008668	0.011542	0.012079	0.048999	0.049853	0.124617
23	0.008591	0.008747	0.011645	0.012084	0.048415	0.049305	0.119108
24	0.008724	0.008820	0.011731	0.012083	0.047849	0.048756	0.113739
25	0.008844	0.008887	0.011802	0.012076	0.047301	0.048208	0.108509
26	0.008952	0.008948	0.011857	0.012063	0.046768	0.047660	0.103419
27	0.009049	0.009003	0.011899	0.012045	0.046251	0.047111	0.098469
28	0.009133	0.009053	0.011926	0.012021	0.045750	0.046563	0.093658
29	0.009207	0.009097	0.011940	0.011992	0.045263	0.046014	0.088987
30	0.009270	0.009134	0.011941	0.011956	0.044791	0.045466	0.084456
31	0.009322	0.009167	0.011930	0.011915	0.044332	0.044918	0.080064
32	0.009364	0.009193	0.011907	0.011868	0.043887	0.044369	0.075812
33	0.009396	0.009213	0.011873	0.011816	0.043455	0.043821	0.071699
34	0.009418	0.009228	0.011827	0.011757	0.043035	0.043273	0.067726
35	0.009430	0.009236	0.011770	0.011693	0.042627	0.042724	0.063893
36	0.009433	0.009239	0.011703	0.011624	0.042232	0.042176	0.060199
37	0.009428	0.009236	0.011626	0.011548	0.041848	0.041628	0.056645
38	0.009413	0.009227	0.011538	0.011467	0.041474	0.041079	0.053231
39	0.009389	0.009213	0.011441	0.011380	0.041112	0.040531	0.049956
40	0.009358	0.009192	0.011335	0.011287	0.040761	0.039982	0.046821
41	0.009318	0.009166	0.011219	0.011189	0.040420	0.039434	0.043826
42	0.009269	0.009134	0.011095	0.011085	0.040088	0.038886	0.040970
43	0.009214	0.009096	0.010961	0.010975	0.039767	0.038337	0.038254
44	0.009150	0.009052	0.010819	0.010859	0.039455	0.037789	0.035677
45	0.009079	0.009003	0.010668	0.010738	0.039152	0.037241	0.033240
46	0.009000	0.008947	0.010509	0.010611	0.038859	0.036692	0.030943

47	0.008915	0.008886	0.010342	0.010478	0.038574	0.036144	0.028785
48	0.008822	0.008819	0.010167	0.010339	0.038299	0.035596	0.026767
49	0.008723	0.008746	0.009984	0.010195	0.038031	0.035047	0.024889
50	0.008617	0.008667	0.009793	0.010045	0.037772	0.034499	0.023150
51	0.008504	0.008583	0.009595	0.009889	0.037522	0.033951	0.021551
52	0.008385	0.008492	0.009389	0.009727	0.037279	0.033402	0.020091
53	0.008260	0.008396	0.009175	0.009560	0.037044	0.032854	0.018771
54	0.008128	0.008294	0.008954	0.009387	0.036817	0.032305	0.017591
55	0.007990	0.008186	0.008726	0.009209	0.036597	0.031757	0.016550
56	0.007847	0.008072	0.008490	0.009024	0.036385	0.031209	0.015649
57	0.007698	0.007953	0.008247	0.008834	0.036180	0.030660	0.014888
58	0.007543	0.007827	0.007997	0.008638	0.035983	0.030112	0.014266
59	0.007382	0.007696	0.007740	0.008436	0.035792	0.029564	0.013784
60	0.007216	0.007559	0.007475	0.008229	0.035609	0.029015	0.013442

The second method is to use the regression analysis for density, shown in Equation 6.6. Setting the density ρ_x (rho_x) equal to 998 kg/m³, the voltage V_x as a function of temperature is obtained:

$$V_x = (998. - b_{0x} - b_{1x} T - b_{2x} T^2) / (b_{3x} + b_{5x} T + b_{6x} T^2) \quad (7.3)$$

This represents three equations, where $x = BC, DE,$ and FF . The values of the coefficients are given in Table 6.2. Therefore, the voltage V_x as a function of temperature is obtained, as shown in Tables 7.5 and 7.6 under the heading “305 series eqn.”

Of the two methods, the second method, using Equation 7.3 above, is probably the more accurate, since it was obtained for many liquids over a temperature range of 20 C to 60 C. For example, the temperature for the water calibration experiments was obtained up to a temperature of approximately 50 C.

7.4.3 Setting Amplifier Gains

Run the code using automatic gain control set to “off.” The objective is to set the amplifier gain settings so that one can see, at a quick glance at the data screen, whether the expected voltages are being observed. Table 7.7 lists the dB gain settings for Probe 1 and Probe 2.

Table 7.7 Gain settings for probes 1 and 2

Transducer Pair	Gain Settings for Probe 1	Gain Settings for Probe 2
	(dB)	(dB)
BC	27 (27.26)	33 (32.84)
DE	20 (20.03)	31 (31.02)
AA	2 (1.72)	10 (9.86)
FF	14 (13.97)	18 (18.23)

Table 7.8 and Table 7.9 show the variation of the voltages with temperature. For these calculations, the relationship between the actual (or measured) voltage and the adjusted voltage is obtained by inverting Equation 7.2. The values of the adjusted voltage are those obtained by using the “305 series eqn,” as shown in Table 7.5 and 7.6.

Table 7.8 Example of voltage variation with temperature for Probe 1

Probe 1								
Temp	water VBC 305 series eqn	Voltage BC reading at gain setting = 27 dB	VDE 305 series eqn	Voltage DE reading at gain setting = 20 dB	VFF 305 series eqn	Voltage FF reading at gain setting = 14 dB	AA water cal	Voltage AA reading at gain setting = 2 dB
C								
20	0.015131	0.349041	0.036497	0.366233	0.086353	0.431299	0.320737	0.390975
21	0.015440	0.356170	0.036174	0.362992	0.085410	0.426588	0.317355	0.386852
22	0.015718	0.362570	0.035847	0.359712	0.084495	0.422018	0.313515	0.382171
23	0.015965	0.368284	0.035516	0.356388	0.083608	0.417586	0.309240	0.376961
24	0.016185	0.373352	0.035180	0.353012	0.082747	0.413287	0.304556	0.371250
25	0.016378	0.377809	0.034838	0.349580	0.081912	0.409118	0.299486	0.365070
26	0.016547	0.381690	0.034489	0.346086	0.081103	0.405076	0.294054	0.358449
27	0.016691	0.385021	0.034134	0.342524	0.080318	0.401158	0.288286	0.351418
28	0.016813	0.387830	0.033772	0.338889	0.079558	0.397361	0.282205	0.344005
29	0.016913	0.390140	0.033402	0.335175	0.078822	0.393682	0.275835	0.336240
30	0.016992	0.391972	0.033023	0.331377	0.078108	0.390119	0.269202	0.328154
31	0.017052	0.393347	0.032636	0.327489	0.077417	0.386668	0.262328	0.319775
32	0.017093	0.394281	0.032239	0.323506	0.076749	0.383328	0.255239	0.311134
33	0.017115	0.394790	0.031832	0.319423	0.076102	0.380096	0.247959	0.302259
34	0.017119	0.394889	0.031415	0.315232	0.075476	0.376970	0.240511	0.293181
35	0.017106	0.394589	0.030986	0.310929	0.074870	0.373947	0.232921	0.283929
36	0.017076	0.393903	0.030545	0.306506	0.074286	0.371026	0.225213	0.274532
37	0.017030	0.392841	0.030092	0.301958	0.073721	0.368205	0.217411	0.265021
38	0.016968	0.391412	0.029625	0.297276	0.073175	0.365481	0.209539	0.255425
39	0.016891	0.389624	0.029145	0.292454	0.072649	0.362854	0.201621	0.245774
40	0.016798	0.387483	0.028649	0.287484	0.072142	0.360321	0.193682	0.236097
41	0.016690	0.384997	0.028138	0.282358	0.071654	0.357881	0.185747	0.226424
42	0.016567	0.382170	0.027611	0.277066	0.071183	0.355531	0.177839	0.216784
43	0.016430	0.379008	0.027066	0.271601	0.070731	0.353272	0.169983	0.207207
44	0.016279	0.375513	0.026503	0.265951	0.070296	0.351100	0.162203	0.197723
45	0.016113	0.371688	0.025921	0.260106	0.069879	0.349016	0.154523	0.188362
46	0.015933	0.367537	0.025318	0.254056	0.069479	0.347018	0.146967	0.179152
47	0.015739	0.363061	0.024693	0.247788	0.069095	0.345103	0.139561	0.170124
48	0.015531	0.358261	0.024046	0.241289	0.068729	0.343273	0.132328	0.161307

49	0.015309	0.353136	0.023374	0.234545	0.068379	0.341524	0.125293	0.152731
50	0.015073	0.347688	0.022676	0.227542	0.068045	0.339857	0.118479	0.144425
51	0.014822	0.341915	0.021950	0.220263	0.067727	0.338270	0.111912	0.136420
52	0.014558	0.335816	0.021196	0.212691	0.067425	0.336763	0.105615	0.128744
53	0.014279	0.329389	0.020410	0.204807	0.067139	0.335334	0.099613	0.121427
54	0.013986	0.322631	0.019591	0.196590	0.066869	0.333983	0.093930	0.114499
55	0.013679	0.315539	0.018737	0.188020	0.066614	0.332708	0.088590	0.107990
56	0.013357	0.308110	0.017845	0.179070	0.066374	0.331511	0.083618	0.101929
57	0.013020	0.300340	0.016913	0.169716	0.066149	0.330388	0.079038	0.096346
58	0.012668	0.292223	0.015938	0.159927	0.065940	0.329341	0.074874	0.091271
59	0.012301	0.283754	0.014916	0.149674	0.065745	0.328369	0.071151	0.086732
60	0.011918	0.274927	0.013844	0.138920	0.065565	0.327470	0.067892	0.082760

Table 7.9 Example of voltage variation with temperature for Probe 2

Probe 2								
Temp	Water VBC 305 series eqn	Voltage BC reading at gain setting = 33 dB	VDE 305 series eqn	Voltage DE reading at gain setting = 31 dB	VFF 305 series eqn	Voltage FF reading at gain setting = 18 dB	AA water cal	Voltage AA reading at gain setting = 10 dB
C								
20	0.008113	0.355798	0.011284	0.401306	0.050221	0.409621	0.136053	0.423359
21	0.008286	0.363370	0.011422	0.406211	0.049600	0.404560	0.130265	0.405348
22	0.008445	0.370344	0.011542	0.410476	0.048999	0.399653	0.124617	0.387772
23	0.008591	0.376735	0.011645	0.414129	0.048415	0.394895	0.119108	0.370630
24	0.008724	0.382562	0.011731	0.417199	0.047849	0.390280	0.113739	0.353922
25	0.008844	0.387839	0.011802	0.419712	0.047301	0.385804	0.108509	0.337649
26	0.008952	0.392583	0.011857	0.421690	0.046768	0.381461	0.103419	0.321811
27	0.009049	0.396809	0.011899	0.423155	0.046251	0.377246	0.098469	0.306407
28	0.009133	0.400530	0.011926	0.424128	0.045750	0.373156	0.093658	0.291437
29	0.009207	0.403761	0.011940	0.424628	0.045263	0.369187	0.088987	0.276902
30	0.009270	0.406514	0.011941	0.424672	0.044791	0.365333	0.084456	0.262802
31	0.009322	0.408802	0.011930	0.424277	0.044332	0.361592	0.080064	0.249136
32	0.009364	0.410638	0.011907	0.423456	0.043887	0.357961	0.075812	0.235904
33	0.009396	0.412033	0.011873	0.422225	0.043455	0.354435	0.071699	0.223107
34	0.009418	0.412999	0.011827	0.420597	0.043035	0.351011	0.067726	0.210745
35	0.009430	0.413546	0.011770	0.418583	0.042627	0.347687	0.063893	0.198817
36	0.009433	0.413685	0.011703	0.416195	0.042232	0.344460	0.060199	0.187323
37	0.009428	0.413426	0.011626	0.413444	0.041848	0.341326	0.056645	0.176264
38	0.009413	0.412779	0.011538	0.410339	0.041474	0.338284	0.053231	0.165640
39	0.009389	0.411753	0.011441	0.406890	0.041112	0.335330	0.049956	0.155450
40	0.009358	0.410358	0.011335	0.403105	0.040761	0.332462	0.046821	0.145694
41	0.009318	0.408602	0.011219	0.398992	0.040420	0.329679	0.043826	0.136373

42	0.009269	0.406494	0.011095	0.394559	0.040088	0.326977	0.040970	0.127486
43	0.009214	0.404041	0.010961	0.389812	0.039767	0.324356	0.038254	0.119034
44	0.009150	0.401252	0.010819	0.384757	0.039455	0.321812	0.035677	0.111017
45	0.009079	0.398135	0.010668	0.379402	0.039152	0.319344	0.033240	0.103434
46	0.009000	0.394697	0.010509	0.373751	0.038859	0.316951	0.030943	0.096285
47	0.008915	0.390945	0.010342	0.367809	0.038574	0.314630	0.028785	0.089571
48	0.008822	0.386885	0.010167	0.361581	0.038299	0.312380	0.026767	0.083292
49	0.008723	0.382526	0.009984	0.355072	0.038031	0.310200	0.024889	0.077446
50	0.008617	0.377872	0.009793	0.348285	0.037772	0.308088	0.023150	0.072036
51	0.008504	0.372931	0.009595	0.341225	0.037522	0.306042	0.021551	0.067060
52	0.008385	0.367708	0.009389	0.333894	0.037279	0.304062	0.020091	0.062518
53	0.008260	0.362209	0.009175	0.326297	0.037044	0.302146	0.018771	0.058411
54	0.008128	0.356441	0.008954	0.318435	0.036817	0.300293	0.017591	0.054738
55	0.007990	0.350408	0.008726	0.310311	0.036597	0.298502	0.016550	0.051500
56	0.007847	0.344116	0.008490	0.301928	0.036385	0.296772	0.015649	0.048697
57	0.007698	0.337570	0.008247	0.293287	0.036180	0.295102	0.014888	0.046327
58	0.007543	0.330775	0.007997	0.284391	0.035983	0.293491	0.014266	0.044393
59	0.007382	0.323736	0.007740	0.275241	0.035792	0.291937	0.013784	0.042893
60	0.007216	0.316458	0.007475	0.265839	0.035609	0.290442	0.013442	0.041827

7.4.4 Adjustment to System and/or Changes to Input File.

If there have been no changes in the transducer performance, since the tests in Bldg 305, then the voltages shown on the data sheet for a loop test should be the same as those in Table 7.8 (or 7.9) when water is in the pipeline. If they are, then no adjustments are needed.

However, if they are not the same, then some adjustments are needed. The two most important transducers for the measurement of density are DE and FF. The first step is to use the adjustment of the pulser voltage. One reason is that the cable lengths used on site may not be exactly the same as those used during the calibration. The difference in cable lengths can be adjusted by changing the pulser voltage. For example, suppose that the voltage on DE and FF are below the expected value in Table 7.8 (or 7.9). By increasing the pulser voltage, we can increase the voltage on DE and FF and try to get them equal to the desired values. Ideally, both DE and FF will do that. If not, then the values of *corrde*, *corrff*, *addsubde*, and *addsubff* need to be changed to accomplish this. The objective is to use the correction factors so that whatever voltage is measured, the correction factor converts the measured value to the desired value. The multiplicative correction factor *corr_x* will probably work the best. If one can obtain data on the voltage values as a function of temperature, then one can determine *corr_x* and *addsub_x* from the data for two temperatures. One notes that the correction factors in Equation 7.1 refer to the adjusted voltages, so that all voltages are on an “equal footing,” regardless of the amplifier gain.

Example

1. At 20 C, the voltage measured on DE is 0.340 volts at an amplifier gain of 20.03 dB. The adjusted voltage is 0.033883 volts. The expected voltage at this temperature is 0.366 volts, as shown in Table 7.8. This adjusted voltage is 0.036497 volts.
2. At 40 C, the voltage measured on DE is 0.270 volts at an amplifier gain of 20.03 dB. The adjusted voltage is 0.026907 volts. The expected voltage at this temperature is 0.287484 volts, which gives an adjusted voltage of 0.028648 volts.

The two equations become:

$$0.036497 = \text{corrde} \cdot 0.033883 + \text{addsubde} \quad (7.4)$$

$$0.028648 = \text{corrde} \cdot 0.026907 + \text{addsubde} \quad (7.5)$$

Solving these two equations for corrde and addsubde, we find corrde = 1.125 and addsubde = -0.002621 volts.

If the voltages on the transducers are not the same as the expected values, then the first step is to adjust the pulser voltage, as stated above. The second step is then to use the correction factor. Some judgment is needed to determine exactly how this is done. The above example serves only as a guide.

8.0 Density Sensor Deployment at SY-101 Site

In FY-2001, the density sensor was installed at the SY-101 site. In FY-2002 the densimeter performance will be demonstrated during water flushes and waste transfers from tank SY-101. Tank SY-101 is being used as a staging tank for interim stabilization of salt well pumping liquors that are removed from the single-shell tanks. Salt well pumping liquors, retrieved from the SSTs are stored in SY-101 prior to cross-site transport. Based on the densimeter location in the prefabricated pump pit, all fluids stored in tank SY-101 that are transported out of this tank will pass through the densimeter.

8.1 Installation

In FY-2001 the densimeter incorporated as a part of the modified process manifold (MPM) was installed in the prefabricated pump pit (PPP) at the SY-101 site. The PPP configuration is shown in Figure 8.1. The densimeter installation, before and after addition of the insulating jacket, is shown in Figures 8.2 and 8.3. The densimeter was installed with the wedges at an angle of 22.5 deg below horizontal, as observed by the tilt of the densimeter cover in Figure 8.2. This orientation was selected so that the sensor would be in contact with the bulk of the fluid layer and not be affected by any pockets of air that could accumulate at the top of the pipe or any solids that could potentially settle on the face of the sensor. Electrical connections are made in the field (Figure 8.4) and in the DACS trailer (Figures 8.5 and 8.6).

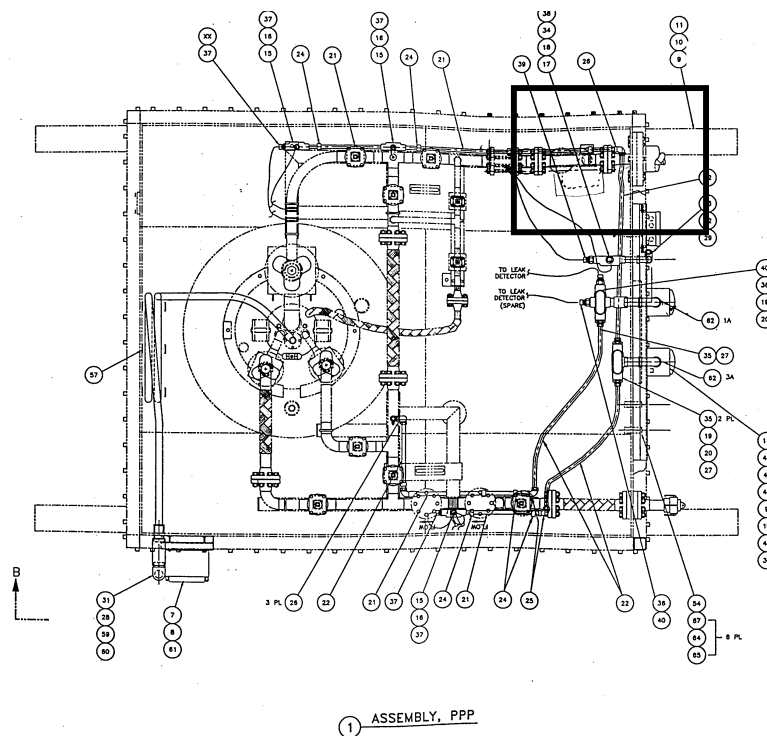


Figure 8.1 Densimeter location in the prefabricated pump pit (upper right corner – penetrating wall)

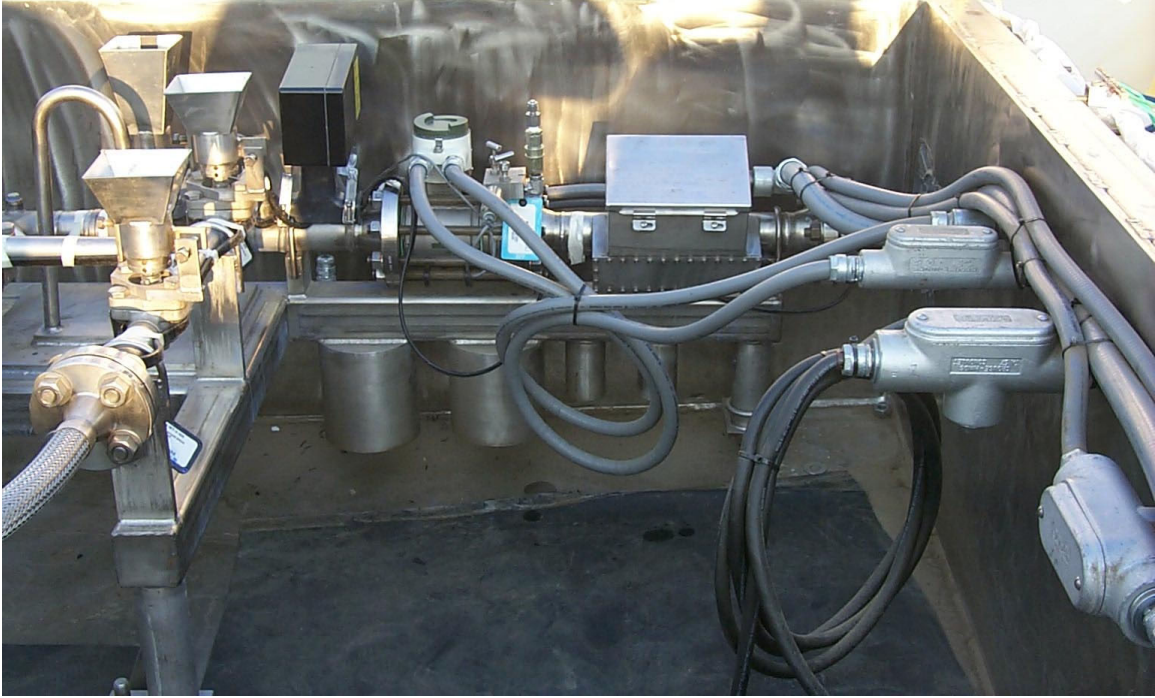


Figure 8.2 Densimeter installed in the MPM inside the PPP

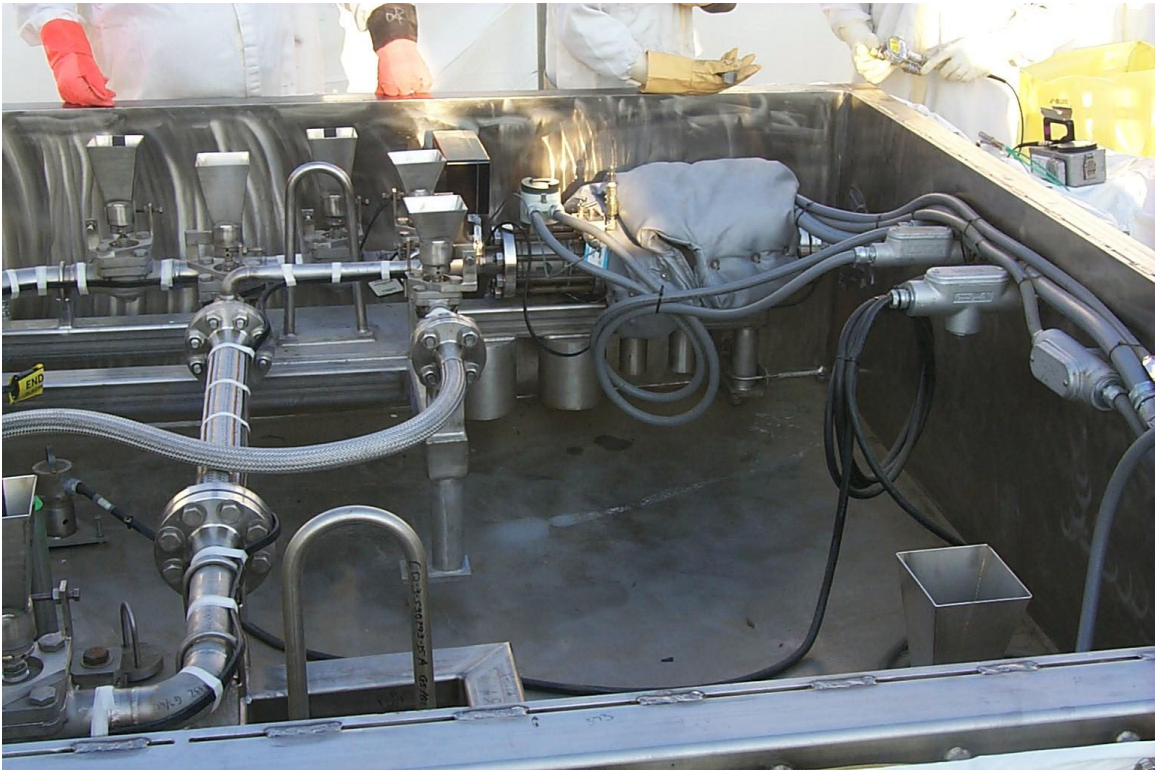


Figure 8.3 Densimeter after installation of blanket insulation



Figure 8.4 Densimeter cable field connections in PPP (left) and junction box (right)



Figure 8.5 Densimeter cables inside panel in DACS trailer

8.1.1 Equipment in the DACS Trailer

The densimeter computer controller, described in Section 4.4, will be operated from the data acquisition and control system (DACs) trailer. The density computer system has 3 components:

1. Computer: foot print of 51 cm x 61 cm (20 in wide x 24 in deep) or minimally could use a space 56 cm deep with a 5 cm 22 in deep with 2 in overhang
2. Strawberry tree data shuttle, for temperature measurements: foot print of 15 cm wide x 31 cm deep (6 in. wide x 12 in. deep). If this is stored on edge then its foot print would be 5 cm wide x 31 cm deep (2 in. wide x 12 in. deep)
3. Printer Laserjet III: foot print of 48 cm wide x 48 cm deep (19 in. wide x 19 in. deep), if the printer is mounted with an overhang.

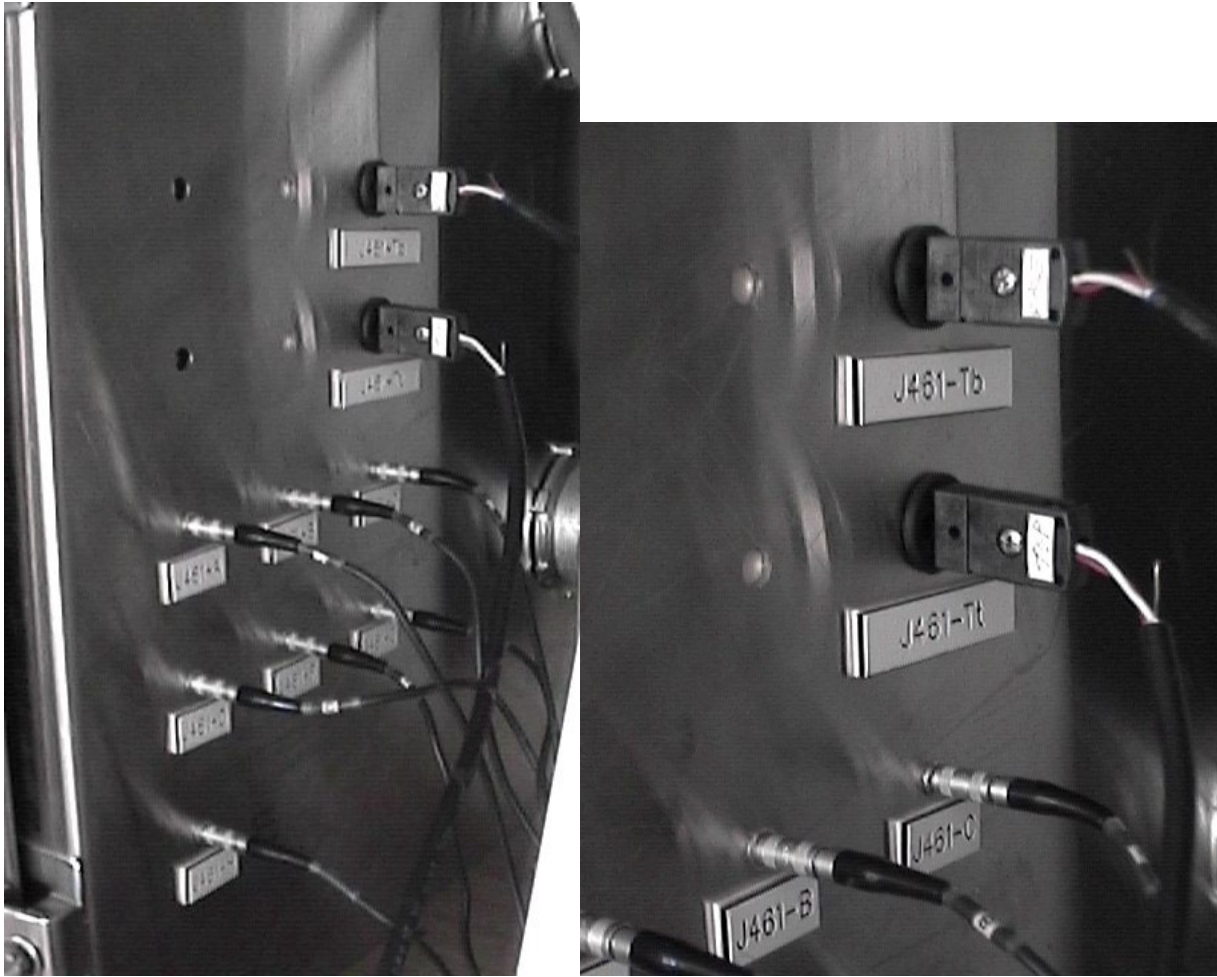


Figure 8.6 Density sensor connector locations on panel in DACS trailer

8.2 Density Sensor Operational Check

After the density sensor and cabling were installed at SY-101 and prior to the last planned work in the PPP, system operation was verified by observing the wave forms for each transducer with the transducer exposed to the air in the MPM piping. The waveforms, which are unique in shape, for each of the transducer, are shown in Figures 8.7 through 8.11. The densimeter was run for one cycle using the auto test command. The results of this run, which represent data obtained with the probes in air, are shown in Table 8.1. In addition, the pulser voltage was measured to determine whether it varied from the value obtained during tests in 305 Building. The pulser voltage is shown in Figure 8.12. The voltage obtained (49.8 V) was very similar to the 50 V measured in 305 Building. To measure the pulser voltage a 4.6-m (15-ft) cable was connected to transducer FF at the computer; this was connected to the oscilloscope using a 10:1 probe. The output measured is shown in Figure 8.12.

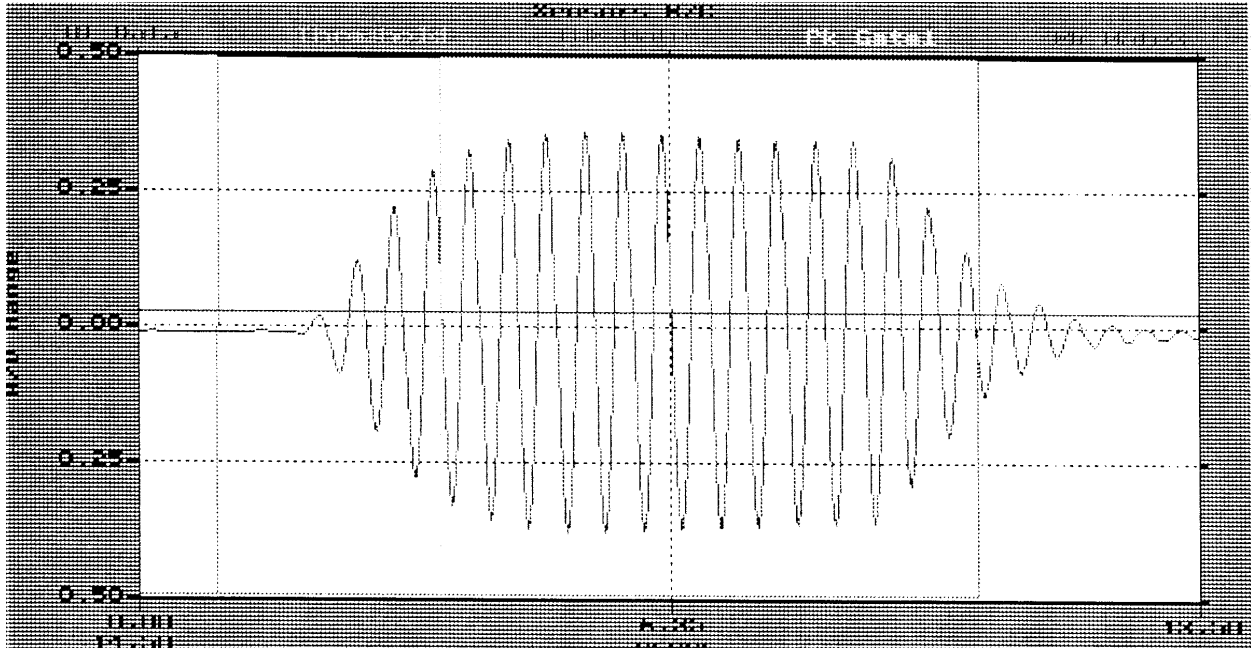


Figure 8.7 Wave form for longitudinal wave transducer pair BC in air

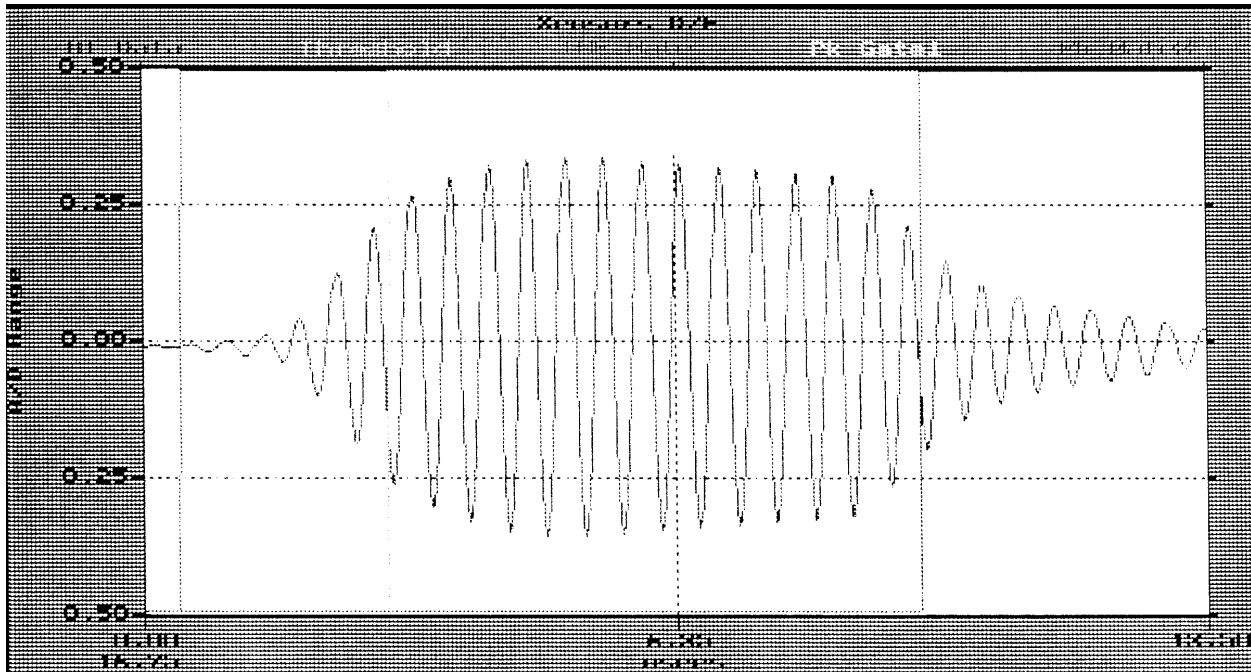


Figure 8.8 Wave form for longitudinal wave transducer pair DE in air

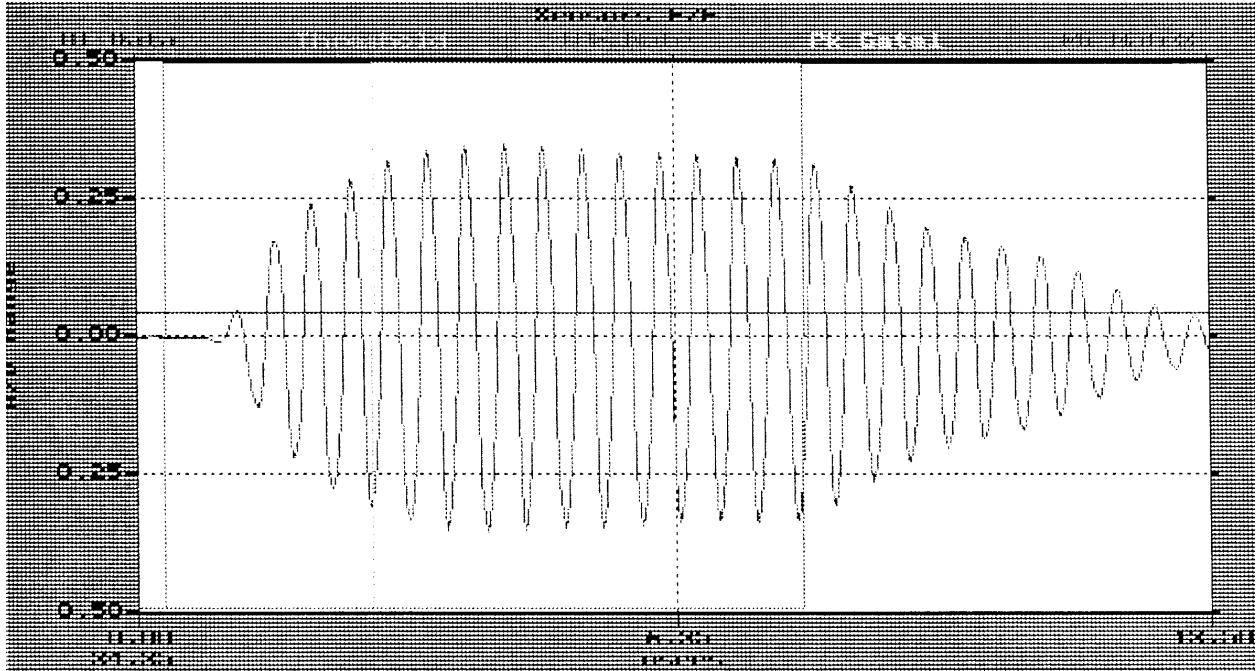


Figure 8.9 Wave form for longitudinal wave transducer FF in air

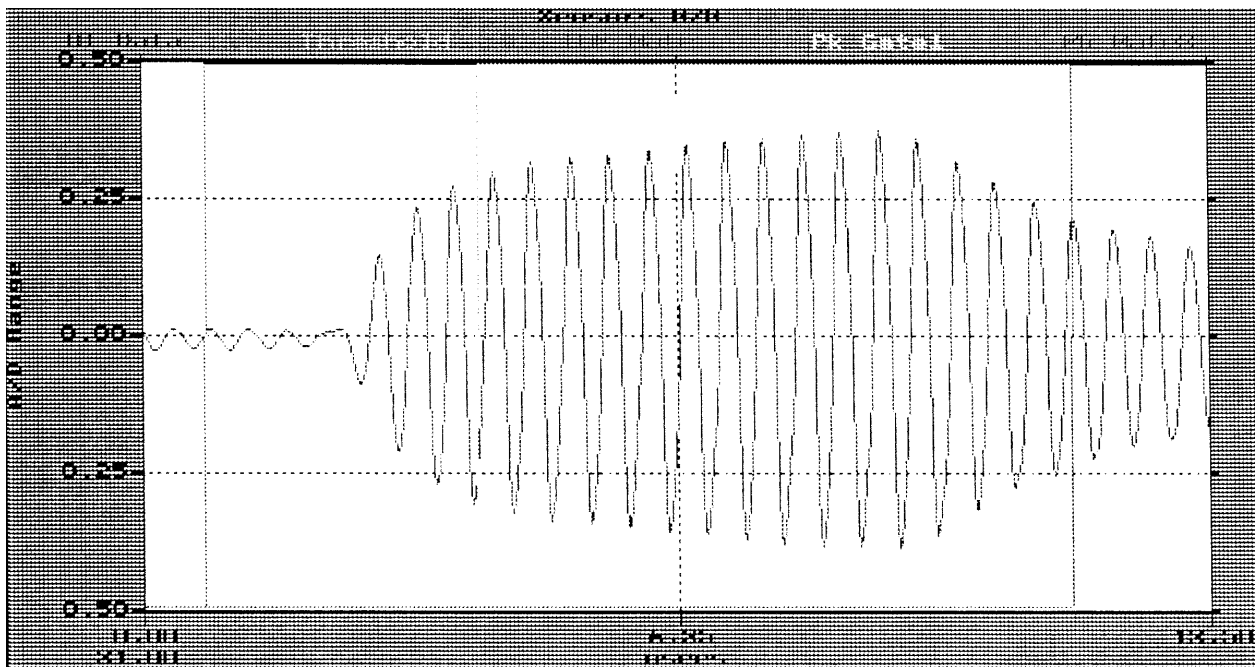


Figure 8.10 Wave form for longitudinal wave transducer GG in air

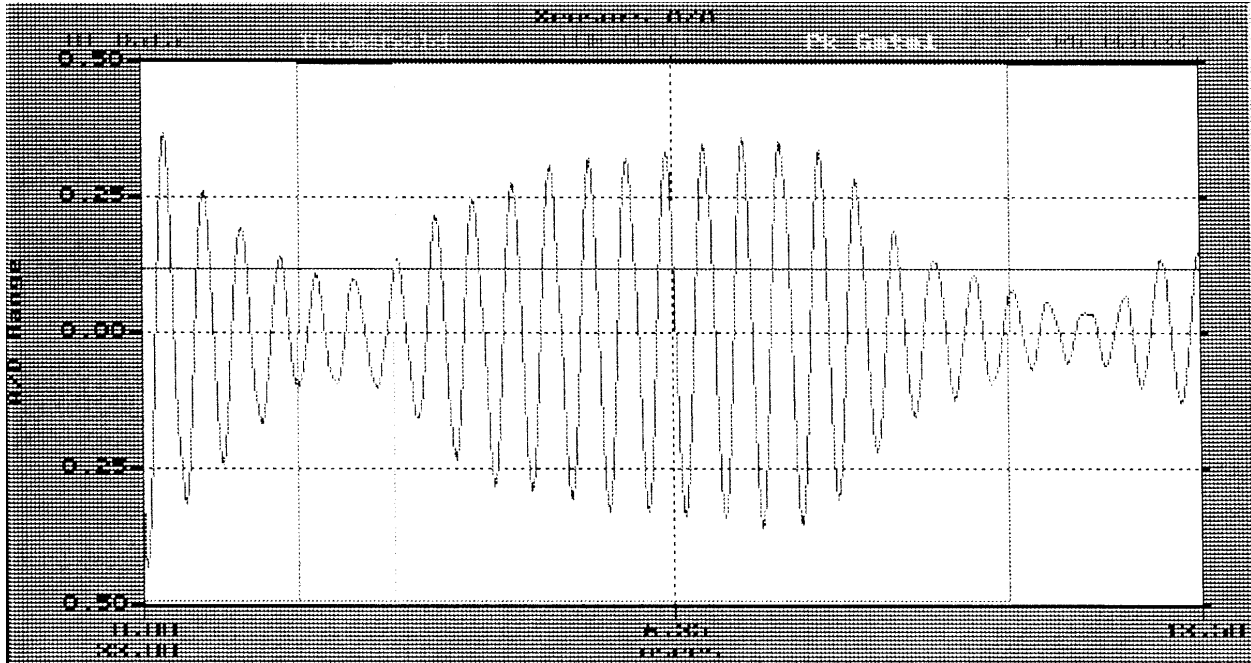


Figure 8.11 Wave form for shear wave transducer AA in air

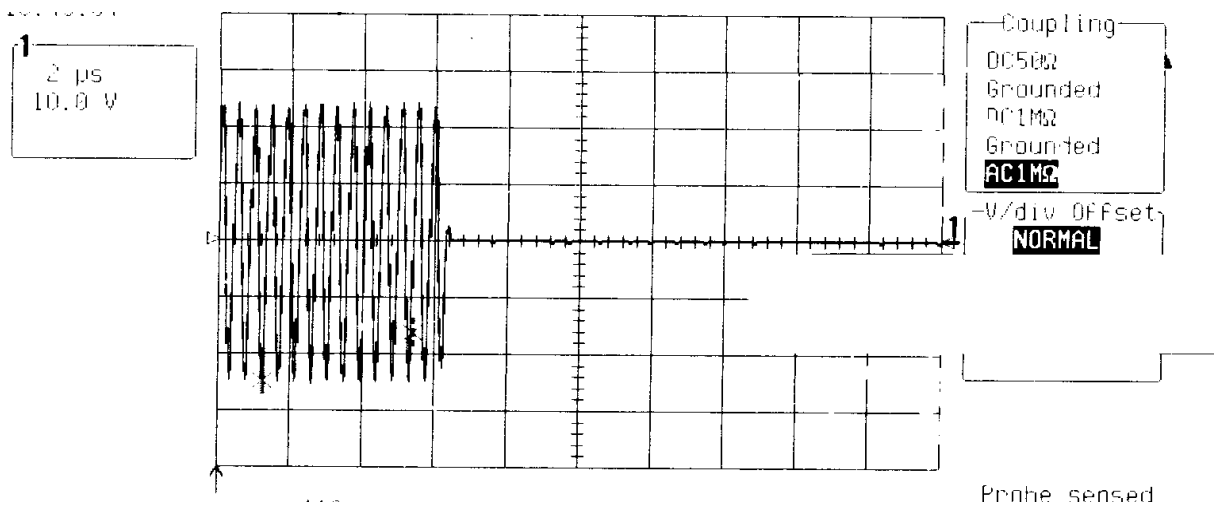


Figure 8.12 Evaluation of pulser voltage obtained in DACS trailer

Results obtained from these operational tests showed that the densimeter is correctly connected and ready for operation during planned activities of line flushing and waste transfers. The data taken in air will serve as a baseline for comparison prior to the initiation of any transfers.

Table 8.1 Output from auto test of densimeter with probes in contact with air.

```

UT DENSITY DATA
Sensor ordering: B/C, D/E, A/A, F/F
  -tofs in usecs          -peaks in volts
  avg tof      tof std    avg pk      pk std      max      min
16.952607     0.000534    0.370740    0.000325    0.373047    0.367432
18.922850     0.000506    0.344507    0.000341    0.348145    0.342285
0.000000      3.188486     0.362000    0.000255    0.364258    0.359863
25.286402     0.000608    0.351904    0.000316    0.354004    0.349609
23.646727     0.000583    0.377002    0.000256    0.379639    0.375244

Density(kg/m^3)=1240.4801      Velocity(m/sec)=999.0000      Viscosity(cP)=109.33

Date: 6/27/01      Time: 9:51

Pipe Temp-C=0.000
Base Temp-C=17.538
Top Temp-C=17.538

Probe ID=2      Gain ID=2      ISol=2      INoise=0
Dnlqexpi=75.8804      0.0000      47.0000      60.000000
Dnz42=75.8804      2702.2335      75.8804      0.000000
Alpha=47.00      60.00      0.00      0.000000

Vtref2=0.015677      0.037906      0.326955      0.084930
Gnref2=0.000000      0.000000      0.000000      0.000000

AGC Flg(1=YES)=0

          Lkup Cfg File
UT Gain db-BC.....10
          -DE.....12
          -AA.....3
          -FF.....6
          -GG.....8
UT Freq Index.....3
UT # TB Cycles-BC.....15
          -DE.....15
          -AA.....12
          -FF.....15
          -GG.....15
UT # Data Set Avgs.....20
UT TOF Gate Pt-BC.....618
          -DE.....688
          -AA.....1394
          -FF.....984
          -GG.....870
UT Gate1 Pt-BC.....722
          -DE.....786
          -AA.....1440
          -FF.....1080
          -GG.....998
UT Gate2 Pt-BC.....976
          -DE.....1036
          -AA.....1730
          -FF.....1280
UT Threshold-BC.....106
          -DE.....311
          -AA.....474
          -FF.....174

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-GG.....374

A/D Clk Index.....7
A/D Start Pt-BC.....580
  -DE.....670
  -AA.....1320
  -FF.....970
  -GG.....840
A/D # Sample Pts-BC.....500
  -DE .....500
  -AA .....500
  -FF .....500
  -GG .....500
A/D Trig Dly Clk Index-BC.....7
  -DE.....7
  -AA.....7
  -FF.....7
  -GG.....7
A/D Trig Dly Factor Index-BC..0
  -DE..0
  -AA..0
  -FF..0
  -GG..0
A/D # Waveforms to Avg.....15.00
A/D Bias-BC.....2.50
  -DE.....2.50
  -AA.....2.50
  -FF.....2.50
  -GG.....2.50
Pk Flg(1=Pk,0=Pk-to-Pk)-BC.....0
  -DE.....0
  -AA.....0
  -FF.....0
  -GG.....0

```

9.0 Density Sensor Improvements – Through-Wall Sensor

The density sensor design installed in FY-2001 at Tank SY-101 is based on the original density sensor concept proposed in FY-1996 and evaluated at ORNL in FY-1997. The original plan was to demonstrate this concept at Hanford in FY-1998. However, based on project cancellations and reassignments the initial densimeter concept will finally be demonstrated in FY-2002. Upgrades to the SY-101 densimeter include the ability to operate over an increased pressure range (based on design of a new spool piece) and an enhanced calibration scheme that incorporates the effects of temperature into the methodology.

Concurrent with the density sensor demonstration project, Laboratory Directed Research and Development (LDRD) funded research to investigate coupling transducers directly to metal, eliminating the need for a plastic wedge. This approach could lead to coupling the transducers directly to the external surface of a pipe or even a transducer arrangement that can be clamped onto the pipe.

Interesting developments from the FY-2000 and FY-2001 LDRD that lead to a new configuration density sensor are now presented.

9.1 Approach to Through-Wall Measurement of Density

New methods are needed to characterize liquids and slurries that involve real-time, nonintrusive sensors. A new approach has been found to measure the density *through* the stainless steel wall of the pipe or vessel. While stainless steel is used in many applications, the method is also applicable to walls of other materials, such as glass.

The objective is to develop an ultrasonic sensor that: 1) can be attached permanently to a pipeline wall, possibly as a spool piece inserted into the line or 2) can clamp onto an existing pipeline wall and be movable to another location. An analysis method has been developed to make the measurement self-calibrating. This is a very important feature, since it makes a clamp-on sensor feasible because the signal strength is sensitive to the pressure with which the transducer is coupled to the pipe.

This approach is very similar to the approach used for the density sensor, with stainless steel substituted for the “non-traditional” plastic wedge. In the new approach, a transducer (1.3 cm x 2.5 cm x 0.16 cm [0.5 in. x 1 in. x 1/16 in.]) affixed to the outside of the pipeline wall sends ultrasound through the stainless steel. When the ultrasound strikes the liquid, some fraction of the ultrasound, denoted by the term “reflection coefficient,” is reflected back to the transducer. That is, the stainless steel wall itself becomes the sensing material. The amount of ultrasound reflected at the stainless-steel-liquid interface depends upon the density of the liquid and the speed of sound in the liquid.

The focus of this research was to determine the acoustic impedance (Z) of the liquid, defined as the product of the density (ρ) and speed of sound (c). By measuring the speed of sound by well-known methods, the density can be determined. For these investigations, a square-wave pulser provided a high voltage pulse of short duration to the transducer. The self-calibrating feature that has been developed, a major step in this research, means that a change in the pulser voltage does NOT affect the measurement of

the acoustic impedance. The data were obtained using a digital oscilloscope and saved to a disk. The sensor was calibrated using water. A separate Matlab[™] code was then used to analyze the data. Comparison of the voltages for the liquid and those for water yield the reflection coefficient. These measurements combined with the knowledge of the acoustic impedance of stainless steel yield the acoustic impedance of the liquid or slurry.

Laboratory measurements were carried out in which a transducer was mounted permanently upon a thin plate. The base of the plate was in contact with the liquid and the reflection of the ultrasound from the solid-liquid interface was also monitored by the same transducer. Data have been obtained using the following plates:

- 0.64-cm- (0.25-in.-) thick stainless steel plate
- 0.38-cm- (0.15-in.-) thick stainless steel plate
- 0.64-cm- (0.25-in.-) thick aluminum plate
- 0.64-cm- (0.25-in.-) thick fused quartz plate (very similar to glass).

A clamp-on sensor suitable for a Schedule 40 stainless steel pipe (O. D. = 2.375 in. [6 cm] and wall thickness = 0.154 in. [0.39 cm]) is shown in Figure 9.1. Data will be obtained and compared with that from the very similar design using the 0.38-cm- (0.15-in.-) thick stainless steel plate.

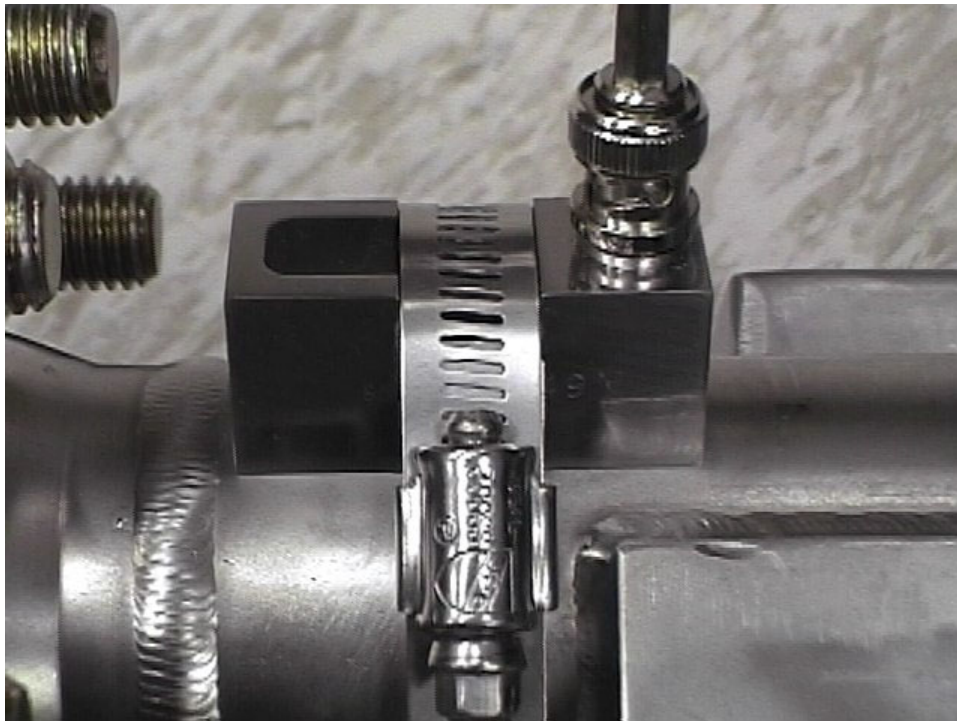


Figure 9.1 Clamp-on sensor applied to 2-in. Schedule 40 pipe

Tables 9.1 and 9.2 show the results for the two stainless steel plates. The performance was evaluated by measuring sugar water (SW) solutions of various concentrations. The concentration is indicated by the percentage of sugar in a given weight of the solution. The density of the solution, given in the second column, was obtained by measuring the weight of a known volume of liquid. The speed of sound in the liquid was also measured. These values lead to an independent value of the acoustic impedance of the liquid. Analysis of the signals from the transducer is used to determine the reflection coefficient, which, in turn, yields the acoustic impedance of the liquid. In the tables the acoustic impedance obtained using the sensor is compared with that obtained independently. The percentage error is also shown.

Table 9.1 Data obtained with the 0.064-cm- (0.25-in.-) thick stainless steel plate

Liquid	Measured Density	Measured Reflection Coefficient	Sensor Measurement of Acoustic Impedance	Independent Measurement of Acoustic Impedance	Percent Error
	(kg/m ³)		(kg/m ² sec) x 10 ⁶	(kg/m ² sec) x 10 ⁶	
2.5% SW	1006	0.9389	1.4622	1.4994	-2.5
5.0% SW	1016	0.9354	1.5489	1.5213	1.8
7.5% SW	1026	0.9368	1.5146	1.5447	-2.0
10% SW	1038	0.9357	1.5425	1.5696	-1.7
15% SW	1065	0.9334	1.5982	1.6239	-1.6
20% SW	1097	0.9304	1.6726	1.6844	-0.7

Table 9.2 Data obtained with the 0.38-cm- (0.15-in.-) thick stainless steel plate

Liquid	Measured Density	Measured Reflection Coefficient	Sensor Measurement of Acoustic Impedance	Independent Measurement of Acoustic Impedance	Percent Error
	(kg/m ³)		(kg/m ² sec) x 10 ⁶	(kg/m ² sec) x 10 ⁶	
5% SW	1010	0.9359	1.5378	1.525	0.8
10% SW	1027	0.9347	1.5668	1.5782	-0.7
15% SW	1057	0.9310	1.6581	1.6265	1.9
20% SW	1074	0.9305	1.6709	1.6856	-0.8
30% SW	1115	0.9188	1.9652	1.8087	8.7
40% SW	1170	0.9139	2.0885	1.9635	6.4

The analysis method enables very small changes in the reflection coefficient to be measured and thus, to distinguish between very small changes in the density of the liquid or slurry. The effectiveness of these methods can be observed by noting that two different experiments give values of the reflection coefficients that are extremely close. That is, the amount of reflection is determined by the solid-liquid interface alone, and is not dependent upon the thickness of the plate. Thus, a 20% sugar water solution gives a reflection coefficient of 0.9304 in one experiment and 0.9305 in the second.

The data shown in the tables was obtained using signal averaging, but show only *one* set of data. Percentage errors can be reduced by averaging several sets of data performed in a very short time, if automated. The digital oscilloscope had a 100 MHz digitizer with 8-bit resolution. Increased accuracy

can be obtained by analyzing the signals with a higher digitizer rate and with 10-bit or 12-bit digitizer resolution.

Some conclusions are as follows:

- The analysis method provides a way to measure very small changes in reflection coefficient, and hence, very small changes in the density through stainless steel (or other solids).
- The self-calibrating feature makes it possible to design a clamp-on sensor.
- The self-calibrating feature means that changes in the pulser voltage do not affect the measurement.
- The self-calibrating feature reduces the calibrating time.
- Wireless technology could be used to design a sensor to measure density and speed of sound and thus eliminate the long cables from the sensor to the computer acquisition system.

9.2 Clamp-on Sensor Applications

This investigation has shown the path forward to develop clamp-on sensors for measurement of fluid and slurry density. This method is especially attractive for applications such as Hanford where radioactive fluids are routinely transported because the sensors could be applied to existing equipment without the need to penetrate the pipe pressure boundary or to open the system to install new equipment. The two plate thicknesses evaluated (0.38 and 0.64 cm [0.15 and 0.25 in.]) are very similar to pipe wall thicknesses that are in use at Hanford. Schedule 40 2 in. pipe has a wall thickness of 0.39 cm (0.154 in.) similar to the smaller thickness tested, and Schedule 40 4-in. pipe has a wall thickness of 0.60 cm (0.237 in.) similar to the larger thickness tested.

10.0 Economic Advantages of Slurry Monitoring

Inclusion of slurry monitoring instrumentation into the slurry transfer lines will result in significant cost savings in preventing pipeline plugging by enabling early detection of plugging event occurrences and enabling the operators to take early steps to offset such occurrences. An economic assessment of the benefits of incorporating slurry monitoring at Hanford and other DOE Sites was conducted as a part of the ASTD analysis of pipeline slurry monitors (Bontha et al. 2000). Salient points from that analysis are reiterated here.

10.1 Densimeter Cost Estimate

Two densimeter probes shown in Figures 4.1 and 4.2c and Figures 4.5 and 4.6 have been constructed embedded in pipeline spool pieces for measuring density during pipeline transport. Two immersion probes have been constructed, one for measuring density in a tank shown in Figure 4.2a, and another table top system for measuring density of fluids when less than 100 ml of fluid is required. Each of these densimeter systems includes two major components: the probe that houses the density sensor and the computer control system. The major components of the sensor are the plastic wedge, transducers, and cable connectors. The wedge must be constructed to withstand the temperature, pressure, chemical and physical characteristics of the fluid being interrogated. The computer control system must be constructed to withstand the physical and chemical environment in which it will be operated. An office or laboratory system may not be required to be as rugged as a system designed for installation in a plant or outdoor environment. These factors must be taken into account when assessing the cost of densimeter deployment.

10.1.1 Cost of Initial Deployments

After completion of the densimeter evaluation at ORNL (Hylton et al 1998) the costs of deployment of the densimeter were estimated. The spool piece was projected to have an off-the-shelf cost of \$4K and the computer-based controller was projected to have an off-the-shelf cost of \$14K.

The densimeter probe designed for deployment at SY-101 is more complex than the system designed for deployment at ORNL. For SY-101 deployment, the densimeter design pressure increased from 690 kPa (g) to 2.8 MPa (g) (100 psig to 400 psig). To meet this pressure requirement, the densimeter spool piece and wedge configuration were redesigned from the ORNL configuration. For the system to be deployed at SY-101, the costs are associated with four major components: the stainless steel spool piece with flanges, the transducer wedge, the customized computer board and the computer in which it is installed. In addition, for deployment at the site, radiation-hardened cables are required. The costs associated with each of these items are listed in Table 10.1. In addition to these procurement costs, the densimeter must be assembled, pressure tested, and calibrated. Costs for these items are in addition to the hardware listed in Table 10.1.

Table 10.1 Cost of densimeter for SY-101 deployment

Component	Hardware Procurement Cost	Comments
Stainless steel spool piece	\$ 7 K	The spool piece is constructed and pressure tested to operate at design conditions
Transducer wedge	\$ 3 K	The transducer wedges are machined to fit in the spool piece. The transducers are bonded to the wedge.
Custom computer board	\$ 4 K	The major design for this board was initiated during development of the system evaluated at ORNL. Some upgrades were incorporated in this new board configuration.
Cable	\$ 1 K	Radiation hardened co-axial cable is required in the pump pit. A long cable run to the data acquisition location may be required.
Computer	\$ 5 K	This off-the-shelf computer must withstand plant operating conditions and be designed to accommodate the custom computer board.
Hardware Cost	\$20 K	

10.1.2 Estimates of Cost of Future Deployments

The major cost of the densimeter system is associated with the pressure boundary. During development for deployment at SY-101 the following items have been identified and addressed. Materials were evaluated and selected for the probe body, O-ring seals, wedge, transducer and bonding material to permit continued operation at high pH and in a high radiation field. Designs for deployment in 5-cm- and 10-cm (2-in.- and 4-in.-) diameter piping systems have been developed. The length of the spool piece and the connecting flanges are dictated by the deployment configuration. These items may be customized for each deployment, or for mass production, a limited choice may be provided.

A significant savings may be associated with development of a mass-produced computer control system. Many ultrasonic components and functions are integrated into customized boards. In the future, the need for a computer-controller may be eliminated and the sensor control system may be a single board that is plugged into the existing plant data acquisition system. Estimates of the costs associated with future deployments are listed in Table 10.2.

Table 10.2 Estimated cost of future density sensor deployments

Component	Procurement Cost	Comments
Stainless steel spool piece	\$ 5 K	The spool piece is constructed and pressure tested to operate at design conditions. A streamlined design that incorporates a smaller wedge design or a clamp-on wedge design is envisioned.
Transducer wedge	\$ 2 K	A more streamlined wedge with fewer transducers is envisioned. The transducers are bonded to the wedge. The wedge material may be stainless steel for easy mounting to the pipe wall.
Custom computer board	\$ 3 K	A new board design will integrate pulser, digitization, and analysis features for the sensor.
Computer	\$ 0 K	Not required. Computer board will insert into the plant data acquisition system
Wiring	\$ 1 K	Radiation-hardened wire
System Cost	\$11 K	

10.2 Impacts of Plugged Pipelines

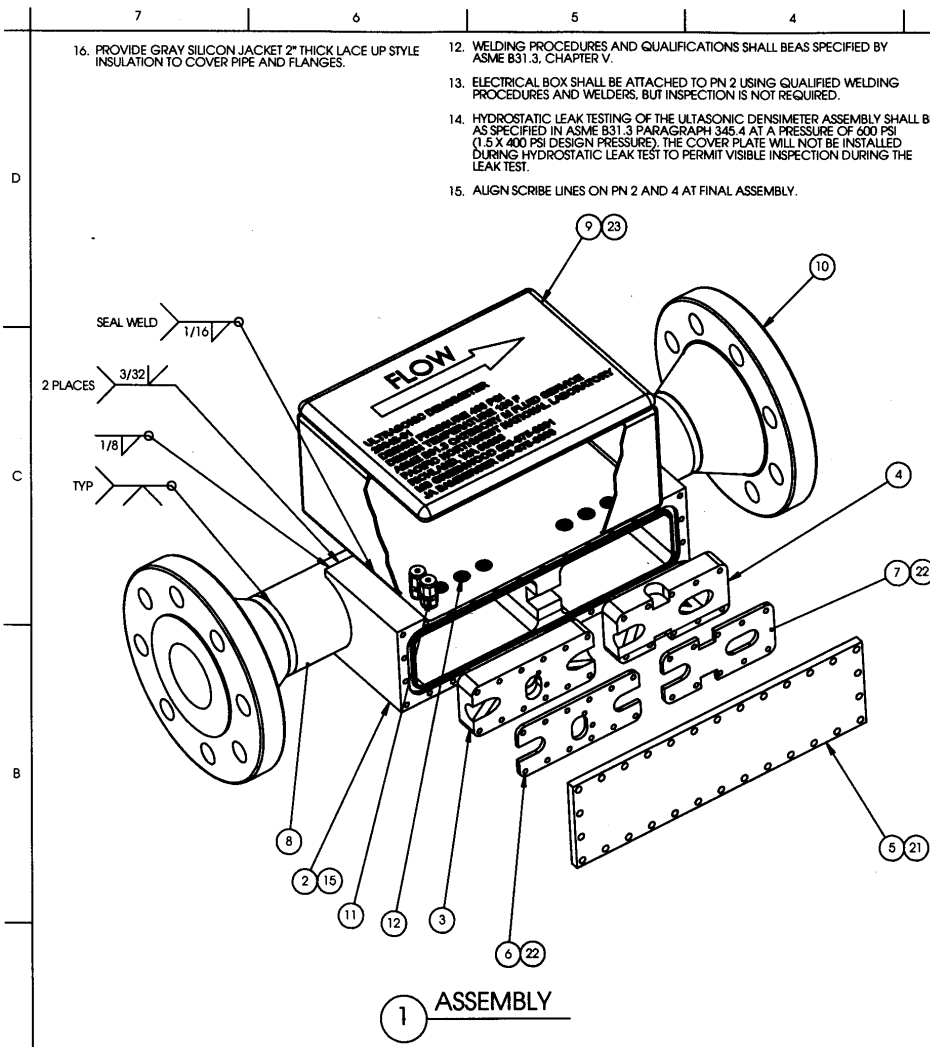
When a pipeline becomes plugged, efforts are made to unplug the line. These efforts include flushing with hot water and pressurizing the pipeline. To flush or to pressurize, connections must be made to the plugged pipeline in a contaminated zone. This results in exposure to radiation and/or contamination. If the unplugging efforts are unsuccessful, the pipeline must be replaced, and the new pipeline must have a hot tie-in to the existing system. Any time a radioactive pipeline must be cut and a hot tie-in made, people are exposed to radiation and contamination. Even with extensive flushing, significant dose may be incurred. A project at Hanford, sluicing of 241-C-106, incurred 25 person rems during construction (Bontha et al 2000). Construction of project W-320 included installation of a 460-m (1500-ft) pipeline with four hot tie-ins to contaminated systems as well as equipment installation in two tanks. Any replacement of plugged lines will require two hot tie-ins. If these hot tie-ins are made inside a tank farm, the excavation may encounter contaminated soil and additional human exposure and equipment contamination.

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12.0 Appendix Densimeter Prints



1 ASSEMBLY

16. PROVIDE GRAY SILICON JACKET 2" THICK LACE UP STYLE INSULATION TO COVER PIPE AND FLANGES.
17. WELDING PROCEDURES AND QUALIFICATIONS SHALL BE AS SPECIFIED BY ASME B31.3, CHAPTER V.
18. ELECTRICAL BOX SHALL BE ATTACHED TO PN 2 USING QUALIFIED WELDING PROCEDURES AND WELDERS, BUT INSPECTION IS NOT REQUIRED.
19. HYDROSTATIC LEAK TESTING OF THE ULTRASONIC DENSIMETER ASSEMBLY SHALL BE AS SPECIFIED IN ASME B31.3 PARAGRAPH 345.4 AT A PRESSURE OF 600 PSI (1.5 X 400 PSI DESIGN PRESSURE). THE COVER PLATE WILL NOT BE INSTALLED DURING HYDROSTATIC LEAK TEST TO PERMIT VISIBLE INSPECTION DURING THE LEAK TEST.
20. ALIGN SCRIBE LINES ON PN 2 AND 4 AT FINAL ASSEMBLY.

QTY	PN	DESCRIPTION	MATL/REF
1	1	2 INCH PIPE	
2	13	OMEGA THERMOCOUPLE	#EL1101210HTTC12-J-18U-1.25-GG
6	14	3 DIA. PZT5A 2.25MHZ LONGITUDINAL TRANSDUCER WITH 6" LEAD WIRES	STAVELEY INSTRUMENTS INC
1	15	PARKER O-RING	#2-261-E740-70
1	16	PARKER O-RING	#2-039-E740-70
1	17	PARKER O-RING	#2-037-E740-70
1	18	PARKER O-RING	#2-036-E740-70
1	19	PARKER O-RING	#2-034-E740-70
6	20	SET SCREW #2-56UNC-2A X 1/8" LONG	ASTM A316 SST
30	21	CAP SCREW, SOCKET HEAD #10-24UNC-2A X 5/8" LONG	ASTM A316 SST
22	22	CAP SCREW, SOCKET HEAD #6-32UNC-2A X 1" LONG	ASTM A316 SST
1	23	LIQUID TIGHT CONDUIT CONNECTION	NEWARK #92F7820
1	24	3 DIA. PZT5A 2.25MHZ SHEAR TRANSDUCER WITH 6" LEAD WIRES	STAVELEY INSTRUMENTS INC
2	1	MOUNT PLATE	
3	1	TRANS 80-2INCH	
4	1	TRANS 47-2INCH	
6	1	47 COVER	
6	1	2 INCH 80-COVER	
7	1	2 INCH COVER	
8	1	NEMA BOX	SHEET 14
9	1	NEMA LID	
10	2	TC FITTING	
11	2	2 INCH WELD NECK	
12	7	LEMO	

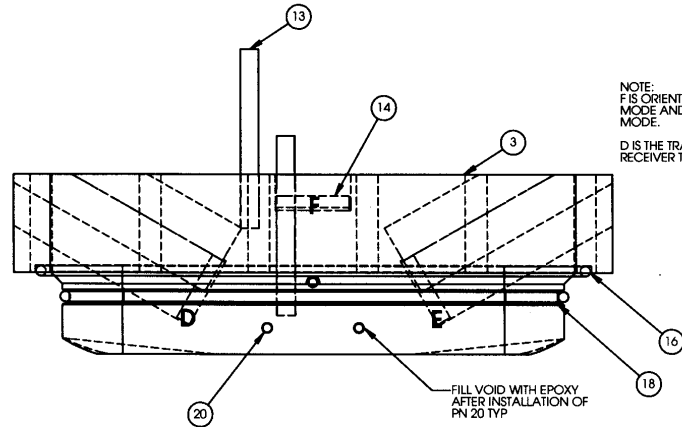
GENERAL NOTES
(UNLESS OTHERWISE SPECIFIED)

1. ALL MATERIALS SHALL BE AS SPECIFIED OR APPROVED EQUAL.
2. DIMENSIONING AND TOLERANCING ARE PER ANSI Y14.5M-82.
3. DIMENSIONS ARE IN INCHES.
4. TOLERANCES: DECIMALS: X = ±.1 , .XX = ±.01 , .XXX = ±.005
ANGLES: X = ±1° , X = ±.02°
5. ALL MACHINED SURFACES SHALL BE .64 MICROINCH OR BETTER IN ACCORDANCE WITH ANSI B46.1, 1978.
6. BREAK ALL SHARP EDGES AND REMOVE ALL BURRS.
7. ALL UNSPECIFIED MACHINE TOOL RADII SHALL BE .015" MAXIMUM.
8. MACHINE CUTOUPS AFTER WELDMENT IS COMPLETE.
9. PIPE SPOOL MODIFICATIONS SHALL MEET THE REQUIREMENTS FOR ASME B31.3, 1996 EDITION, AND "CATEGORY M FLUID SERVICE."
10. EXAMINATION PERSONNEL QUALIFICATIONS SHALL BE SPECIFIED BY ASME B31.3, PARAGRAPH 342.
11. PIPE SPOOL MODIFICATIONS SHALL BE EXAMINED AS SPECIFIED IN ASME B31.3 PARAGRAPH M340. EXTENT OF EXAMINATION SHALL BE PER PARAGRAPH M341.4 - VISUAL FOR ALL FABRICATION (M341.4(G)) AND IN PROCESS EXAMINATION FOR ALL WELDS (M341.4(D)(2)). THIS WILL INCLUDE LIQUID PENETRANT EXAMINATION PER PARAGRAPH 344.4 AND 341.3 OF THE FINAL PASS FOR EACH OF THE WELDS.

DRAWN MD RIPPILINGER	DATE 5/24/98	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE	
CHECKED		PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE	
DFTG-APVD		ULTRASONIC DENSIMETER ASSEMBLY	
ENGR JA BAMBERGER		2" PIPE TRANSDUCER ASSEMBLY	
APVD X		APPROVED FOR IMPLEMENTATION	
OTHER		PROJ TITLE C	REV NO 0
RR	MF	QA BY	DATE
ENGR BY	DATE	CHR BY	DATE
REV BY	DATE	DESCRIPTION	REV NO
DRAWING NO		DRAWING TITLE	
REFERENCE DRAWINGS			
CAD CODE		CAD FILE WS000598_001_00	
NEXT USED ON			

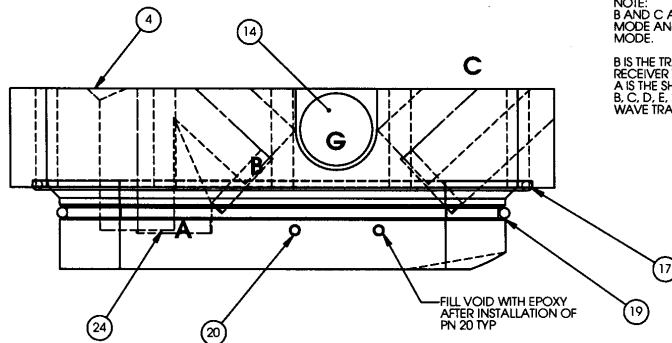
12.2

12.3



60° DETAIL

NOTE:
F IS ORIENTED IN PULSE-ECHO
MODE AND D AND E ARE IN PITCH-CATCH
MODE.
D IS THE TRANSMITTER AND E IS THE
RECEIVER TRANSDUCER



47° DETAIL

NOTE:
B AND C ARE ORIENTED IN PITCH-CATCH
MODE AND A AND G ARE IN PULSE-ECHO
MODE.
B IS THE TRANSMITTER AND C IS THE
RECEIVER TRANSDUCER
A IS THE SHEARWAVE TRANSDUCER
B, C, D, E, F, AND G ARE LONGITUDINAL
WAVE TRANSDUCERS

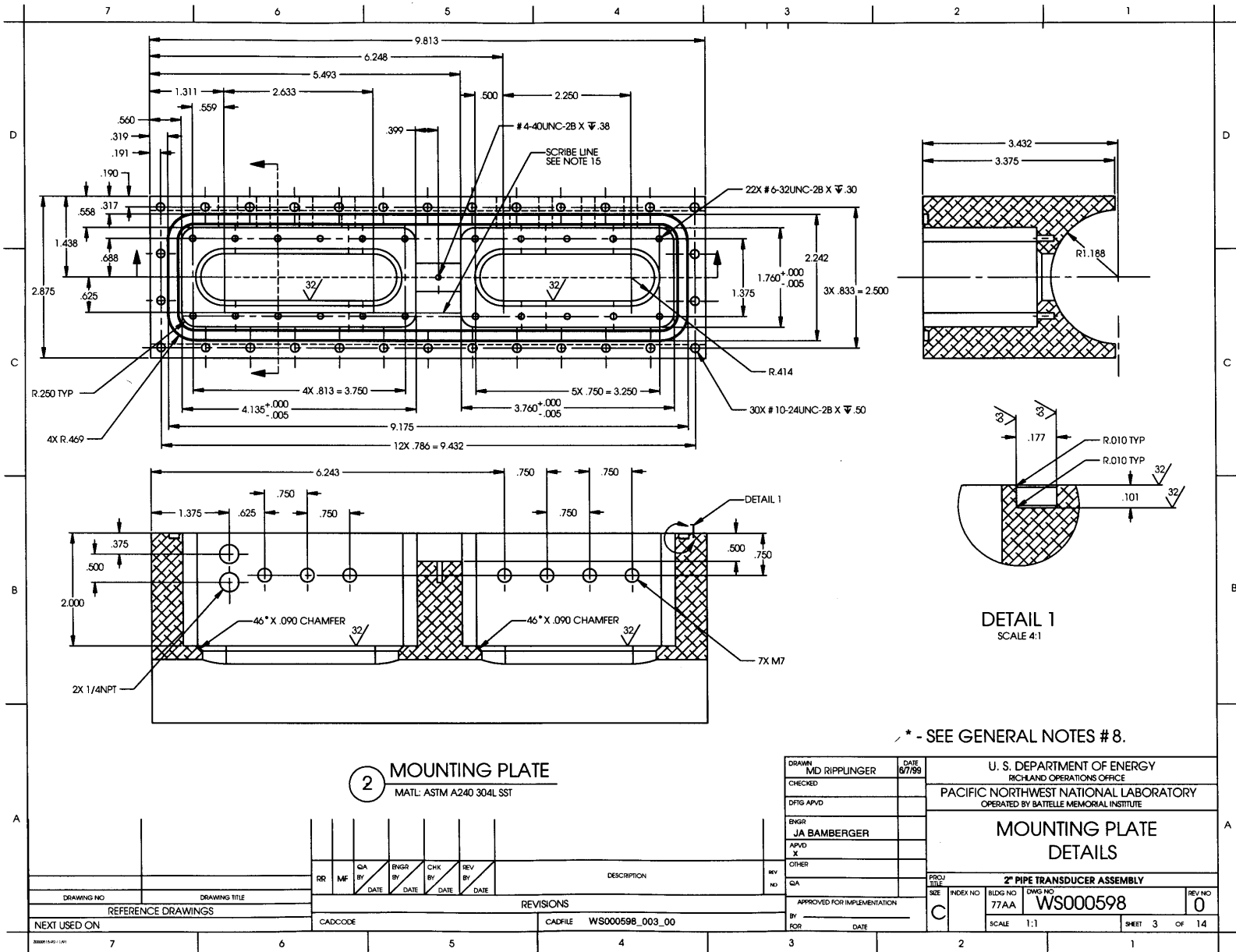
NOTE:
1. ATTACH TRANSDUCER USING ECHO45 EPOXY.
2. TUNE TRANSDUCERS TO REDUCE SIGNAL RING DOWN.
3. TRANSDUCER LEAD LENGTH: 6 INCH 30 GAUGE WIRE;
INSURE INSULATION DOES NOT CONTAIN TEFLON.

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	REFERENCE DRAWINGS								
NEXT USED ON		CADCODE		CADFILE: WS000598_002_00					

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CHECKED	
DFIG APVD	
ENGR JA BAMBERGER	
APVD K	
OTHER	
QA	
APPROVED FOR IMPLEMENTATION	
BY	DATE

U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE			
PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE			
ULTRASONIC DENSIMETER ASSEMBLY			
2" PIPE TRANSDUCER ASSEMBLY			
PROJ SITE C	BLDG NO 77AA	DWG NO WS000598	REV NO 0
SCALE NONE	SHEET 2 OF 14		

12.4

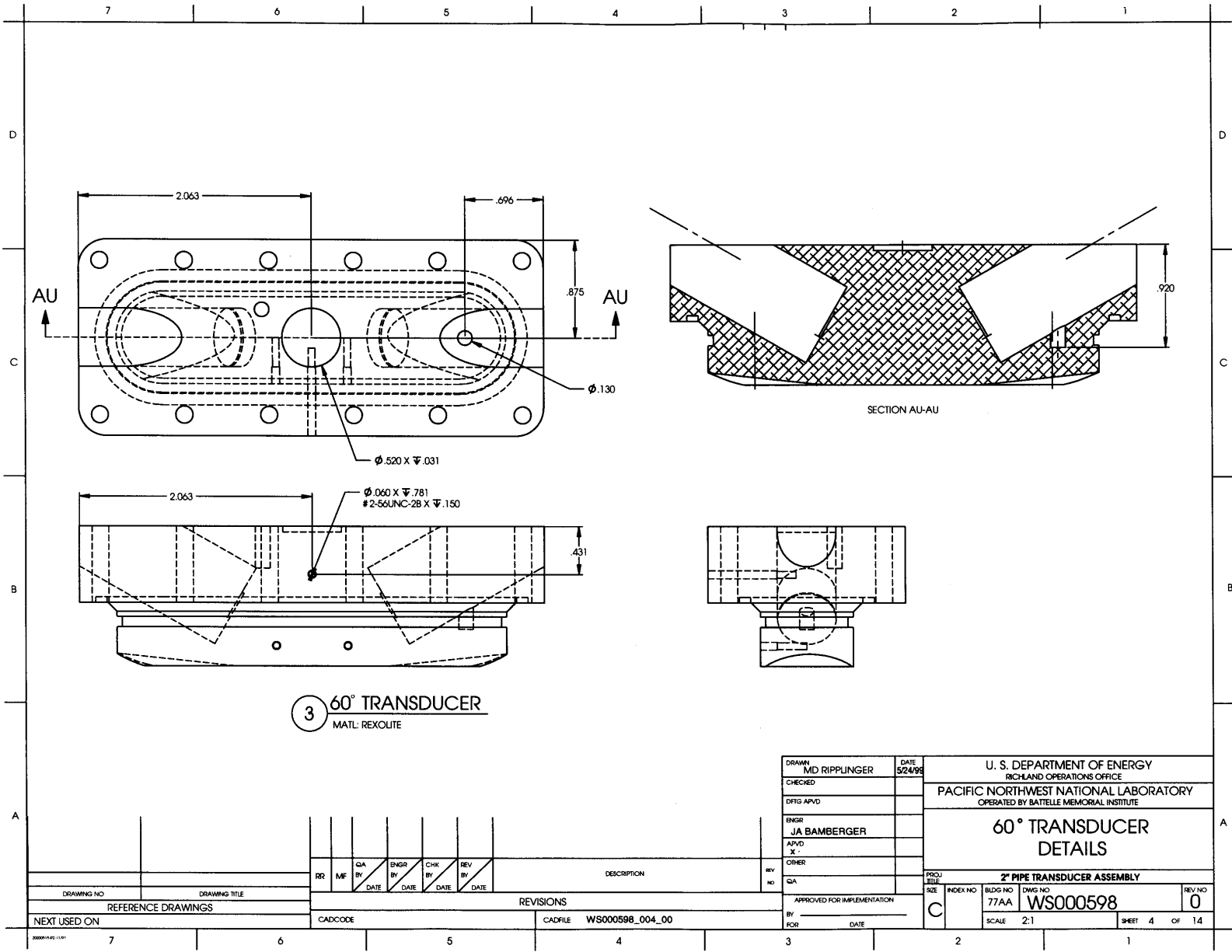


2 MOUNTING PLATE
 MATL: ASTM A240 304L SST

* - SEE GENERAL NOTES # 8.

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CHECKED				RICHLAND OPERATIONS OFFICE			
DFIG APVD				PACIFIC NORTHWEST NATIONAL LABORATORY			
				OPERATED BY BATTELLE MEMORIAL INSTITUTE			
ENGR JA BAMBERGER				MOUNTING PLATE			
APVD X							
OTHER							
				2" PIPE TRANSDUCER ASSEMBLY			
APPROVED FOR IMPLEMENTATION				PROJ 77AA	INDEX NO 77AA	DWG NO WS000598	REV NO 0
BY ROR		DATE		SCALE 1:1	SHEET 3 OF 14		

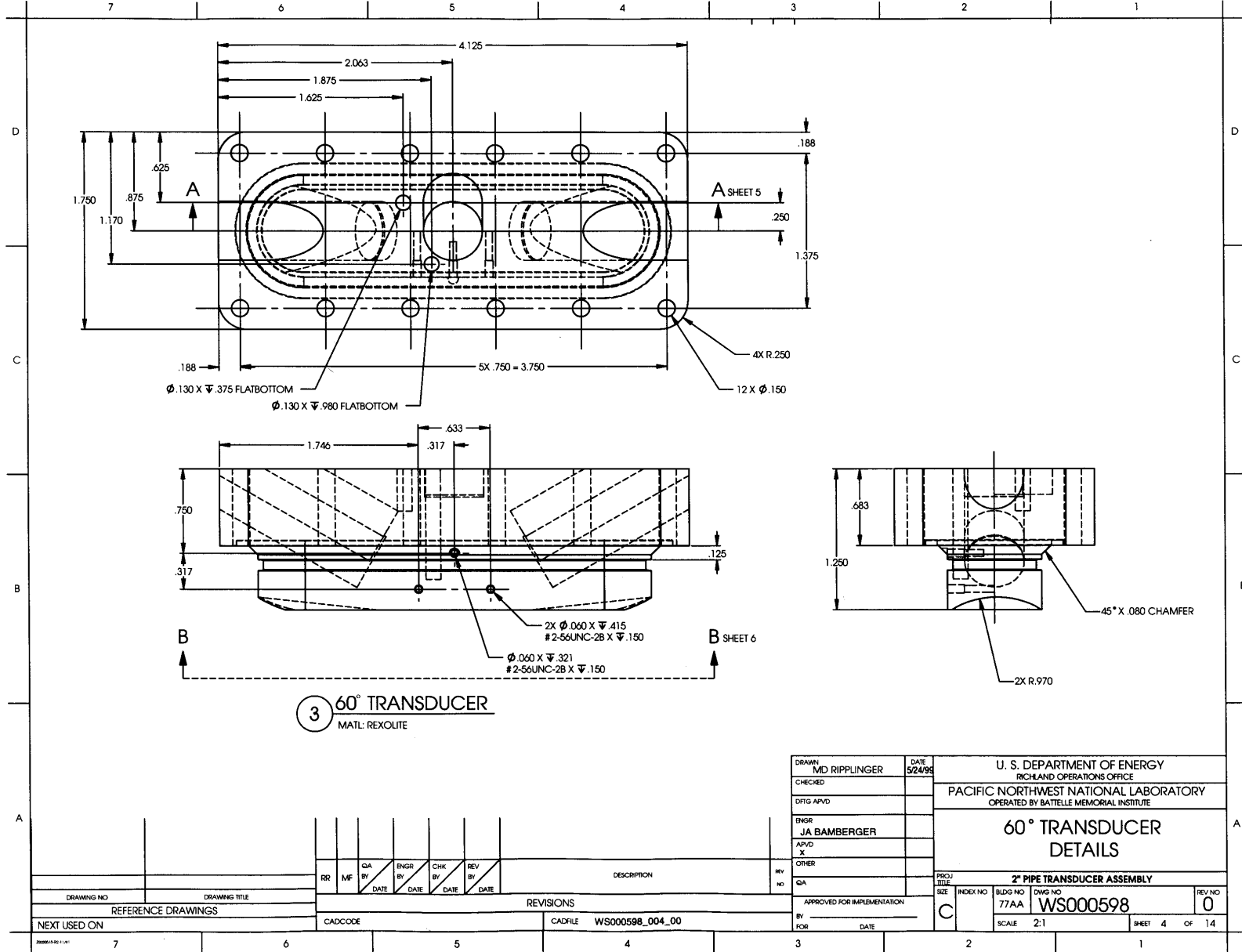


12.5

3 60° TRANSDUCER
MATL: REXOLITE

DRAWING NO.		DRAWING TITLE		RR	MF	QA BY	ENGR BY	CHK BY	REV BY	DESCRIPTION	RIV NO	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATELLE MEMORIAL INSTITUTE 60° TRANSDUCER DETAILS						
REVISIONS REFERENCE DRAWINGS NEXT USED ON												ENGR JA BAMBERGER APVD X OTHER QA	DATE 5/24/98	PROJ FILE 2" PIPE TRANSDUCER ASSEMBLY	INDEX NO 77AA	BLDG NO 77AA	DWG NO WS000598	REV NO 0
				CADCODE		CADFILE		WS000598_004_00				APPROVED FOR IMPLEMENTATION BY FOR	SCALE 2:1	SHEET 4 OF 14				

12.6

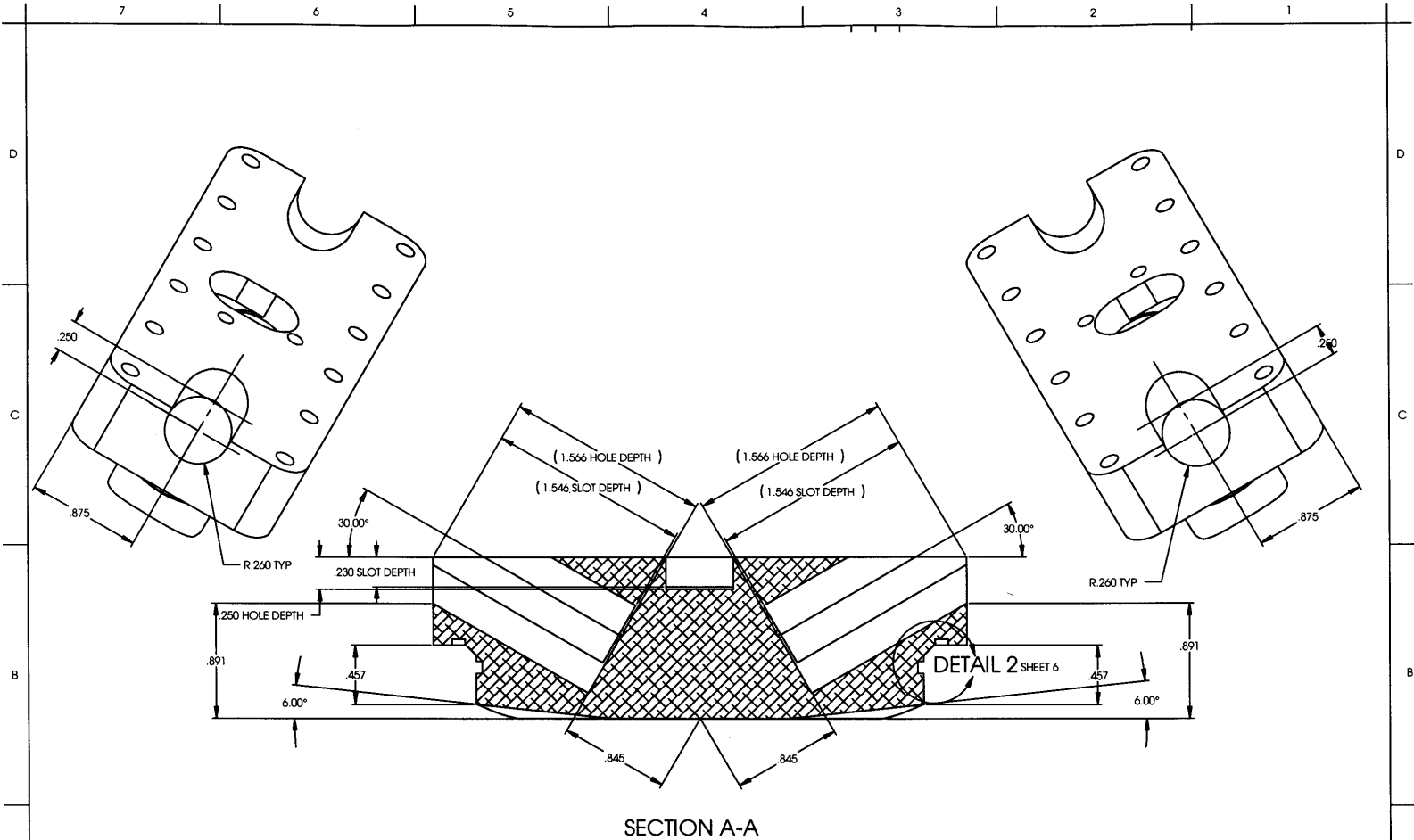


3 60° TRANSDUCER
MATERIAL: REXOLITE

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DATE	DATE	DATE	DATE	DATE	DATE		
REFERENCE DRAWINGS							
NEXT USED ON							
CADCODE				CADFILE WS000598_004_00			

DRAWN MD RIPPLINGER	DATE 5/24/95	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE	
CHECKED		PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE	
DTG-APVD		60° TRANSDUCER DETAILS	
ENGR JA BAMBERGER		2" PIPE TRANSDUCER ASSEMBLY	
APVD X		PROJ TITLE C	INDEX NO
OTHER		BLDG NO 77AA	DWG NO WS000598
QA		SCALE 2:1	REV NO 0
APPROVED FOR IMPLEMENTATION		SHEET 4 OF 14	
BY	DATE		

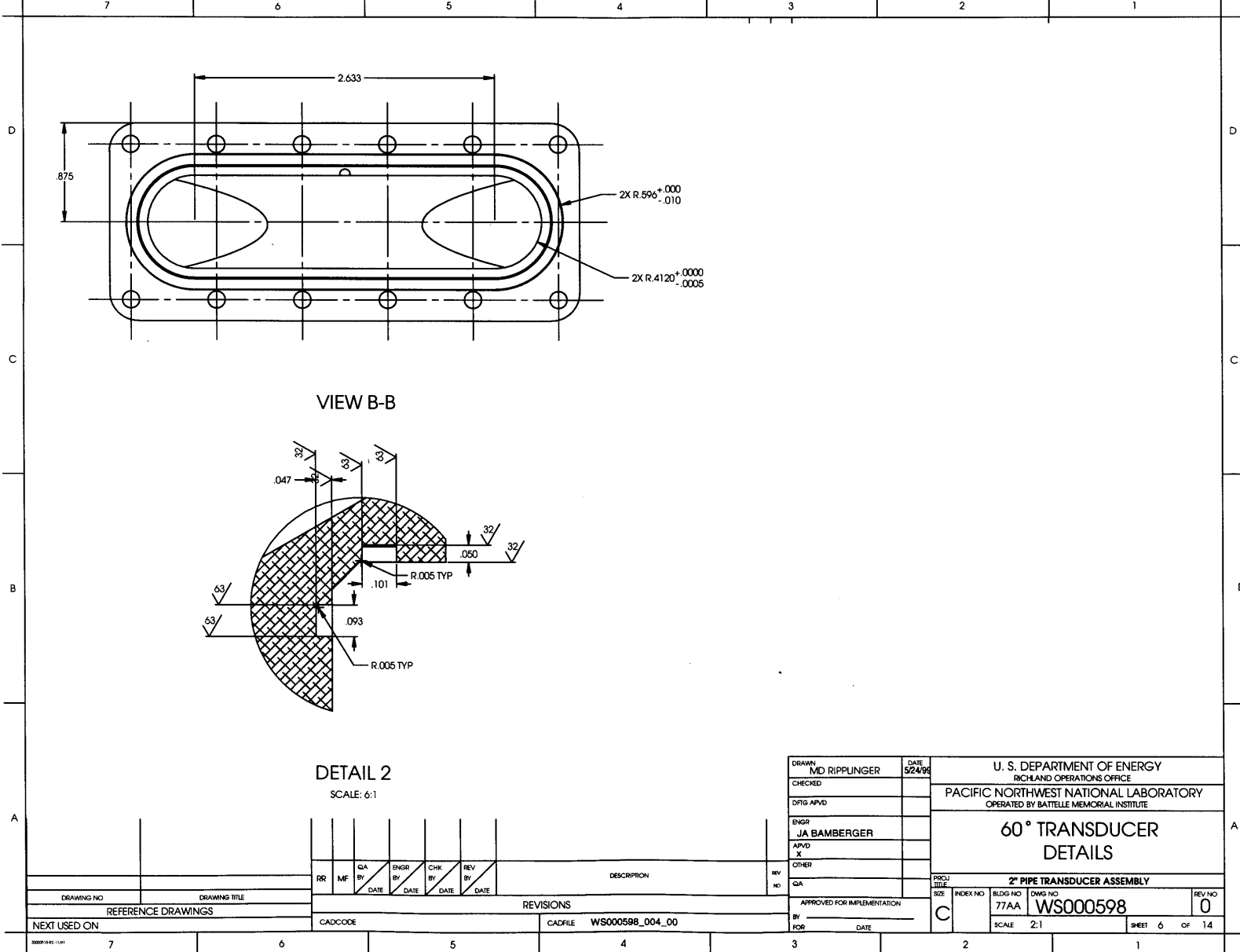
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SECTION A-A

DRAWN MD RIPPINGER CHECKED DFIG APVD ENGR JA BAMBERGER APVD X OTHER	DATE 8/1/99	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE 60° TRANSDUCER SECTION AND DETAILS
PROJECT TITLE 2" PIPE TRANSDUCER ASSEMBLY		BLDG NO 77AA DWS NO WS000598 REV NO 0
APPROVED FOR IMPLEMENTATION BY FOR DATE		SCALE 2:1 SHEET 5 OF 14

RR	MF	QA	ENGR	CHK	REV	DESCRIPTION	REV
BY	BY	BY	BY	BY	BY		NO
DATE	DATE	DATE	DATE	DATE	DATE		
REVISIONS							
DRAWING NO		DRAWING TITLE		CADCODE		CADFILE WS000598_004_00	
NEXT USED ON		REFERENCE DRAWINGS					



VIEW B-B

DETAIL 2

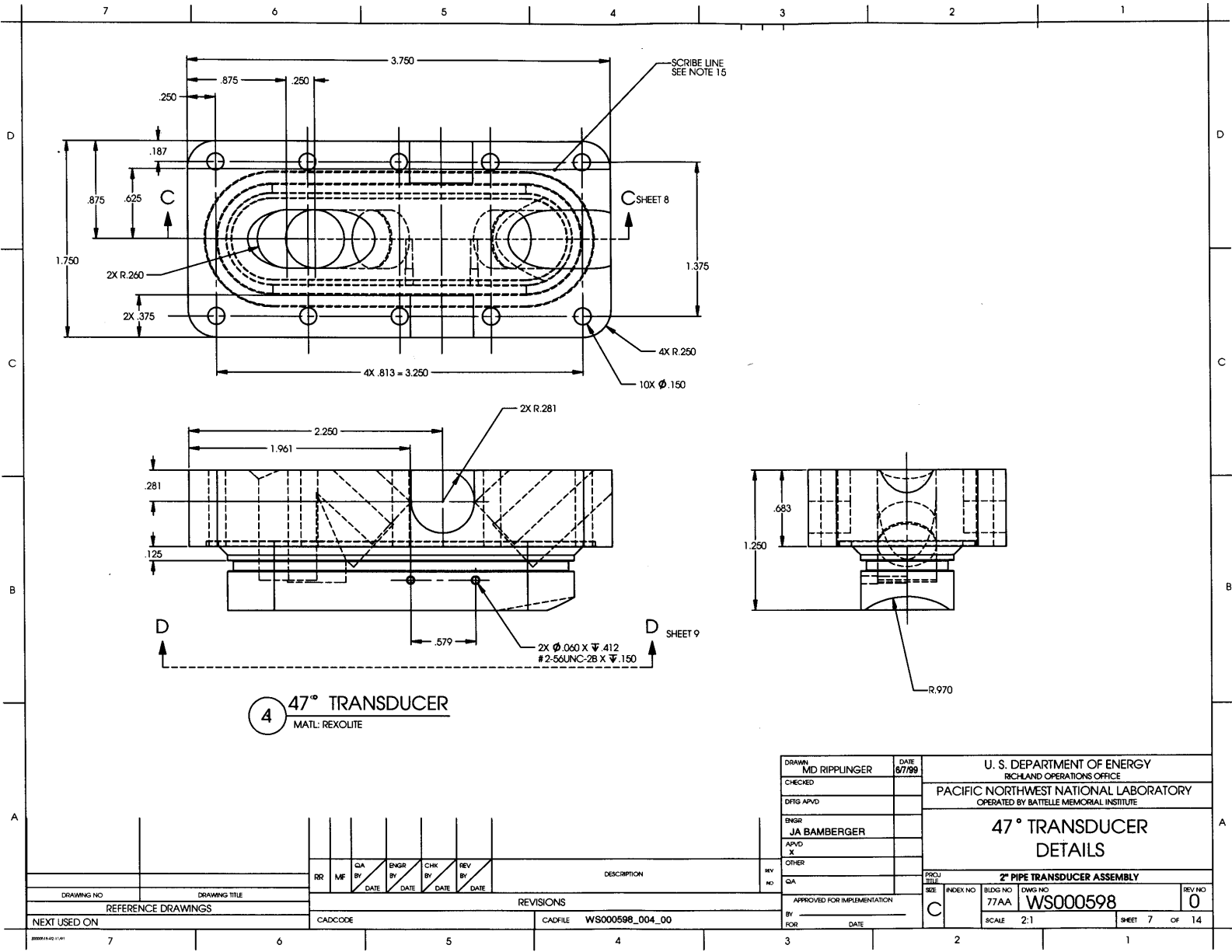
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CHECKED			PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE	
DTG: APVD			60° TRANSDUCER DETAILS	
ENGR JA BAMBERGER				
APVD X				
OTHER				
QA			2" PIPE TRANSDUCER ASSEMBLY	
APPROVED FOR IMPLEMENTATION			PROJ ID: C	
BY FOR		DATE	INDEX NO 77AA	BLDG NO WS000598
			DWG NO 0	REV NO
			SCALE 2:1	SHEET 6 OF 14

DRAWING NO	DRAWING TITLE	RR	MF	QA	ENGR	CHK	REV	DESCRIPTION	REV NO	
										BY
REVISIONS										
NEXT USED ON					CADCODE					CADFILE WS000598_004_00

12.8

12.9

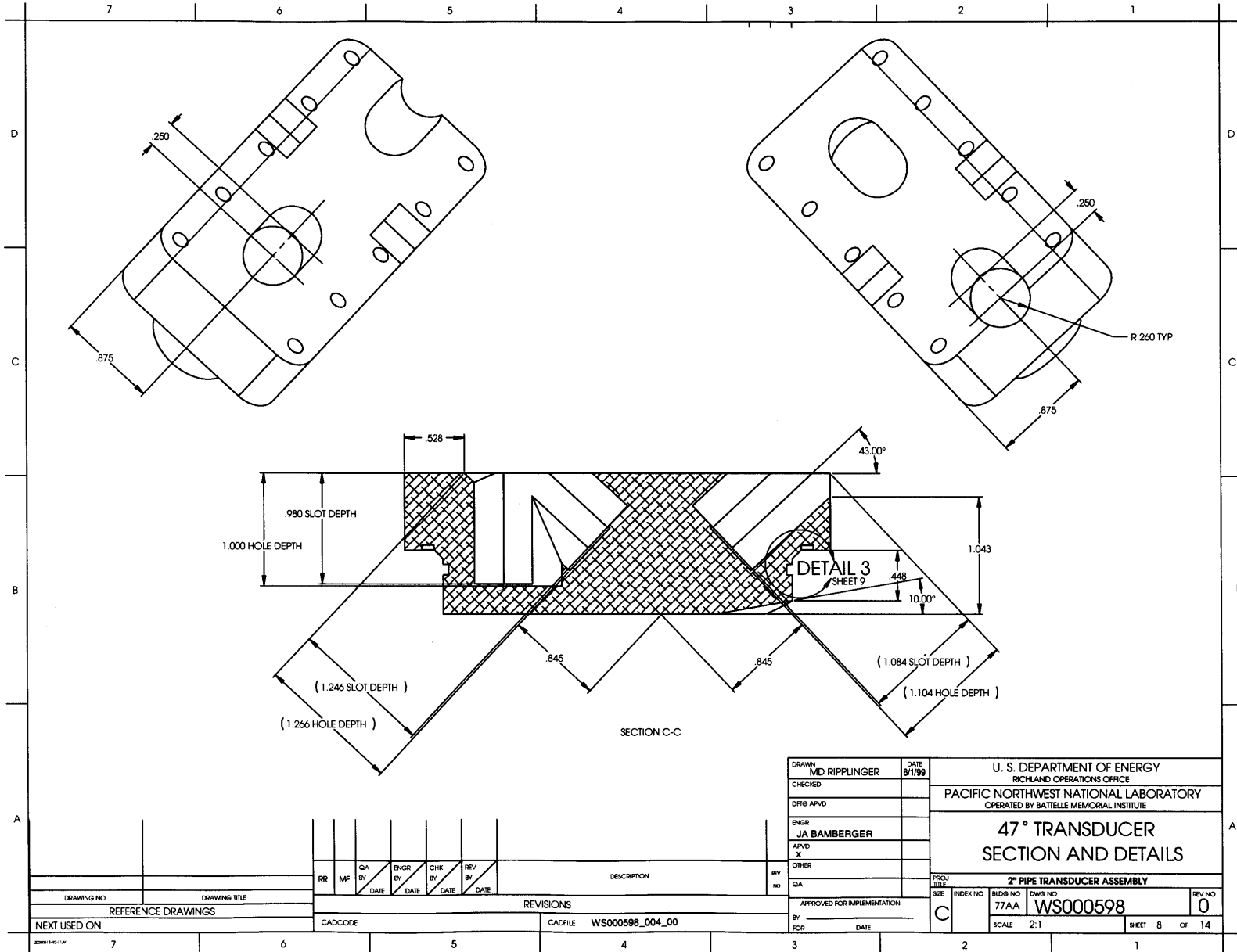


4 47° TRANSDUCER
MATL: REXOLITE

DRAWN MD RIPPINGER	DATE 6/7/99	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE	
CHECKED		PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE	
ENGR JA BAMBERGER		47° TRANSDUCER DETAILS	
APVD X		2" PIPE TRANSDUCER ASSEMBLY	
OTHER		PROJ C	REV NO 0
QA		INDEX NO 77AA	DWG NO WS000598
APPROVED FOR IMPLEMENTATION		SCALE 2:1	SHEET 7 OF 14
BY	DATE		

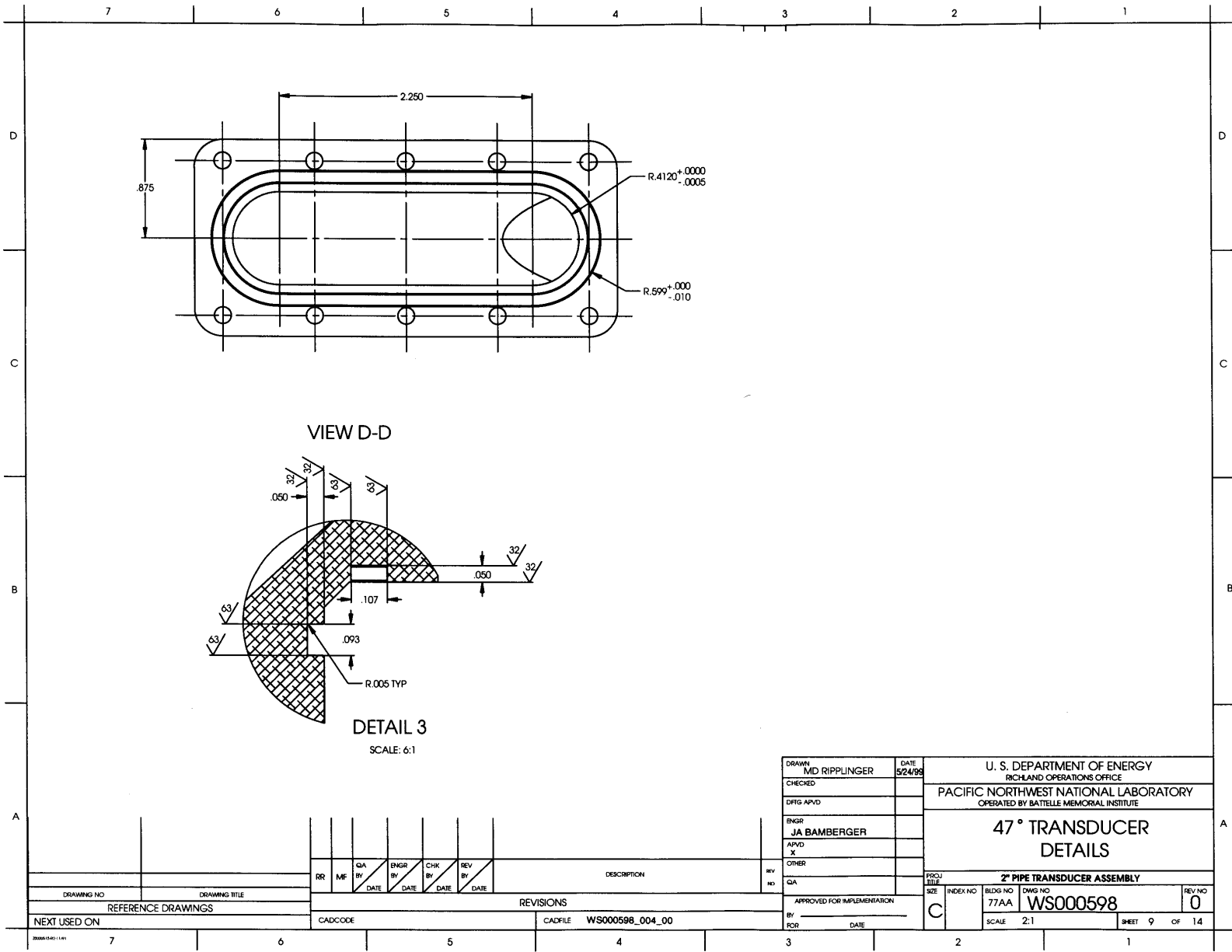
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NEXT USED ON							

12.10



RR	MF	QA BY	ENGR BY	CHK BY	REV BY	DATE	DATE	DATE	DATE	DESCRIPTION	REV NO
REVISIONS											
CADCODE											
CADFILE WS000598_004_00											
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DRAWING TITLE											
REFERENCE DRAWINGS											
NEXT USED ON											

DRAWN MD RIPPLINGER	DATE 8/1/99	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE	
CHECKED		PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE	
DTG APVD		47° TRANSDUCER SECTION AND DETAILS	
ENGR JA BAMBERGER		2" PIPE TRANSDUCER ASSEMBLY	
APVD X		PROJ TITLE	
OTHER		SIZE C	
QA		INDEX NO 77AA	REV NO 0
APPROVED FOR IMPLEMENTATION		BUILDG NO 77AA	DWG NO WS000598
BY	DATE	SCALE 2:1	SHEET 8 OF 14

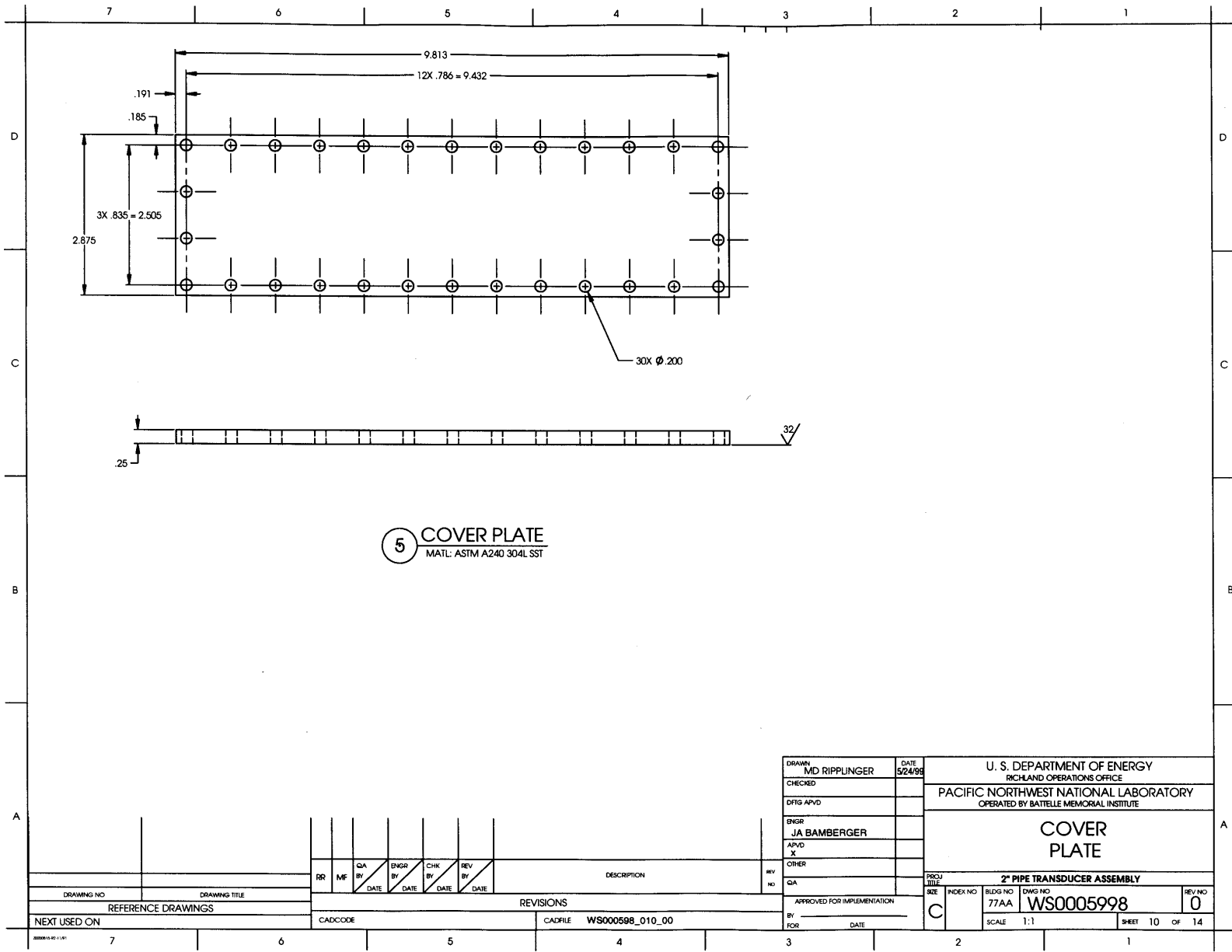


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ENGR JA BAMBERGER		47° TRANSDUCER DETAILS			
APVD X		2" PIPE TRANSDUCER ASSEMBLY			
OTHER		FIG./ TITLE	INDEX NO	BLDG NO	DWG NO
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BY FOR	DATE				REV NO 0

12.12

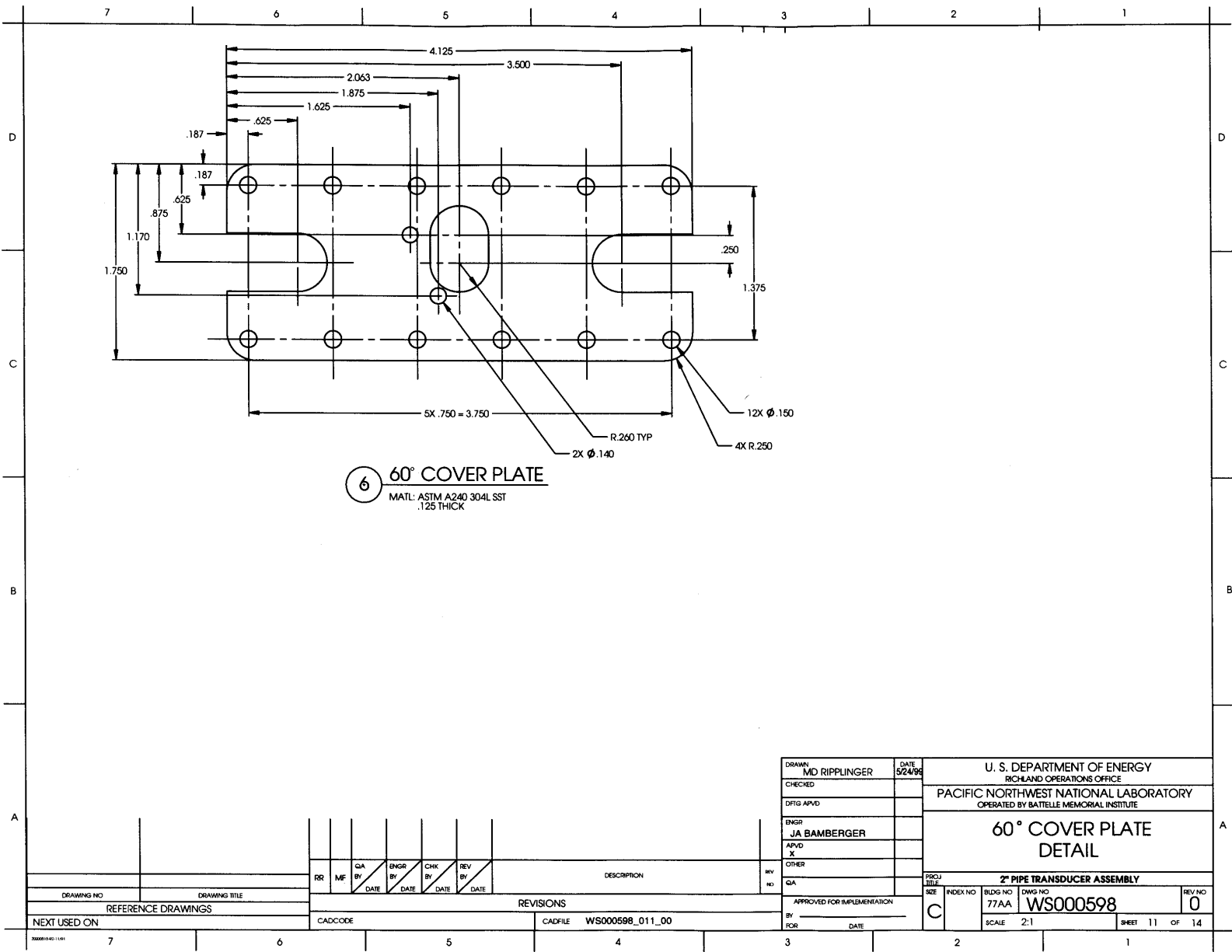


5 COVER PLATE
MATL: ASTM A240 304L SST

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DATE	DATE	DATE	DATE	DATE	DATE		
REVISIONS							
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CHECKED:								
DFIG APVD:				PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE				
ENGR: JA BAMBERGER				COVER PLATE				
APVD: X								
OTHER:								
APPROVED FOR IMPLEMENTATION				PROJECT TITLE: 2" PIPE TRANSDUCER ASSEMBLY				
BY: FOR:		DATE:		SIZE: C	INDEX NO: 77AA	BLDG NO: 77AA	DWG NO: WS0005998	REV NO: 0
				SCALE: 1:1		SHEET 10 OF 14		

12.13

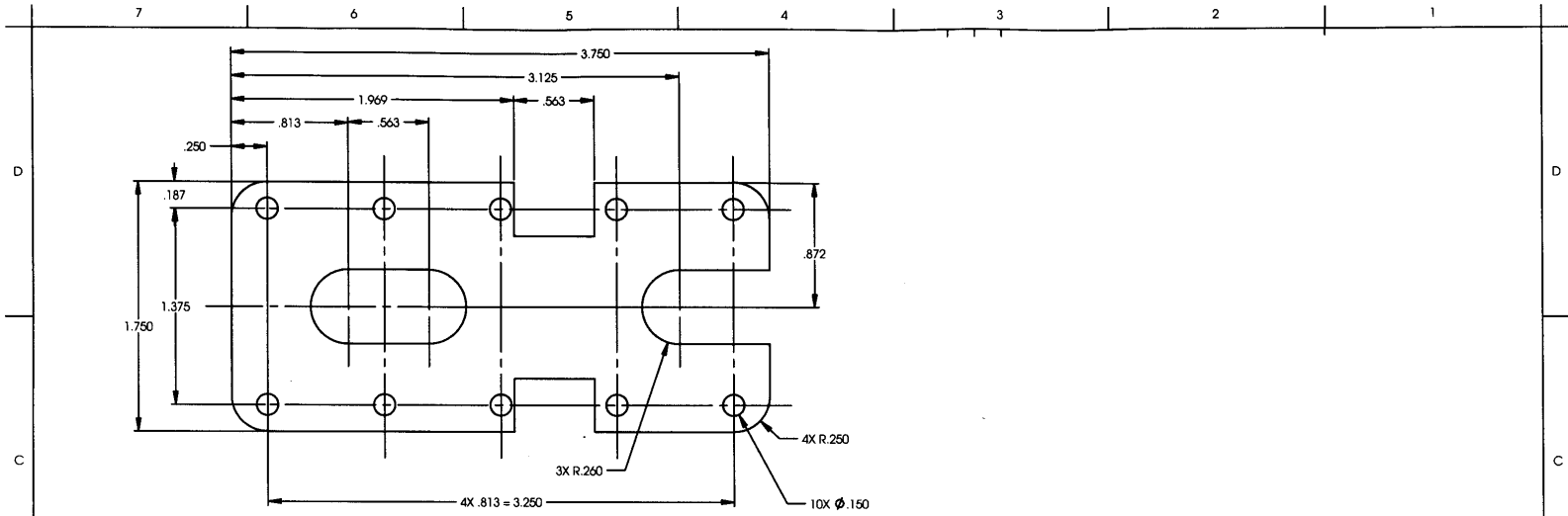


6 60° COVER PLATE
 MATL: ASTM A240 304L SST
 .125 THICK

RR	MF	QA BY	ENGR BY	CHK BY	REV BY	DESCRIPTION	REV NO
REVISIONS							
DRAWING NO		DRAWING TITLE		CADCODE		CADFILE WS000598_011_00	
NEXT USED ON							

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CHECKED		PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTELLE MEMORIAL INSTITUTE	
ENGR JA BAMBERGER		60° COVER PLATE DETAIL	
APVD X			
OTHER			
QA		2" PIPE TRANSDUCER ASSEMBLY	
APPROVED FOR IMPLEMENTATION		INDEX NO 77AA	BLDG NO 77AA
BY	DATE	DWG NO WS000598	REV NO 0
		SCALE 2:1	SHEET 11 OF 14

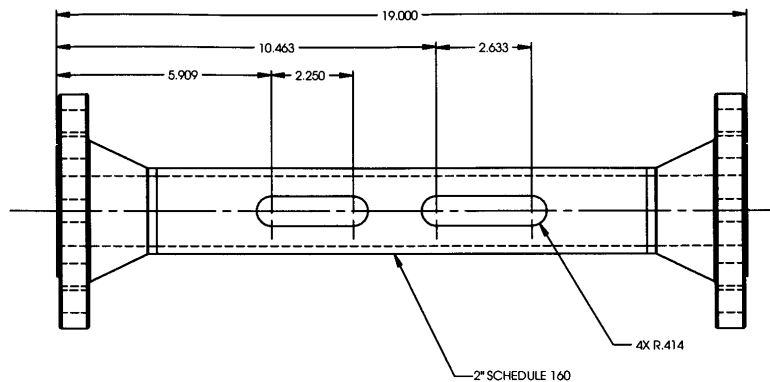
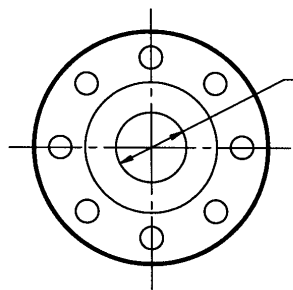
12.14



7 47° COVER PLATE
 MATL: ASTM A240 304L SST
 .125 THICK

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NEXT USED ON		REFERENCE DRAWINGS										2" PIPE TRANSDUCER ASSEMBLY 77AA WS000598 SCALE 2:1 SHEET 12 OF 14			
CADCODE		CADFILE		ENGR BY		CHK BY		REV BY		DATE		APPROVED FOR IMPLEMENTATION BY: FOR: DATE:			
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12.15

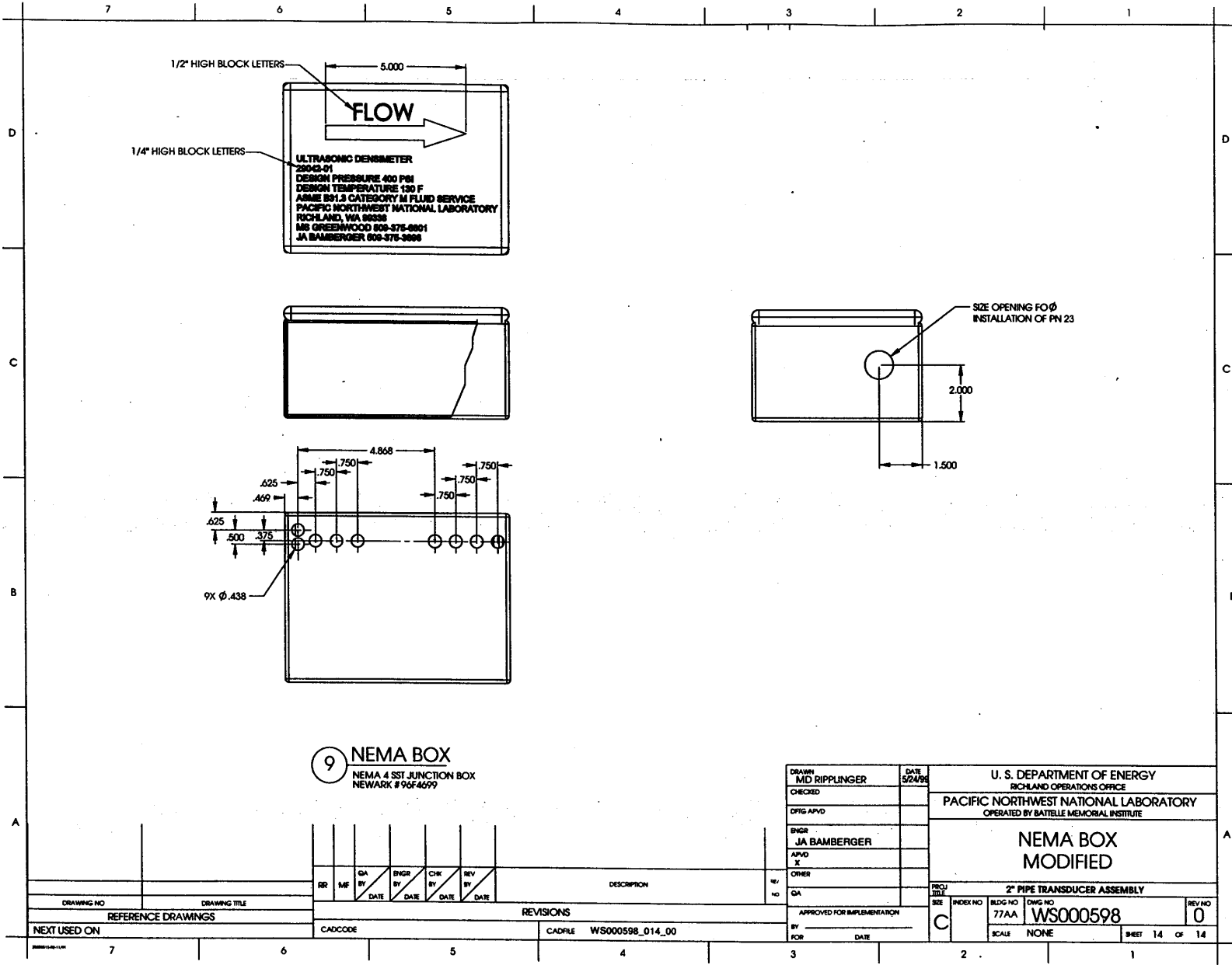


8 PIPE
MATL: ASTM A 312 GR TP 304L SST

* - SEE GENERAL NOTES # 8.

DRAWING NO.		DRAWING TITLE		RR	MF	QA	ENGR	CHK	REV	RY	NO	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATTTELLE MEMORIAL INSTITUTE							
NEXT USED ON		REFERENCE DRAWINGS		DATE	BY	DATE	BY	DATE	BY	DATE	DATE	PIPE DETAIL							
CADCODE		CADFILE		REVISIONS				2" PIPE TRANSDUCER ASSEMBLY				PRCJ	SIZE	INDEX NO	BLDG NO	DWG NO	REV NO		
		WS000598_013_00						APPROVED FOR IMPLEMENTATION BY: _____ FOR: _____ DATE: _____				C		77AA	WS000598	0			
														SCALE	1:2	SHEET	13	OF	14

12.16



9 NEMA BOX
NEMA 4 SST JUNCTION BOX
NEWARK # 90F4699

DRAWN MD RIPPPLINGER CHECKED DFIG APVD ENGR JA BAMBERGER APVD X OTHER	DATE 5/24/98	U. S. DEPARTMENT OF ENERGY RICHLAND OPERATIONS OFFICE PACIFIC NORTHWEST NATIONAL LABORATORY OPERATED BY BATELLE MEMORIAL INSTITUTE NEMA BOX MODIFIED
APPROVED FOR IMPLEMENTATION BY FOR DATE	PROJ/ TITLE 2" PIPE TRANSDUCER ASSEMBLY SIZE C INDEX NO 77AA BLDG NO 77AA DWG NO WS000598 SCALE NONE	REV NO 0 SHEET 14 OF 14

REV NO	DATE	BY	CHK BY	ENGR BY	QA BY	DESCRIPTION

DRAWING NO REFERENCE DRAWINGS	DRAWING TITLE CADCODE	CADFILE WS000598_014_00
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