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Qualification of Three On-line Slurry Monitoring Devices for Application during Waste-Retrieval Operations at DOE Sites

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Summary

Millions of gallons of radioactive liquid and sludge wastes must be retrieved from underground storage tanks at the U.S. Department of Energy sites to be staged and transferred to treatment facilities and processed into final waste forms. Retrieval operations involve mixing solid and liquid wastes to create slurries that can be transported via underground pipelines to specified locations 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.

Technologies Evaluated

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 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, process monitoring, including measuring the slurry density and particle size distribution and measuring the pressure drop in the transfer lines, represents several significant on-line, real-time methods for measuring the quantity of waste transferred and monitoring for process control and early detection/prevention of pipeline plugging.

To reduce the likelihood of pipeline blockage during waste-transfer operations, the Accelerated Site Technology Deployment (ASTD) project, with funding from Project W-320 (Waste-Retrieval Sluicing System) and Hanford Tanks Initiative (HTI), evaluated three on-line slurry-monitoring devices for use at the Hanford and Oak Ridge National Laboratory (ORNL) sites and for potential use at other U.S. Department of Energy (DOE) sites. These instruments include: (1) the Lasentec M600 Particle Size Analyzer[a] developed by Laser Sensor Technology, Inc., Redmond, Washington, (2) the Red Valve Pressure Sensor manufactured by Red Valve Company, Inc., Pittsburgh, Pennsylvania, and (3) an ultrasonic densimeter developed at the Pacific Northwest National Laboratory (PNNL).[b]

These 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:

(a) The Lasentec M600 is an in-line analyzer for measuring chord-length distribution of suspended solid particles. Chord length and particle size are not exactly equivalent terms, but there is a direct correlation between the two. For the purposes of the testing performed, the Lasentec M600 was used to evaluate the particle size distribution of the suspended solid particles in the slurries. As such, the instrument will be referred to as a particle size analyzer elsewhere in this report.

(b) The Ultrasonic Densimeter development was also cofunded by the U.S. DOE EM-50 and the Hanford Site SY-101 Surface Level Rise Remediation Project.

- early detection and prevention of pipeline plugging events
- real-time process data of the particle size distribution, density, and pressure drop during the transfer process
- reduction or elimination of grab sampling and off-line analysis
- reduced radiation exposure for workers.

Criteria for Evaluation

Several criteria were used for assessing the various slurry-monitoring instruments for application at Hanford, Oak Ridge, and other DOE sites: (1) maturity of the technology, (2) ease of adaptability, (3) reliability, and (4) cost.

Two of the instruments, the Lasentec Particle Size Analyzer and the Red Valve Pressure Sensor, were off-the-shelf instruments that required no further development and were evaluated as received from the manufacturers. The densimeter, on the other hand, is a relatively new instrument and was developed at PNNL based on the need to provide a small, robust instrument that can be retrofitted into existing pump pit manifolds and transfer lines.

Technology Summary

Lasentec Particle Size Analyzer

The Lasentec M600 in-line particle size analyzer was installed at ORNL in August 1998 to support retrieval of waste from the Gunite and Associated Tanks (GAAT). Before installation at ORNL, the sensor underwent validation testing at the PNNL Instrument Validation Facility (IVF). Mechanically, the instrument worked well during validation testing and met all expectations. Operationally, much was learned about optimum ways to display and interpret the data. Slurry samples taken during the in-line tests at PNNL were shipped to the vendor for analysis with a bench-top Lasentec sensor. These experiments were performed to determine if off-line analyses yield particle size distributions similar to those generated by the in-line sensor. It was determined that the Lasentec sensor measures repeatable chord lengths as long as particles are "presented" to the sensor window the same way. After the initial non-radioactive simulant testing at PNNL, the instrument was shipped for radioactive validation and qualification testing in the Slurry Monitoring Test System connected to Tank W-9 of the GAATs at ORNL. For all qualification tests conducted at ORNL, the variation in the chord-length distribution and the total particle count corresponded very well with the slurry density data as determined using an in-line Promass 63M Coriolis meter. Based on the performance results obtained, the Lasentec M600 focused beam reflectance measurement (FBRM) is expected to meet the requirements for measuring the particle size distribution during the slurry-transfer operations at Hanford and Oak Ridge GAAT remediation project and can also be deployed at other DOE sites.

Red Valve Pressure Sensor

The Red Valve Pressure Sensor was qualified for use at the Hanford Site following instrument validation tests at PNNL's IVF and was used during the retrieval of the sludge from Tank 241-C-106. While this instrument measures pressure within a transfer line, this type of pressure sensor could be configured to measure pressure drop over time. In turn, the onset of plugging of a slurry transfer could be inferred from the pressure-drop measurement.

In 1998, four Red Valve Pressure Sensors (with Sensotech Model AE-213 pressure transducers) were installed before and after the booster pumps of the 4-in. slurry (SL-200) and supernatant (SN-200) transfer lines between Tank 241-C-106 and Tank 241-AY-102. These pressure sensors have been operated for over 1 year and have been trouble-free according to the operators involved with slurry and supernatant transfer operations. Based on these observations, it is apparent that the Red Valve Pressure Sensors can be installed at the end of the slurry transfer lines and used to measure the pressure drop in the system. Also, if the pressure drop is coupled with a volumetric flow rate measurement device and integrated over time, it can provide useful information regarding the mass of slurry transferred.

Ultrasonic Densimeter

The U.S. Department of Energy Environmental and Waste Management (EM) 50, through the Characterization, Monitoring, and Sensor Technology Crosscutting Program, initially funded densimeter development for slurry-transfer pipeline deployment. In 1997, the initial densimeter configuration was installed in a pipe spool piece and evaluated during tests at ORNL.

Also in 1997, the densimeter was included as a part of the Slurry Monitoring Technology Deployment Initiative 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 for monitoring slurry properties during waste transfer from Tank 241-C-106 to Tank 241-AY-102. In late 1998, the Hanford Site priorities changed, and the date for deployment and probe evaluation in the Tank 241-C-106 transfer line became uncertain. Negotiations between the U.S. Department of Energy Office of Science and Technology Tanks Focus Area and the Hanford Site Office of River Protection 241-SY-101 Surface Level Rise Remediation Project led to development of a Memorandum of Understanding to deploy the densimeter to demonstrate the measurement of density during waste transfers from Tank 241-SY-101 to Tank 241-SY-102. Preparations for this deployment are continuing, and the densimeter is to be incorporated into the prefabricated pump pit module that will be installed at the Hanford Site in FY 2001. This deployment will also be used to monitor transfers from Tank 241-SY-101 for cross-site transfers.

To support deployment, the densimeter performance was evaluated during pipeline tests conducted at PNNL's IVF. During these tests, conducted with liquids and slurries, the densimeter tracked changes in density but not absolute density. Further investigation showed that input variations in the pulser voltage were the cause of this offset. During the instrument calibration, the pulser voltage was set, and calibration measurements were made. However, during the testing at PNNL's IVF, the pulser voltage changed, and this change was not reflected in the software developed to compute the slurry density. A procedure to take into account input voltage was developed by monitoring and adjusting the pulser voltage to reflect the correct setting for which the calibration data were made. Using the modified setup, the densimeter was found to predict the absolute density to within ±2%. Currently, the densimeter has been installed in the SY-101 prefabricated pump pit modified process manifold. Before installation of this process manifold at the Hanford site, the performance operation of the manifold and its components are being evaluated in the Fluor Hanford Engineering Laboratory in the 305 building.

Acronyms

AGTS	Aboveground Transport System
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTD	Accelerated Site Technology Deployment
ASTM	American Society of Testing and Materials
CHG	CH2M Hill Hanford Group, Inc.
CMST	Characterization, Monitoring, and Sensor Technology
DOE	U.S. Department of Energy
DST	Double Shell Tank
EM	Environmental and Waste Management (U.S. Department of Energy)
FBRM	Focused Beam Reflectance Measurement
FDH	Fluor Daniel Hanford
GAAT	Gunite and Associated Tanks
HTI	Hanford Tanks Initiative
IVF	Instrument Validation Facility
ITSR	Innovative Technology Survey Report
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SMTS	Slurry Monitoring Test System
SST	Single Shell Tank
TDI	Technology Deployment Initiative
UGTS	Underground Transport System

Acknowledgments

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The U.S. Department of Energy Office of Science and Technology Tanks Focus Area and the Hanford 241-SY-101 Surface Level Rise Remediation Project have also collaboratively supported densimeter development and deployment. This work was conducted in conjunction with Tanks Focus Area Technology Integration Manager Tom Thomas from Idaho National Engineering and Environmental Laboratory and Characterization, Monitoring, and Sensor Technology Crosscutting Program manager Glenn Bastiaans from the U.S. Department of Energy Ames Laboratory.

Carl Hanson, Cogema, Roger Bauer, CH2M Hill Hanford Group, Inc., and project manager Joe Brothers from Pacific Northwest National Laboratory have provided SY-101 project support. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RL0 1830.

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1.0 Introduction

1.1 Historical Background

The U. S. Department of Energy (DOE) is responsible for eventual disposal of millions of gallons of radioactive liquid and sludge wastes that are stored in the underground storage tanks at Hanford and other DOE sites (Table 1.1).

Table 1.1. Details of the Highly Hazardous Radioactive Waste Stored At the DOE Sites (DOE 1996)

	Hanford	Savannah River	Idaho	West Valley
Total Tanks	177	51	11	4
Total Waste Volume (10^6 Gallons)	54	34	3	0.5[a]
Total Radioactivity (10^6 Curies)	190	493	48	22
Total Curies in Capsules (10^6 Curies)	143	0	0	0

(a) Most of West Valley's waste has now been vitrified.

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.

There are several methods to transport the high/low-level radioactive wastes, including Underground Transport System (UGTS), Aboveground Transport System (AGTS), and the Rail Tanker Car Transport System. Of these, the UGTS, despite its high initial capital investment, represents the lowest overall cost and minimum radiation exposure to operating personnel (Vo and Epperson 1995). Despite the advantages of the UGTS, the possibility of pipeline plugging remains a significant issue regarding timely delivery of the feed to meet DOE remediation milestones. Also, 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.

Plugging of underground slurry transfer pipelines is not uncommon. Cross-site transfer lines between the 200 East and 200 West Areas of the Hanford Site have existed for about 40 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. Four of the six transfer lines that have been built are permanently plugged.

At Hanford, the tank waste must be staged to provide the right 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 (Project W-523). This waste must be resuspended and mixed

(Project W-521) and then transferred cross-site (Project W-058) to either the AM or AP farm. The waste may then again be resuspended and mixed (Project W-211) and transferred to the AY farm before it is eventually sent to the vitrification facility (Project W-521). The numerous transfers before the waste is finally sent to the vitrification plant increase the probability that a pipeline will plug.

Three main factors contribute to transfer-line plugging: (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 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 Project Background

To reduce the likelihood of pipeline blockage during waste-transfer operations, the Accelerated Site Technology Deployment (ASTD) project,[a] with funding from Project W-320 (Waste-Retrieval Sluicing System) and Hanford Tanks Initiative (HTI), evaluated three on-line slurry monitoring devices for use at the Hanford and Oak Ridge National Laboratory (ORNL) sites: (1) the Lasentec M600 Particle Size Analyzer developed by Laser Sensor Technology, Inc., Redmond, Washington,[b] (2) the Red Valve Pressure Sensor manufactured by Red Valve Company, Inc., Pittsburgh, Pennsylvania, and (3) an ultrasonic densimeter developed at Pacific Northwest National Laboratory (PNNL).[c]

These 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.

(a) Further information about the Slurry Monitoring ASTD project can be found in the *Slurry Monitoring TDI Deployment Plan*, Fluor Daniel Hanford Company, Richland, Washington (1997) and the report entitled *Slurry Monitoring ASTD Project Supplemental Information*, Fluor Daniel Hanford Company, Richland, Washington (1998).

(b) The Lasentec M600 is an in-line analyzer for measuring chord-length distribution of suspended solid particles. Chord length and particle size are not exactly equivalent terms, but there is a direct correlation between the two. For the purposes of the testing performed, the Lasentec M600 was used to evaluate the particle size distribution of the suspended solid particles in the slurries. As such, the instrument will be referred to as a particle size analyzer elsewhere in this report.

(c) The densimeter development work was co-funded by the US DOE EM-30 and the Hanford SY-101 Surface Level Rise Remediation Project

There are three phases of instrument evaluation: (1) qualification, (2) implementation, and (3) deployment. Instruments are procured and/or fabricated, calibrated, and installed in their target system during the qualification phase. For the densimeter, which is not commercially available, this phase also included instrument and analytical method development as well as engineering. At the end of the qualification phase, the instruments undergo acceptance testing and are made available to operations. Instrument performance is documented and shared with all complex-wide slurry-transfer projects during the deployment phase. In the final implementation phase, the slurry monitors are intended to monitor waste slurries during tank waste-retrieval operations.

The HTI was the original customer for the slurry monitoring technology. The HTI planned to remove a hard heel from SST 241-C-106 with a vehicular deployed retrieval system and transfer the waste to DST 241-AY-102. Due to Hanford budget constraints, HTI was delayed. Some portions of HTI have been picked up by Project W-523 that will retrieve SST 241-C-104 and transfer the waste to 241-AY-101. The slurry-monitoring technology from this study may be deployed on W-523. Project W-320, sluicing of 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 Gunite and Associated Tanks (GAAT). The Hanford SY-101 Surface Level Rise Remediation Project will demonstrate the densimeter, and the results will be published after the completion of the demonstration tests.

1.3 Scope

This report documents the qualification of the three on-line slurry-monitoring devices for application during the waste-retrieval operations at DOE sites. A technical summary of the qualification tests, along with recommendations, is presented in Section 2.0. Testing approaches and results of the qualification tests for the Lasentec Particle Size Analyzer, the Red Valve Pressure Sensor, and the ultrasonic densimeter are presented in Sections, 3.0, 4.0, and 5.0, respectively. The technical details of these instruments are presented in the appendices.

2.0 Conclusions and Recommendations

This section summarizes the technical achievements of the Lasentec Particle Size Analyzer, Red Valve Pressure Sensor, and the ultrasonic densimeter based on validation and qualification test results and offers recommendations for using these instruments for process monitoring and liquid/slurry characterization.

2.1 Lasentec Particle Size Analyzer

The Lasentec M600 in-line particle size analyzer was installed at ORNL in August 1998 to support sludge retrieval from the GAATs. Before installation at ORNL, the sensor underwent validation testing with waste slurry simulants (non-radioactive, non-hazardous analogs of nuclear tank waste). These tests were performed at the PNNL Instrument Validation Facility (IVF). Eight simulants were chosen to test the Lasentec: four different silica/kaolin weight ratios at two total solids concentrations, 5-wt% and 10-wt% solids. Kaolin particles were around 1 μm in size, whereas the silica particles were around 100 to 1000 μm in size. The full range of the Lasentec sensor (0.8 to 1000 μm) was validated by using silica and kaolin.

Mechanically, the instrument worked well during validation testing and met all expectations. Operationally, much was learned about optimum ways to display and interpret the data. Scan time, the amount of time that particles are measured and counted by the Lasentec sensor, was found to be important. If the scan time is less than 1 min, the data, particularly for larger particles, were too noisy and inconsistent to be of much use. At 1 min or greater scan times, noise in the data was dramatically reduced. The Lasentec calculated several statistical particle size averages by manipulating collected data: unweighted or number average, length-weighted average, length-squared weighted average, and length-cubed weighted average particle size. Only the length-cubed weighted particle size average showed any significant variation during the eight test cases. The other average values calculated by the Lasentec software remained fairly constant, despite changes in the silica/kaolin weight ratio. This result was unexpected because an increase in the amount of silica, i.e., large particles, should increase the average particle size. Even though only one statistic appears to be particularly relevant when tracking process changes, the histograms can be very valuable. For example, a sieve analysis on the silica added to the pipe loop was almost perfectly matched by the Lasentec sensor.

Slurry samples taken during the in-line tests at PNNL were shipped to the vendor for analysis with a bench-top Lasentec sensor. These experiments were performed to determine if off-line analyses yield particle size distributions similar to those generated by the in-line sensor. Although the in-line Lasentec data did not match those produced by the bench-top model, several different bench-top units and in-line units (operating in a static mode) measured the same chord-length weighted histograms for the same sample. These results suggest that the Lasentec sensor measures repeatable chord lengths as long as particles are "presented" to the sensor window the same way. The laboratory and in-line measured length-weighted mean particle sizes did not match. This may have been caused by potential deficiencies in mixing the samples during the bench-top tests (e.g., the fast-settling silica particles are difficult to keep homogeneous in the sample bottle) and sampling slurries from the pipe loop, or perhaps by stratifying solids within the test-loop pipe near the in-line sensor. This finding should be used as a caveat when comparing Lasentec in-line data to bench-top data in the future. If comparisons between in-line and laboratory sensors are desired, it is important to compare Lasentec in-line data to a Lasentec bench-top sensor. Note that the solids must be homogeneous, both in the pipe and the bench-top beaker, for results from both sensors to match.

After the initial non-radioactive simulant testing at PNNL, the instrument was shipped for radioactive validation and qualification testing in the Slurry Monitoring Test System (SMTS) connected to the Tank W-9 of the GAATs at ORNL. At ORNL, the acceptance the criterion for transferring slurries through the cross-site pipeline is that the particles be less than 100 μm in size. For all qualification tests conducted at ORNL, the variation in the chord length distribution and the total particle count corresponded very well with the slurry density data as determined using an in-line Promass 63M Coriolis meter. In addition, the results also show that > 99.9% of the particles have chord lengths <105 μm and that the instrument was extremely sensitive to small variations in the particle size distribution. Based on the performance results obtained, the Lasentec Focused Beam Reflectance Measurement (FBRM) is expected to meet the requirements of the GAAT Remediation Project for measuring the particle size distribution during the slurry-transfer operations at ORNL.

2.2 Red Valve Pressure Sensor

The Red Valve Pressure Sensor was qualified for use at the Hanford Site following instrument validation tests at PNNL and is currently in operation in the Tank 241-C-106 pump pit. While this instrument measures pressure within a transfer line, this type of pressure sensor could be configured to measure pressure drop over time. In turn, the status of a slurry transfer could be inferred from the pressure-drop measurement. The Red Valve Pressure Sensor is certified to ±1% of full scale or 1.0 psig on a 1-to-100 psig scale. Pressure measurement data validated the sensor in the 40 psig to 100-psig ranges. The pressure measured by the Red Valve Pressure Sensor in validation tests is within 1% of the actual direct pressure-tap readings obtained by the Rosemount Model 3051CG sensor.

The principle behind the Red Valve Pressure Sensor operation suggests that the transducer plugging and fouling issues can be eliminated.[a] In 1998, four Red Valve Pressure Sensors (with Sensotech Model AE-213 pressure transducers) were installed before and after the booster pumps of the 4-in. slurry (SL-200) and supernatant (SN-200) transfer lines between Tank 241-C-106 and Tank 241-AY-102. The sensor responds rapidly to changes in the booster pump discharge pressure and appears to be extremely sensitive to variations in the discharge pressure. The pressure sensor components in the SL-200 and SN-200 transfer lines are exposed to a total radiation exposure rate on the order of 300 R/yr. These pressure sensors have been in operation for over 2 years, and to date, the sensors have been trouble-free according to the operators involved with slurry and supernatant transfer operations. Based on these

(a) Unlike conventional pressure sensors where the slurry through a Bourdon tube to act against the sensors diaphragm, in the Red Valve Pressure Sensor, a silicone fluid acts as an intermediate transmitting fluid so that the slurry never contacts the sensor's diaphragm.

observations, it is apparent that the Red Valve Pressure Sensors could be installed at the end of the slurry transfer lines and used to measure the pressure drop in the system.

2.3 Ultrasonic Densimeter

The ultrasonic densimeter sensing system was developed to monitor radioactive waste density during transport. 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. By installing multiple sensors at different angular orientations (at the top, side and bottom) around the perimeter of the pipe, the densimeter can be used to (1) detect bubbles and partial filling of the pipes by measurements made with the sensor at the top of the pipe, (2) measure bulk density using the sensor along the side of the pipe, and (3) detect stratification and onset of sedimentation in the transfer pipelines and radioactive waste storage vessels with the sensor at the bottom of the pipe

The instrument uses ultrasonic signal reflection at the fluid-probe interface (located flush with the pipe wall) to quantify density *in situ* in real-time. The sensor is mounted in the wall of the pipe spool piece. The sensor is powered by a customized computer data-acquisition system. The sensor was selected for monitoring radioactive waste transport based on several characteristics: (1) it is non-intrusive and does not affect the slurry flow (the sensor is located flush with the pipeline wall), (2) it is not affected by entrained air that could be present during waste retrieval and transfer, (3) it is not affected by electromagnetic noise from nearby pumps and other equipment, and (4) it is compact.

The sensor performance has been evaluated for measuring the density of liquids and slurries over the density range from 980 to 1800 kg/m^3 at temperatures from 20 to ~ 60°C. The probe components can operate up to 100°C; however, the initial deployment does not require operation at this elevated temperature. The sensor is installed in a nominal 5-cm (2-in.) pipe spool piece with a design pressure of 2.8 MPa (400 psi). The probe wedge in contact with the slurry was selected to operate up to pH 14, and the probe components were radiation tested at exposures of $1x10^6$ R in a gamma cell.

During the performance evaluation tests, the densimeter tracked changes in density, but not absolute density. Further investigation showed that input variations in the pulser voltage were the cause of this offset. During the instrument calibration, the pulser voltage was set, and calibration measurements were made. However, during the testing at PNNL's IVF, the pulser voltage changed, and this change was not reflected in the software developed to compute the slurry density. A procedure to take into account input voltage was developed by monitoring and adjusting the pulser voltage to reflect the correct setting for which the calibration data were made. Using the modified setup, the densimeter was found to predict the absolute density to within ±2%. Based on these results, the densimeter is expected to meet the requirements for monitoring the slurry density during the waste-transfer operations at Hanford and other DOE sites.

Currently, the densimeter has been installed in the SY-101 prefabricated pump pit modified process manifold. Before installation of this process manifold at the Hanford site, the performance operation of the manifold and its components are being evaluated in the Fluor Hanford Engineering Laboratory in the 305 building.

2.4 Recommendations

Based on the performance results obtained, the Lasentec M600 FBRM, Red Valve Pressure Sensor, and the ultrasonic densimeter are expected to meet the slurry monitoring requirements for measuring the particle size distribution, pressure drop, and density during the feed delivery, storage, and disposal missions at Hanford and the ORNL GAAT remediation project, and these instruments can also be deployed at other DOE sites. Their use during the slurry-transfer operations could lead to significant savings in costs associated with preventing pipeline-plugging events while enabling better process control of the slurry-transfer operations.

3.0 Lasentec Particle Size Analyzer

The mean particle size data presented in this section are either the "unweighted mean particle size" or the "length-cubed weighted mean particle size." The mean size is the most familiar particle size statistic for operators, and the length-cubed weighted mean is the most sensitive to changes on the course end of the distribution, our primary area of investigation. Details of the theory and function of the Lasentec Particle Size Analyzer and the equations for computing the "unweighted mean particle size" and the "length-cubed weighted mean particle size" from the measured chord length distribution are discussed in Appendix A.

3.1 Qualification Testing at PNNL

In 1996 and 1998, the Lasentec particle size and M300 and M600 population monitors were cold tested at PNNL's IVF that houses a 3-in. (7.62 cm) Schedule 40 inner-diameter pipe loop, a 946-L (250-gal) feed tank, and an 851.6 lpm (225-gpm) centrifugal pump. A schematic of the test loop is provided in Figure 3.1. For validation tests, the slurry was passed through the W-211 loop. More detailed drawings of the IVF are presented in Reynolds et al. (1996).

According to the Lasentec manual and marketing literature, the monitor should not be installed in the down-flow configuration because fluid may not completely fill the pipe in this configuration. Lasentec also argues that the solids in the pipe will distribute differently in the up-flow configuration as opposed to the down-flow configuration. However, installation of the Lasentec analyzer in the down-flow leg of the pipe loop did not significantly affect test results for the following two reasons:

1. There is no evidence that the fluid does not fill the pipe in the down-flow leg of the test loop. If the flow were discontinuous as Lasentec argues, then the instrument readings would fluctuate with time. No such fluctuations in the total particle counts were observed.

2. There is no evidence that solids stratified differently in the up-flow and the down-flow configurations. This is evidenced by similar density-cup measurements of the samples taken from the up- and down-leg sample ports, which indicates there is probably little difference in the solids concentration in the two legs (refer to Figure 3.2).

Validation tests in 1998 were performed using the simulant test matrix shown in Table 3.1. In addition to varying the particle size distribution, other parameters that were investigated during the Lasentec qualification testing at PNNL include the effect of (1) air bubbles in the system, (2) solids that could coat the probe window, (3) simulant color, (4) flow rate, and (5) scan time. Additionally, grab samples of the slurry also were collected and analyzed off-line to determine the correlation between the in-line and off-line measurements. The results from these investigations are described in the following paragraphs.

3.1.1 Effect of Air Bubbles

Because retrieval of tank waste may entrain air bubbles into the slurry line, the instrument must be able to yield relatively stable, useful readings in the presence of air bubbles. To study the effect of air bubbles in the system, the average particle size of a 2-vol% graphite slurry was compared before and after air was injected at 1 cfm into the flow loop. The results from this test are illustrated in Figure 3.3. This figure shows that although bubbles increased the noise in the Lasentec monitor's measurement, the measured mean particle size changed by less than 1% from the value before air was introduced.

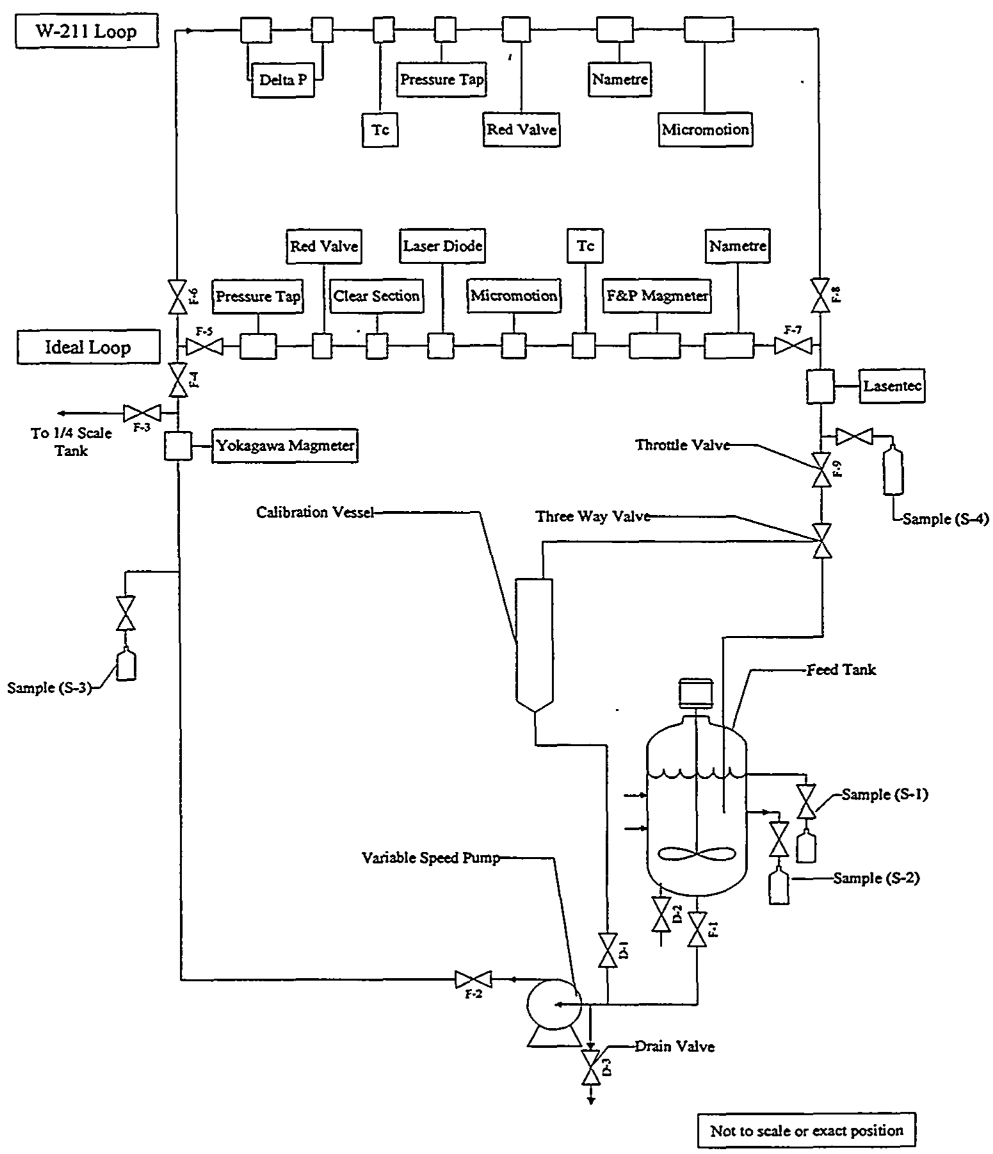

Figure 3.1. Schematic of the Test Loop at the Instrument Validation Facility at PNNL (Reynolds et al. 1996)

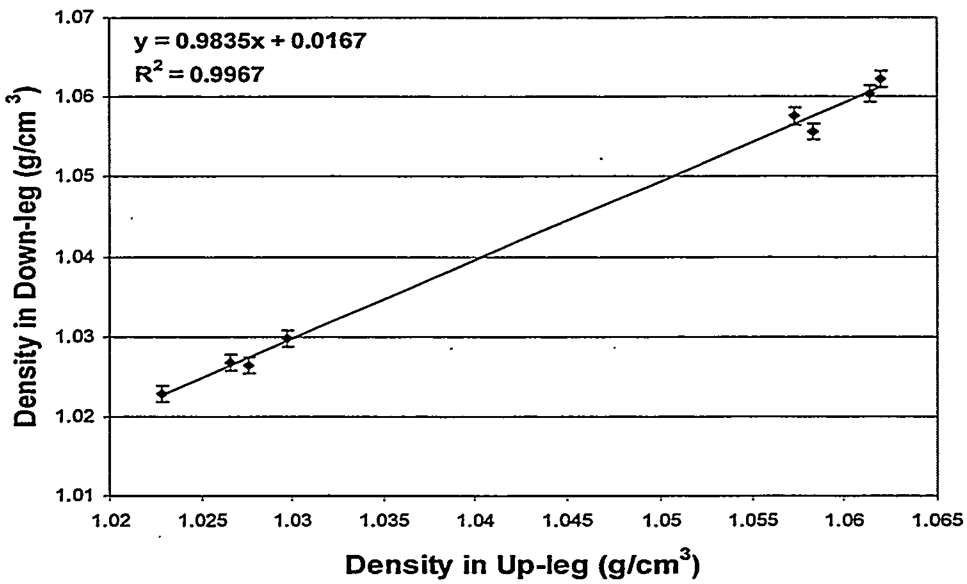

Figure 3.2. Density in Down-Leg vs. Density in the Up-Leg Section of the Pipe Loop as Determined by the Density Cup Measurements[(a)]

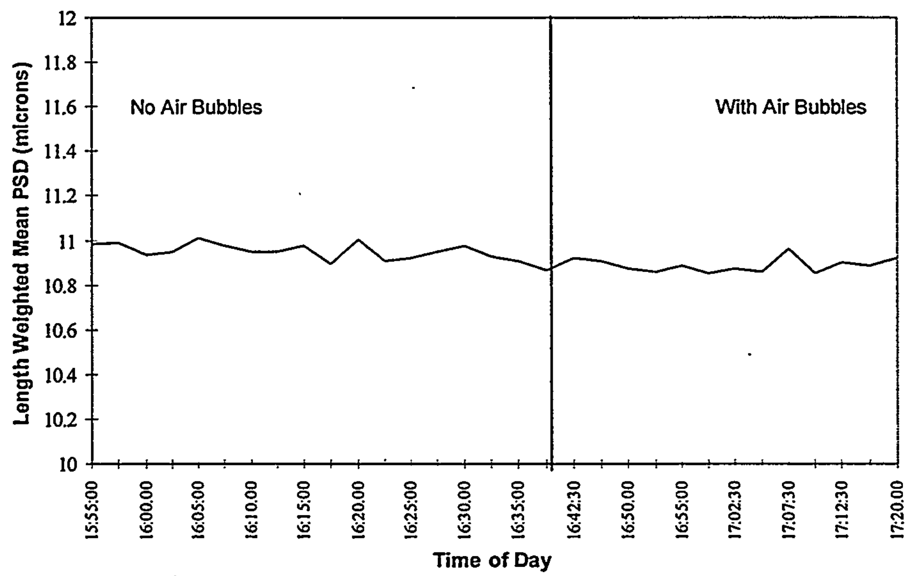

Figure 3.3. Lasentec Mean Particle Size Obtained Using Graphite Slurry With and Without Air Bubbles Introduced into the Pipeline[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

Table 3.1. Matrix of Simulant Slurries Used to Validate the Instruments at the Hanford Site

Solids Material(s)	Solids Concentration (wt%)	Lasentec Monitor Tested
Graphite (mean size: 4 μm)	6 11 15	M300
Gibbsite (mean size: 7.5 μm)	11 45 53	M300
Graphite and Gibbsite	9% Graphite, 13% Gibbsite 11% Graphite, 16% Gibbsite 6% Graphite, 25% Gibbsite	M300
Bentonite (mean size: 0.8 μm)	3 6 11	M300
Bentonite and Mica flakes (Mica mean size: 6 μm)	10% Bentonite, 4% Mica	M300
Silica (mean size: 3.5 μm)	12 34 54	M300
Plastic Beads (mean size: 18 μm)	5 20 35	M300
Kaolin (Kaolin mean size: 0.8 μm)	5 10	M600
Kaolin and Silica (Silica mean size: 410 μm)	4.2% Kaolin, 0.8% Silica 3.5% Kaolin, 1.5% Silica 2.8% Kaolin, 2.2% Silica 8.5% Kaolin, 1.5% Silica 7.0% Kaolin, 3.0% Silica 5.5% Kaolin, 4.5% Silica	M600

3.1.2 Effect of Solids Coating

A sapphire window that is chemically compatible with the caustic and highly radioactive tank waste protects the Lasentec monitor optics. One concern was whether solids could coat the window and hinder accurate particle size measurements. To address this concern, the M300 monitor was tested with graphite slurries that coated the entire pipeline. As a result of the coating nature of the graphite slurries, two magnetic flow meters installed in the pipe loop had to be removed and cleaned on two separate occasions. Because the Lasentec probe is inserted into the flow direction at a 45° angle, the sapphire window is self-cleaning. No residue was found on the probe window when the monitor was removed from the pipe loop after flow tests with graphite were completed.

3.1.3 Effect of Simulant Color

The color of tank waste could vary slightly during waste-retrieval operations, and some concern exists about whether color changes would affect the monitor's capability to adequately measure particle size. During one simulant test (4 vol% bentonite), a total of 0.76 L (0.2 gal) of red and orange food coloring were added to the feed tank containing 795 L (210 gal) of slurry to change the color of the simulant. As a result of the food coloring, the bentonite slurry changed color from olive-green to peach. The results of the mean particle size distribution obtained before and after adding the coloring agent to the simulant are shown in Figure 3.4. This figure shows that the Lasentec showed no significant change in the average particle size distribution after the food coloring was added to the slurry.

3.1.4 Effect of Change in the Simulant Flow Rate

For most of the Lasentec monitor validation tests, a nominal flow rate of 9 L/s (2.4 gal/s) was selected, corresponding to an average velocity of about 1.8 m/s (6 ft/s) in the 3-in. (7.62 cm) inner-diameter pipe. This slurry velocity was selected because it is the target velocity for the pipeline in the GAATs at ORNL. There is some concern as to the effect that the flow-rate change would have on the sensitivity of the instrument, as flow rates tend to fluctuate during normal operation of the slurry-transfer lines. Also, another concern was that the Lasentec monitor does not directly account for the velocity of particles as they pass the monitor. To offset the effect of flow-rate fluctuations, the focal point of the monitor is scanned at 2 m/s (6.56 ft/s), and it is recommended that the probe be installed in a vertical up-flow section of pipe with the probe window positioned at a 45° angle to the flow. The 2 m/s (6.56 ft/s) scan compensates for fluctuations in the slurry velocity (at average slurry velocities of 1.8 m/s [5.9 ft/s] or slower), whereas the angle of the probe slows the particles in the measurement zone.

According to the manufacturer, in a process with a slurry velocity greater than 1.8 m/s (5.9 ft/s), the flow speed should be held constant so there is a linear offset to the measured data. That is, if the slurry velocity is greater than 1.8 m/s (5.9 ft/s), there is less time for the Lasentec monitor to reflect light off a given particle than if the slurry were traveling at a velocity less than 1.8 m/s (5.9 ft/s). To the Lasentec monitor, if light is reflected off the surface for a shorter period of time, the particle appears smaller. Likewise, the measured particle size would be greater if the velocity is decreased to a new velocity that is still greater than 1.8 m/s (5.9 ft/s). If the flow speed is greater than 1.8 m/s (5.9 ft/s) and fluctuates with time, an external flow-speed measurement should be provided to the Lasentec FBRM electronics for a real-time correction to the shift in measured particle size.

To investigate the effect of the flow rate on the measured particle size distribution in two tests, the flow rate was changed to 2.7 m/s (13 L/s) and 1.3 m/s (6.3 L/s) (8.86 ft/s [3.43 gal/s] and 4.27 ft/s [1.66 gal/s]), respectively. These results are compared to the nominal flow rate of 1.8 m/s (9 L/s) and are shown in Figures 3.5 and 3.6, for the high (2.7 m/s [8.86 ft/s]) and low (1.2 m/s [4.27 ft/s]) flow rates, respectively. Figure 3.5 shows that a 5% shift in the mean particle size was observed when the volumetric flow rate was increased from 1.8 m/s (13 L/s) to 2.7 m/s (9 L/s) (5.9 ft/s [3.43 gal/s] to 8.86 ft/s [2.38 gal/s]). Similarly, Figure 3.7 shows that an 8% increase in the mean particle distribution was observed when the flow rate was decreased from 1.8 m/s (9 L/s) to 1.3 m/s (6.3 L/s) (5.9 ft/s [2.38 gal/s] to 4.3 ft/s [1.66 gal/s]). These shifts in the mean particle size with flow rates are to be expected from the Lasentec monitor.

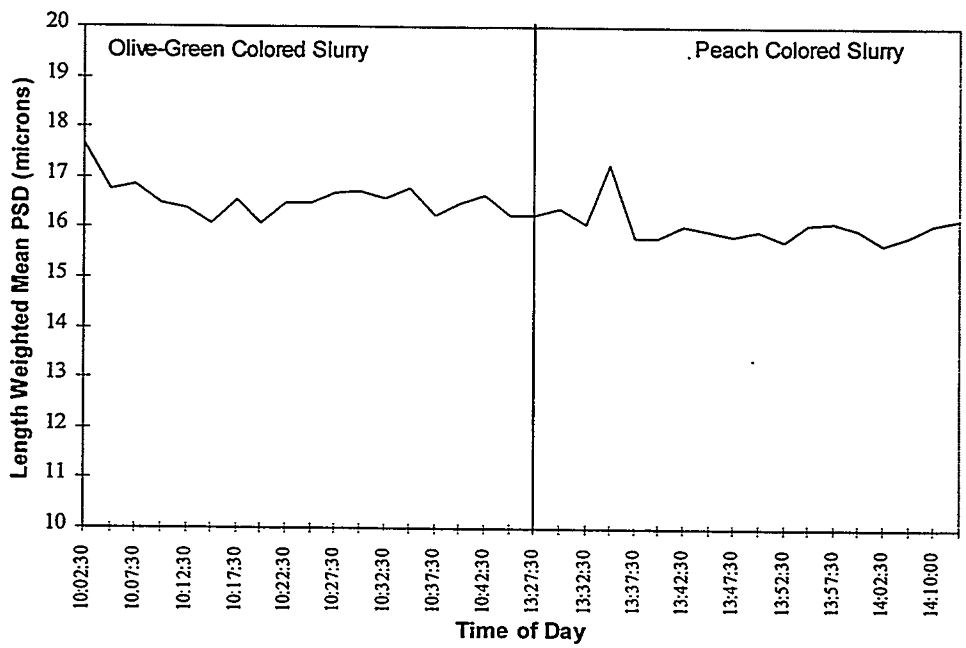

Figure 3.4. Lasentec Mean Particle Size for a Bentonite Slurry With and Without the Addition of Coloring Agent[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

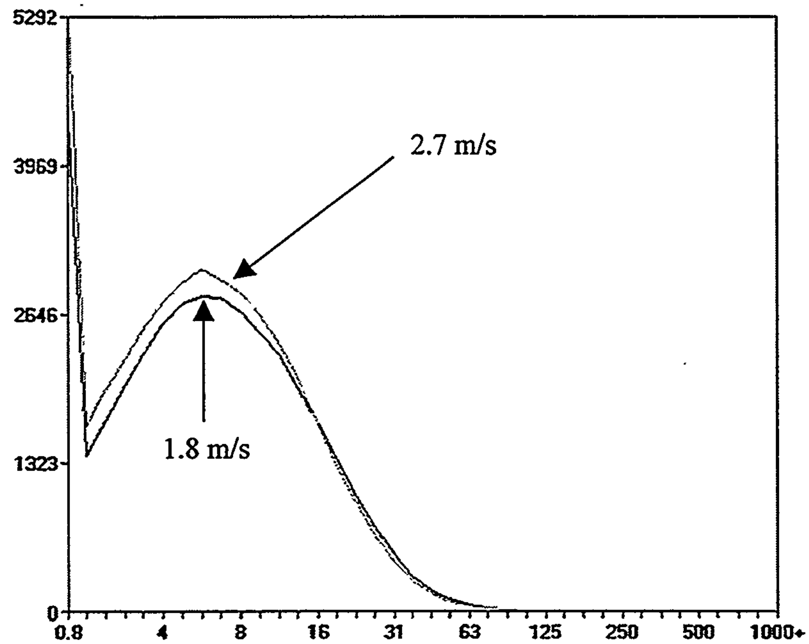

Figure 3.5. Effect of Slurry Velocity on the Lasentec Particle Size Distribution (Chord Length Cubed) for a 3.5-wt% Kaolin and 1.5-wt% Silica Slurry[(a)]

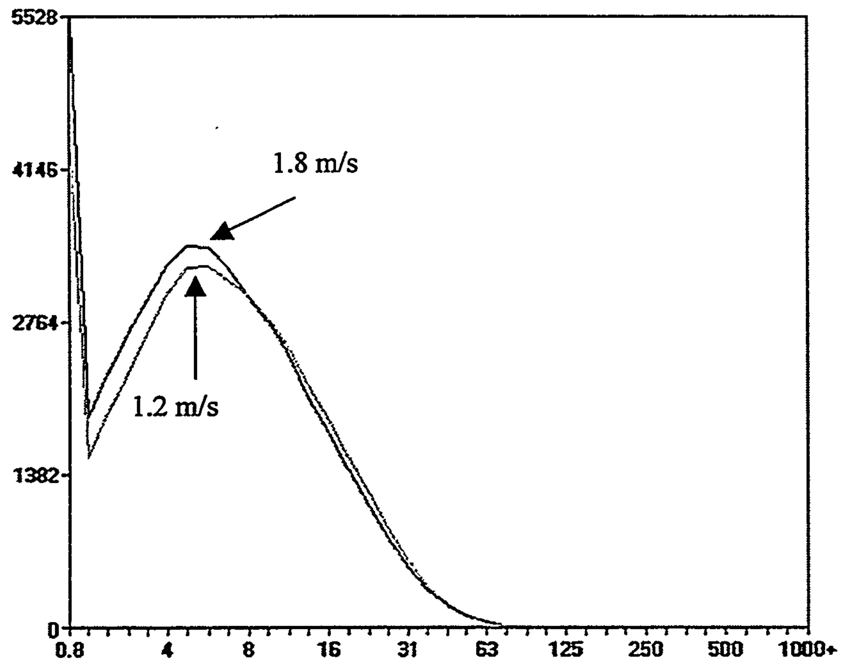

Figure 3.6. Effect of Slurry Velocity on the Lasentec Particle Size Distribution (Chord length Cubed) for a 3.5-wt% Kaolin and 1.5-wt% Silica Slurry[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

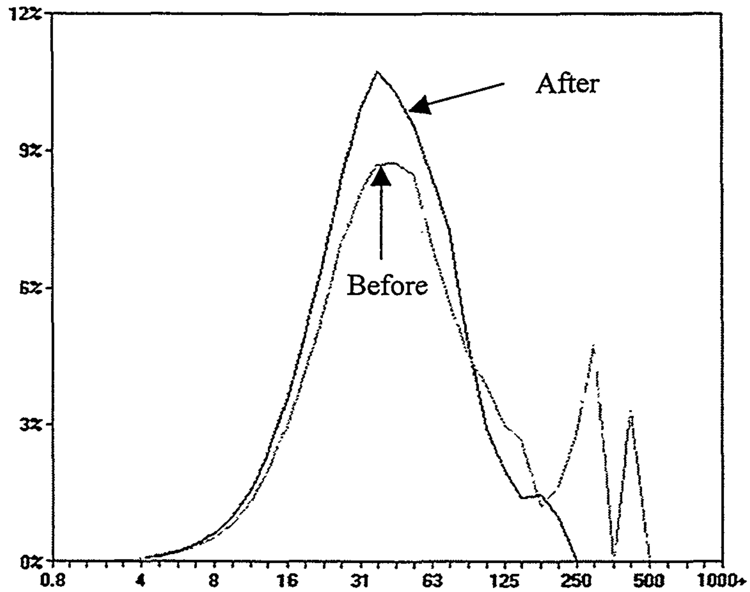

Figure 3.7. Effect of Change in Solids Concentration on the Lasentec Size Particle Size Distribution (Chord Length Cubed) as Observed Before and After the Addition of Silica to a 5-wt% Kaolin Slurry[(a)]

Light reflected for a shorter time causes the decrease in the mean particle size distribution with an increase in the flow rate. According to Equation 1, the chord lengths would be smaller. Similarly, at lower flow rates, the mean particle size would be larger. Also, the observed 5 to 8% shift in mean particle size with flow rate is acceptable for slurry-transport applications at both Hanford and ORNL.

3.1.5 Effect of Changes in Solids Concentration

During the May 1998 qualification testing of the Lasentec M600 monitor, the solids concentration was varied in two ways. First, the ratio of silica (410 µm mean size, as measured by sieve analysis) to kaolin was increased from 0:1 to 1:5.6, 1:2.33, and 1:1.22. Second, the total solids concentration was increased from 5-wt% solids to 10-wt% solids.

A representative result of the effect of adding silica to 5-wt% kaolin is shown in Figure 3.7. Similarly, the effect of adding kaolin to silica slurry (2.5 wt%) is shown in Figure 3.8. For all the silica/kaolin slurries studied, the average particle size was found to increase as the silica/kaolin ratio was increased because more large particles are present in the slurry. Also, the effect of an increased proportion of silica on average particle size was found to become less significant with each incremental increase of silica as the average measured particle size approached that of the silica. At both 5-wt% and 10-wt% solids concentrations, the total number of counts per second decreased by around 13% when the

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

silica/kaolin ratio was changed from 0:1 to 1:1.22. This decrease in the total number of counts per second was expected, as there were fewer particles in the system, and the larger particles had a smaller surface-to-volume ratio.

At 5-wt% solids, the length-cubed weighted mean particle size increased from around 53 μm to 150 μm when the silica/kaolin ratio increased from 0:1 to 1:5.6. A similar increase in particle size was observed at 10-wt% solids for the same change in silica/kaolin ratios (45 μm at a ratio of 0:1 to 156 μm at a ratio of 1:5.6). As expected, when the proportion of silica was further increased, the length-cubed weighted mean particle size did not increase as significantly since the length-cubed weighted mean of the kaolin/silica system was approaching the length-cubed weighted mean of the silica on its own (e.g., the measured length-cubed weighted mean particle size values at 10-wt% solids were 204 μm at a silica/kaolin ratio of 1:2.33, and 214 μm at a silica/kaolin ratio of 1:1.22). Note that the length-cubed weighted mean (which has a similar effect of a volume weight) heavily weights the change to coarse particles at the expense of resolution on the fine-particle side of the distribution.

For the cases where the solids concentration increased with the ratio of silica to kaolin being constant, the average length-cubed weighted mean particle sizes at 5-wt% and 10-wt% solids were nearly the same at each case tested. The total number of particles counted increased by around 20% when the solids concentration was increased from 5-wt% to 10-wt% solids.

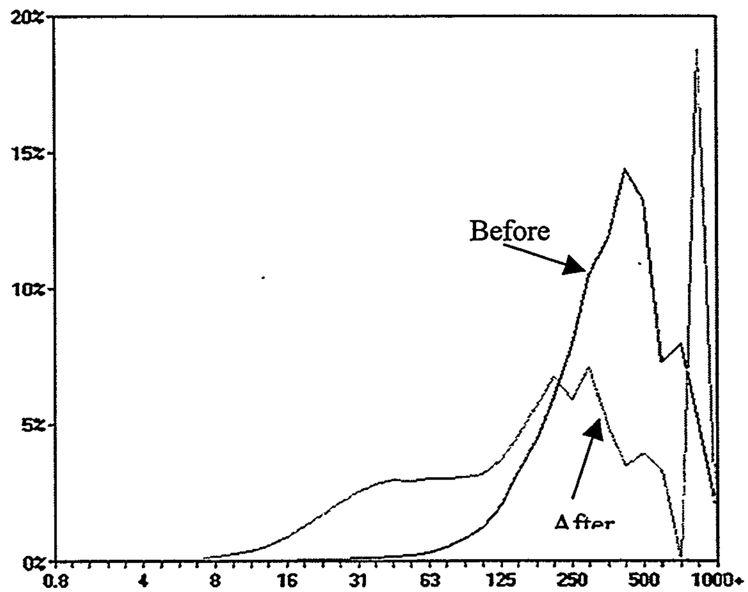

Figure 3.8. Effect of Change in Solids Concentration on the Lasentec Particle Size Distribution (Chord Length Cubed) as Observed Before and After the Addition of Kaolin to a 2.5-wt% Silica Slurry[(a)]

3.1.6 Effect of Scan Time

A high scan time increases the number of counts that contribute to the particle size measurement data. Increasing the number of particles counted results in smoother and more accurate data. However, a large scan time also decreases the frequency at which new data sets can be collected. In a similar manner, low scan rates enable a larger collection of data sample sets at the sacrifice of the quality of the data. The effect of the sampling time on the mean particle size is shown in Figure 3.9. The data in this figure were collected at three sampling intervals of 30 s, 60 s, and 300 s. The 30-s sample time produces the most fluctuation in the data while the 300-s sampling time provides a very uniform mean particle size measurement. Also, at the 60-s scan rate, although some variation in the mean particle size exists, the data are closer to those observed with the 300-s scan time. Therefore, for the Lasentec particle analyzer, the scan time should be 60 s or greater and preferably (if possible) 300 s.

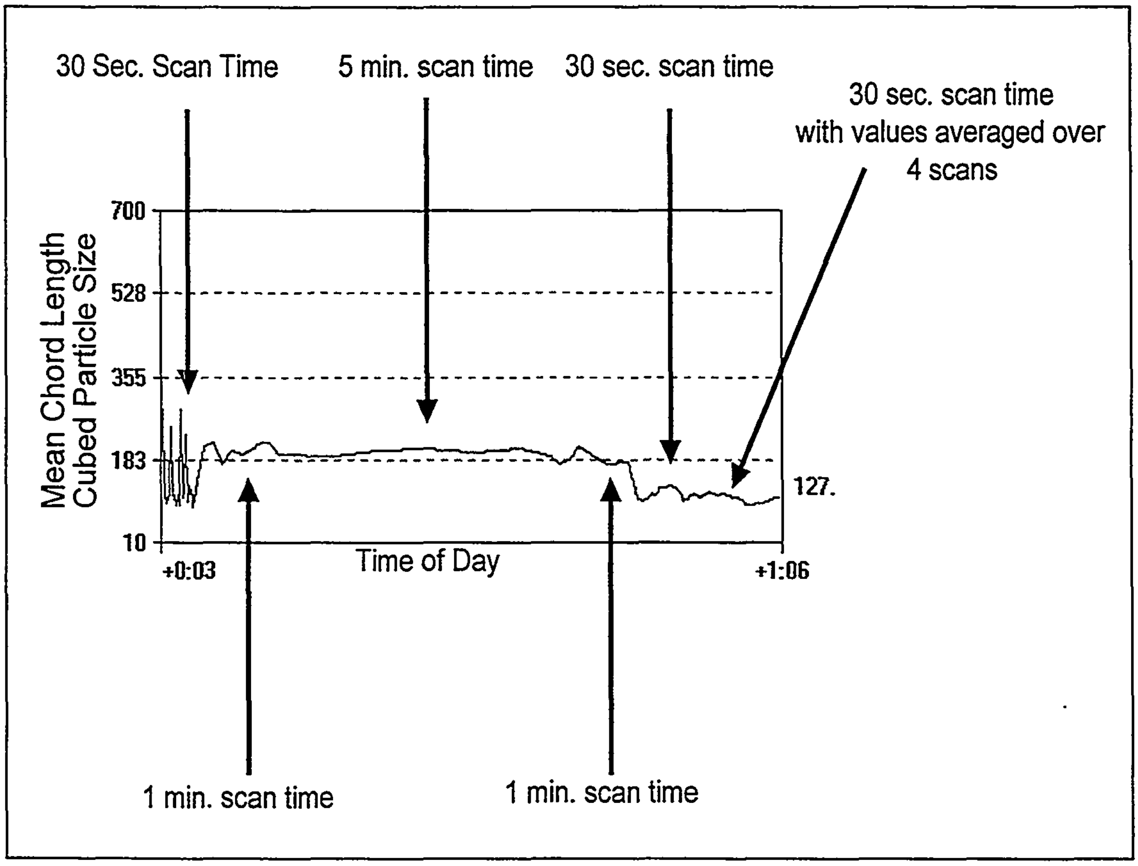

Figure 3.9. Effect of the Scan Time on the Lasentec Mean Particle Size for a 7-wt% Kaolin and 3-wt% Silica Slurry[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

3.1.7 Comparison of In-Line Lasentec Data to Off-Line Sieve Analysis

As described above, the Lasentec FBRM monitor yields particle size histograms by measuring the length of time that laser light backscatters off of particles that pass by the probe window. One important aspect of the Lasentec "qualification tests" was to show that particle size data from the Lasentec monitor could be compared to another (independent) particle size measurement of the same material.

Figure 3.10 compares a sieve analysis performed on dry samples of silica and a particle size histogram for the silica slurry measured with the in-line Lasentec monitor (length-cubed weighted particle size data). When the Lasentec collected these data, the flow rate was 9 L/s (2.38 gal/s) (an average velocity of 6 ft/s [1.83 m/s] in a 3-in. [7.62-cm] pipe). The Lasentec-measured histogram and the sieve analysis match well, suggesting that the length-cubed weighted particle size data may be roughly correlated with a sieve analysis on materials of this type. Depending on the shape of the particles, though, a sieve analysis may not always compare with the particle size distribution measured by a Lasentec FBRM monitor.

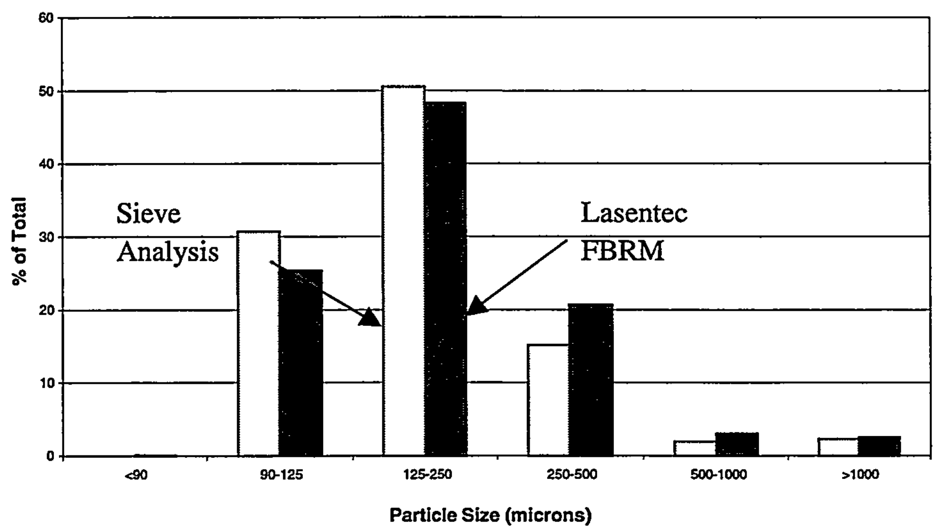

Figure 3.10. Comparison of the Sieve Analysis and the Lasentec Mean Particle Size Obtained Using a 10-wt% Silica Slurry (Daymo 1998)[(a)]

If a certain volume of spherical particles is held constant, but the aspect ratio increased (i.e., the particles become rod-like), a sieve analysis would indicate that the rod-like particles are generally smaller than the spheres. If the same system were measured with an FBRM monitor, the unweighted mean particle size would decrease as the spheres become rod-like because the unweighted mean is strongly

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

dependent on the number of short chords across the width of these rod-like particles. At the same time, the length-cubed weighted mean particle size would increase because of the large chords measured across the longest dimension of the rod-like particle. Although such tests were not performed for this report, the Lasentec FBRM sensor can be used to monitor relative changes in the shapes of particles.

3.1.8 Comparison of In-Line Lasentec Data to Bench-Top (off-line) Lasentec Analyzer

The Lasentec monitor may reduce operational costs if in-line particle size measurements could reduce (or eliminate) the number of laboratory particle size analyses that need to be performed on radioactive grab samples taken before and/or after slurry-transfer operations. Ideally, particle size distributions measured by the in-line Lasentec monitor should correlate well with particle size distributions of grab samples measured off-line by laboratory (i.e., bench-top) monitors.

Samples of kaolin and silica/kaolin slurries collected during "qualification testing" of the Lasentec M600 monitor were sent to the vendor for analysis with a Lasentec M500LF (a laboratory version of the M600 monitor). To make accurate comparisons between in-line and bench-top FBRM monitors, it is crucial that both probes are exposed to identical distributions of particles.

One-liter samples of each slurry type were sent to Lasentec, and aliquots from each 1-L slurry sample container were taken and analyzed with the bench top monitor. Obtaining representative aliquots was difficult for silica/kaolin slurries because the large silica particles settle quickly. In general, the narrower the particle size distribution, the higher the solids concentration, and the smaller theparticles, the easier it is to correctly collect slurry samples.

While the presence of fast-settling silica made it impossible to compare results between the bench-top Lasentec M500LF monitor and the in-line M600 instrument for slurries containing silica, the vendor measured the particle size distribution of the silica/kaolin slurry aliquots using several different (independent) M500LF monitors. The company reported that the independent M500LF monitors measured essentially the same particle size histogram when the same silica/kaolin slurry aliquots were presented to each of the monitors. This result suggests that the FBRM method is highly repeatable.

The in-line Lasentec M600 and the laboratory Lasentec M500LF monitors reported similar length-cubed (weighted) mean particle size for the kaolin slurries. A representative comparison result for a 5-wt% kaolin slurry is shown in Figure 3.11. For the 5-wt% kaolin slurry, the in-line length-cubed weighted mean particle size is 53 μm, whereas the laboratory monitor measured 57 μm. Similarly, at 10-wt% kaolin slurry, the in-line monitor measured the length-cubed weighted mean particle size to be 45 μm, while the laboratory monitor measured 56 μm. This difference between the in-line and laboratory monitors is considered to be acceptable for tank waste-retrieval applications.

3.2 Qualification Testing at ORNL

After the initial non-radioactive simulant testing at PNNL, the instrument was shipped for radioactive validation in the SMTS connected to the Tank W-9 of theGAATs at ORNL. The discussion and results presented in this section are taken from the report prepared by Hylton and Bayne (1999) on the testing of in-line slurry monitoring devices at ORNL. A schematic of the Tank W-9 and the SMTS system is shown in Figure 3.12. A detailed description of the SMTS also is available in Hylton and Bayne (1999).

The ORNL slurry transfer system uses 2-in. (5.08 cm) Schedule 40 piping and was designed for a nominal flow rate of 227 L/min (60 gal/min). This corresponds to a linear velocity of 1.9 m/s (6.23 ft/s). To meet the Lasentec maximum flow-rate requirement of 1.8 m/s (5.9 ft/s), the Lasentec probe was installed in a 2.5-in. (6.35 cm) Schedule 40 pipe. The pipe expansion reduced the slurry velocity to the Lasentec probe to about 1.2 m/s (3.9 ft/s). The probe was installed at an angle of 45° in the up-flow configuration as per the manufacturer's recommendation. Such a configuration makes the probe self-cleaning as the impinging slurry keeps the sludge from building up on the probe's sapphire window. A photograph of the actual probe in the SMTS is shown in Figure 3.13. The SMTS was operated and monitored by three computers. The main computer used Intellution Fix 32 software to control, monitor, and record data for everything except a prototype ultrasonic suspended-solids monitor and the Lasentec

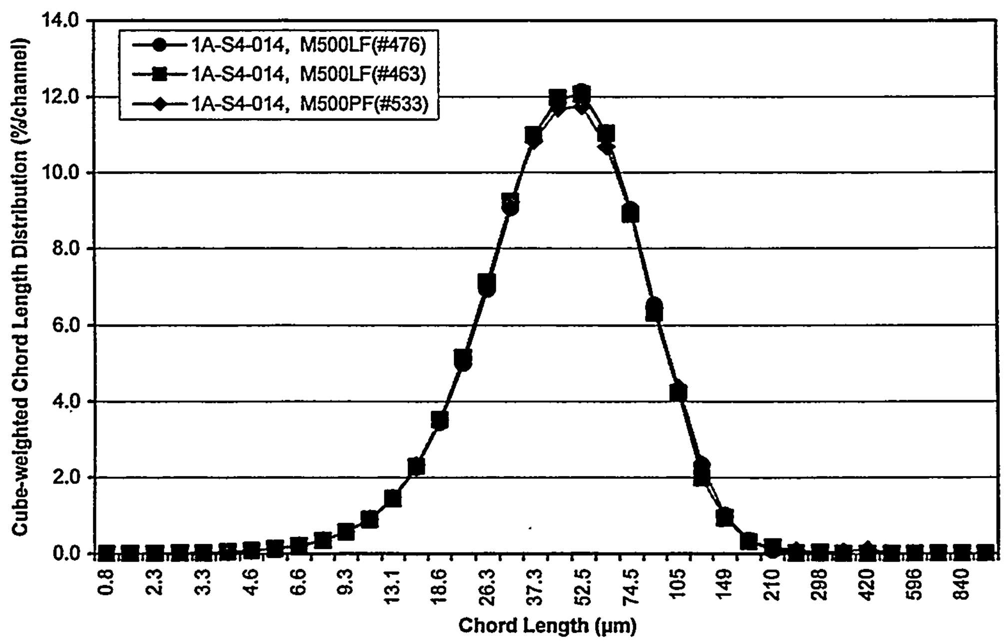

Figure 3.11. Comparison of the Particle Size Distribution (Chord Length Cubed) as Determined by an in-line (M500PF) and Bench Top (M500LF; duplicate) Lasentec Monitor for a 5-wt% Kaolin Slurry[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

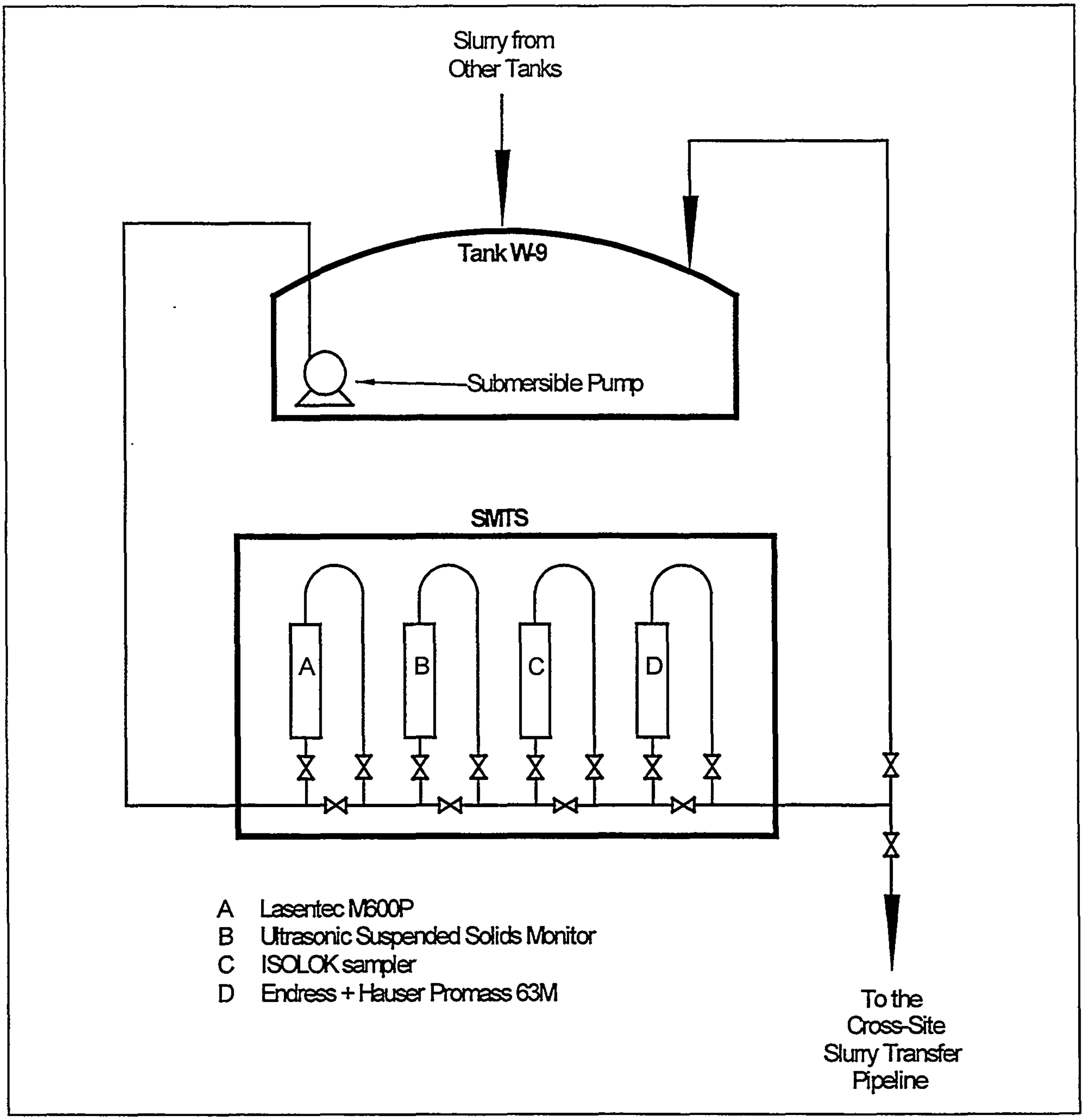

Figure 3.12. Schematic of the Flow Path from Tank W-9 to the Slurry Monitoring Test System (SMTS, Hylton and Bayne 1999)

instrument, which had their own dedicated computers. Data-acquisition hardware was procured from RTP Corporation. To ensure valid comparison between the data collected by the computers, the calendars and clocks for all three computers were synchronized before starting to collect data.

The contents of Tank W-9 were mixed using a technology developed by Pulsair™ Systems, Inc. In this technology, compressed air pulsed from the accumulator plates placed at the bottom of the tank creates a shock wave that immediately displaces the liquid and initiates the mixing process. As the air begins to form a bubble above the accumulator plate, the liquid and sludge particles are swept away from the plate. The bubble begins its rise, and low pressure under the bubble draws liquid and sludge particles back to the accumulator plate. As the bubble rises, the liquid above the bubble is forced up and away and liquid and sludge particles are pulled from the bottom and mixed with the lighter liquid. The bubble breaks on the liquid surface, and the mixing changes from vertical to horizontal. A surface mixing force moves the liquid to the tank wall, where it travels down the wall to the tank bottom to complete the mixing cycle. The operating parameters that were variable for the Pulsair mixing system were (1) dwell time, i.e., time between air injections, (2) injection time, i.e., the amount of time that air was injected, and (3) the air supply pressure. Of these parameters, the dwell time was considered to have the most influence on the mixing performance. Also, since a concentration gradient would exist in the tank, the position of the recirculation pump could also influence the mixing of the tank contents. Therefore, the instrument validation runs were conducted at three different dwell times and two recirculation-pump positions as shown in Table 3.2.

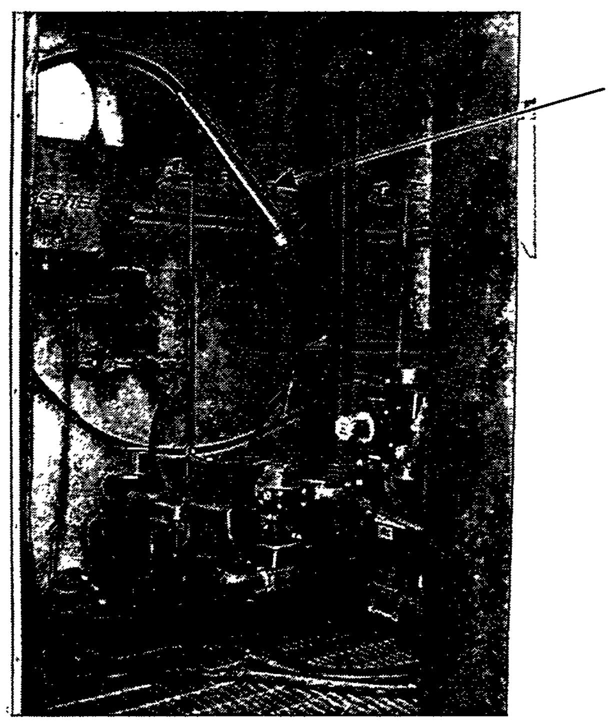

Figure 3.13. The Lasentec M600 Monitor (indicated by the arrow) Installed in the SMTS at ORNL (Hylton and Bayne 1999)

Table 3.2. Conditions for Testing the Slurry Monitors at ORNL

Test Number	Date	Tank W-9 Volume (gal)	Recirculation Pump Position (ft)	Pulsair Mixing Parameters		
				Dwell Time (s)	Injection Time (s)	Air Supply Pressure (psi)
1	02/17/1999	104,000	4	10	1	35
2	02/22/1999	104,000	4	18	1	35
3	02/25/1999	103,000	4	14	1	35
4	03/02/1999	105,000	6	10	1	35
5	03/05/1999	105,000	6	14	1	35
6	03/11/1999	113,000	6	18	1	35

The results of the six qualification tests at ORNL are shown in Figures 3.14 and 3.15. The results in Figure 3.14 (a-e) represent the complete chord-length distributions from the start to the termination of the Pulsair system. The results in Figure 3.15 (a-e) represent the total particle count as a function of time from the start to the termination of the recirculation. The results in Figures 3.16 (a-e) represent the time-dependent variation (from the start to the termination of the recirculation pump) in the number of particles greater than 105 µm. Also shown in Figures 3.15 and 3.16 for comparison purposes are the time-dependent variations in the density of the slurry for the six runs from the start to the termination of the recirculation pump. The following sections present a detailed description of the results included in Figures 3.14 to 3.16.

3.2.1 Slurry Test 1

During the Slurry Test 1, the recirculation pump was operated for 1 h before the Pulsair system was turned on. The tank contents were mixed for approximately 2.5 h before the slurry was pumped through the SMTS, and data collection was initiated. The Pulsair system was then stopped after 12 min of initiating the data collection while the recirculation through the SMTS was continued for another 1.5 h.

The total number of particles measured by the Lasentec instrument includes only those particles that come close to the window to be counted. A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figure 3.14a and 3.15a, respectively, for the Slurry Test 1. Also shown in Figure 3.15a for comparison purposes are the density results for the same test as measured by the Promass 63M Coriolis meter. As might be expected, the results show that the particle count responds in a similar fashion to the density; when the density decreases, the particle count decreases and vice versa.

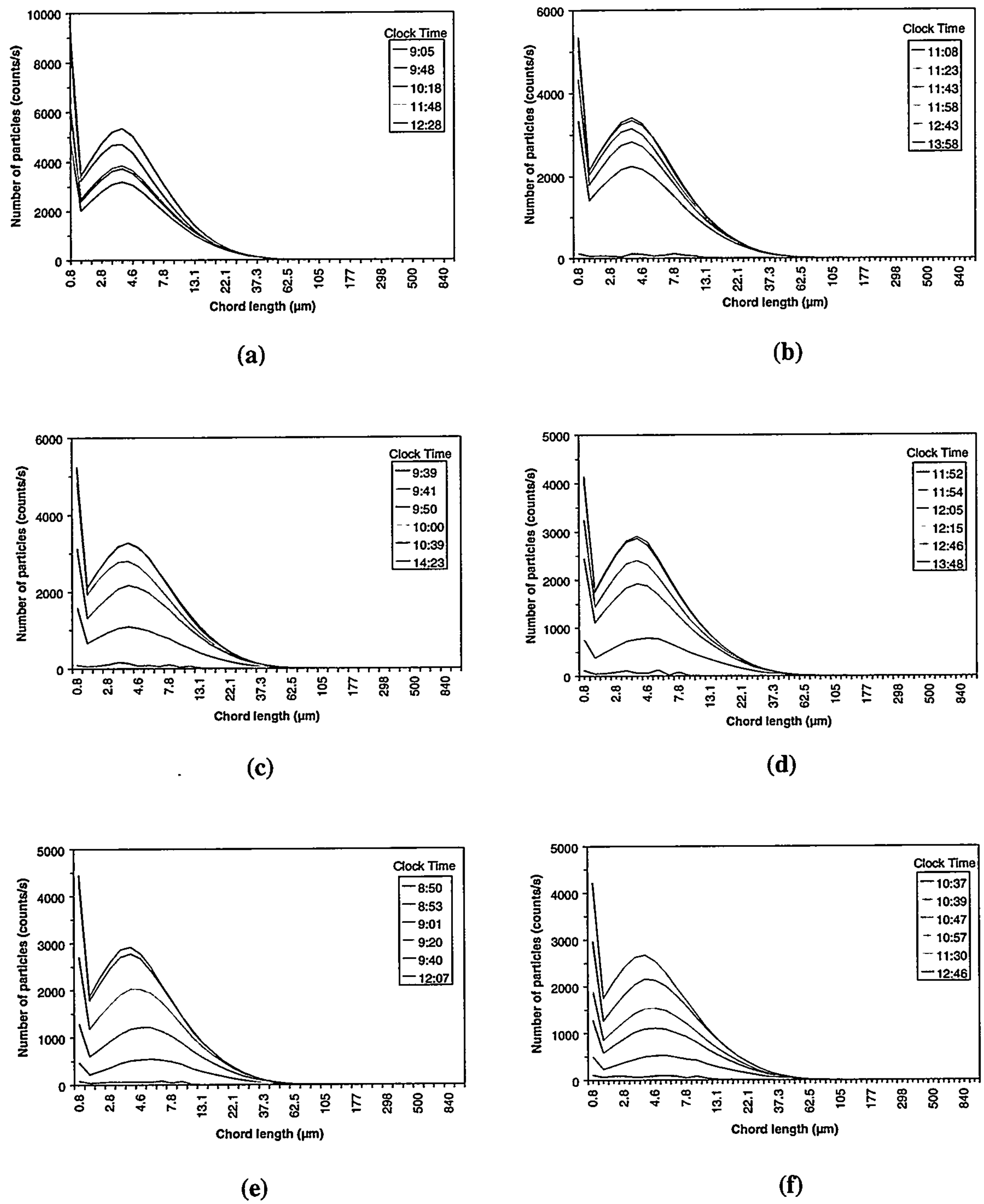

Figure 3.14. Particle Chord Length Distribution as a Function of Time for the Radioactive Qualification Testing of the Lasentec Monitor at ORNL: (a) Test 1, (b) Test 2, (c) Test 3, (d) Test 4, (e) Test 5, and (f) Test 6 (Hylton and Bayne 1999)

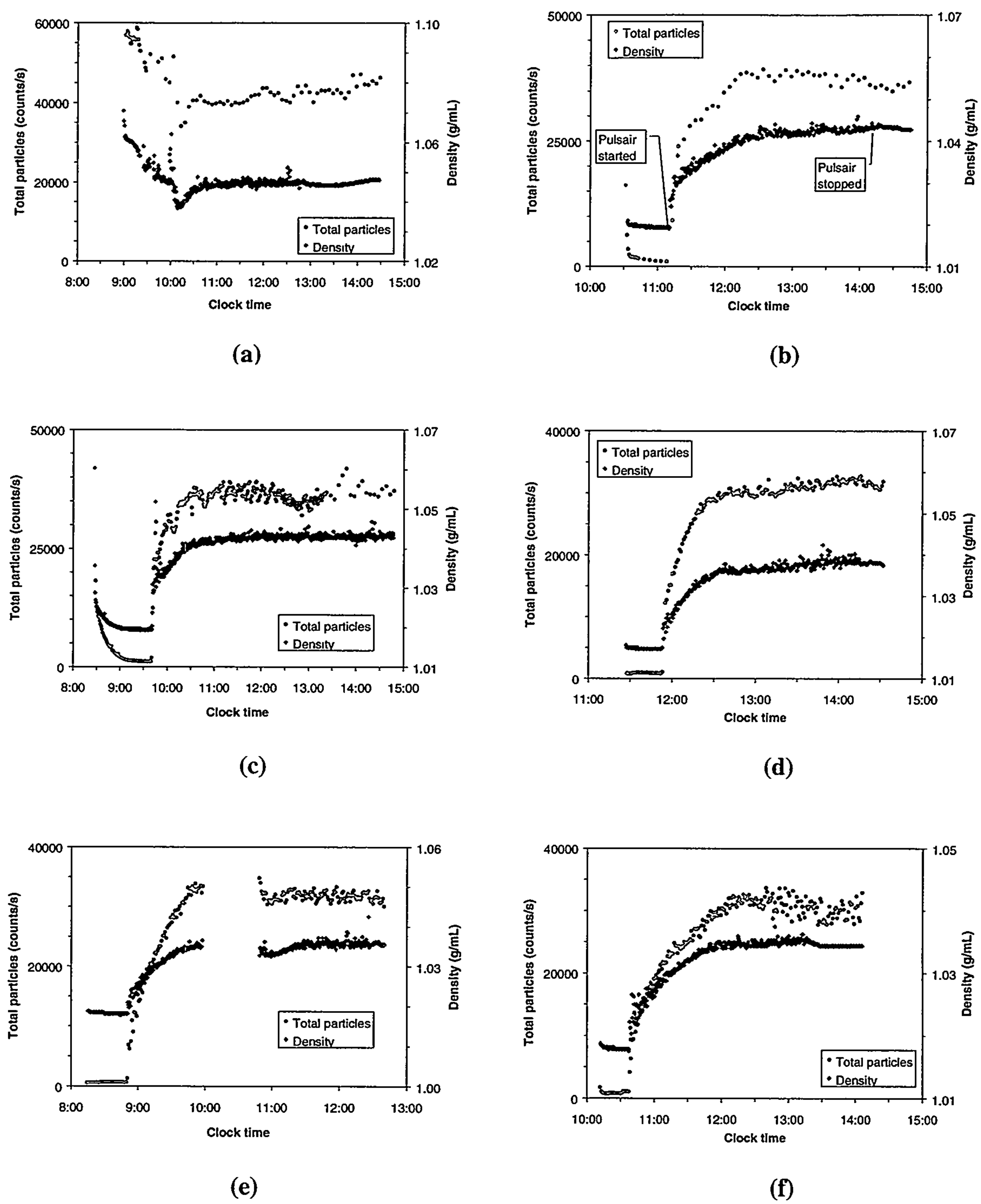

Figure 3.15. Total Particle Count as a Function of Time for the Radioactive Qualification Testing of the Lasentec Monitor at ORNL: (a) Test 1, (b) Test 2, (c) Test 3, (d) Test 4, (e) Test 5, and (f) Test 6 (Hylton and Bayne 1999)

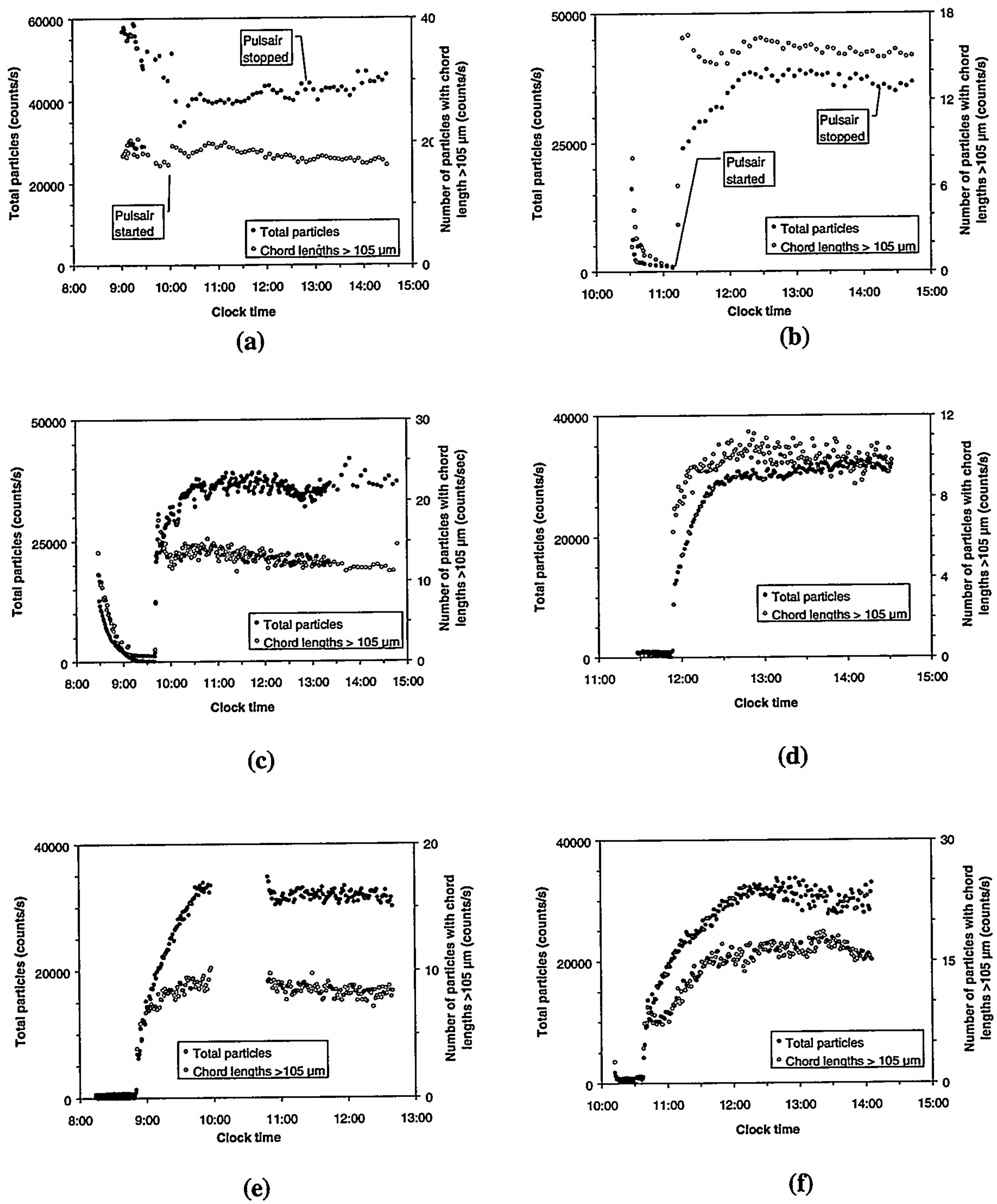

Figure 3.16. Particle Count >105 µm as a Function of Time for the Radioactive Qualification Testing of the Lasentec Monitor at ORNL: (a) Test 1, (b) Test 2, (c) Test 3, (d) Test 4, (e) Test 5, and (f) Test 6 (Hylton and Bayne 1999)

The current qualification criteria for transferring the slurries through the ORNL cross-site pipeline are that the particles be less than 100 µm. The Lasentec software divides the count data by chord lengths into 38 bins as discussed in Chapter 2. The channel closest to the 100-µm bin is 105 µm. Figure 3.16a is a plot of the time variation in the total number of particles and the particles with chord length >105 µm. Although the number of particles that were >105 µm was small, Figure 3.16a shows that this number increased slightly after the Pulsair mixing system was started, indicating that the instrument responds very well to small changes in the particle count.

3.2.2 Slurry Test 2

The contents of the slurry were allowed to settle for approximately 118 h after the termination of Slurry Test 1 so Slurry Test 2 could start with the recirculation pump immersed in the supernatant. The fluid was mixed for about 40 min after the fluid recirculation was initiated through the SMTS, and then the Pulsair system was started. Also, in this case, the Pulsair system was stopped after approximately 3 h while recirculation continued, and data were collected for another 45 min.

A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figures 3.14b and 3.15b, respectively, for the Slurry Test 2. Also shown in Figure 3.15b for comparison purposes are the density results for the same test as measured by the Promass 63M Coriolis meter. As observed with the Slurry Test 1, the chord-length distribution and the total particle count responded similarly to the density results. Since the Coriolis meter indicated that the density was low at the beginning of the test as the pump was only circulating the supernatant, one would expect that the Lasentec instrument would show a low particle count at the beginning of the test. Figure 3.15b shows that the particle count started out at the mid-range, but declined quickly. The mid-range count immediately at the start of the experiment was probably due to a dried film or particles that settled on the probe window from the previous testing. The particle count for the supernate before the start of the Pulsair system was <1000 counts/s.

Figure 3.16b shows the total number of particles and the number of particles with chord length >105 µm. The Lasentec results show that >99.8% of the particles have chord lengths <105 µm. The graph also shows that the number of particles with chord lengths >105 µm increased when the Pulsair system was started. This is another indication that the instrument is very sensitive to small changes in the system.

3.2.3 Slurry Test 3

Before starting Slurry Test 3, the contents of Tank W-9 were allowed to settle for approximately 67 h after the termination of Slurry Test 2. The fluid was recirculated through the SMTS for about 45 min before starting the Pulsair system, and mixing was continued until the recirculation pump was stopped (approximately 5.5 h after the start of the Pulsair system).

A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figure 3.14c and 3.15c, respectively, for Slurry

Test 3. Also shown in Figure 3.15b for comparison purposes are the density results for the same test as measured by the Promass 63M Coriolis meter. The data in these graphs show that the change in the particle size distribution corresponds very well with the density data. Figure 3.16c compares the total number of particles and the number of particles with chord lengths >105 μm. Similar to the findings of the previous tests, the results show that >99.9% of the particles have chord lengths <105 μm.

3.2.4 Slurry Test 4

Before starting Slurry Test 4, the contents of Tank W-9 were allowed to settle for approximately 117 h from the termination of Slurry Test 3. Approximately 30 min after the recirculation pump was turned on, the Pulsair system was started, and the mixing was continued until the recirculation pump was stopped (approximately 2.5 h after the start of the Pulsair system).

A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figures 3.14d and 3.15d, respectively, for Slurry Test 4. Figure 3.16d compares the total number of particles and the number of particles with chord lengths >105 μm. As with previous tests, the variation in the chord-length distribution and the total particle count correspond very well with the density data. Similarly, the results also show that >99.9% of the particles have chord lengths <105 μm.

3.2.5 Slurry Test 5

Before starting Slurry Test 5, the contents of Tank W-9 were allowed to settle for approximately 66 h from the termination of Slurry Test 4. Approximately 30 min after the recirculation pump was turned on, the Pulsair system was started. Both the recirculation pump and the Pulsair system were temporarily stopped for approximately 50 min after about 1 h of initiating the mixing process to facilitate other site operations of the GAAT project. Both units were then restarted, and the mixing continued for approximately another 1.5 h.

A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figures 3.14e and 3.15e, respectively, for Slurry Test 5. Figure 3.16e compares the total number of particles and the number of particles with chord lengths >105 μm. As with previous tests, the variation in the chord-length distribution and the total particle count correspond very well with the density data. Similarly, the results also show that >99.9% of the particles have chord lengths <105 μm.

3.2.6 Slurry Test 6

Before starting Slurry Test 6, the contents of Tank W-9 were allowed to settle for approximately 6 days from the termination of Slurry Test 5. Approximately 30 min after the recirculation pump was turned on, the Pulsair system was started, and the mixing was continued until the recirculation pump was stopped (approximately 3.5 h after the start of the Pulsair system).

A graph of the time-dependent variation of the chord-length distribution and the total number of particles measured by the Lasentec probe is shown in Figures 3.14f and 3.15f, respectively, for Slurry Test 6. Figure 3.16f compares the total number of particles and the number of particles with chord lengths >105 μm. As with previous tests, the variation in the chord-length distribution and the total particle count correspond very well with the density data. Similarly, the results also show that >99.9% of the particles have chord lengths <105 μm.

3.2.7 Statistical Analysis of the Lasentec Performance

The software for the Lasentec M600 counts the number of particles that have chord lengths (measured in micrometers) in 38 intervals that range from (0.8, 1.9) to (1000, 4). The probability distribution of the chord lengths can be estimated by dividing the number of particles in each interval by the total number of counts for all intervals. The average and variance of the chord lengths for each of the six tests can be estimated from these probability distributions by

$$Average = \sum_{j=1}^{38} X_j \, x \, f_j \tag{3.4}$$

and

$$Variance = \sum_{j=1}^{38} (X_j - Average)^2 \, x \, f_j \tag{3.5}$$

where

X_j = midpoint chord length of an interval
f_j = frequency of the j^{th} interval; j = 1, 2, . . ., 38.

The standard deviation is calculated as the square root of the variance. Table 3.3 summarizes the estimated averages and standard deviations for the six tests. Averages and standard deviations in Table 3.3 indicate no effects that are due to either the pump position or the dwell time. An overall average for all six tests is 6.41, with a standard deviation of 7.45.

Figure 3.17 shows the frequency of the midpoint chord length for particles with chord lengths of 50 μm. The unusually large frequency at the beginning is due to the first interval (0.8, 1.9) that contains a large number of counts. A possible improvement in the distribution may be achieved if the first interval is partitioned into smaller intervals. The first interval contains five channels worth of data on a log scale; therefore, a spike occurs. Earlier versions of the FBRM were not capable of discriminating between a 0.8-μm count and a 1.9-μm count. The manufacturer now reports that the latest version of the FBRM can discriminate between 0.5 and 1000 μm in 0.25-μm increments. A theoretical statistical evaluation indicates that the classical Fisher's F-distribution can model the Lasentec M600 frequency distribution.

Table 3.3. Lasentec M600 Particle Distribution Averages and Standard Deviations (in parentheses) of Cord Lengths

Recirculation Pump Position[a]	Particle Chord Length (μm) for Different Pulsair Dwell Times		
	10 s	14 s	18 s
4 ft	6.30 (7.49)	6.42 (7.28)	6.43 (7.48)
6 ft	6.39 (7.24)	6.56 (7.13)	6.42 (8.04)

(a) Pump position is the distance from the bottom of the tank to the pump.

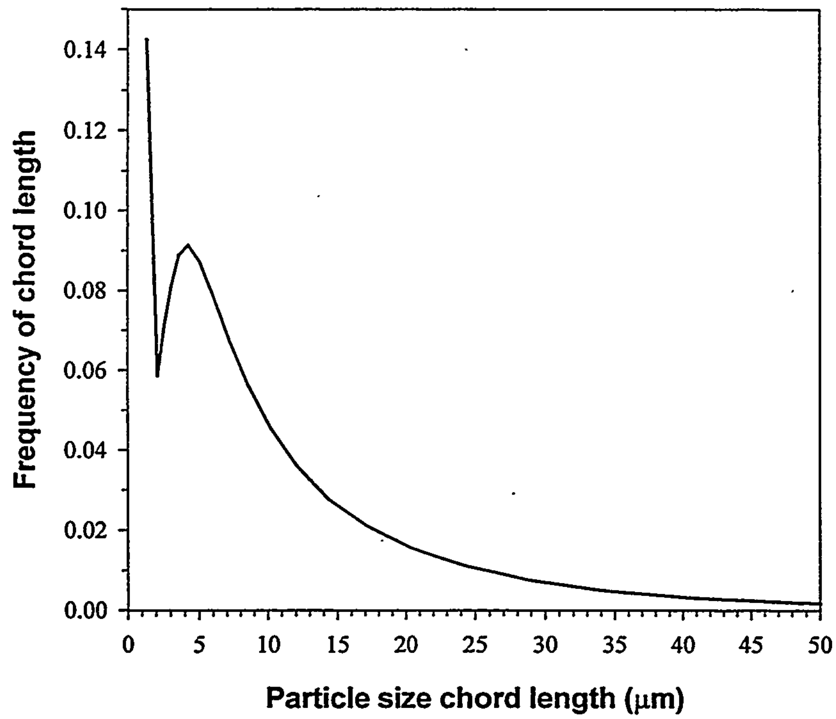

Figure 3.17. Overall Frequency Distribution of Particle Size Chord Lengths for the Six Tests at ORNL (Hylton and Bayne 1999)

3.2.8 Suspended Solids

The number of total counts per second measured by the Lasentec M600 should be directly related to the total suspended solids concentration in the slurry. Figure 3.18 shows the linear correlation between total counts per second with suspended solids (by laboratory analysis). The fitted line has a multiple correlation coefficient of 90.6%, showing good agreement between the two measurements. The linear relationship between the two variables can be expressed as:

$$Counts/s = 11{,}986 + 0.858x(Suspended\ Solids:\ mg/mL) \quad (3.6)$$

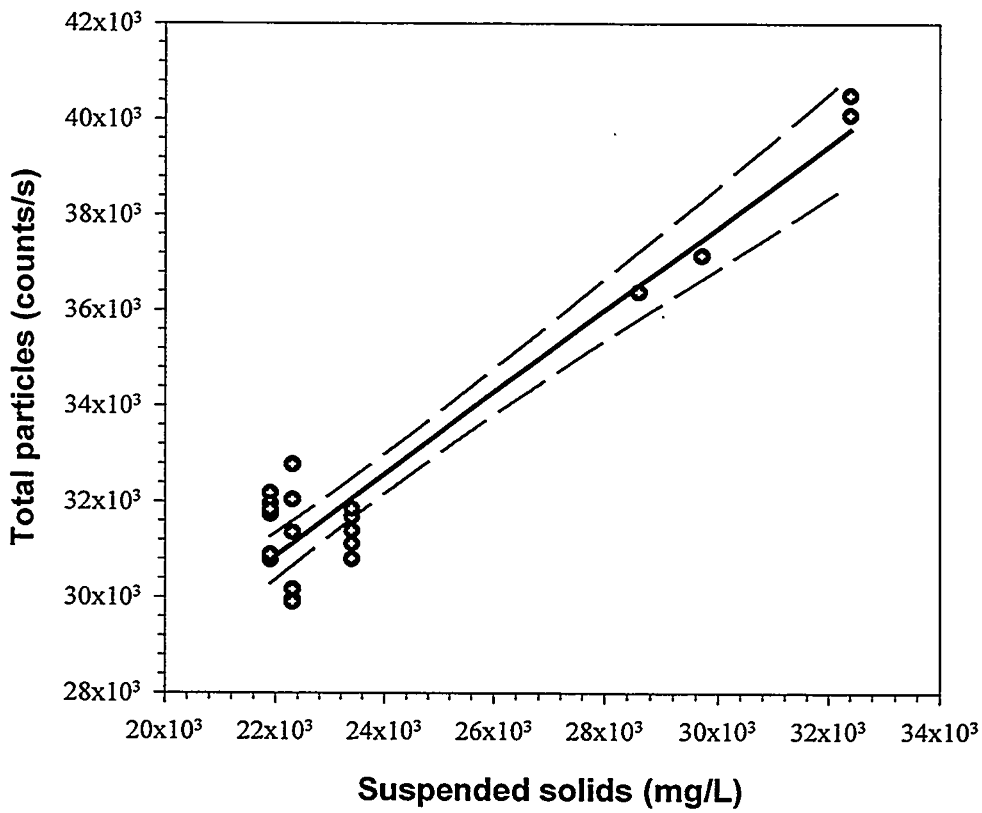

Figure 3.18. Line Fitted to the Lasentec's Total Particle Count Versus Suspended Solids Concentration Data with a 95% Confidence Interval (Hylton and Bayne 1999)

4.0 Red Valve Pressure Sensor

4.1 Qualification Testing At PNNL

The Red Valve Pressure Sensor, Model 1151, Smart Series 48, with Hypalon sleeve and silicon oil sensor fluid (Red Valve Company, Inc., Pittsburgh, Pennsylvania) was validated during FY 1996 in the W-211 loop at the IVF (Reynolds et al. 1996). This instrument is certified to ±1% of full scale or 1.0 psig on a 1-to-100 psig scale. Pressure-measurement data obtained during validation testing are compared with the Rosemount Model 3051CG (Rosemount Measurements, Eden Prairie, Minnesota) direct tap sensor in Figure 4.1. This figure shows that within the test range of 40 psi to 100 psi, the pressure measured by the Red Valve Pressure Sensor is within 1% of the actual direct pressure-tap readings obtained by the Rosemount sensor.

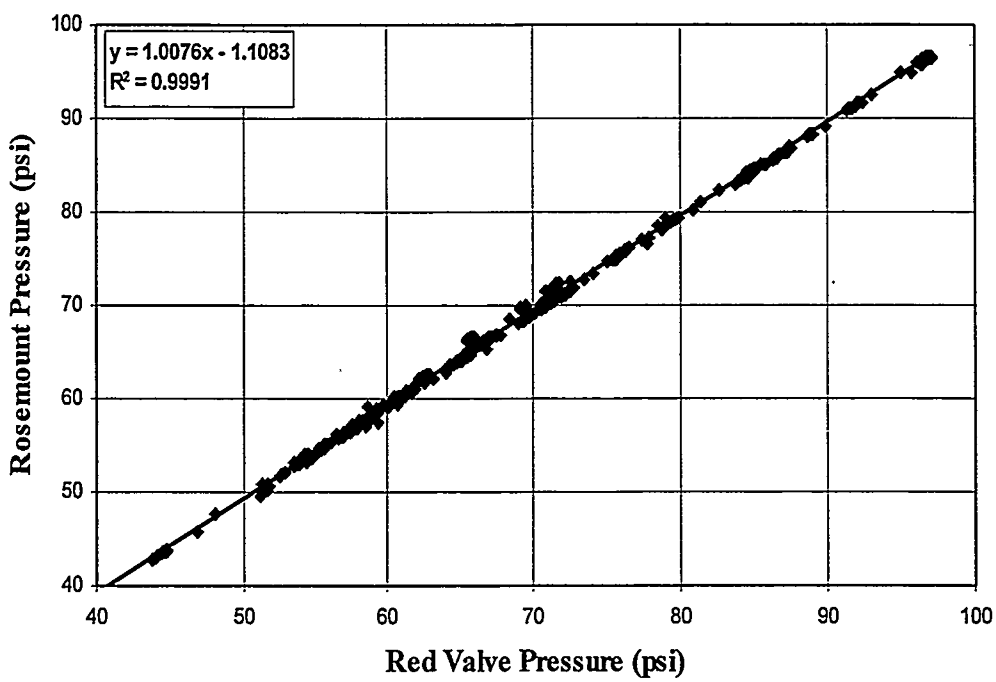

Figure 4.1. Comparison of the Pressure Measured by the Red Valve Pressure Sensor to that Measured by the Direct Tap Rosemount Pressure Sensor (Reynolds et al. 1996)

4.2 241-C-106 Pump Pit Deployment

In 1998, four Red Valve Pressure Sensors (with Sensotech Model AE-213 pressure transducers) were installed before and after the booster pumps of the 4-in. (10.2-cm) slurry (SL-200) and supernatant (SN-200) transfer lines between Tank 241-C-106 and Tank 241-AY-102. Figures 4.2 and 4.3 illustrate the pressure sensor readings from one of the sensors installed in the discharge line of the booster pump in the SL-200 slurry transfer line. The data in these figures were obtained during two recent 12-h operations of the slurry transfer line. These figures show that the sensor responds rapidly to changes in the booster pump discharge pressure. These figures also show that the Red Valve Pressure Sensor is extremely sensitive to variations in the discharge pressure. Note that the pressure fluctuations in these figures are most probably due to changes in the slurry flow to the booster pump and from nitrogen entering the line from the pump pit.

The pressure sensor components in the SL-200 and SN-200 transfer lines are exposed to a total radiation dosage on the order of 300 R/yr. These pressure sensors have been in operation for over 2 yr, and to date, the sensors have been trouble-free according to the operators involved with slurry and supernatant transfer operations. Based on these observations, it is apparent that the Red Valve Pressure Sensors can be installed at the end of the slurry transfer lines and used to measure the pressure drop in the system.

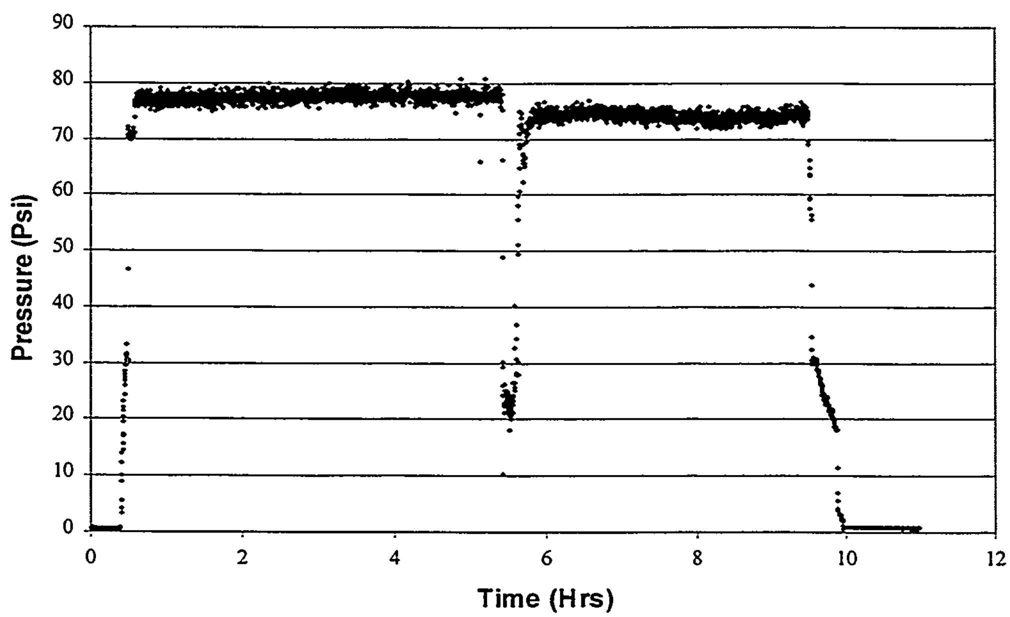

Figure 4.2. Pressure Measurement Data Obtained on September 24, 1999, from the Red Valve Pressure Sensor Installed in the 4-in. (10.2 cm) Discharge Line of the Booster Pump in SL-200 Slurry Transfer Line

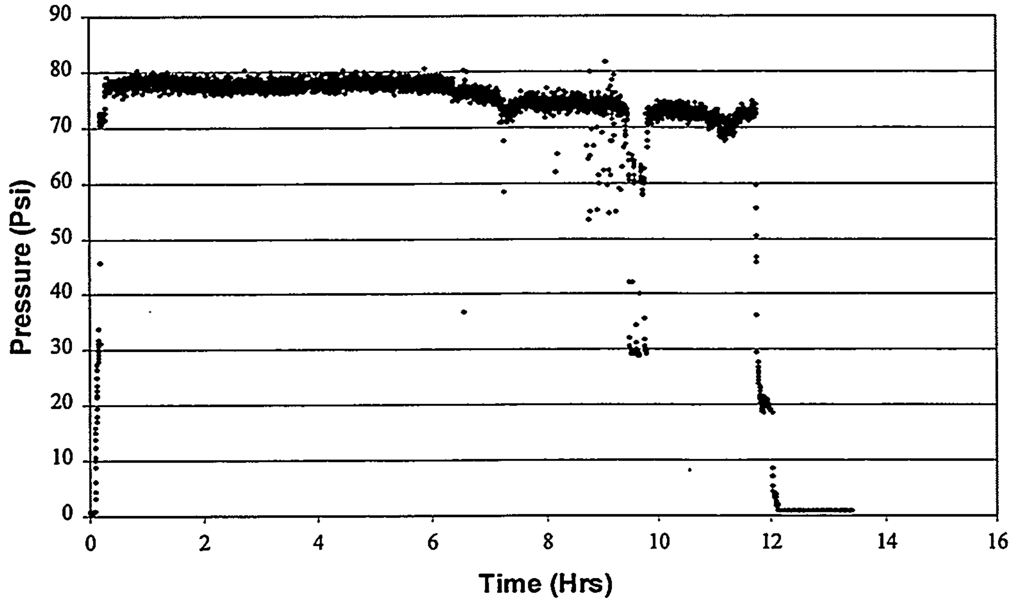

Figure 4.3. Pressure Measurement Data Obtained on September 26, 1999, from the Red Valve Pressure Sensor Installed in the 4-in. (10.2-cm) Discharge Line of the Booster Pump in SL-200 Slurry Transfer Line

5.0 Ultrasonic Densimeter

5.1 Overview of Development

The U.S. Department of Energy Environmental and Waste Management (EM) 50 through the Characterization, Monitoring, and Sensor Technology (CMST) Crosscutting Program initially funded densimeter development for pipeline deployment. In 1997, the initial densimeter configuration (described in Appendix C) was installed in a pipe spool piece, and its performance was evaluated during tests at ORNL (Hylton and Bayne 1999).

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 for monitoring slurry properties during waste transfer from Tank 241-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 241-C-106 transfer line became uncertain. Negotiations between the U.S. Department of Energy Office of Science and Technology Tanks Focus Area and the Hanford Site Office of River Protection SY-101 Surface Level Rise Remediation Project led to development of a Memorandum of Understanding to deploy the densimeter to measure density during waste transfers from Tank 241-SY-101 to Tank 241-SY-102. Preparations for this deployment are continuing, and the densimeter has been incorporated into the prefabricated pump pit module that will be installed at the Hanford Site in FY 2001.

5.1.1 241-C-106 Pump Pit Configuration

To support the Hanford Tanks Initiative, the densimeter was selected for installation in the transfer line between Tank 241-C-106 and Tank AY-102 (Figure 5.1.). The densimeter was to be used to measure the density of the slurry transferred between the two tanks when Project W-340 was implemented. The purpose of Project W-340 was to remove the hard heel remaining on the bottom of the tank after completion of Project W-320, sluicing of the tank to remove mobile solids. It was anticipated that the W-340 transfer would be done in FY1999. To support this deployment, a design for a densimeter spool piece was initiated.

Process parameters defined for this transfer are listed in Table 5.1. A design for a sensor spool piece was developed to meet these operating conditions. The spool piece, shown schematically in Figure 5.2, was designed to be constructed from 4-in. (10.2-cm) Schedule 40, American Society of Testing and Materials (ASTM) 312, Grade 304L stainless pipe using 4-in. (10.2-cm) Class 300-lb ASTM A182 F304L weld-neck flanges with raised face. The overall length (flange-face to flange-face) was 42.2 cm (16.625 in.).

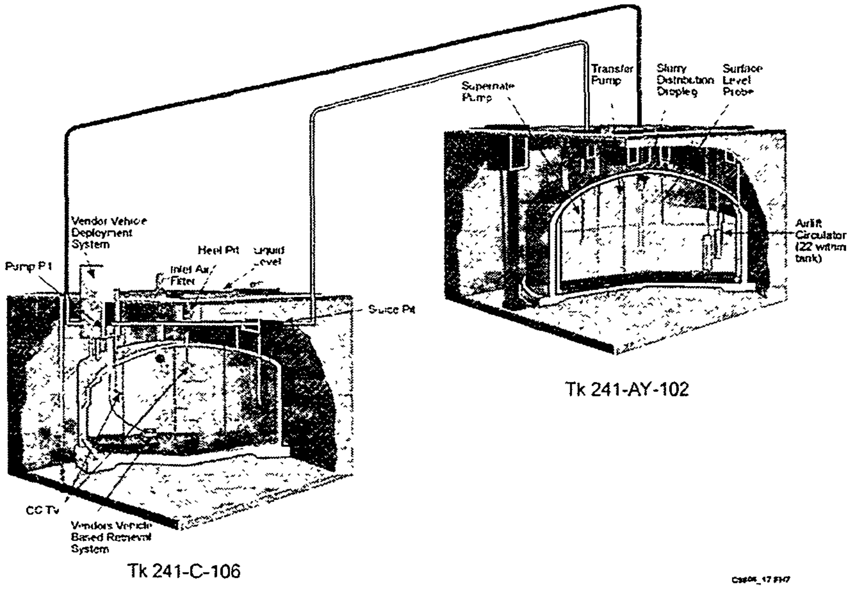

Figure 5.1. Proposed Transfer Configuration from Tank 241-C-106 to Tank AY-102

Table 5.1. Slurry Transport Parameters for Project W-320 and Hanford Tanks Initiative

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 – 1.20	1.15
Percent Solids	0 – 30 wt%	10 wt%
Particle Size	<<1 – 3175 μm[(a)]	50 μm sludge 500 μm hardpan
Radiation	60 R/h inside pipe 40 R/h outside pipe 0.5 R/h 3.04 m (10 ft) away from pipe[(b)]	100 R/h in pipeline

(a) The maximum particle size that can pass through the system is 0.64 cm (0.25 in.).
(b) Calculated using the ISOSHLD code (Engle et al. 1996).

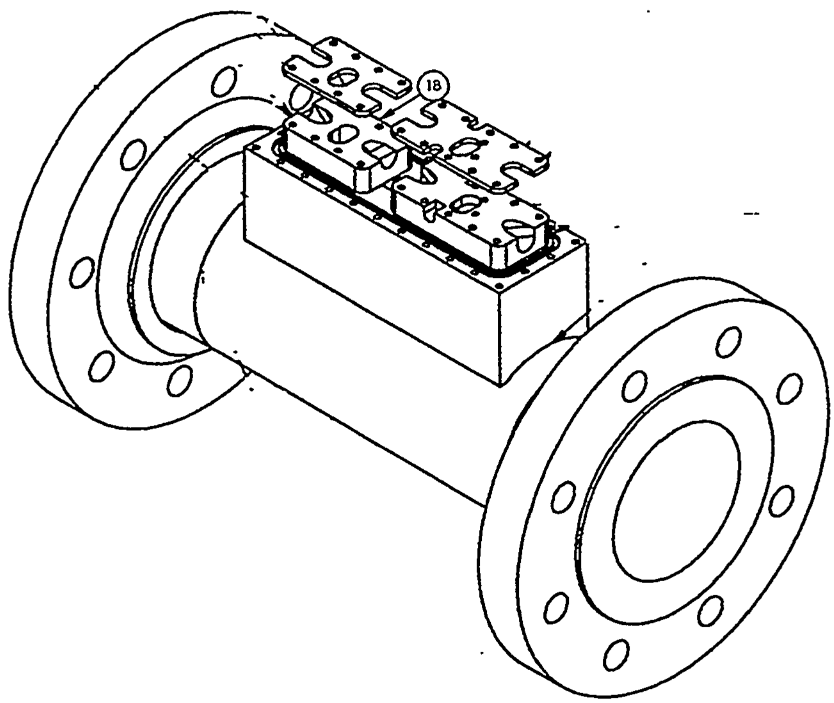

Figure 5.2. Densimeter Configuration for Deployment in the 4-in. (10.2-cm) Transfer Line from Tank 241-C-106 to Tank AY-102

Prior to the probe construction, the project direction changed to support densimeter deployment in the Tank 241-SY-101 2-in. (5-cm) transfer line instead of the Tank 241-C-106 4-in. (10-cm) transfer line.

5.2 Densimeter Configuration for 241-SY-101 Transfer Line

For deployment in the 241-SY-101 transfer line, the densimeter was designed to operate at process operating conditions. Therefore, the probe was designed and constructed to meet the design and operating conditions for the piping system in which it is installed. The process specifications for the densimeter are described. This is followed by the system design, qualification of components, construction, and pressure testing.

5.2.1 Specification for Deployment in the 241-SY-101 Transfer Line

Specifications for densimeter deployment in the 241-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 5.2. 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 Hanford Site Flammable Gas Equipment Advisory Board reviewed the design. This was done to evaluate probe installation and use in an area requiring compliance with Ignition Source Control Set 2. The board ruled[a] that the equipment is 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.

Table 5.2. Densimeter Design and Operational Criteria

Parameter	241-SY-101 Design Criteria	Density Probe
Specific gravity	1.0 to 1.7	Tested over range from 980 to 1800 kg/m^3
Viscosity	0.55 to 600 cP	To be tested over simulant range starting at 1.0 cP
Waste maximum temperature	54°C (130°F)	Components good to 100°C (212°F), calibrated over range from 20 to 60°C (68 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 (230 psi)	Designed to operate at this pressure
Design pressure		2.76 MPa (400 psi)
Remote readout	In DACS trailer	Provide display for density (up to 4 digits kg/m^3) and viscosity (up to 3 digits cP)
ASTM 312 304L	For piping	For piping ASTM A240 304L for pipe saddle
ASME[b] B31.3 Pressure test	At 1.5 x design pressure	4.14 MPa (1.5 x 400 psi = 600 psi)
Spool piece length flange-face to flange-face	Specified by Tony Benegas[a]	48.3 cm (19 in.)
pH	No range specified	Rexolite™ good to pH 14; confirmed by lab tests.
Radiation level	No range specified	100 rad/h in pipeline; tested to $1x10^6$ R total exposure; Rexolite™ good to $1x10^{10}$ rad

(a) Email Communication. From: Tony R. Benegas; Sent: Friday, May 21, 1999 5:33 PM; To: William J. (Bill) Powell and Judith A. Bamberger; Cc: Carl W. Holmes, Joseph R. Buchanan, Raymond E. Merriman, Jerome L. (Jerry)Wilk, Michael F. Erhart, Carl E. Hanson, and Tony R. Benegas; Subject: RE: Densimeter orientation in pipe line.
(b) ASME = American Society of Mechanical Engineers.

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

5.2.2 Design

To meet the design pressure requirement of 2.76 MPa (400 psi) and the pressure test requirement of 4.14 MPa (600 psi), the probe (shown in Figure 5.3) 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. The transducer wedges differ from the design shown in Figure C.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. 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). In this design, an additional transducer G was incorporated into the system. This transducer is oriented to measure the reflected signal at an air-wedge interface and provides a real-time reference not affected by the fluid.

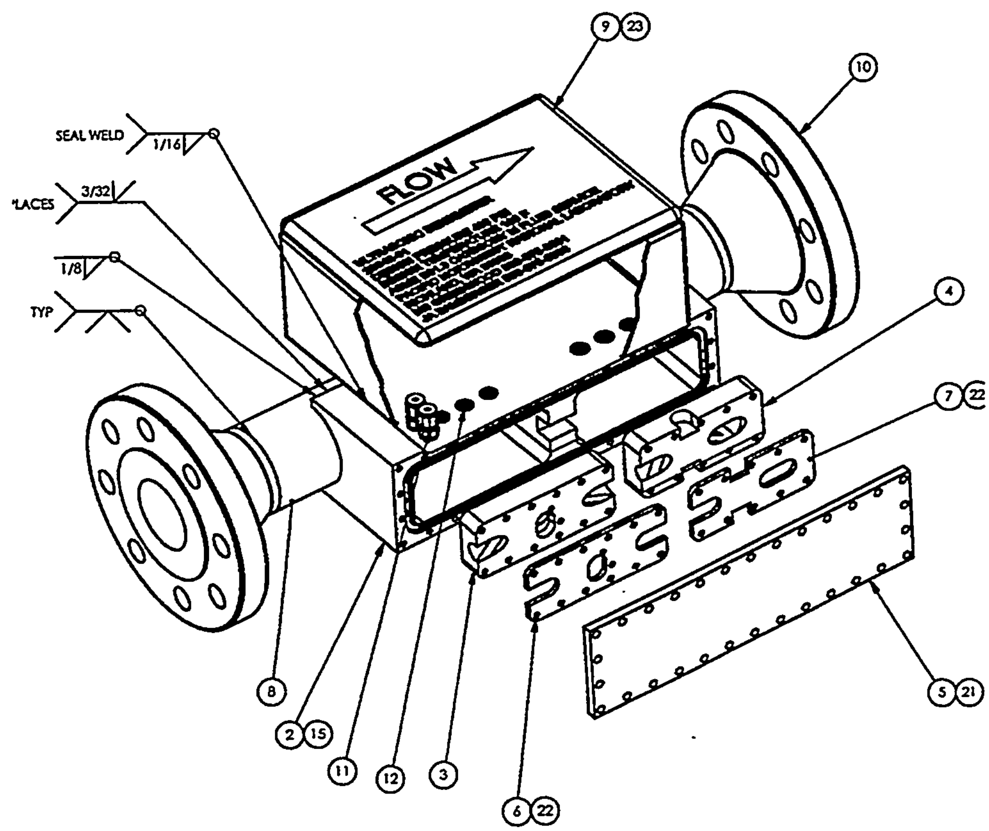

Figure 5.3. Densimeter Components Showing Spoolpiece (8, 10) Wedges (3 – 60 Degree, 4 – 47 Degree), and Electrical Connection Box (9, 23)

The wedges, which penetrate through the wall of the pipe, are shown in Figure 5.4. In-the direction of flow, the wedges are machined flush with the diameter of the pipe and tapered toward the area where the ultrasonic beam, which is flat, is reflected. To incorporate transducer A (the shear wave transducer) at the downstream end of the 47-degree wedge, this interface was not machined to provide a flat surface for beam reflection.

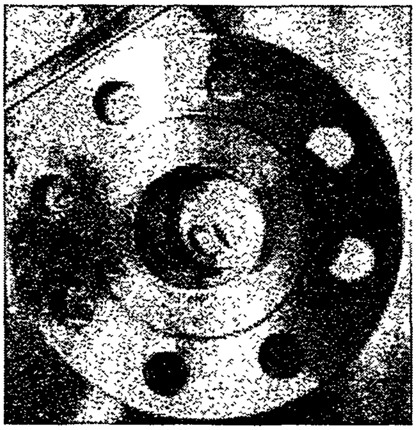

Figure 5.4. View of 47-Degree and 60-Degree Wedges from the Downstream End of the Spool Piece

5.2.3 Materials Qualification

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 were tested in a gamma radiation field and in a chemical waste simulant.

5.2.4 Pressure Test

After the transducers, O-rings, and cover plates (shown in Figure 5.5) were installed, the probe assembly was pressure tested. The pressure test was conducted in accordance with ASME Process Piping Code Section B31.3.

5.3 Qualification Testing at PNNL

In 1999, the performances of two densimeters were evaluated during pipe-loop tests in the IVF at PNNL. The purpose of the tests was to evaluate densimeter performance over a range of operating conditions including transport of water, viscous liquids, and slurry.

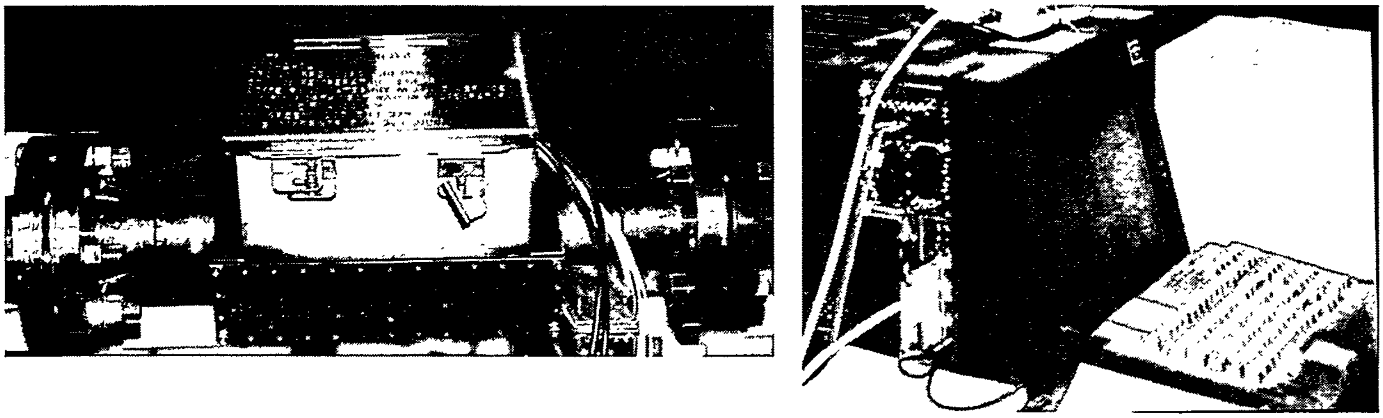

Figure 5.5. Densimeter and Computer Controller

5.3.1 Instrument Validation Facility

The IVF is located on the ground and mezzanine levels of the 336 Building at PNNL. The test facility includes a centrifugal pump and a feed tank with an adjustable mixer. A schematic drawing of the loop is shown in Figure 3.1. The two densimeters were installed in series in the ideal loop in place of the item labeled "Pressure Tap" in Figure 3.1.

5.3.2 Analytical Instrumentation

The density of the slurry was periodically measured using a 100-mL pycnometer. Samples were taken through ports S-3 on the upstream leg of the pipe loop and S-4 on the downstream leg of the pipe loop; the densities of 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.

5.3.3 Process Flow Measurements

The slurry temperature and volumetric flow rate were measured continuously during the tests using the Yokagawa flow meter.

5.3.4 Test Matrix

The test matrix was designed to evaluate the density of water, the density of fluids with densities greater than water, and densities 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 5.3.

Table 5.3. Range of Fluid Properties Evaluated During Pipe Loop Tests

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

5.3.5 Test Procedure

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 a 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 5.4. After the completion of the water tests, sugar was added to the feed tank in 50-lb increments (two 25-lb bags). In addition to the mixer installed in the feed tank, the pump heat and the flow rate were used to dissolve the sugar and mix it throughout the loop. After the sugar was added, a period of ~15 to 20 min elapsed to mix the addition thoroughly, and then grab samples to measure the density of the fluid were obtained. After the addition of all the sugar was completed, the loop operated overnight. The next day, the kaolin was added in 100-lbm increments (two 50-lb bags) to the sugar water mixture. After each addition of kaolin, a density measurement was made.

Table 5.4. Test Sequence and Range of Operating Parameters

Fluid	Duration (hr)	Temperature Range (°C)	Flow Rate Range m^3/min (gpm)
Water	20	50.8 – 53.8	0.33 (87)
Sugar Water	24	48.4 – 50.0	0.32 – 0.33 (86 – 77)
Kaolin in Sugar Water	5	54.7 – 57.8	0.26 – 0.33 (68 – 86)

5.3.6 Data

Voltages received from the densimeter transducers 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 taken in the 336 building were analyzed to further understand the effects of the difference in the input voltage levels for the two locations. From these data, densities were calculated using two methods, based on data from the 0- and 60-degree sensors (transducers FF and DE) and based on data from the 0-, 47-, and 60-degree sensors (transducers FF, BC, and DE). These calculated densities were compared with the densities obtained from the grab samples. These results are summarized in Table 5.5.

Table 5.5. Results of the Densimeter Probe Testing at the IVF at PNNL

Liquid	Date	Time	Density by Wt (kg/m^3)	0 and 60° Solution		0, 47, 60 χ^2 Solution	
				Density (kg/m^3)	Error (%)	Density (kg/m^3)	Error (%)
Sugar Water	12/10/99	11:18	1005	997	-0.8	994	-1.1
		11:30	1020	997	-2.3	992	-2.7
		11:44	1032	1018	-1.4	1017	-1.5
		12:16	1048	1036	-1.1	1035	-1.2
		13:40	1061	1068	0.7	1068	0.7
		13:52	1073	1086	1.2	1085	1.1
		14:03	1085	1091	0.6	1090	0.5
		14:13	1096	1109	1.2	1109	1.2
		14:30	1100	1114	1.3	1114	1.3
Sugar Water	12/11/99	10:38	1100	1129	2.6	1153	4.8
Sugar Water	12/11/99	10:55	1130	1142	1.1	1167	3.3
+ Kaolin		11:29	1165	1170	0.4	1196	2.7
		11:50	1199	1197	-0.2	1231	2.7
		12:18	1226	1217	-0.7	1247	1.7
		12:40	1269	1236	-2.6	1272	0.2
		13:01	1325	1325	0.0	1363	2.9
		13:30	1384	1353	-2.2	1395	0.8
		14:29	1425	1363	-4.4	1424	-0.1
		15:00	1425	1371	-3.8	1417	-0.6
		15:35	1455	1359	-6.6	1422	-2.3

5.3.7 Path Forward

Based on the results obtained during the pipe-loop tests at the 336 building and the understanding of effects of input voltage, additional calibration data were obtained over a range of temperatures, fluid densities, and input voltage levels $\pm$10% about the mean voltage for both Probe 1 and Probe 2. This understanding will be incorporated into the assessment of sensor performance during the pipe-loop tests in the 305 building.

5.4 Deployment

The densimeter system is planned for deployment in the 241-SY-101 prefabricated pump pit modified process manifold (Witwer 1999). This equipment supports the SY-101 cross-site connection project, which will provide the capability of using the 241-SY-101 transfer pump to directly transfer waste from Tank 241-SY-101 across the site.

5.4.1 Densimeter Installation in the Modified Process Manifold

To support deployment, the densimeter has been installed in the modified process manifold. Two densimeters are currently installed in this manifold as shown in Figure 5.6. 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 during the test sequence that is currently planned. Densimeter 2 will be removed after testing and will be not installed in the site. Both densimeters were included in the system when it was pressure tested at 4.13 MPa (600 psi). To ensure that the densimeter is in contact with the slurry, the densimeters are to be installed at the 3-o'clock position or lower when observed from the upstream end. Densimeter 1 on the left is installed at the ~4-o'clock position to accommodate the hole pattern of the densimeter flange and its mating flange in the manifold. Densimeter 2 is installed in the 3-o'clock position.

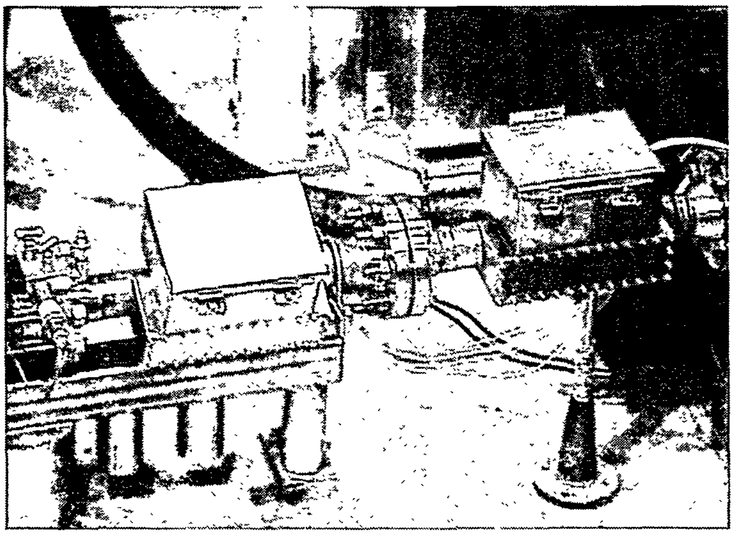

Figure 5.6. Densimeter 1 (left) and Densimeter 2 (right) Installed in the Modified Process Manifold

5.4.2 Densimeter Evaluation in the Modified Process Manifold

The complete process manifold is visible as the steel piping in the center of Figure 5.7. The test system includes the manifold, centrifugal pump, and tank. In addition, a Coriolis mass flow meter installed downstream from the densimeter is being used to provide a second real-time measure of slurry density. The Coriolus mass flow meter is visible as the large rectangular spool piece with attached steel case behind the densimeters. An item this large would be difficult to retrofit into existing pump pits on the Hanford site. The size of the densimeter is very attractive to permit retrofit installation in existing pump pits at the Hanford site. Tests of the densimeters installed in the process manifold are planned over a range of water, sugar water, and kaolin clay in sugar water mixtures. The data will provide an *in situ* calibration verification for the densimeter assembly based on its installation in the process manifold.

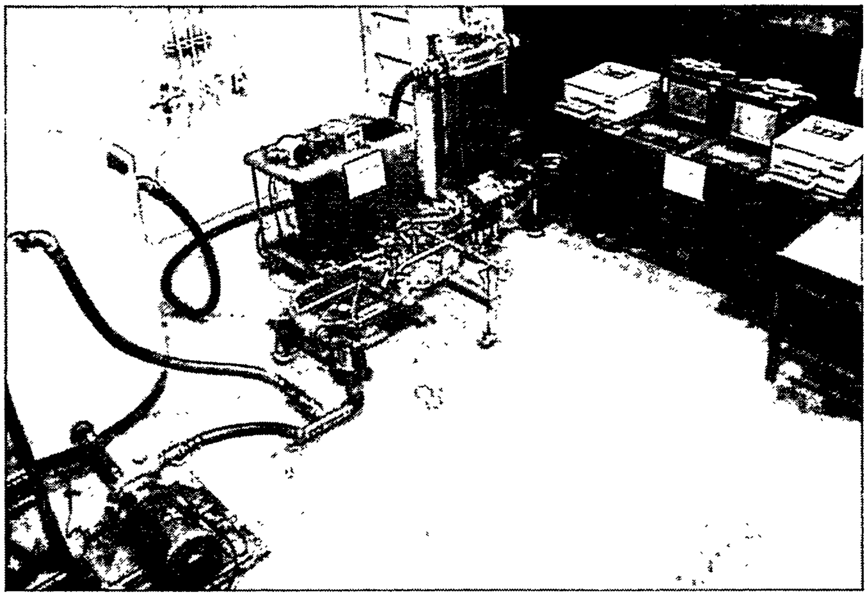

Figure 5.7. Densimeter Evaluation Process Manifold

6.0 Economic Assessment

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.

6.1 Investment of the ASTD Project

A summary of the overall funding for the project with the associated costs of PNNL, ORNL, and Lockheed/Fluor Daniel Hanford are provided in Table 6.1.

Table 6.1. ASTD Project Funding for the Slurry Monitoring Instrument Development and Qualification Testing

	Project (K)	Spent (K)	Organization	Carryover (K)
FY98	$220	$179	34.3 PNNL (Lasentec Acceptance Testing) 145 Lockheed/FDH[a] (85K Lasentec; 25K Red Valve)	$41
FY99 and FY00	$510	$551	411 PNNL (15K to ORNL; 25K Slurry Loop Modification & Red Valve Testing; 275K Densitometers for SY-101, 96K PM and FY99 and FY00 Report) 67 Lockheed/FDH/CHG[b]	$0
Total	$730	$730	445 PNNL 285 Lockheed/FDH/CHG (~105K Equipment)	$0

(a) FDH = Fluor Daniel Hanford
(b) CHG = CH2M Hill Hanford Group, Inc.

6.2 Slurry Monitoring Costs

Table 6.2 shows the expected life cycle costs (equipment procurement costs, calibration, installation and maintenance) for the deployment of the Lasentec M600 particle size analyzer, Red Valve Pressure Sensor, and the Ultrasonic Densitometer.

6.3 Cost Savings At Hanford

The slurry monitoring instruments tested in this project could be installed during the slurry-transfer operations associated with Project W-523, Project W-521, Project W-211, and Salt Well Pumping. Installing three additional slurry-monitoring instruments on a transfer line would cost about $250,000. These instruments provide process information that could prevent plugging of the (1) 1500-ft transfer line from SSTs to DSTs (Project W-523), (2) 300-ft transfer line between the DSTs (Project W-211), and (3) 7200-ft transfer line from tank farms to the vitrification plant (Project W-521).

Table 6.2. Life Cycle Costs for Deployment of the Various Slurry Monitoring Equipment

Item	Lasentec M600[a] (K)	Red Valve Pressure Sensor[a] (K)	Ultrasonic Densimeter[b] (K)
Capital Equipment	85	25	19
Calibration	5	3	5
Installation	30	30	30
Operation and Maintenance	6	6	6
Total	**126**	**64**	**61**

(a) Cost data for the Calibration, Installation, and Operation and Maintenance are taken from the Innovative Technology Survey Report (ITSR 1999).

(b) See Appendix C for Details.

The various volumes of fluid transferred during each project are listed in Table 6.3, and costs associated with hot tie-ins for pipeline replacement are presented in Table 6.4. Costs associated with vitrification plant idle time for Project W-521 are listed in Table 6.5. Total costs associated with the replacement of the blocked pipelines and maintaining idle employees during the downtime are presented in Table 6.6. The cost data in Table 6.6 do not include the costs for grab-sampling analysis due to insufficient information regarding the number of samples collected during each transfer operation. Typical grab-sampling costs and analysis costs can be on the order of several thousands of dollars per sample. Avoiding this expenditure could result in further savings because of the installation of the various slurry-monitoring instruments.

Table 6.7 summarizes the cost savings from including the three pieces of slurry-monitoring equipment. The cost analysis indicates that for Project W-521, about $2,000,000 could be avoided in repair costs and lost production in tank farms. This in turn could affect the operation of the vitrification plant. Costs for idling the vitrification plant are significant and could run up to $10,000,000. Other projects at the Hanford site, such as W-523, could avoid unplugging costs in excess of $1,000,000.

Table 6.3. Expected Volumes of Feed Processed for Various Projects During Phase 1[(a)]

Feed Tank(s)	Staging Tank	Project	Volume (ML)	Volume (Gal)
AZ-101	AZ-101	W-521	3.05	805,812
AY-101/C-104	AY-101	W-521	3.37	890,357
AN-104/AW-103	AW-104	W-521	3.06	808,454
			Total for W-521	**2,504,623**[(b)]
AZ-102	AZ-102	W-211	3.23	853,369
AY-102/C-106	AY-102	W-211	2.08	549,538
SY-102	AZ-101	W-211	2.08	549,538
			Total for W-211	**5,857,332**[(c)]
C-107/AW-103	AY-102	W-523	3.2	845,443
			Total for W-523	**8,454,425**[(d)]

(a) Data Taken from Tables 3-1.1 and 4.1-1 of Kirkbridge (2000)
(b) The volume of waste transferred for Project W-521 was not escalated since majority of the costs are associated the long transfer line between the tank farms and the vitrification plant which happens in a single pass
(c) The volume of waste transferred for Project W-211 was assumed to be a factor of 3 (could be as high as a factor of 5) greater in order to account for staging discussed in the introduction section.
(d) Assumed to be a factor of 10 greater than the total volume of slurry transferred based on present slurry-transfer operations during W-523, which is typically on the order of ~350 gpm for 90 days at 12 h/day (this includes transfer of supernate from Tank AY-102 to Tank C-107).

Table 6.4. Itemized Costs for Hot Tie-ins to Repair Plugged Pipelines at Hanford (Boyen et al. 1998)

Item	Cost ($)
Excavation Permit	10,000
Construction Permit	34,000
Multiple Flushing of the Line	10,000
Evaporation of Flush Water	10,000
Design and Drawing Changes	10,000
Excavation	30,000
Greenhouse	60,000
Cut and Tap Lines	5,000
Install Supports	20,000
Pressure Test	25,000
Install Cathodic Protection	14,000
Cathodic Protection Testing	2,000
Back Fill	6,000
Remove Greenhouse	6,000
Radioactive Waste Disposal	20,000
Total	**300,000**

Table 6.5. Itemized Costs for Vitrification Plant Idle Time (Project W-521 only)

Item	Unit
Average Duration (Days)	180 Days
Number of Idled Vitrification Plant Employees	325
Hours per Day	8 h
Charge Rate	$75/h
Cost For Vitrification Plant Idle Time per Blockage	**$35,000,000**

Table 6.6. Potential per Plugging Pipeline Event at Hanford During Phase 1 Operations[(a)]

Cost Item	Project			
	W-523	W-521	W-211	Salt Well Liquor
A. Cost For Pipeline Replacement per Blockage				
A1. Transfer Line Length	1,500-ft	7200-ft	300-ft	300-ft
A2. Cost of Pipeline Replacement per Foot	$1,000	$1000	$1000	$250
A3. Cost of Pipeline Replacement per Blockage (= A1 x A2)	$1,500,000	$7,200,000	$300,000	$75,000
B. Cost for Hot Tie-ins (From Table 6.4) per Blockage	$300,000	$300,000	$300,000	$300,000
C. Cost for Downtime per Blockage				
B1. Average Blockage Duration (Days)	90	180	90	30
B2. Number of Idle Employees	6	12	3	3
B3. Hrs per Day	8	8	8	8
B4. Charge/h	75	75	75	75
Cost of Maintaining Idle Employees	*$324,000*	*$1,296,000*	*$162,000*	*$54,000*
D. Cost of Plugging per Event per Project = Pipeline Replacement Cost + Cost for Hot Tie In + Cost for Maintaining Idle Employees	**$2,124,000**	**$8,796,000**	**$762,000**	**$429,000**
E. Cost of Plugging Event Including Vitrification Plant Idle Time (Table 6.5; Project W-521 only)		**$43,796,000**		
F. Total Cost per Plugging Events During Phase 1 Operations = Total Cost of per Plugging Events for W-523 + W-521 + W211 + Salt Well Pumping (Excluding Vitrification Plant Idle Time – Project W-521 only)				**$12,111,000**

(a) Costs rounded to the nearest $1000.
(b) Data from Table 6.3.
(c) Potential number of blockages was assumed to be 0.1 due to insufficient information on the total volume of waste processed.
(d) Personnel Communication from L. A. Fort to E. A. Daymo 10/97.

Table 6.7. Cost Savings and Return of Investment for the Deployment of the Three Slurry Monitoring Instruments at Hanford

	W-523	W-521	W-211	SWP
Total Cost of Plugging per Event During Phase 1 Operations[a]	$2,124,000	$8,796,000 ($43,796,000)[b]	$762,000	$429,000
Volume of Waste Transferred[c]	8,454,425	2,504,623	5,857,332	No Info Available
Potential Number of Blockages (1% for every 100,000 Gal Processed)[d]	0.85	0.25	0.59	0.6[e]
Total Cost at 1% Probability of Plugging for every 100,000 Gal Processed = Potential Number of Blockages x Cost per Blockage	$1,805,000	$2,199,000 ($10,949,000)[b]	$450,000	$257,000
Cost of Slurry Monitoring Instrument Deployment[f]	$250,000	$250,000	$250,000	$250,000
Cost Savings[g]	**$1,555,000**	**$1,949,000 ($10,699,000)[b]**	**$200,000**	**$7,000**
Return of Investment for $730,000 ASTD Investment[h] (Minus Net Assets of Hardware of Lasentec and the Densimeter = $90,000)	**2.43**	**3.05 (16.7)[b]**	**0.31**	**0.01**
Return of Investment per Year[i]	**243%**	**33.9%**	**3.44%**	**0.33%**

(a) From Table 6.6, Row D.
(b) With Vitrification Plant Idle Time
(c) From Table 6.3
(d) Personnel Communication from L. A. Fort to E. A. Daymo 10/97.
(e) Assumed to be 0.6 due to insufficient information on the total volume of waste processed
(f) From Table 6.2
(g) Cost Savings = Total Cost of Pipeline Plugging – Cost of Slurry Monitoring Instruments
(h) **Return Of Investment = (Total Cost of Plugging Event – Cost of Slurry Monitoring Instrument Deployment)/ASTD Project Investment.**
(i) Operation times for Project W-523, W521, W-211, and Salt Well Pumping are estimated to be 1, 9, 9, and 3-yrs, respectively.

6.4 Cost Savings At ORNL

A cost analysis associated with the ORNL operations was provided by PNNL and reported in ITSR (1999). For the sake of continuity, the analysis for inclusion of just the Lasentec Particle Size Analyzer is presented in Table 6.8.

Table 6.8. Potential Cost Savings at ORNL

Cost Item	Estimate
A. Cost For Pipeline Replacement per Blockage[a]	
A1. Transfer Line Length (ft)	100
A2. Cost of Pipeline Replacement per Foot ($)	1,000
A3. Cost of Pipeline Replacement per Blockage (= A1 x A2) ($)	100,000
A4. Volume of Waste Transferred (gal)	420,000
A5. Potential Number of Blockages	1.00
Pipeline Replacement Cost = Potential Number of Blockages x Cost of Repair per Blockage	***$100,000***
B. Cost for Downtime per Blockage[a]	
B1. Average Blockage Duration (Days)	10
B2. Number of Idle Employees	20
B3. Hrs per Day	8
B4. Charge/h ($)	100
Cost of Maintaining Idle Employees	***$160,000***
C. Sampling Costs[a]	**$37,000**
D. Radiological Analytical Costs[a]	**$148,000**
E. Downtime During Analysis[a]	**$302,000**
F. Total Cost	**$747,000**
G. Cost of Slurry Monitoring Instrument Deployment[b]	**$126,000**
H. Total Cost Savings	**$621,000**

(a) For specific details, see ITSR (1999).
(b) Lasentec Particle Size Analyzer Only

6.5 Impact of ALARA on the Cost Estimate

The impact of ALARA (As Low As Reasonably Achievable) is not included in the cost estimate. 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, W-320 Sluicing of 241-C-106, incurred 25 person rems during construction. Construction of Project W-320 included installation of a 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.

7.0 References

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Appendix A

Details of Lasentec Particle Size Analyzer

Appendix A – Details of Lasentec Particle Size Analyzer

The Lasentec M600 is an in-line analyzer that was developed by Laser Sensor Technology, Inc., Redmond, Washington, for measuring chord-length distribution of suspended solid particles. Although chord length and particle size are not exactly equivalent terms, there is a direct correlation between the two. For the purposes of the testing performed, the Lasentec M600 was used to evaluate the particle size distribution of the suspended solid particles in the slurries. As such, the instrument will be referred to as a particle size analyzer elsewhere in this report. This instrument uses a technique known as Focused Beam Reflectance Measurement (FBRM) to provide continuous in-process and real-time measurement of the rate and degree of change of the particle dimension and particle count. A schematic of the FBRM probe tip consisting of a laser beam source, rotating optics, and a sapphire glass window is shown in Figure A.1.

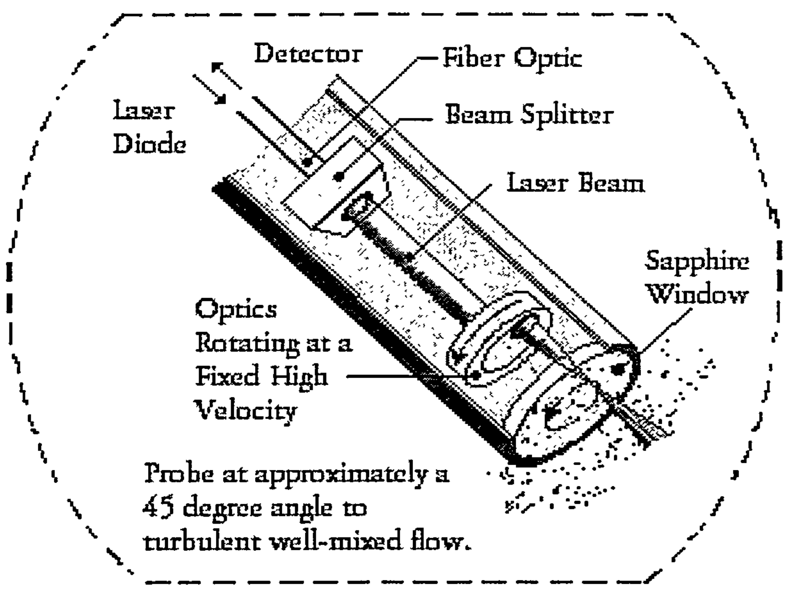


Figure A.1. Schematic of the FBRM Probe Tip©; Copyright 1999, Laser Sensor Technology, Inc., Reprinted with Permission

The most intense part of the focused beam (or beam waist) is approximately 2 μm in dimension and 10 μm in depth. The light intensity is distributed across the cross section of the beam spot in Gaussian fashion with the center being more intense than the edges. The focal point, which is just outside the probe window, is rotated around the window at a linear velocity of 2 m/s. When the focal point intersects the edge of a particle, the particle begins to backscatter light as shown in Figure A.2. The particle continues to backscatter light until the focused beam has reached the edge of the particle. This backscatter is collected by the FBRM optics and converted into an electronic signal. A unique discrimination circuit is then used to isolate the time period of backscatter from one edge of an individual particle to its opposite edge. This time period (t) is multiplied by the scan speed (v), to yield a distance or chord length (c), according to the following equation:

$$c = v \times t \tag{3.1}$$

The chord length, *c,* in Equation 3.1 is the straight-line distance between any two edges of a particle and is a function of the particle shape. Typically, thousands of chord lengths are measured per second and counted by the FBRM electronics. The resulting chord length by number distribution is a robust thumbprint of the particle size distribution in the slurry. Any change in the size distribution will have a corresponding change in the chord-length distribution.

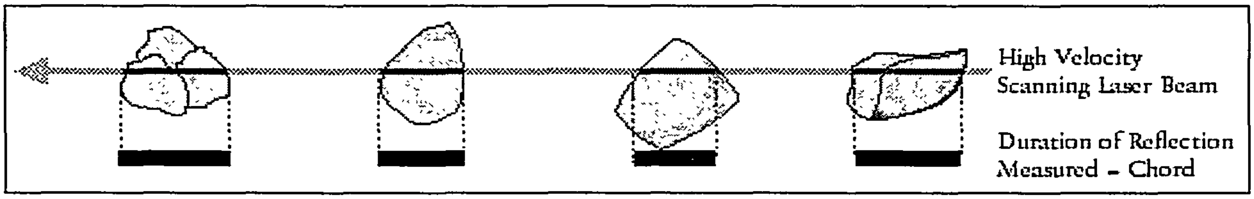


Figure A.2. FBRM Approach for Measuring the Chord Length Using Lasentec Chord Length Analyzer©; Copyright 1999, Laser Sensor Technology, Inc., Reprinted with Permission

The electronics associated with the Lasentec monitor "sort" the measured chord lengths into 38 "bins." The "bins" are on a log scale from 1.9 μm to 1000 μm with an extended bottom "bin" from 0.8 μm to 1.9 μm and an extended top "bin" for counts greater than 1000 μm. At the end of the user-defined measurement duration (between 2 s and 5 min), the Lasentec software constructs a histogram of the measured chord lengths from the number of particles classified in each "bin." Figure A.3 is an example of the chord-length distribution obtained with the Lasentec monitor during instrument validation tests at Pacific Northwest National Laboratory (PNNL).[(a)]

The software that accompanies the Lasentec monitor not only calculates the mean particle size, but also the length, length-squared, and length-cubed weighted mean values. Each weighted mean particle size value is, successively, more heavily influenced by the presence of large particles than the unweighted mean particle size value. The mean particle size data presented in this report are either the "unweighted mean particle size" or the "length-cubed weighted mean particle size." The mean size is the most familiar particle size statistic for operators, and the length-cubed weighted mean is the most sensitive to changes on the course end of the distribution, our primary area of investigation. The unweighted mean particle size is defined as

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

$$\overline{C}_u = \frac{\sum_{i=1}^{k} Y_{i,u} M_i}{\sum_{i=1}^{k} Y_{i,u}} = \frac{\sum_{i=1}^{k}\left[\left(\frac{n_i}{\sum_{i=1}^{k} n_i}\right) M_i\right]}{\sum_{i=1}^{k}\left(\frac{n_i}{\sum_{i=1}^{k} n_i}\right)} = \frac{\sum_{i=1}^{k} n_i M_i^1}{\sum_{i=1}^{k} n_i M_i^0} \tag{3.2}$$

where

n_i = Counts in an individual measurement channel
(there are 38 channels over the 0.8- to 1000-μm range of the Lasentec monitor)
M_i = Midpoint size of an individual channel
Y_i = Percentage (%) of counts per channel
$\overline{C}_u$ = Unweighted mean particle size
k = Upper channel # ($2 \le k \le 38$)
u = Unweighted value.

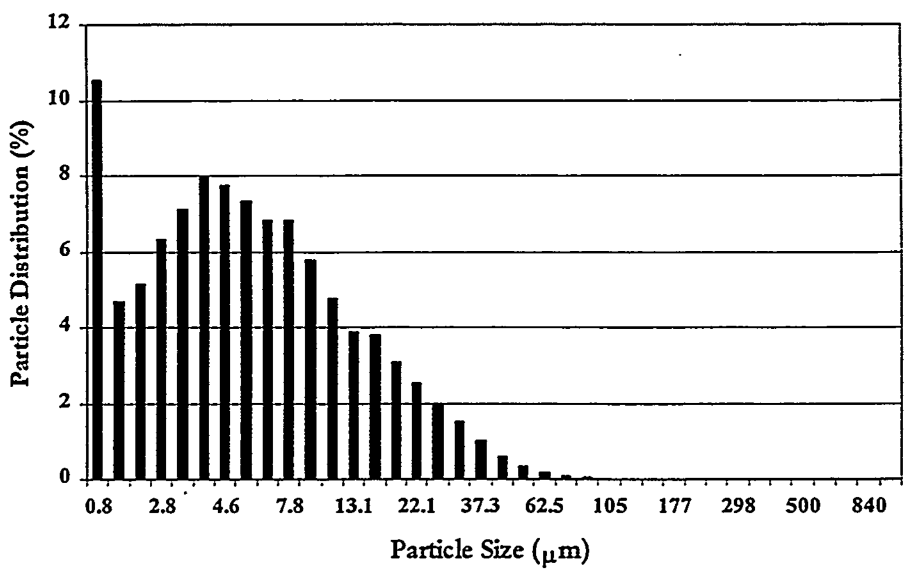


Figure A.3. Typical Chord Length Distribution from an in-line Lasentec FBRM Monitor Obtained at PNNL Using a 30 vol% Gibbsite/Graphite Slurry at a Slurry Velocity of 1.8 m/s (Daymo et al. 1998)[(a)]

(a) E. A., Daymo, G. R. Golcar, and L. K. Jagoda. *Alternate On-Line Slurry Measurement Techniques.* Letter Report, Pacific Northwest National Laboratory, Richland, Washington (1996).

Similarly, the length-cubed weighted mean is defined as

$$\overline{C}_c = \frac{\sum_{i=1}^{k} Y_{i,c} M_i}{\sum_{i=1}^{k} Y_{i,c}} = \frac{\sum_{i=1}^{k} \left[\left(\frac{n_i M_i^3}{\sum_{i=1}^{k} n_i M_i^3} \right) M_i \right]}{\sum_{i=1}^{k} \left(\frac{n_i M_i^3}{\sum_{i=1}^{k} n_i M_i^3} \right)} = \frac{\sum_{i=1}^{k} n_i M_i^4}{\sum_{i=1}^{k} n_i M_i^3} \tag{3.3}$$

where

$\overline{C}_c$ = length-cubed weighted mean particle size
c = length-cubed value.

The Lasentec monitor does not directly account for the velocity of particles as they pass the monitor. To offset this effect, the focal point is scanned at 2 m/s. In addition, the manufacturer recommends that the probe be installed in a vertical up-flow section of pipe with the probe window positioned at a 45° angle to the flow. The 2 m/s scan compensates for fluctuations in the slurry velocity (at average slurry velocities of 1.8 m/s or slower), whereas the angle of the probe slows the particles in the measurement zone. The slurry flow should also be turbulent because turbulence mixes the particles in the pipe and ensures that "uniformly random" material is presented to the probe window.

According to the manufacturer, in a process with a slurry velocity greater than 1.8 m/s, the flow speed should be held constant, so there is a linear offset to the measured data. That is, if the slurry velocity is greater than 1.8 m/s, there is less time for the Lasentec monitor to reflect light off a given particle than if the slurry were traveling at a velocity less than 1.8 m/s. To the Lasentec monitor, if light is reflected off the surface for a shorter period of time, the particle appears smaller. Likewise, the measured particle size would be greater if the velocity is decreased to a new velocity that is still greater than 1.8 m/s. If the flow speed is greater than 1.8 m/s and fluctuates with time, an external flow-speed measurement should be provided to the Lasentec FBRM electronics for a real-time correction to the shift in measured particle size.

Reference

E. A. Daymo, T. D. Hylton, and T. H. May. 1998. "Acceptance testing of the Lasentec Focused Beam Reflectance Measurement (FBRM) monitor for slurry transfer applications at Hanford and Oak Ridge." In: *SPIE Conference on Nuclear Waste Instrumentation Engineering,* Vol. 3536, pp. 82–92.

Appendix B
Details of the Red Valve Pressure Sensor

Appendix B – Details of the Red Valve Pressure Sensor

The Red Valve Pressure Transducer is widely used in the nuclear field. The differences between the conventional and the Red Valve Pressure Sensor are shown in Figure B.1. Unlike conventional pressure sensors where the slurry travels through a Bourdon tube to act against the sensor's diaphragm, in the Red Valve Pressure Sensor, a silicone fluid acts as an intermediate transmitting fluid so that the slurry never contacts the sensor's diaphragm. The line pressure is sensed 360° through the flexible rubber sleeve. The captive fluid is displaced through the pressure sensor body to the instrument's Bourdon tube. All instruments are isolated and protected from the process, assuring positive and accurate readings.

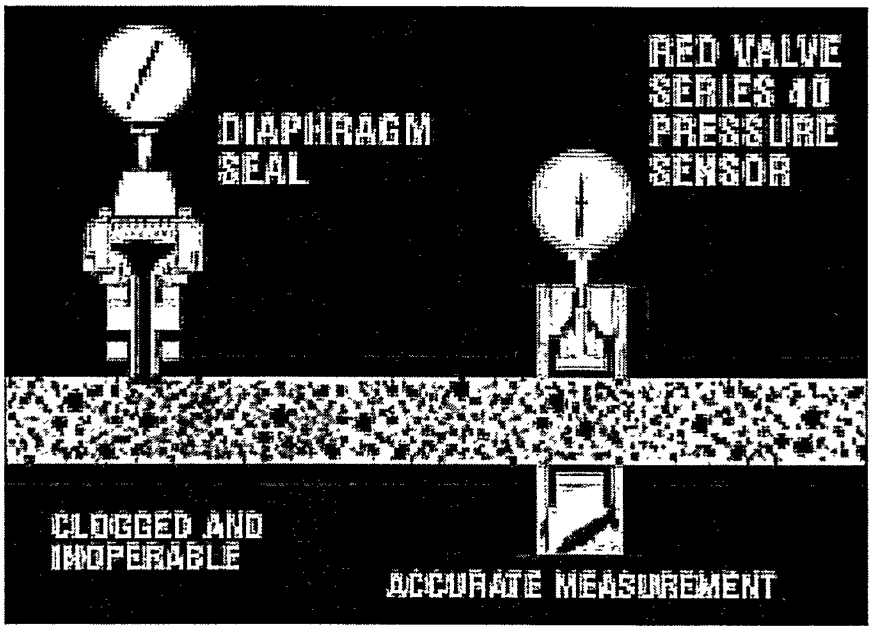


Figure B.1. Schematic Representation of the Function of Conventional and Red Valve Pressure Sensors

It should be noted that the Red Valve sensor unit is a sealed system. These sensors must be properly filled with the sensing fluid and sealed before any pressure is applied. If the sensor is dismantled or removed after installation, air could be introduced into the sensing fluid, which can cause inaccurate readings. Therefore, great care must be taken to eliminate air in the system during installation. Also, users should be aware that the sensing fluid could enter the process stream if the elastomer supporting the sensing fluid should happen to breach.

Appendix C

Details of the Ultrasonic Densimeter

Appendix C – Details of the Ultrasonic Densimeter

C.1 Background

The on-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; Greenwood and Harris 1999). 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 the presence of air bubbles or partially fully 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 to determine the density of the contents, and several sensors at different elevations and radial locations in the vessel can be used to determine its homogeneity. 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.

C.2 Densimeter Theory

The ultrasonic density sensor, shown schematically in Figure C.1, consists of longitudinal (B, C, D, E, and F) and shear wave (A) transducers mounted upon a Rexolite™[(a)] wedge. Analysis of the signals reflected from the wedge-fluid interface is used to determine the fluid properties of density, speed of sound, and viscosity. 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 receiving transducer, is dependent upon the densities and sound speeds in the liquid and the wedge material. The reflection coefficient is measured by comparing the voltage on the receiving transducer when the base is immersed in the liquid to that when it is immersed in a reference liquid, usually water. The sensor operates by measuring the reflection coefficient at two angles of incidence and solving for the density of the liquid and speed of sound in the liquid, based upon previously determined properties of the wedge material.

[a] C-LEC Plastics, Inc. 215-708-7731

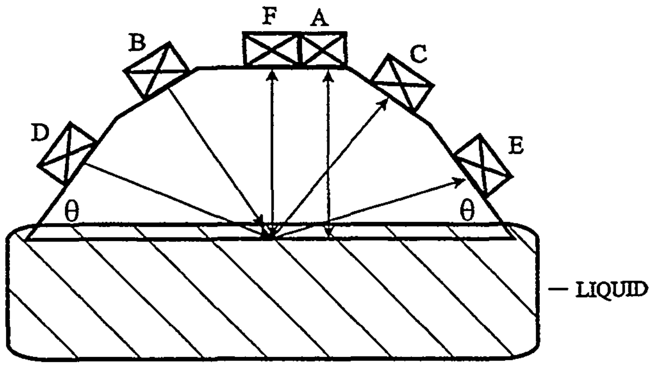


Figure C.1. Schematic Diagram of Wedge Design

C.2.1 Measuring the Reflection Coefficient

The essence of the measurement consists of sending an ultrasonic toneburst signal to the sending transducer and measuring the amplitude of the signal obtained by the receiving transducer. To determine the reflection coefficient (RC_{liq}), the amplitude of the received signal when the base of the wedge is immersed in the liquid is compared with that when it is immersed in 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:

$$RC_{liq} / RC_{water} = V_{liq} / V_{water} \tag{C.1}$$

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

$$RC_{liq} = RC_{water}(V_{liq} / V_{water}) \tag{C.2}$$

The reflection coefficient for water (RC_{water}) can be determined theoretically because the speeds of sound in 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.

C.2.2 Reflection and Transmission Coefficient

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

$$RC = (Z_{liq} - Z_{solid})/(Z_{liq} + Z_{solid}) \tag{C.3}$$

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° phase change upon reflection.

Krautkramer and Krautkramer (1983) provided the reflection and transmission coefficients for the acoustic pressure by using the notation shown in Figure C.2. Since the relationship for the reflected longitudinal reflection coefficient is used so often, the notation is simplified as follows:

$$G = (c_T / c_L)^2 \sin 2\alpha_L \sin 2\alpha_T \tag{C.4}$$

$$H = \cos^2 2\alpha_T \tag{C.5}$$

$$J = \rho c \cos \alpha_L / \rho_s c_L \cos \alpha \tag{C.6}$$

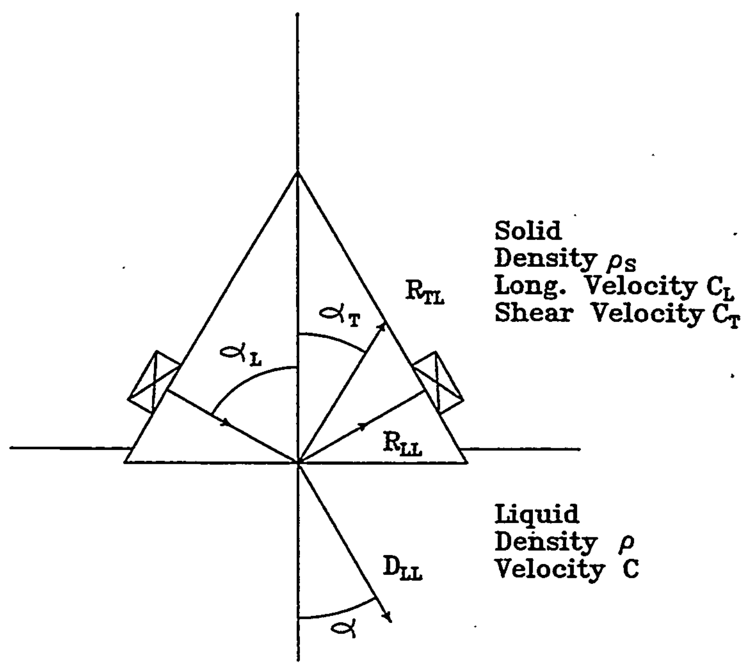


Figure C.2. Definition of Terminology Used in Equations of Reflection and Transmission Coefficients

The reflection coefficient for the reflected longitudinal wave is given by

$$R_{LL} = (1/N)\,(G - H + J) \tag{C.7}$$

where

$$N = G + H + J \tag{C.8}$$

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 C.7 and Equation C.8 reduce to Equation C.3. The reflection coefficients for the reflected shear wave, R_{TL}, and the transmitted longitudinal wave, D_{LL}, are given as follows:

$$R_{TL} = (2/N)\,(c_T/c_L)^2 \sin 2\alpha_L \cos 2\alpha_T \tag{C.9}$$

$$D_{LL} = (2/N)\,(\rho\, c \cos \alpha_L \cos 2\alpha_T) / (\rho_s\, c_L \cos \alpha) \tag{C.10}$$

C.2.3 Determining the Density of a Liquid Using 0- and 60-Degree Angles of Incidence

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. In this initial implementation, one angle of incidence must be 0°. The non-zero angle was chosen to be 60°. Denote RCZ as the experimental value for the perpendicular reflection coefficient and RLLX, as that at a non-zero angle. The density and velocities for the wedge are known. Solving Equation C.7 for J yields

$$J = -G + H(1 + RLLX) / (1 - RLLX) \tag{C.11}$$

Since all terms on the right are known, J can be determined. Solving Equation C.3 for the acoustic impedance of the liquid Z_{liq} we find

$$Z_{liq} = Z_{solid}\,(1 + RCZ) / (1 - RCZ) \tag{C.12}$$

When Z_{liq} is substituted into the definition of J in Equation C.6, the only unknown in the resulting equation is cos α, which is given by

$$\cos \alpha = Z_{liq} \cos \alpha_L / J\, \rho_s\, c_L \tag{C.13}$$

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.

$$c = c_L\,(\sin \alpha / \sin \alpha_L) \tag{C.14}$$

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

$$\rho = Z_{liq} / c \qquad (C.15)$$

Equation C.13 is an important step in the inverse problem. The question is, how much does cos α change when the density of the liquid changes slightly? If c is less than c_L, then from Equation C.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 C.13 increases as angle α, and likewise α_L, increases. This is one reason why angle α was chosen to be 60°. In Figure C.1, the central ray from transducer D makes an angle of 60° with the normal to the surface.

In Figure C.3, the reflection coefficient for ultrasound striking a Rexolite™-water interface is plotted versus the incident angle. At both 0° and 60°, 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° 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 crossover point. This feature can be used to detect small changes in the density of a liquid.

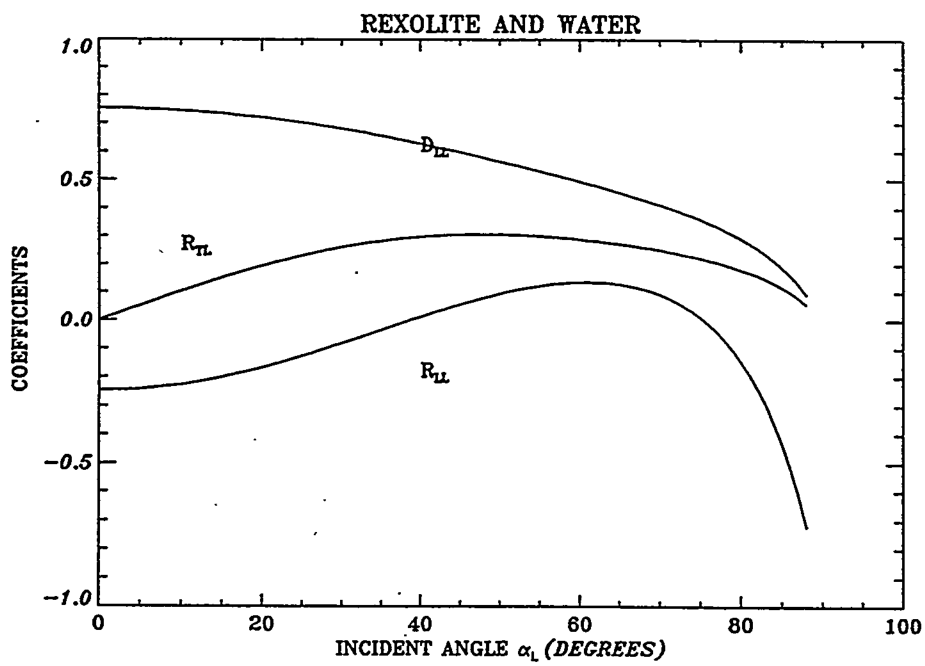


Figure C.3. Graph Showing the Reflection and Transmission Coefficient for a Rexolite™ Wedge in Contact with Water

C.2.4 Determining the Density Using Three Angles of Incidence

The previous analysis used angles of 0° and 60° for determining the value of the density, while the third angle was used to determine the sign of the reflection coefficients. An alternate approach is to determine the sign by examining the phase shift between the signals from the liquid and air. In that case, the third angle can be used to determine the density, which will increase the accuracy of the density measurement.

In this design, the Rexolite™-liquid interface is in the near field, and the receive transducer is also in the near field or just slightly beyond the near-field region. In the near field region, the rays do not diverge, and the reflection coefficient for a single ray applies exactly. To use three angles in the determination of the density, a chi-squared analysis is used.

$$X^2 = \sum_{i=1}^{3} [RCX_i - RCT_i(\text{constants}, \rho, c)]^2 / \sigma_i^2 \tag{C.16}$$

RCX is the experimental value of the reflection coefficient at a given angle, and RCT is the theoretical value calculated using Equation C.7. The term "constants" in Equation C.16 indicates known values of the wedge material and known angles. The objective is to find the value of the density, ρ, and speed of sound, c, so they produce a minimum chi-squared value. A numerical method is used to determine this minimum value. The steps in this analysis are as follows:

- The analysis using 0° and 60° angles is used to determine the "approximate" values of the density and speed of sound.
- Then a two-dimensional matrix of values around these two approximate values is set up, and the value of chi-squared is calculated.
- The two-dimensional matrix is searched for the minimum value of chi-squared, and this corresponds to the best value for the density and speed of sound.

To test the analysis, a model problem was considered for a sugar water solution having a density of 1083.0 kg/m^3 and a speed of sound of 1564.3 m/s. The reflection coefficients were calculated for three angles and then varied slightly to yield the ersatz "experimental" reflection coefficients. Values of the standard deviation, σ, were also assigned. Ten values of the density between 1080.5 kg/m^3 and 1085.0 kg/m^3 and ten values of the speed of sound between 1559.30 m/s and 1568.30 m/s were used to calculate a 10 x 10 matrix of chi-squared. However, this matrix yielded several local minima! When the values of the acoustic impedance were calculated for each minimum, the values were the same. This indicated that the acoustic impedance and the speed of sound were the primary variables. This is perhaps not surprising since the reflection at the interface is governed by the impedance difference. Thus, a matrix obtained by varying the acoustic impedance and the speed of sound should be used instead. That is, Equation C.6 and Equation C.16 should be rewritten in terms of acoustic impedance of the liquid rather than density. After determining the values of the acoustic impedance and speed of sound that yield the minimum value of chi-squared, the density can be obtained.

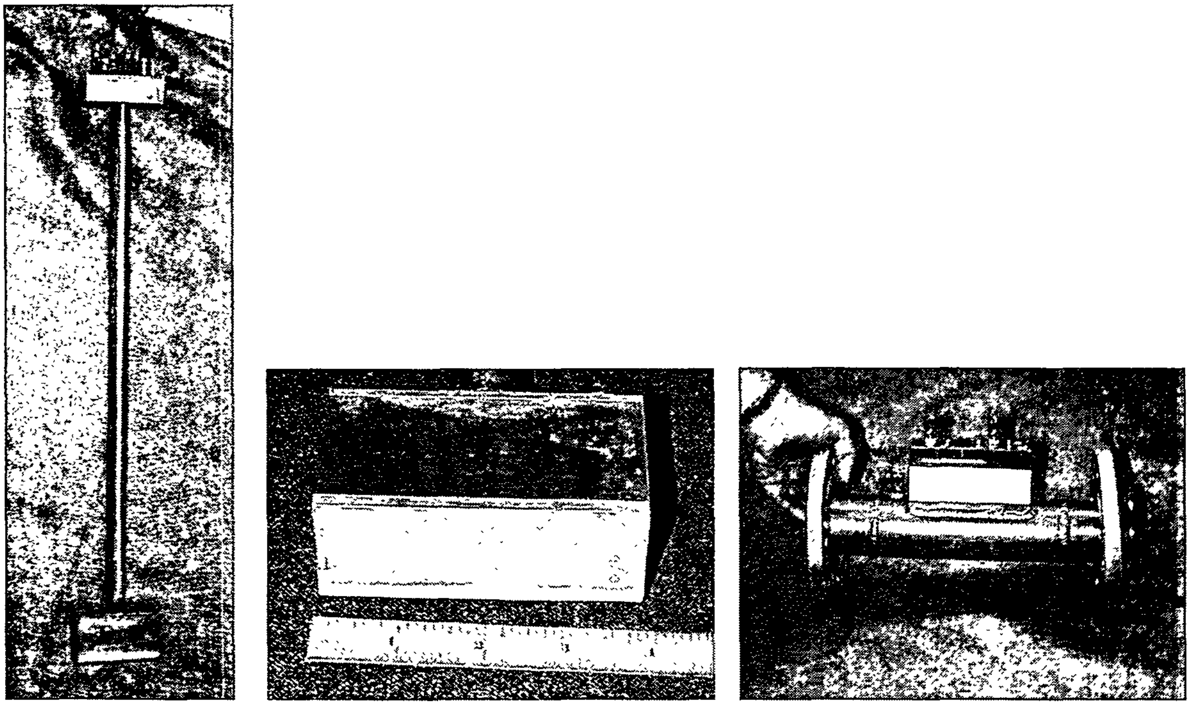
C.3 Initial Probe Design

For the most effective operation of the sensor, a wedge material that has a low acoustic impedance is required. Reflection at the boundary between a liquid and a solid occurs because of the difference in the acoustic impedances of the liquid and the solid. If the acoustic impedance of the solid is very large (i.e., a metal), then a small change in the density of the liquid is hard to detect. On the other hand, if the acoustic impedance of the solid has a smaller value (i.e., a plastic), then small changes in the density of the liquid can produce detectable changes in the reflection of the ultrasound. The plastic, Rexolite™, was selected for the wedge material because it has a density of 1049 kg/m^3 and low acoustic impedance. Also, it has superior resistance to mechanical deterioration by ionizing radiation. Alkalis, such as sodium hydroxide or potassium hydroxide, have no effect upon it, according to information supplied by the manufacturer.

Figure C.4 shows photographs of two early models of the density sensor. Figure C.4a shows the tank sensor (Model I), and Figure C.4b shows a close-up of its probe, which has dimensions of 9.6 cm x 3.5 cm x 5.6 cm. The Rexolite™ wedge is placed within the stainless steel case, and the angles of incidence are 0°, 40°, and 60°. Thermocouples are placed in the wedge very near the base of the wedge and at the top of the wedge to determine the 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 C.4c 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°, 42°, and 60°. 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.

C.4 Computer Controlled Data Acquisition System

The electronic system for measuring density consists of a personal computer with a single ultrasonic (UT) data acquisition card that is a custom Pacific Northwest National Laboratory (PNNL) design. It contains an ultrasonic pulser, receiver, a high-speed, high-resolution digitizer, and a multiplexer. The board typically would replace two commercially available cards, but in addition, it offers overall improved performance required for the precision of the measurements. It is a full-sized printed circuit card, using miniature surface-mounted electronic components, that 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.



(a) (b) (c)

Figure C.4. 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)

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. 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 was written in "C" and operates on a DOS-based platform on a PC.

Instrument setup consists of setting parameters for the pulser (frequency and number of cycles), receiver (gain), and digitizer (sample rate and sample delay). Figure C.5 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 C.5) 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 C.5 by a dotted line slightly above the time axis (TH). 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 sending transducer to the receiving 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.

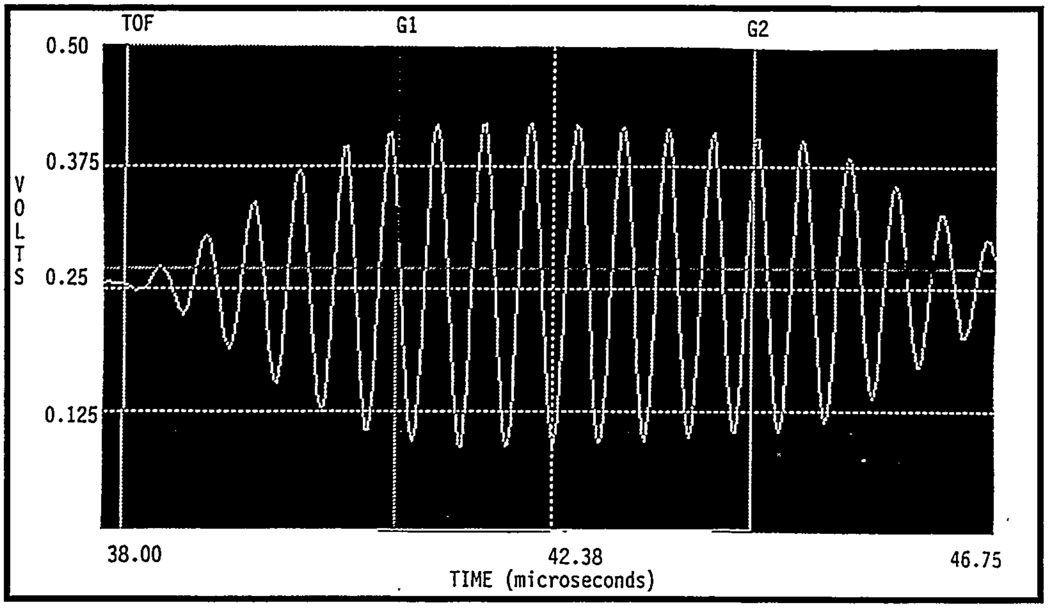


Figure C.5. Toneburst Signal Appearing on the Computer Monitor

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.

C.5 Data Analysis

To determine the density and speed of sound, the longitudinal and shear speeds in Rexolite™ and the measured reflection coefficients must be determined. The first section describes how the speeds vary as a function of temperature. Obtaining the magnitude and sign of the reflection coefficient are described in the second section. The third section describes how the measured voltages and other parameters are used to determine the density and speed of sound.

C.5.1 Temperature Effects

The longitudinal speed and shear speed in Rexolite™ were measured as a function of temperature from 15.5°C to 82.2°C, and the results are given by:

$$c_L = -0.0064202\, T^2 - 1.5906566\, T + 2374.3089 \qquad (C.25)$$

$$c_T = -0.00316062\, T^2 - 0.6816773\, T + 1173.4053 \qquad (C.26)$$

where the units of speed are m/s, and the temperature T is given in °C. At room temperature (21.5 °C), the density of 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 speed of sound in water (ASNT 1991) is given by:

$$c = -0.0291948\ T^2 + 4.4899485\ T + 1404.8373 \tag{C.27}$$

These relationships were used in the computer code, and the temperature at the base of the wedge was used to determine c_L, c_T, and c.

C.5.2 Reference Voltage Values

The reflection coefficient of a liquid is determined experimentally by comparing the voltage of the received signal when the base of the Rexolite™ wedge is immersed in the liquid compared to that when immersed in water. Equation C.2 gives this relationship. In the initial studies carried out at room temperature, the voltages when the base was immersed in water were measured, and these values were then entered into a file. When the base was immersed in a fluid, the reference values were read from this file and the density value determined. However, this procedure has been automated. When the temperature increases, the voltage on a receive transducer changes. This is due in part to the changing speed of sound in Rexolite™ that affects the reflection coefficient and also to a change in the attenuation of the ultrasound as a function of temperature. The reference voltages for water were measured as a function of temperature and entered into the computer code. The temperatures measured by the two thermocouples in the wedge were then used to select the appropriate values of the reference transducer voltage. The automated procedure relies on the repeatability of the voltage values to give an accurate value of the density. To test the repeatability, data were obtained for the Model I sensor over a 2-week period. No attempt was made to control the temperature of the wedge during these tests. The computer was turned off at night, turned on in the morning, and allowed to warm up for at least 2 h. For transducer F, shown in Figure C.1, the results for 15 measurements for water at room temperature (20.4 $\pm$ 0.5 °C) showed an average voltage of 0.357075 volts with a standard deviation of 0.002543 volts (0.7%).

C.5.3 Calculation of the Density and Speed of Sound

The first step in the analysis of the data is to obtain a so-called "adjusted voltage," which is defined as the voltage that would have been obtained if the amplifier gain had been set to 0.0 dB. The second step is to calculate the reflection coefficient for the reference fluid (usually water) using Equations C.7 and C.8, where all of the angles, densities, and speeds are known quantities. The third step is to determine the reflection coefficient at the fluid-wedge interface using Equation C.2, where the voltages refer to the adjusted voltages. The sign of the reflection coefficient is determined from the phase shift. The final step is to determine the density and speed of sound using Equation C.11 through Equation C.15.

C.6 Cost of Initial Deployments

After completion of 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 100 psi to 400 psi. 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. The costs associated with each of these items are listed in Table C.1.

Table C.1. Cost of Densimeter for 241-SY-101 Deployment

Component	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.
Computer	5 K	This off-the-shelf computer must withstand plant operating conditions and be designed to accommodate the custom computer board.
System Cost	**19 K**	

C.7 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 C.2.

Table C.2. Estimated Cost of Future Densimeter 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 is envisioned.
Transducer wedge	2 K	A more streamlined wedge with fewer transducers is envisioned. The transducers are bonded to the wedge.
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.
System Cost	**10 K**	

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