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Performance Evaluation of the Quarter-Scale Russian Retrieval Equipment for the Removal of Hazardous Waste

C. W. Enderlin
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September 1997

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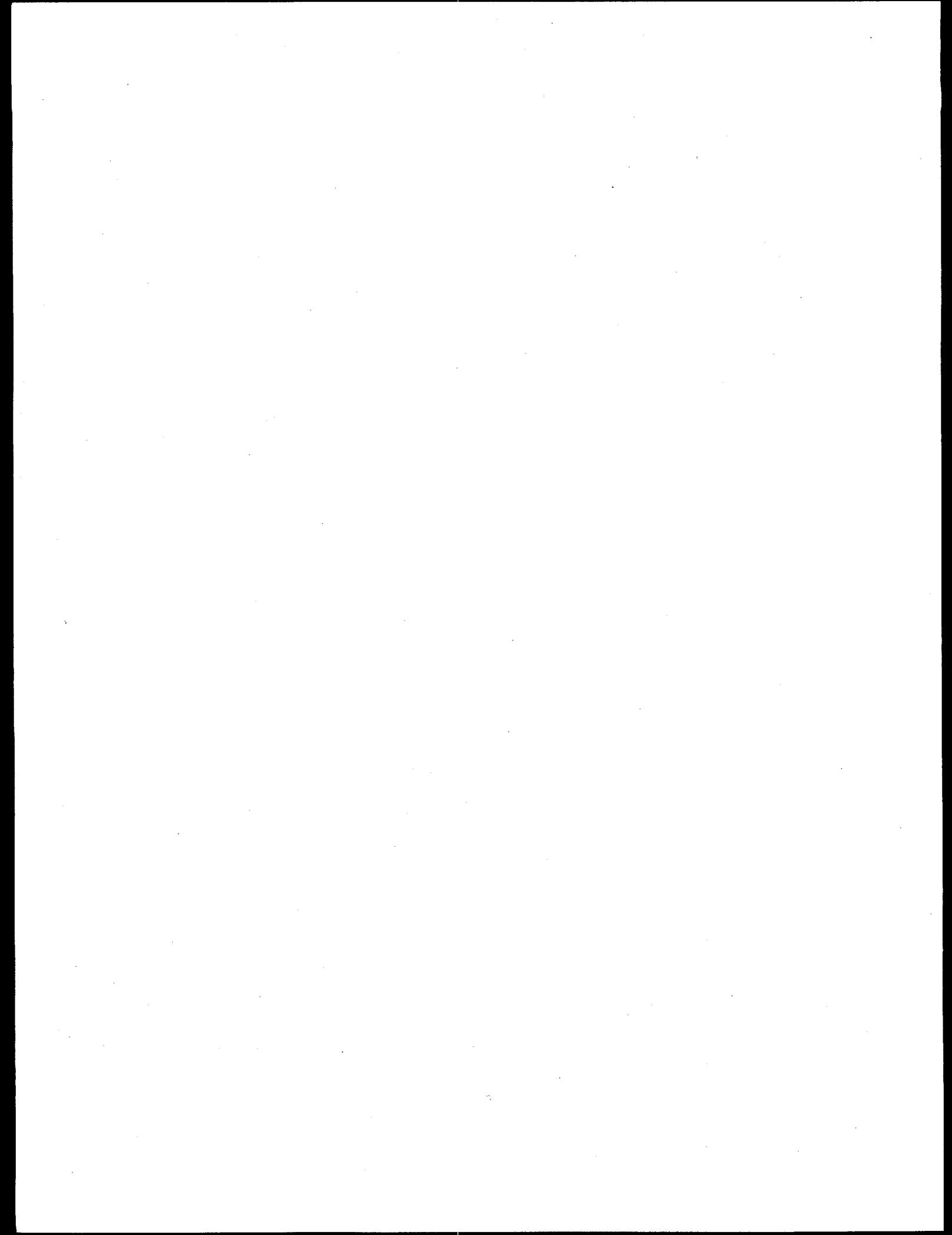
**Performance Evaluation of the Quarter-Scale
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Executive Summary

Several systems for the retrieval of radioactive waste have been developed, tested, and deployed by the Integrated Mining Chemical Company (IMCC) in Russia. The technologies for waste removal developed in Russia may have application to certain waste forms within the United States (U.S.) Department of Energy (DOE) tank complex. The Tank Focus Area (TFA), in conjunction with Environmental Management International Programs, sponsored the design, fabrication and testing of Russian Retrieval Equipment for High-Level Waste supernatant and sludge retrieval. The Russian specialists designed, fabricated, and cold tested geometrically scaled models of this equipment for the Department of Energy at Krasnoyarsk, Russia, to aid in the evaluation of the equipment for deployment in the U.S. The TFA funded the Retrieval Process Development and Enhancement (RPD&E) Project to work with the Russian specialists to test the retrieval equipment. The documentation and evaluation of the initial tests are contained in this report.

The main components of the equipment include the Pulsating Pump (a reciprocating air-powered retrieval pump), the Hydroelevator (a liquid-liquid jet pump), the Hydromonitor (a jet mixer powered by a constant pressurized liquid source), and the Pulsating Monitor (a jet mixer powered by a reciprocating air supply). Performance testing and demonstrations of the Pulsating Pump (PP) and the Pulsating Monitor (PM) were conducted at the Pacific Northwest National Laboratory (PNNL) to determine the viability of the equipment for applications associated with waste retrieval in the U.S.

Data related to the response of each system to various operating conditions were collected, reduced, and analyzed for various performance tests using waste tank slurry simulants. Measurements of the operating pressures for the PP and PM along with the mass flow rate and slurry density of the pumped waste stream were taken. The low-frequency oscillatory operation of the PP and PM resulted in steady state operating conditions that yielded time periodic data. Careful reduction and assessment of the data was necessary to select purely periodic data (indicative of proper pump operation) from which time-averaged parameters were calculated. The detailed assessment of the data allowed for the development of a physically meaningful correlation.

A systematic analysis of the data provided a comprehensive understanding of the equipment operation as a whole and how its performance departs from ideal behavior. Observations of these departures led to suggestions for improvements in the efficiency and reliability of the system, and for the development of a proper monitoring and control system necessary for remote operation for U.S. applications. Both, the PP and PM show promise for application in the DOE tanks; however, there are significant technical/design issues that need to be addressed before they are ready for deployment.

The advantages of using the PM and the PP for mobilizing and retrieving waste from underground storage tanks include:

- robust and simple of operations with minimal in-tank moving parts,
- the ability to operate with a wide range of fluid densities and rheologies and at low liquid levels,
- inexpensive and lightweight equipment that can be easily adapted to various tank inlets,
- the potential to be monitored and regulated with a feedback control strategy/system (absent in the current design).

In addition, the absence of rotating shafts in this equipment eliminates the possibility of adding water to the waste in the event of a failed seal as may occur when using jet-mixer pumps that have water-filled columns.

Recommendations for improving the PP and PM include:

- development of a feedback control and monitoring system for the equipment utilizing commercially available software and instrumentation,
- improvement of the check valve and inlet design to allow transport of larger particles and prevent in-tank debris from fouling the operation of the system,
- increase flexibility of the valve configuration for the system to provide independent control of the supply and vacuum line pressures, and
- expansion and improvement of the back-flush capability of the system to include the PM and the capability for decontamination of all wetted parts.

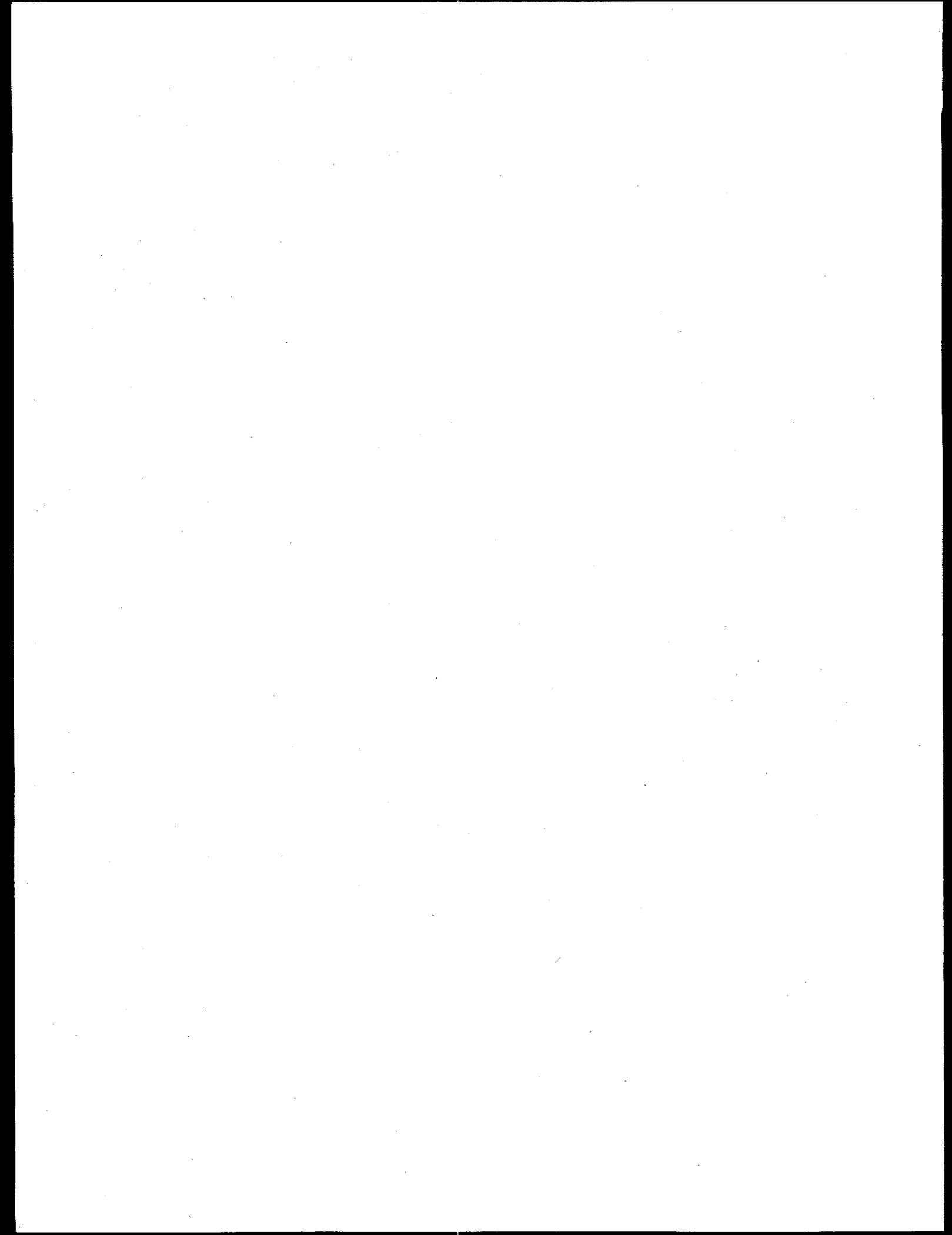
The options and limitations for placing the air eductor, used to provide rarefaction, inside of the waste tank must be determined or other alternatives selected for the vacuum source to alleviate the problem of contaminated aerosols.

In summary, the PP and PM have potential for retrieval applications within the DOE complex. The concept of operation is straightforward and has been demonstrated using simulants with physical properties within the ranges of that predicted/measured for waste tank mixtures. However, there are a number of design and operational issues to be addressed before the PP and PM systems are ready for deployment. Additional work should concentrate on developing a remote feedback monitoring and control system, improving the current system design for remote operations, improving the pump's ability to transport larger particulate, and testing of the system over a wider range of both operational parameters and waste properties.

Acknowledgments

The authors gratefully acknowledge the support of PNNL staff who participated in the completion of this project. First, the authors are indebted to William Combs and Michael White, PNNL, for lots of midnight oil and grace under pressure. Thanks are due to Michael Rinker, RPD&E project manager at PNNL, for his managerial support and for providing assistance in the lab when needed. We also thank Michael Powell, RPD&E staff scientist, for providing simulant characterization information that was essential for analyzing the data. Thanks are also due to PNNL craft services for timely response to fabrication needs.

Our collaboration with the Russian team was amicable and very productive. We appreciate having had the opportunity to work and learn from our Russian team members Boris Barakov, Yuri Kiselev, Michael Ekaterinichev, and Vasily Dzjubenko.



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1.0 Introduction

This report describes the test program for evaluating the Russian Retrieval Equipment fabricated by the Integrated Mining Chemical Company (IMCC) and delivered to the U.S. by Radiochem Services Company (RCSC), both of Russia. The testing and fabrication of this equipment were sponsored by the U.S. Department of Energy (DOE). The tests described in this report were conducted at the Pacific Northwest National Laboratory (PNNL) at the DOE Hanford Site by the Retrieval Process Development and Enhancement (RPD&E) team of the Tank Focus Area program (TFA).

Tests were carried out jointly by Russian and U.S. personnel for the purpose of evaluating the Russian Retrieval Equipment for potential deployment within the DOE complex. Section 1.0 of this report presents the objectives and a brief background for the test program. The Russian Equipment is described in Section 2.0. Section 3.0 describes the approach taken for testing the equipment. The results of the tests and an analysis of the data are described in Section 4.0. The results and observations obtained from the tests are discussed in Section 5.0. Recommendations and conclusions are presented in Section 6.0.

1.1 Objectives

The objective of this test program was to characterize the performance of the Russian Retrieval Equipment and evaluate its potential for application in the U.S. Department of Energy's hazardous waste retrieval activities. The following tasks were identified for achieving the objective:

- Equipment testing is to be conducted in the Quarter Scale Double Shell Tank Test Facility at PNNL by Russian and U.S. personnel from MCC, RCSC, and PNNL.
- Baseline tests of the Russian Equipment are to be conducted using water as the test solution.
- Performance tests of the Russian Equipment are to be carried out with kaolin clay slurries ranging in specific gravity from 1.1 to 1.4.
- Results of the tests and an evaluation of the equipment are to be presented to potential end users in a published report.

1.2 Background

The Russian Retrieval Equipment consists of four devices, a Hydroelevator (HE), a Hydromonitor (HM), a Pulsating Pump (PP), and a Pulsating Monitor (PM), which are described in Section 2.0. In addition to the four retrieval devices, there are two pieces of accompanying support equipment, a Flow Control Unit (FCU) and a vacuum eductor. Scaled models of this

equipment were designed, fabricated, and cold tested in Russia by specialists from IMCC. These tasks were performed for the U.S. DOE to evaluate for potential deployment in high-level waste tanks for supernatant liquid and sludge retrieval.

After the completion of performance testing in Russia by IMCC, the equipment was shipped to the U.S. DOE Hanford Site in June of 1997 by RCSC for installation in the Quarter Scale Double Shell Tank Test Facility at PNNL. The performance and operation of the equipment was to be evaluated by the RPD&E team of the TFA for potential DOE applications. The RPD&E team specialist from PNNL prepared the facility and equipment for testing. In July of 1997, performance testing and demonstrations of the PP and the PM were conducted at PNNL by a team comprised of IMCC, RCSC, and RPD&E specialist.

2.0 Description of Equipment

In this section, the main components, four retrieval devices and two pieces of support equipment, of the Russian Retrieval Equipment shipped to PNNL are described. The figures in this section are conceptual drawings edited from early versions of the designs. They illustrate the functional concepts of the equipment and are not intended for displaying design details.

2.1 Pulsating Pump

The Pulsating Pump (PP), shown in Figure 2.1, consists of an upright cylindrical reservoir, a foot-check valve with an inlet screen, a working gas supply pipe, a discharge pipe, and a discharge check valve at the riser head. The gas supply pipe is plumbed to a rotary control valve, which alternates the exposure of the line between a vacuum and air supply source. In operation, the waste is drawn into the reservoir through the foot-check valve when the supply pipe is valved to the vacuum source. The supply pipe is then pressurized with supply air expelling the waste out of the pump through the discharge pipe and check valve into the downstream balance of the system piping. The foot-check valve is a captive metallic ball, made of stainless steel and coated with tungsten or titanium nitride, set in a conical metal seat. The inlet screen is a short cylinder with side ports, extending beyond the base of the reservoir. It is removable for access to the check valve.

The upper discharge check valve is a captive ball valve riding in a cage including the conical check valve seat. The entire check valve assembly can be lifted off a secondary seat so that back flush water introduced via the discharge port will both agitate and rinse the upper and lower check valves and back flush the discharge pipe. When installed in a tank, the PP makes contact with the floor of the tank.

2.2 Pulsating Monitor

The Pulsating Monitor (PM), shown in Figure 2.2, consists of an upright cylindrical reservoir, a foot-check valve with no inlet screen (on the test article), a working gas supply pipe, a discharge manifold, and jet nozzles. The operation is similar to that of the PP except that the pressurized air discharges the fluid out of the monitor reservoir and back into the tank through jet nozzles instead of out of the tank through a discharge pipe. No provision exists for back flushing the check valves of the PM.

The proto type PM is supported by a riser cover plate on a swivel bearing/seal, which allows operators to manually turn, it to direct the nozzle jets in different directions. The working gas supply is delivered by a hose connected to a swivel 90° elbow fitting at the top of the monitor. For the experimental setup, rotation of the PM required the swivel fitting to be loosened, thus interrupting the operation. If four nozzles are used during deployment, hose flexure may accommodate the 90° of rotation required for continuous rotation.

Only two jet nozzles were used during testing; however, there are four ports for jets in the head. The preliminary drawings showed a fifth nozzle directed axially downward on the centerline of the monitor, but the port for that jet was not present on the test article. The foot-check valve is a simple captive ball in a replaceable seat. The ball and seat were coated with titanium nitride for hardness and corrosion resistance.

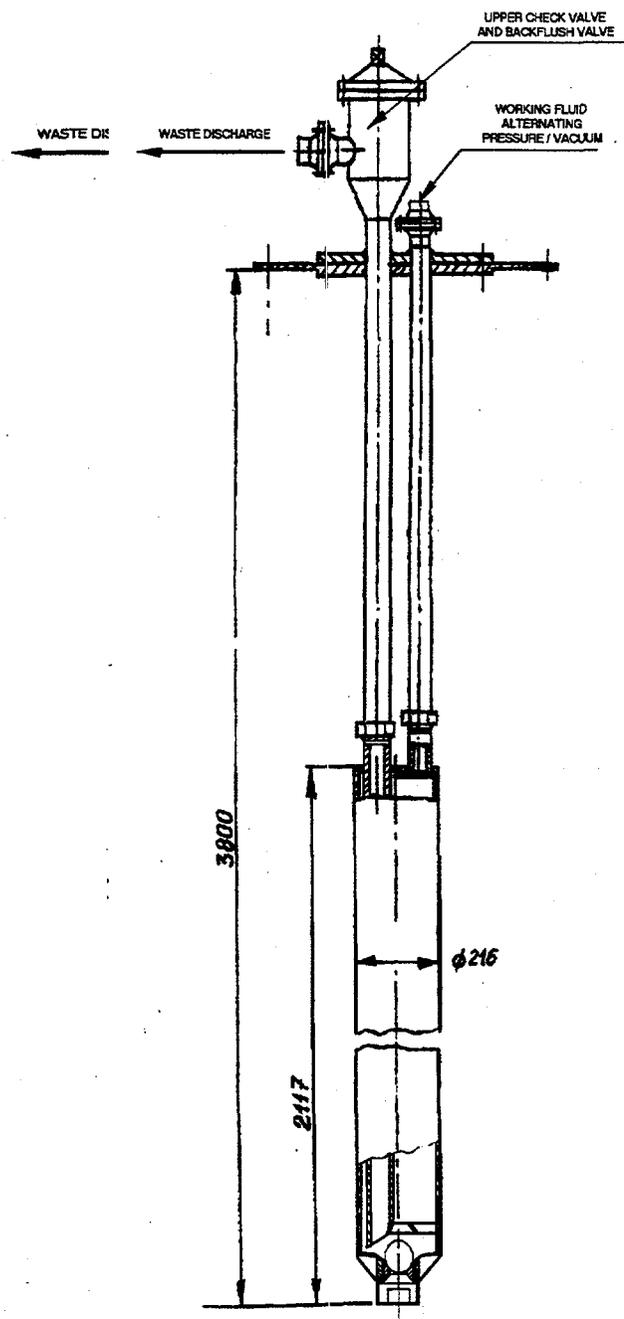


Figure 2.1 Pulsating Pump

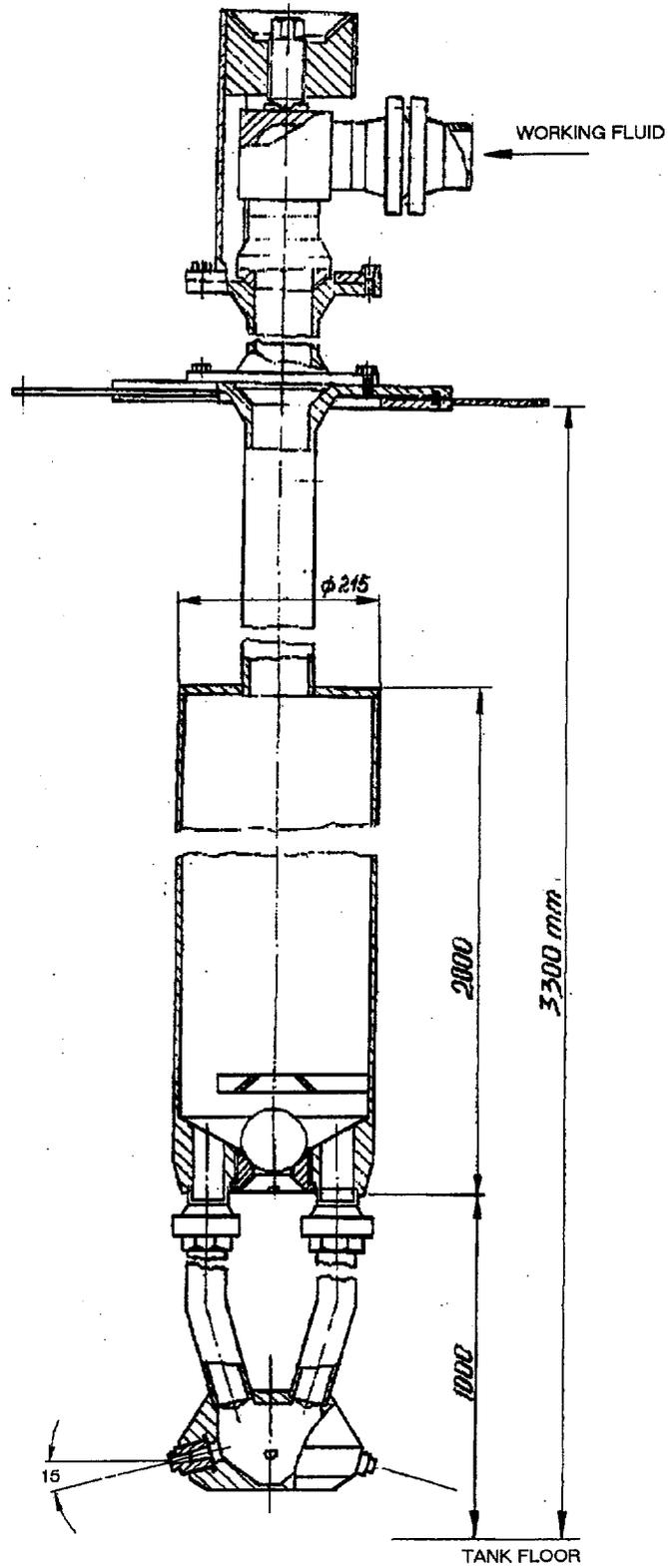


Figure 2.2 Pulsating Monitor

2.3 Flow Control Unit

The Flow Control Unit (FCU), shown in Figure 2.3, contains the valve manifold for the PP, the PM, and back flush supply water and a rotary control valve which delivers alternating pulses of gas pressure and vacuum to the pulsating equipment. A schematic of the FCU manifold is given in Figure 2.4. As furnished, the rotary valve working parts were two discs made of tetra fluoroethylene (referred to as PTFE or TFE), one having a single round port open to the working gas delivery manifold and the other having a pair of elongated ports positioned over the working gas and vacuum supply ports in the valve body. The angles spanned by the elongated ports define the dwell times and open times for the valve, and the rotating plate with the single port governs the frequency of operation. The valve is intended to be exposed only to working gas in normal operation.

The vacuum supply to the pulsating equipment was provided by an axial-jet eductor furnished with the equipment.

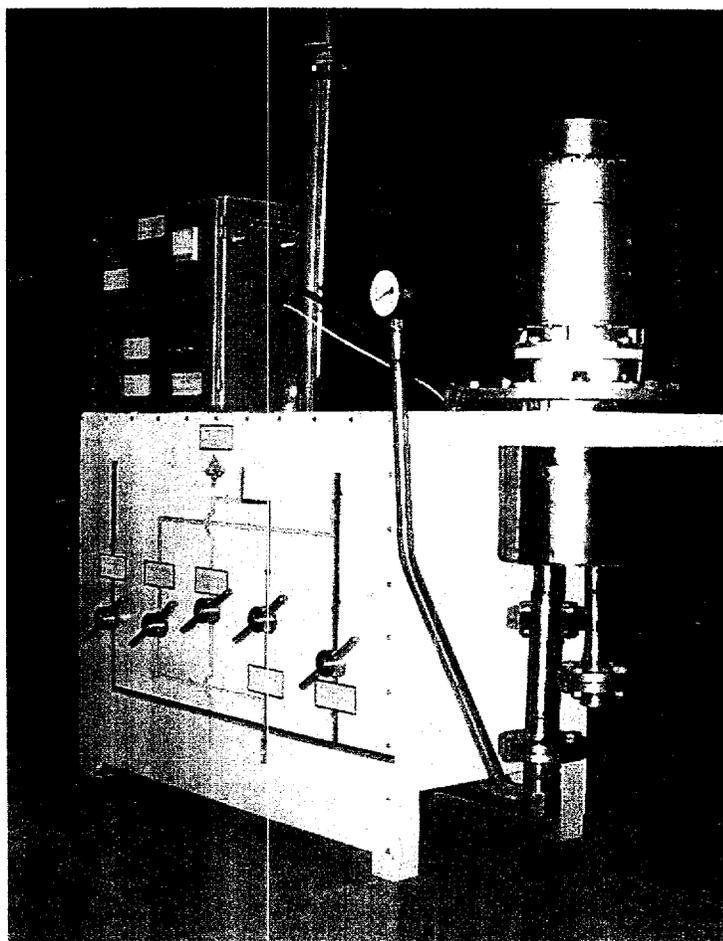


Figure 2.3 Flow Control Unit.

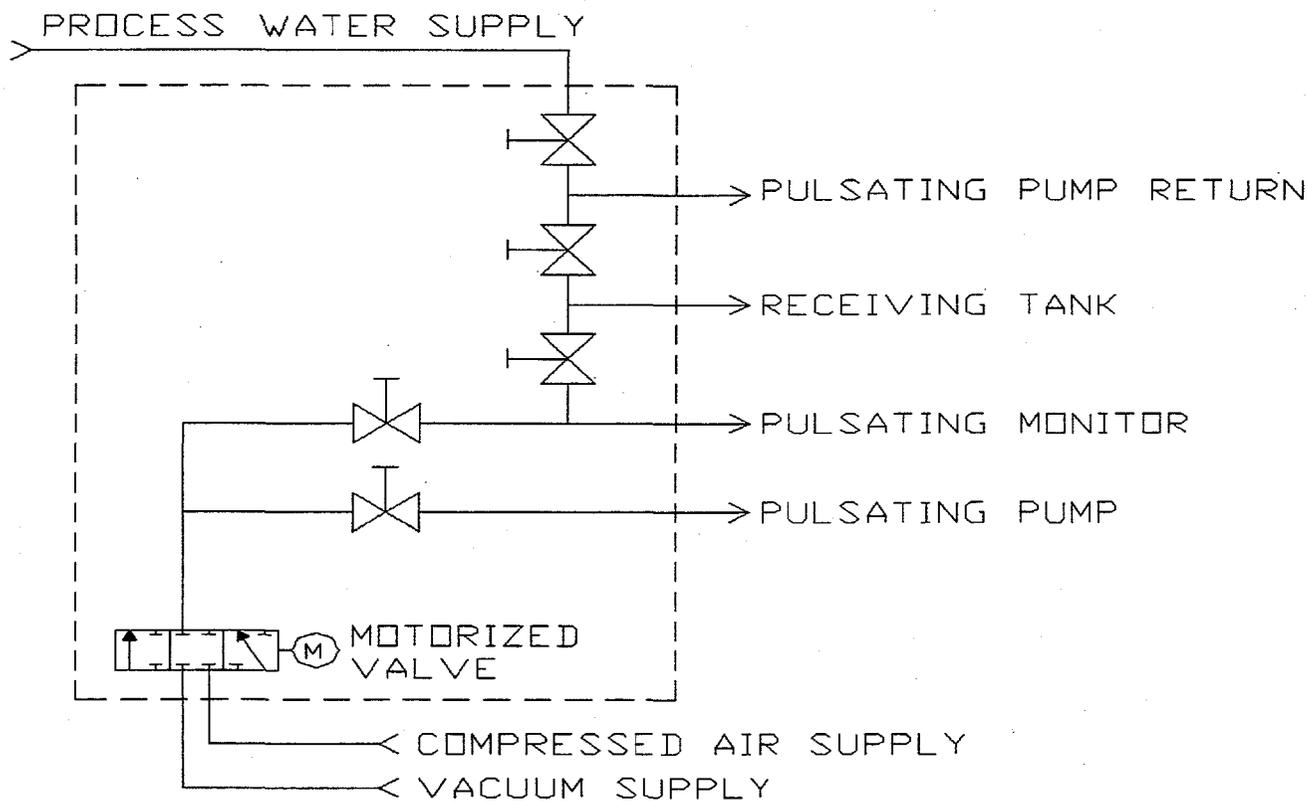


Figure 2.4 Schematic of the Flow Control Unit.

2.4 Hydromonitor

The Hydromonitor (HM), shown in Figure 2.5, is a sluicing device comprised of two diametrically opposed 10-mm jet nozzles inclined at 30° down from horizontal. The nozzles are mounted in the end of a vertical pipe stem. The pipe stem is inserted through a small riser and can be rotated about the vertical axis. The working fluid connection is made to a 90° elbow swivel fitting. The unit delivered is designed for operation at 500 to 1000 kPa gage (73 to 145 psig). The average pressure at the headpiece during the pressurized portion of the operating cycle is 1000 to 2200 kPa gage (145 to 319 psig). The above values were specified by the IMCC^a.

^a Yu. A. Revenko. "Development of Equipment for Extraction of Radioactive Pulps and Cakes from Storage Facilities in Krasnoyarsk and Hanford." Quarterly Progress Report (Oct. 1996). Integrated Mining Chemical Company and Radiochem Service Company.

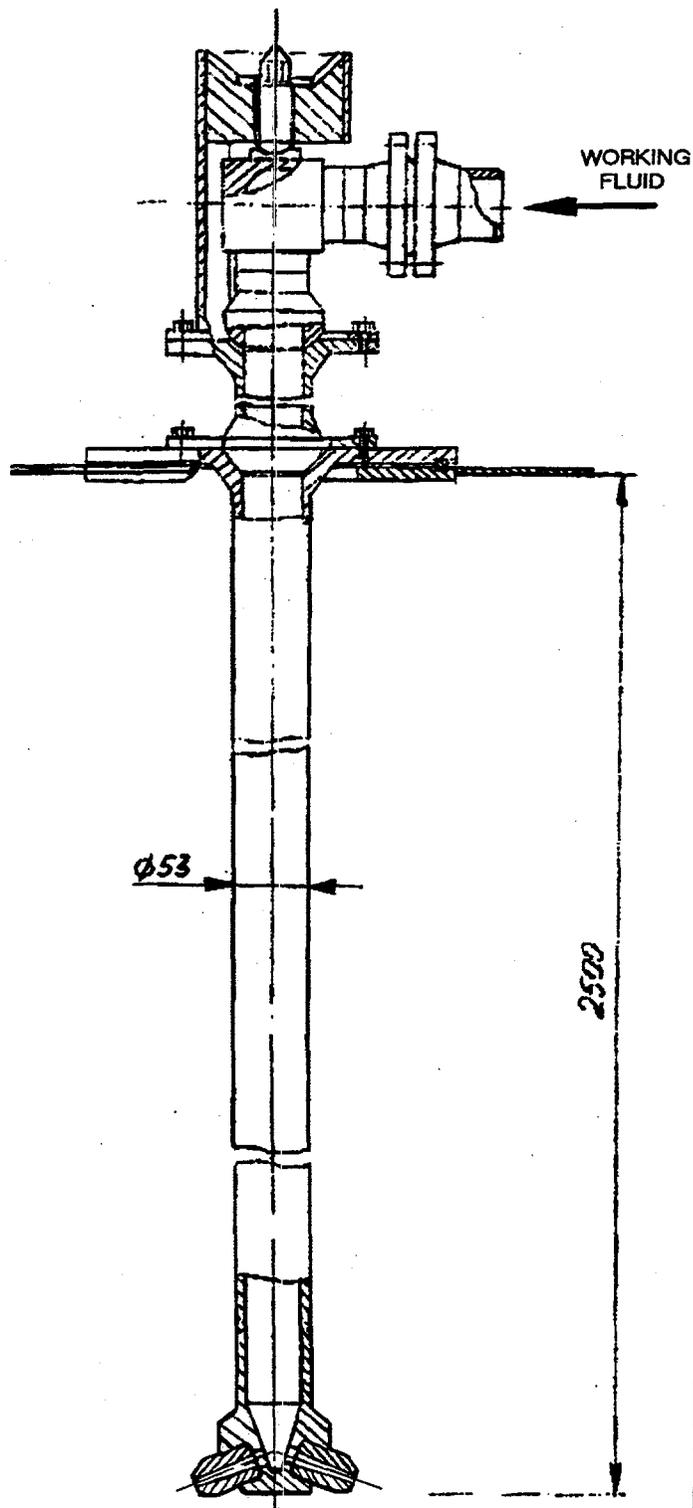


Figure 2.5 Hydromonitor.

2.5 Hydroelevator

The Hydroelevator (HE), shown in Figure 2.6, is a conventional axial jet pump. The motive fluid for the jet pump is introduced into the mixing section through a single centered nozzle. The capacity of the jet pump was specified as 2 to 3 m³/hr of pumped slurry (specific gravity of 1.4) for 6 to 9 m³/hr of motive fluid supplied at 500 to 1100 kPa gages (73 to 160 psig). The calculated outlet pressure is 330-kPa gage (48 psig). The above values were specified by the IMCC.

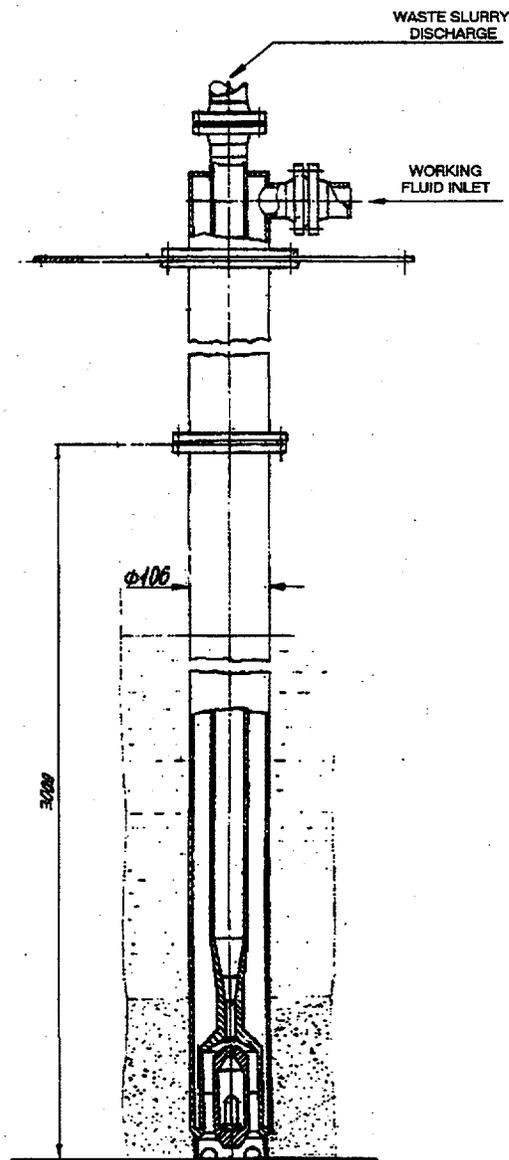


Figure 2.6 Hydroelevator.

3.0 Approach

In July of 1997, the Russian Equipment described in Section 2.0 was installed in the Quarter Scale Double Shell Tank (1/4 scale DST) test Facility in the 336 Building of the 300 Area at the Hanford Site. Due to limited time and resources, the testing of the equipment was prioritized. PNNL and IMCC personnel agreed to test the Pulsating Pump (PP) with both water and slurry simulant and to conduct a demonstration of the Pulsating Monitor (PM) in water.

The Hydroelevator (HE) and Hydromonitor (HM) are forms of a liquid-liquid jet pump and a conventional liquid jet mixer, respectively. These devices utilize pressurized liquid to mix and convey waste. In the U.S., the development related to nuclear waste, of similar devices has been extensive and on going. The PP and PM are air-powered equipment that had been developed in Russia for the purpose of nuclear waste retrieval. In the U.S., limited work related to the application of similar technologies for waste retrieval has been conducted. Therefore, the testing of the PP and PM was considered the highest priority. Testing of the HE and HM (viewed as lower priority) could not be carried out given the funding and time constraints of the project.

The PP was tested with water and slurry simulants consisting of kaolin clay and water. To evaluate the effects of larger particles on the PP, both fine and coarse sand was added to the simulant with the highest concentration of kaolin clay. The highest concentration of kaolin clay used in the tests resulted in the highest viscosity simulant. By adding the sand to the most viscous simulant, the potential for particle transport into and through the PP was maximized from the aspect of slurry rheology.

A test was to be performed at steady state operating conditions. The DAS was used to take measurements of the system control pressures, the discharge pressure of the PP, and the flow rate and specific gravity of the retrieved slurry, and to analyze the system response for various simulant compositions. The test matrix for the PP called for:

- Conducting water tests at varying pump cycle durations. Increasing and decreasing the pulse duration by 20% from the optimal cycle duration specified by IMCC.
- Testing with slurries of kaolin clay and water that have specific gravities of 1.1, 1.2, 1.3, and 1.4. If slurry with a specific gravity of 1.4 could not be transported by the PP, then the maximum specific gravity of the slurry that the PP was capable of pumping would be determined.
- Performing a draw-down test with the slurry to evaluate the effect of low liquid levels.
- Evaluating the effects on the performance of the PP of adding particulate sand to the test slurry.
- Operating and evaluating the back-flush capability of the integrated system.

The PM works on the same principle as the PP, thus some of the information obtained from testing the PP was to be used for evaluating the PM. The test matrix for the PM consisted of conducting a demonstration of the PM in the 1/4 scale DST using water.

The operation of the PM was demonstrated using water and medium grain sand spread over the tank bottom. The size of the sand was selected to be large enough that it could not be mobilized by the PM jets operating at the control settings selected for the demonstration. The purpose of the sand was to provide flow visualization of the influence that the PM jets have settled solids on the test tank floor.

The PM was not tested further because time and budget constraints did not allow for the development of a meaningful test matrix. A complete evaluation of the PM will require comparison to non-pulsating continual flow mixing jets (e.g. jet mixer/mobilization pumps). Before meaningful comparisons can be made, an analysis is required to determine what parameters should be evaluated. The purpose of the demonstration was to provide an initial evaluation as to whether the PM technology merited further consideration for applications to the U.S. waste tanks and to provide insight for the development of a more extensive test matrix.

The test setup, equipment, instrumentation, simulant, and procedure are discussed in sections 3.1 through 3.4.

3.1 Test Setup

The four pieces of Russian Retrieval Equipment, the flow control unit (FCU), and the eductor were integrated into the 1/4 Scale DST Test Facility. However, the Hydromonitor (HM) was never installed into the 1/4 Scale DST. Figure 3.1 shows an overview of the test installation in the 1/4 Scale DST including the HM. The Hydroelevators (HE) and the PP were inserted into small test tanks. The small test tanks allow retrieval tests to be conducted at various waste levels without having to produce large volumes of simulant. The PP and HE test tanks are displayed in Figure 3.2. The FCU was installed on the equipment bridge above the 1/4 Scale DST.

Hoses with cam and groove connectors were used for plumbing the system. The hoses allowed for the option of rearranging test equipment to various locations in the 1/4 scale DST. Since the HE and the HM were not tested, the remainder of the test description focuses on the PP and PM.

A diesel-powered trailer mounted compressor was used for supplying compressed air to the PP and the vacuum eductor. The eductor was located outside of the 336 Building and was partially enclosed to attenuate the noise and stop any expelled material. The FCU was connected to the 336 Building Process Water Line [approximately 550-kPa gage (80-psig)] to provide back-flush water to the PP.

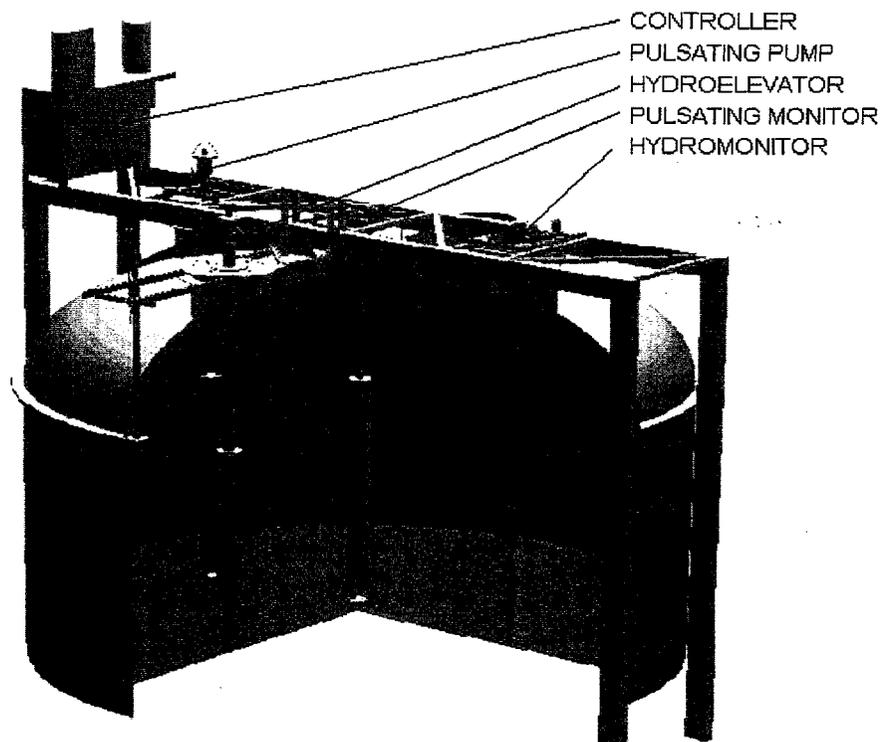


Figure 3.1 Overview of Test Installation in the Quarter Scale Double Shell Tank.

The PP was setup to be tested in a closed loop system. The retrieval line went from the PP through a shut-off in the FCU and passed through a MicroMotion Coriolis Mass Flow Measurement System before discharging into a funneled return line at the upper elevation of the flow loop. The line was opened to atmosphere at the funnel to avoid a siphon effect in the retrieval line. The slurry was returned to the test tank through the return line via gravity feed.

For both the PP and the PM, the pressures of the vacuum and supply lines were measured at the rotary control valve on the FCU. Measurements taken during the testing of the PP also consisted of the pressure, density, and mass flow rate of the slurry retrieval line. The pressure in the retrieval line was measured just down stream of the PP discharge check valve (referred to as the PP Discharge or Exit Pressure). During several tests, bottle samples were taken at the outlet of the return line for characterization of the slurry. A schematic diagram depicting the elevation of the test loop and measurement points is presented in Figure 3.3. A weigh tank (not included in Figure 3.3), for obtaining flow rate measurements to compare against those obtained from the retrieval line flow meter, was also part of the test setup.

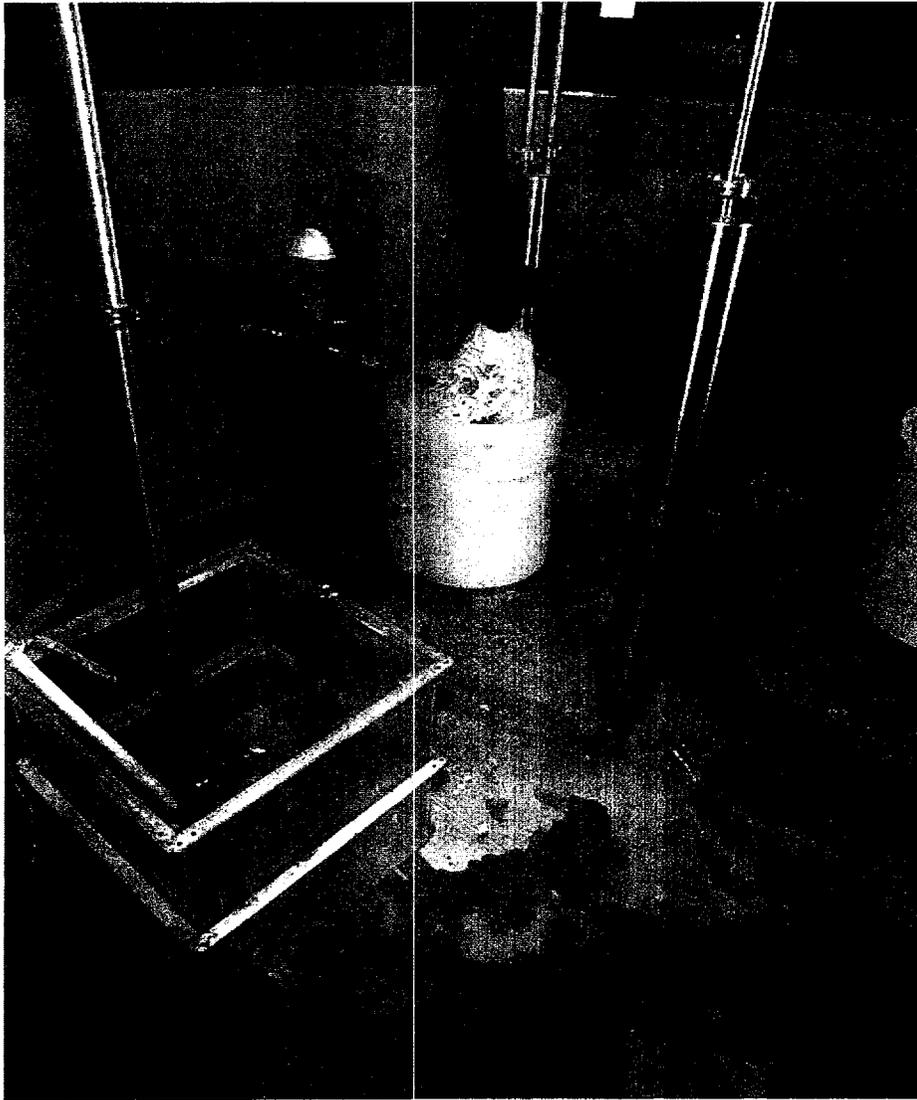


Figure 3.2 The Hydroelevator (shown on the left of photograph) is inserted into a Test Tank, the Pulsating Pump (in the center) has Slurry flowing from the return line into a Test Tank and the Pulsating Monitor (on the right) has no Test Tank.

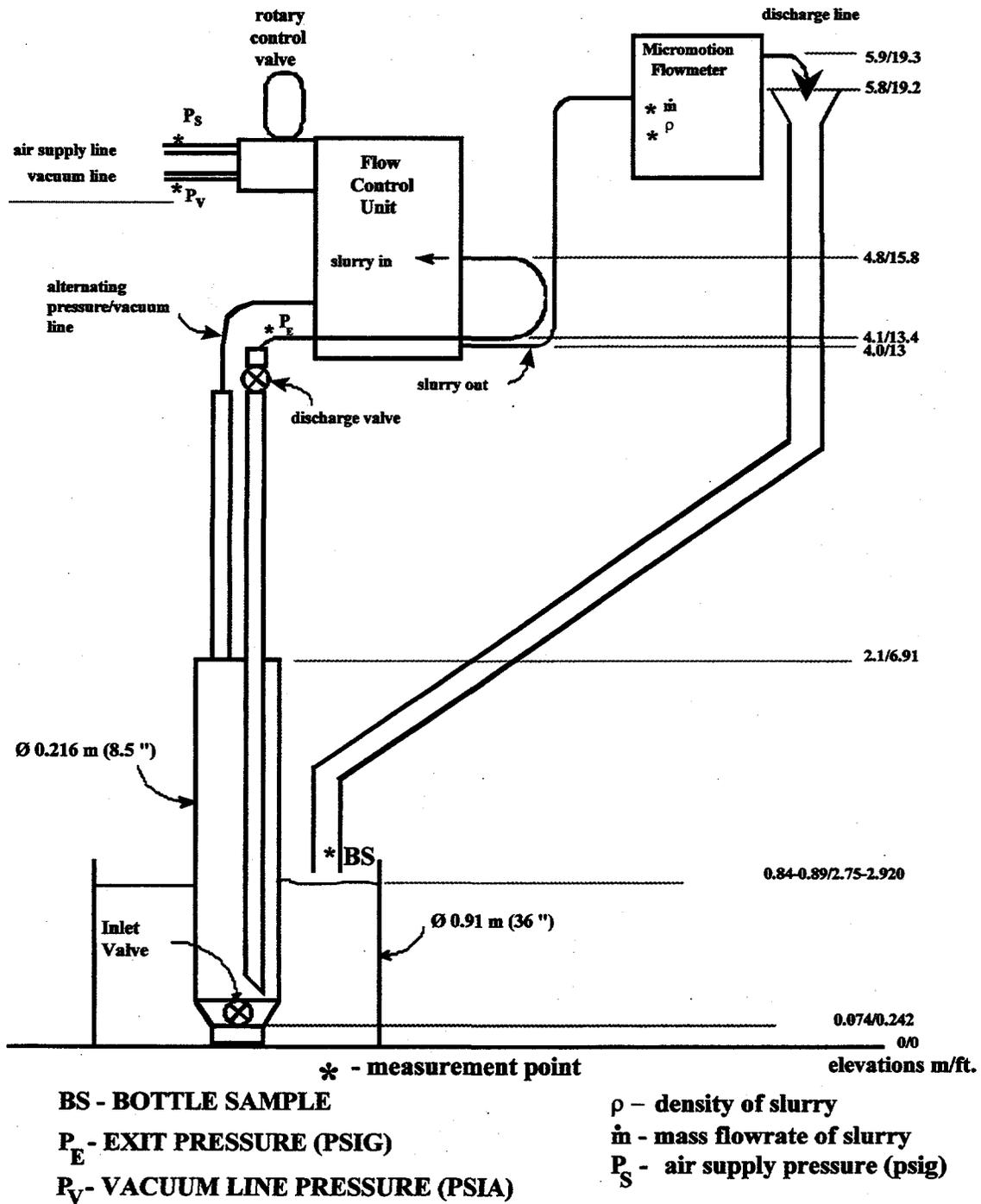


Figure 3.3 Elevation Diagram of Pulsating Pump Test Loop.

3.2 Test Equipment and Instrumentation

Sections 3.2.1 and 3.2.2 provide a description of the test equipment and instrumentation respectively.

3.2.1 Equipment

1/4 Scale DST - A 5.7 m (18.75 ft) diameter, 59 m³ (15,625 gal), stainless steel, cylindrical tank with an equipment bridge over the top and a viewing platform located around one quarter of the tank circumference. During testing, three quarters of the tank dome remained in place. The dome contains access ports for the installation of test equipment.

PP Test Tank - A 0.9 m (36-in.) diameter, 0.66 m³ (173 gal), polyethylene cylindrical tank (see Figures 3.3 and 3.4).

Air Compressor - A Sullair[®] Q385 diesel-powered screw-type compressor regulated to 725 kPa gage (105 psig) and capable of delivering 0.18 m³/s (385 scfm) at 827 kPa gage (120 psig).

Eductor - The eductor was supplied and specified by IMCC as requiring 4 m³/min (141 cfm) of air delivered at approximately 480 kPa gage (70 psig) to produce 40 Kpa gage (5.8 psig) of vacuum. The air supply line to the eductor was at a 725 kPa gage (105 psig) and was throttled to obtain the desired vacuum line pressure. The actual air flow rate to the eductor was not measured. The eductor was placed at ground level outside of the 336 Building.

A concern for deployment was the noise level of the eductor. A noise survey was conducted by PNNL safety personnel. The following sound levels, on the A-weighted scale [dB (A)], were obtained at various distances from the outlet of the eductor: 102-108 dB (A) at 0.9 m (3 ft), 97-102 dB (A) at 1.5 m (5 ft), 92-97 dB (A) at 3.0 m (10 ft), and 92 dB (A) at 6.1 m (20 ft).

Connecting Hoses - The hoses used for plumbing the PP and PM were either Puma[®] Tank Truck Hose or Goodyear[®] Plicord Flexwing Petroleum Hose depending on availability from the supplier. All of the connections were made with 51-mm (2-in) hose except for the air supply to the eductor and the FCU, which was made with 38-mm (1.5-in) hose.

Weigh Tank - The weigh tank consisted of a 0.45 m³ (120-gal) tank on a support frame, which was placed on a platform scale.

3.2.1 Instrumentation

Data Acquisition System - The Data Acquisition System (DAS) consisted of a Gateway[®] 486-DX2-66E PC with a Strawberry Tree[®] ACPC-12-16 analog input card and a T-21 terminal panel. Strawberry Tree[®] Work Bench PC DOS[®], version 2.4.0 was the data acquisition software used. The instrumentation specified in this section was connected to the DAS. All of the on line measurements made during the tests were recorded by the DAS at a frequency of 10 Hz. The analog outputs were recorded to the data file without any time averaging. The conversion of the analog signals to engineering units that were recorded to the data file and output to the DAS display screen, was a continuous one second average (i.e., at 10 Hz, average of last ten readings).

Vacuum Line Pressure Sensor/Transmitter - Sensor Endevco® model 8530C-15, serial # AELK1 D 214 024 with a range of 0 -15 psia \pm 0.5% of calibrated span. The sensor requires an API 4058G transmitter to convert the low-level strain gage signal to a 4-20 mA output for the DAS. The transmitter is fully adjustable and is not provided with a manufacture specified uncertainty. The estimate for the overall uncertainty of the vacuum channel is \pm 1% of calibrated span (based on previous work).

Air Supply Line Pressure Transmitter - Ametek® model 88F, serial # 40173-1-18 with a range of 0-2070 kPa-gage (0-300 psig) \pm 0.25% of calibrated span. Provides an analog output of 4-20 mA to the DAS that is proportional to the pressure.

PP Discharge Pressure Transmitter - Ametek® model 88F, serial # 40173-1-4 with a range of 2070 kPa-gage (0-300 psig) \pm 0.25% of calibrated span. Provides an analog output of 4-20 mA to the DAS that is proportional to the pressure.

MicroMotion® Coriolis Mass Flow Measurement System - The System consisted of a coriolis sensor and an accompanying transmitter. The sensor was a MicroMotion® model DS300S15SU, serial # 162938. The transmitter was a model RFT9739, serial # 23033. The sensor/transmitter system has a minimum flow range of 0 to 159 kg/min (0 to 350 lbm/min) and a maximum flow range of 0 to 3180 kg/min (0 to 7000 lbm/min). The zero stability of the system is 0.32 kg/min (0.70 lbm/min). The accuracy of the measurements for flow rate and density are \pm 0.2% of flow rate \pm the zero stability and \pm 0.001 g/cc, respectively. The coriolis sensor outputs two frequency signals to the transmitter. The transmitter calculates the mass flow rate and density from the sensor output signals and provides two analog output signals of 4-20 mA to the DAS, which are proportional to the desired quantities. The signal averaging of the sensor was set at one second. The density range was maintained at a specific gravity of 1 to 2 throughout the test program. The range of the mass flow rate was adjusted several times to provide adequate resolution and yet ensure the output signal was maintained below 20 mA.

Weigh Tank Platform Scale - The platform scale was a Hardy® FLB-3030-.5K (the serial number was unreadable). The low-level signal from the load cell output was converted by a BLH Lcp-100 weigh processor, serial # 6461392. The uncertainty of the weigh system is \pm 1% of calibrated span. The BLH Lcp-100 weigh processor provides a 4-20 mA signal to the DAS.

3.3 Simulants

Water for testing and mixing simulants was obtained from the process water supply for the 336 Building. Kaolin clay was used to create the slurry simulant. Kaolin clay (kaolinite) is a naturally occurring hydrous aluminum silicate mineral. The specific gravity of the particle material is reported as ranging between 2.6 to 2.65. Table 3.1 provides the results of a particle size analysis of the dry kaolin clay material.

TABLE 3.1 Results of Particle Size Analysis (Volume %) of Dry Kaolin Clay.

Partical Size Range (μm)	Volume % for Specified Range (Vol. %)	Cumulative Volume % (Vol. %)	
		Under	Over
0.0 - 1.0	3.19	3.19	96.81
1.0 - 2.0	8.26	11.45	88.55
2.0 - 3.0	8.83	20.28	79.72
3.0 - 4.0	10.49	30.77	69.23
4.0 - 5.0	12.81	43.58	56.42
5.0 - 6.0	10.83	54.42	45.58
6.0 - 7.0	6.83	61.25	38.75
7.0 - 8.0	2.85	64.10	35.90
8.0 - 9.0	3.15	67.24	32.76
9.0 - 10.0	1.82	69.07	30.93
10.0 - 20.0	22.41	91.47	8.53
20.0 - 30.0	8.53	100.0	0.00
30.0 - 40.0	0.00	100.0	0.00

Fine and medium grain sands were added to the kaolin slurry for some tests to evaluate the effect of larger particle on the performance of the PP. The specific gravity of the sand material was measured at 2.83 ± 0.02 and 2.86 ± 0.02 for the fine and medium grain material respectively. Table 3.2 provides the averaged results of particle size screening tests. The sieving time for all tests was 10 minutes.

The viscosity and yield stress of the slurries was not measured for this project. In Section 4.3 estimates are made for these quantities using data from rheological measurements made on kaolin/water slurries in a previous project.

TABLE 3.2 Results of Sand Particle Size Screening Tests.

Sieve Size USA sieve # opening(μm)	Fine Sand (% mass)		Medium Sand (% mass)	
	retained	passing	retained	passing
4 (4760)	0.7	99.3	0.0	100.0
8 (2380)	1.3	98.0	0.0	100.0
18 (1000)	4.2	94.0	94.5	5.5
30 (595)	36.6	57.2	2.0	3.5
50 (297)	50.3	6.9	2.6	0.9
100 (149)	4.7	2.2	0.4	0.5
pan	2.2	NA	0.5	NA

3.4 Procedure

Testing of the PP was initiated by pressurizing the air supply line to the FCU and the PP. The pressure of the FCU (i.e., PP) air supply line was adjusted to the predetermined setting. The supply pressure to the vacuum eductor was maintained at 725 kPa gage (105 psig) and the flow rate to the eductor was throttled to provide the desired vacuum line pressure. The speed of the rotary control valve was adjusted to obtain the desired cycle duration. The DAS output was monitored and the vacuum and air supply pressures adjusted until a periodic flow rate in the retrieval line was achieved.

Once the flow rate was considered satisfactory, the DAS log was started and the online measurements were recorded to the data file at 10 Hz. Data sampling occurred over 5 to 10-minute intervals to maintain reasonably sized data files that are easily processed.

During the recording of some of the data sets, bottle samples were taken from the return line slurry or the flow in the return line was diverted to the weigh tank for 1 to 2 minutes. The averaged flow rate calculated from the weigh tank output was used for comparison to the output from the MicroMotion[®] System.

4.0 Results

Data sets for each test were recorded via the data acquisition system (DAS) and were numbered sequentially for each piece of equipment tested. Twenty-four data sets were recorded for the Pulsating Pump (PP). The recorded data for the PP is presented and explained in Section 4.1. Four data sets were recorded during the demonstration of the Pulsating Monitor (PM) and are presented in Section 4.2. Calculated results and analysis are described in Section 4.3. Discussion and observations of the system and test results are presented in Section 5.

The PP was first tested with water and then with several kaolin clay-based slurries whose density and rheological characteristics were changed by varying the concentration of the clay. The initial plan called for incrementally increasing the specific gravity of the slurry up to a maximum of 1.4 by the addition of kaolin clay. However, the addition of clay results in an increase in the slurry viscosity and yield stress. The increased apparent viscosity allowed entrained air to remain in the slurry as micro bubbles. The volume of entrained air increased with the addition of kaolin clay, maintaining the specific gravity of the three-phase mixtures in the range of approximately 1.1 to 1.2. The specific gravity of slurry is reduced from 1.2 to 1.1 with the addition of approximately 8% (by volume) of air.

The air was entrained in the fluid as it flowed down the return pipe from the siphon break. Between several tests the fluid was agitated with a vibrator to reduce the volume of entrained air from the slurry. The MicroMotion® System provided density readings for the three-phase mixture and bottle samples were taken from the return duct to provide the concentration of kaolin clay and an estimate of the amount of entrained air. During several tests the return flow was diverted to a weigh tank system to provide for a comparison of the time averaged flow rate obtained from the MicroMotion® System. The weigh system yielded results within 2% of those obtained from the MicroMotion® System readings.

The PP was tested using the 0.65 m³ (172-gal.) test tank. The liquid was maintained at a height between 0.84 - 0.89 m (33 - 35 in.) which was measured when the pump was not operating. The height of the liquid was reduced when fluid was transferred to the weigh tank. A drawdown test was run in which the liquid level in the test tank was reduced until air intake was visually observed at the inlet of the PP.

Two different particle size sands were added to the kaolin slurry in an attempt to test the performance of the PP with slurries of a specific gravity greater than 1.2 and to evaluate the response of the pump to increased particle size. Values of specific gravity between 1.3 and 1.6 were measured by the MicroMotion® System during the sand tests. Grab samples taken during testing yielded sand concentrations of 12 to 27 wt percent. While the specific gravity of the slurry was increased with the addition of sand, a periodic response of the system over 2- to 5-minute intervals was never obtained. Hold-up of particulate in the system, and the effect of the particulate on the check valves, created erratic readings for the flow rate, discharge line density, and the discharge line pressure of the pump. The sand also caused plugging in the discharge line, becoming plugged to the point that the back-flushing capability of the system was unable to

unplug the line. The observation and results from these tests are discussed further in later sections.

To visualize the effect of the jets in the transport of particulate on the tank bottom, the PM was run using the 1/4 Scale DST as the test tank. The test utilized water as a supernatant liquid and medium size (1-2.4 mm) sand, with the fines removed, for settled solids. The sand was washed of fine particulate to maintain a clear liquid so that the influence of the jets on the particulate could be visualized. The PM contained two diametrically opposed, 8-mm (0.31-in.) diameter nozzles. Along the centerline of the nozzles the PM cleared the material to within approximately 0.45-m (12-in.) of the tank wall.

4.1. Data Measurements for the PP

The data sets for the Pulsating Pump (PP) will be identified by their test number, 1 to 24. However, data from all twenty-four data sets will not be included in this report. The reason for not including some of the individual data sets will be explained in an attempt to make this report as complete an experimental record as possible.

The mass flow rate and density of the slurry were obtained from the MicroMotion® System. The vacuum line and air supply pressures were measured at the motor-driven rotary valve on the Flow Control Unit (FCU). The discharge pressure (i.e., exit pressure) was measured just downstream of the discharge check valve for the PP. The data was sampled and logged to the data file at 10 Hz. The MicroMotion® System transmitter was set up for a continuous one second averaging of the sensor signal.

Tests 1 through 3 were run with water as the test fluid. The pressures were still being adjusted during Test 1 and so a steady state operating condition was not obtained. Periodic data was obtained for tests 4 through 10, 13, 14, and 16. Test 16 included a drawdown of the liquid level in the test tank. Test 16 begins with the discharge fluid being returned to the test tank (i.e., closed loop). Data from this beginning period of Test 16 was considered to be at steady state operating conditions. During Test 16 the return line was then diverted to the weigh tank and the liquid level in the test tank was lowered. Test 16 is the only test where the mass flow rate measured by the MicroMotion® System did not agree with the results obtained from the weigh tank. Based on the data from the MicroMotion® System and the discharge pressure sensor it appeared the MicroMotion® System experienced a zero offset during Test 16. After accounting for the estimated zero offset, the MicroMotion® System's readings for mass flow rate were within 0.5% of those obtained from the weigh tank.

Prior to Test 9, a modification was made to the discharge line in an attempt to reduce the air entertainment in the slurry. In addition, during Test 9 it appeared conditions changed so that the ratio of the supply pressure to the vacuum line pressure was no longer adequate to maintain a steady state operating condition. From the data, it appeared that air from the pump was being passed into the discharge line. These conditions resulted in the slurry foaming and the data measurements becoming erratic. Readings from the initial periodic response of the system that occurred at the beginning of Test 9 were used to obtain time-averaged measurements. At the completion of the test the discharge line was returned to its original configuration.

Table 4.1 contains the time averages of the periodic data (from the recorded data sets) that were obtained under steady state operating conditions. The period is the time of a complete fill and discharge cycle. The vacuum line pressure, the air supply pressure, and the mass flow rate are expected to behave as periodic functions. The mass flow rate is equal to zero as the pump is filling, increases in value as the discharge check valve opens, reaches a peak value, decreases as the rotary valve begins to cut off the air supply and the pressure in the chamber of the pump attempts to equilibrate, and then returns to zero when the vacuum line is opened to the pump chamber drawing the discharge valve closed. The time average for the mass flow rate was obtained by averaging the data throughout a period of steady state operating conditions including the zero flow periods of the pump cycle. A graphical illustration of the measurements for the mass flow rate obtained during Test 4 over approximately three cycles are provided in Figure 4.1. The figure is a plot of the mass flow rate and specific gravity of the slurry as a function of time. The time average of the mass flow rate is indicated on the plot.

A plot of the vacuum and air supply line pressures as a function of time for approximately three cycles during Test 4 is shown in Figure 4.2. The action of the rotary control valve for the air supply and vacuum lines can be observed in this plot. There is a delay between each change from one pressure condition to the other, during which both the supply and vacuum lines are isolated from the pump chamber. There is also a response time associated with the opening and closing of the rotary valve. When the vacuum line is opened to the pump reservoir, the pressure in the vacuum line spikes upward as a result of the pressurized air space that is rarefied. The pressure remains practically constant while fluid is drawn into the pump chamber and then begins to fall as the valve closes. The vacuum line reaches its lowest pressure while isolated from the pump chamber. In Figure 4.2, the vacuum line is opened at times of 110, 125, and 140 seconds and closed at times of 117, 132, and 147 seconds.

As the supply line is opened to the pump chamber, the supply line pressure spikes down as a result of having to pressurize the rarefied gas space in the pump. The pressure then increases and remains fairly constant as fluid is discharged from the pump. The pressure increases slightly as the rotary valve closes. Once the valve is closed, the supply line pressure reduces to an equilibrium value. This reduction in pressure, upon the closing of the valve, is not due to the PP system but rather a result of the test setup. The air supply line was plumbed to the compressor using a pressure regulator. The regulator has a small pressure difference between opening and closing and the gradual decline in pressure is possibly due to a small air leak. In Figure 4.2, the supply line is opened at times of 104, 119, 133, and 148 seconds and closed at times of 110, 124, and 139 seconds.

The mass flow rate and discharge pressures as a function of time for three cycles during Test 4 are shown in Figure 4.3. The discharge pressure is observed to remain constant until the discharge valve opens which is indicated by the increase in the mass flow rate. The discharge pressure spikes upward and then remains nearly constant at an elevated pressure through the remaining flow pulse. The flow rate appears to be slightly ahead of the discharge pressure in phase because the pressure sensor is providing an instantaneous reading and the flow meter signal is a continuous one-second average of the flow rate. The discharge pressure and the flow rate decrease during the delay period after the supply line valve closes and before the vacuum

line valve opens. With the opening of the vacuum line valve, the discharge line pressure spikes down and returns to its no-flow value.

TABLE 4.1 Time Averages of Measured Data for Steady State Operating Conditions.

All cases are for kaolin clay/water mixtures unless noted.

Case Test No.	Period (sec)	Vacuum Line Pressure kPa-absolute <i>psia</i>	Supply Line Pressure kPa-gage <i>psig</i>	Discharge Pressure kPa-gage <i>psig</i>	Density (SG)	Mass Flow Rate kg/s <i>lbm/min</i>	Volume Flow Rate m^3/hr <i>gpm</i>
2 ^w	15	77.3	399	29.1	1.00	1.34	4.8
		11.2	57.9	4.2		177	21.2
3 ^w	23	70.3	402	31.7	1.00	1.31	4.7
		10.2	58.4	4.6		174	20.7
4	15	62.2	410	33.8	1.09	1.41	4.6
		9.0	59.4	4.9		186	20.5
5	19	83.2	391	32.4	1.07	1.33	4.5
		12.1	56.8	4.7		176	19.7
6	25	82.2	392	33.1	1.06	1.30	4.4
		11.9	56.9	4.8		172	19.6
7	20	76.0	445	36.5	1.12	1.48	4.7
		11.0	64.5	5.3		195	20.8
8	20	76.4	444	37.2	1.10	1.50	4.9
		11.1	64.4	5.4		198	21.6
9	20	83.2	433	33.3	1.10	1.58	5.1
		12.1	62.9	4.8		209	22.7
10	20	80.0	457	-6.41	1.09	1.39	4.5
		11.6	66.3	-0.93		182	20.1
13	21	79.4	379	-8.96	1.19	1.53	4.6
		11.5	55.0	-1.3		203	20.5
14	21	79.0	378	-7.58	1.19	1.45	4.4
		11.5	54.9	-1.1		192	19.5
16	21	73.5	367	-14.3	1.15	1.46 ^{**}	4.5
		10.6	53.3	-2.1		193 ^{**}	20.1

^(w) Denotes case with water as the test fluid.

^(**) Micro Motion flow rate appeared to have a zero offset, therefore, the weigh tank readings were used to determine the flow rate.

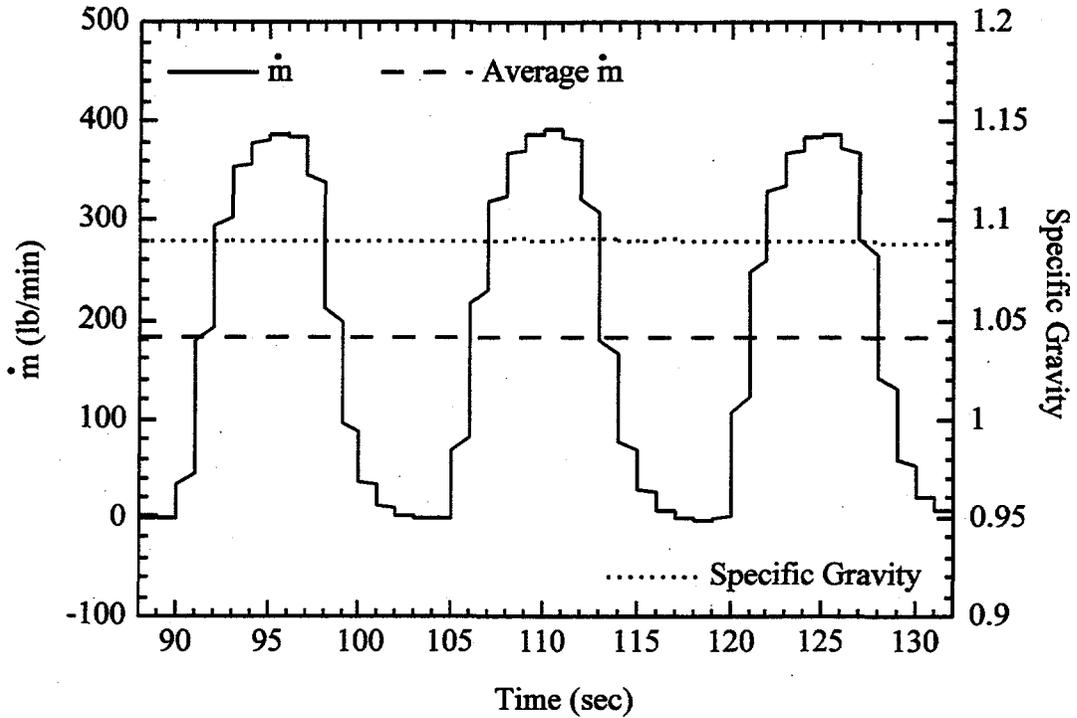


Figure 4.1 Mass Flow Rate and Specific Gravity of the Slurry versus Time for Three Cycles of Test 4.

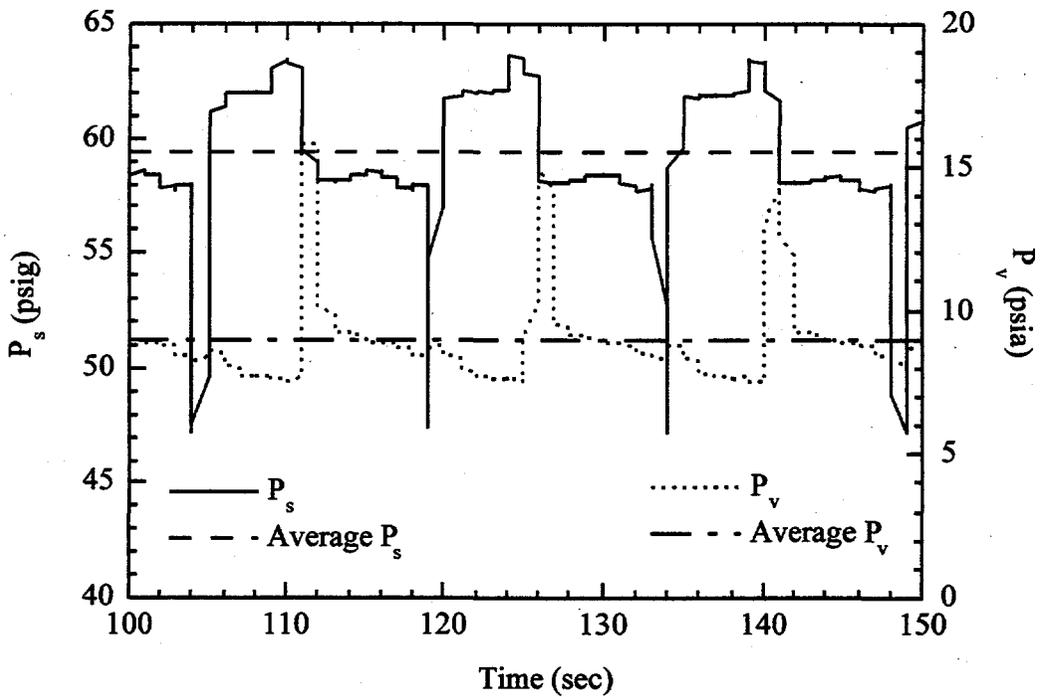


Figure 4.2 Vacuum and Air Supply Line Pressures versus Time for Three Cycles of Test 4.

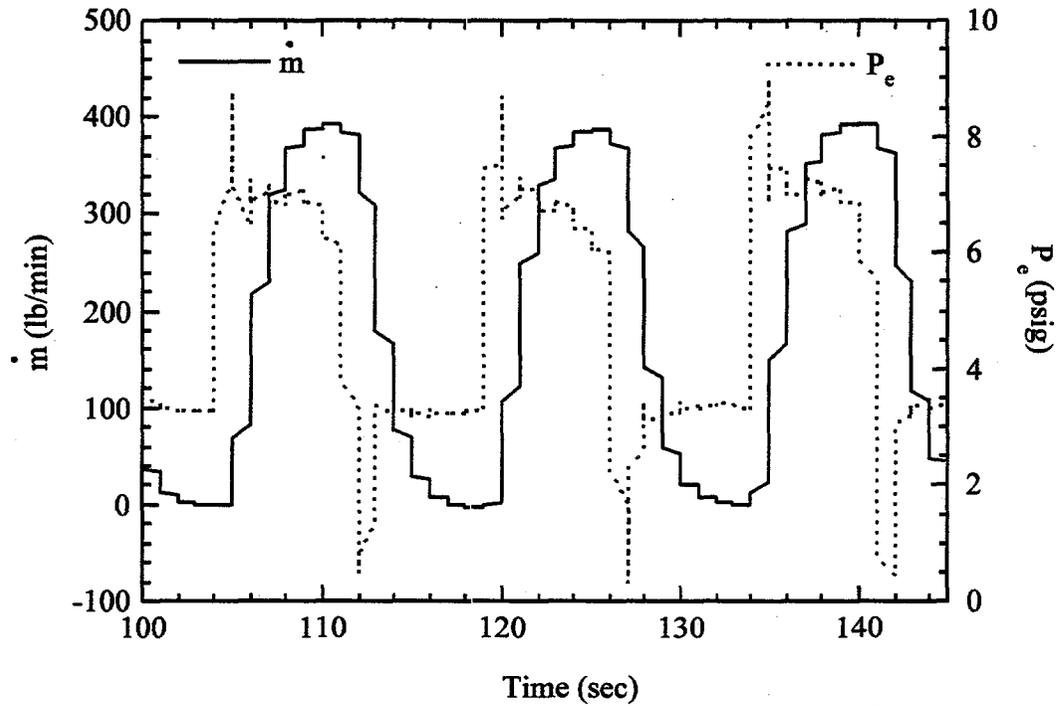


Figure 4.3 Mass Flow Rate and Discharge Pressure versus Time for Three Cycles of Test 4.

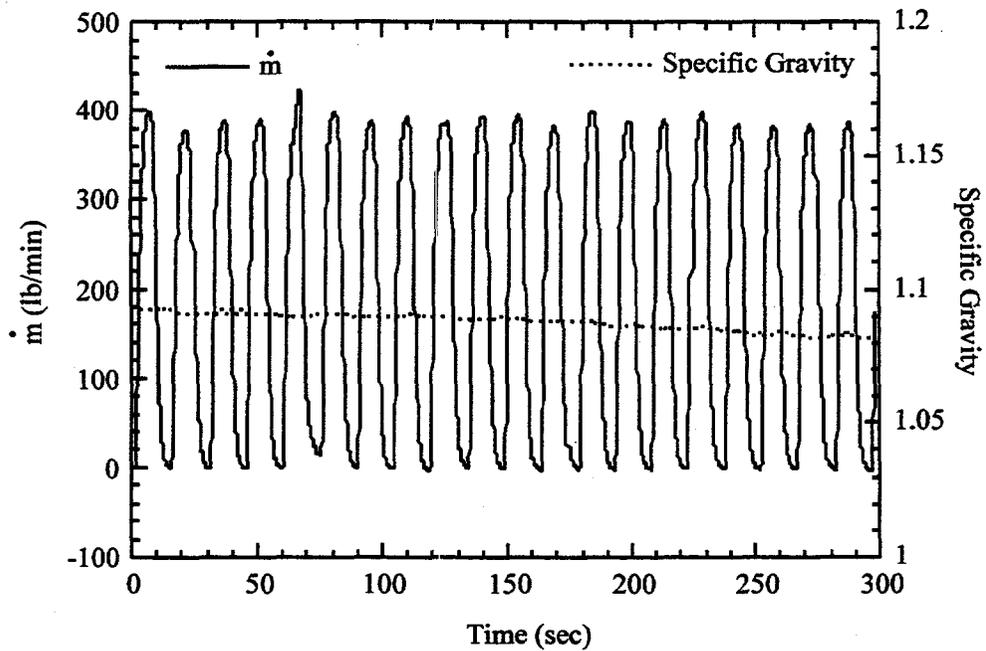


Figure 4.4 Mass Flow Rate and Specific Gravity versus Time for the Entire Duration of Test 4.

The measurement of the discharge pressure shows when the discharge check valve is not closing completely due to sticking or grit in the check valve. This condition is identified by the discharge pressure falling below zero gage pressure during a no-flow period. This condition allows fluid to flow back into the pump. If the condition is severe, the MicroMotion® System will indicate negative flows.

A plot of the mass flow rate and specific gravity as a function of time for the entire duration of Test 4 is given in Figure 4.4. The decrease in the specific gravity of the slurry, due to the entrainment of air, is seen in this figure.

During testing, the vacuum and supply pressures were adjusted according to their minimum and peak values, respectively, which occur simultaneously while the supply air is discharging fluid from the pump. The discharge of fluid from the PP is dictated by the peak pressure of the air supply line and the filling of the pump by the approximately constant vacuum pressure obtained after the upward pressure spike. Table 4.2 gives the time-averaged pressures and an estimate of the peak supply and minimum vacuum line pressures to which the operating parameters were set. The estimates were obtained by averaging the pressure measurements during the period of peak supply pressure for just 2 to 3 cycles of a data set. These estimated values are presented to show the differences between the extreme and time-averaged pressures. The discharge pressure was included in the table to evaluate whether a negative value for the time average of the discharge pressure had an impact on the relationship between the extreme and averaged values for the air-line pressures.

Bottle samples were taken from the discharge line during several of the tests. The samples were used to provide a comparison to the densities being measured by the MicroMotion® System. A number of the samples were saved for determining the concentration of kaolin clay and air in the slurry. The saved samples were allowed to sit for six weeks so that the entrained air could escape. This was confirmed by the reduction of the sample volume along with an increase in the density of the mixture. Using the slurry densities measured from the grab samples after six weeks and those obtained from the MicroMotion® System during testing, the volume fraction of entrained air was estimated for several tests. Table 4.3 provides the estimated volume fraction of entrained air for the steady state cases for which bottle samples were saved.

Test 16 consisted of a drawdown test in which the fluid was removed from the test tank to the weigh tank to determine the lowest allowable fluid level at which the PP would operate. Visual observation was used to detect the entrainment of air into the PP inlet. During Test 16, the slurry level in the test tank was reduced from 0.84 to 0.28 m (33 to 11 in.) at which time the test was terminated for lack of holding capacity in the weigh tank. The mass flow rate and specific gravity as a function of time are shown in Figure 4.5. As the liquid level in the test tank decreases, so does the pressure drop across the inlet of the PP during the fill portion of the pump cycle. Therefore, a smaller volume of slurry enters the PP at the start of each new cycle.

TABLE 4.2 Comparison of Time Averaged Pressure Measurements and Estimated Extreme Pressures for Supply and Vacuum Lines.

Case	Vacuum Line Pressure kPa-absolute <i>psia</i>		Supply Line Pressure kPa-gage <i>psig</i>		Discharge Pressure kPa-gage <i>psig</i>
	Averaged	Estimated min.	Averaged	Estimated max.	
2 ^w	77.3	70.3	399	427	29.1
3 ^w	11.2	10.2	57.9	62.0	4.2
	70.3	62.0	402	426	31.7
4	10.2	9.0	58.4	61.8	4.6
	62.2	55.1	410	433	33.8
5	9.0	8.0	59.4	62.8	4.9
	83.2	77.2	391	414	32.4
6	12.1	11.2	56.8	60.1	4.7
	82.2	77.9	392	412	33.1
7	11.9	11.3	56.9	59.8	4.8
	76.0	69.6	445	467	36.5
8	11.0	10.1	64.5	67.7	5.3
	76.4	70.3	444	467	37.2
9	11.1	10.2	64.4	67.7	5.4
	83.2	78.6	433	458	33.3
10	12.1	11.4	62.9	66.5	4.8
	80.0	75.1	457	482	-6.41*
13	11.6	10.9	66.3	69.9	-0.93*
	79.4	73.8	379	397	-8.96*
14	11.5	10.7	55.0	57.6	-1.3*
	79.0	73.8	378	395	-7.58*
16	11.5	10.7	54.9	57.3	-1.1*
	73.5	66.2	367	386	-14.3*
	10.6	9.6	53.3	56	-2.1*

(*) A negative value (less than atmospheric pressure) for discharge pressure indicates discharge check valve was not closing completely.

However, the air supply pressure, controlled by a pressure regulator, used to discharge liquid from the pump reservoir remains constant. Therefore, a constant volume of slurry is discharged from the reservoir at each cycle as long as some liquid remains within the pump reservoir throughout the course of a cycle. When the pump reservoir is emptied of liquid during the course of a cycle, then air passes into the retrieval line for the remainder of the pressurized portion of the cycle. As a decreasing volume of slurry is drawn into the chamber with each cycle, a larger volume of air passes into the retrieval line, which is observed in Figure 4.5 by the cyclical decrease in the density.

Table 4.3 Estimate of Volume Percent of Entrained Air in Slurry for Steady State Cases.

Case No.	Average of Slurry Densities obtained from Bottle Samples after Entrained Air allowed to Escape (SG)	Average of Slurry Densities obtained from MicroMotion® System during Testing (SG)	Estimated Volume Percent of Entrained Air in Test Slurry Volume %
4	1.087	1.089	0
5	1.087	1.067	1.9
6	1.077	1.056	2.0
9	1.137	1.105	2.8

The draw-down test was continued with Test 17. The fluid level in the test tank was reduced from 0.28 to 0.23 m (11 to 9 in.) before air was visually observed being drawn into the pump inlet at which time Test 17 was terminated.

Test equipment failure (not the PP or FCU) and outputs by the MicroMotion® Sensor exceeding 20 mA (beyond operational limits) resulted in Test 11 being terminated early. The system response during Test 11 was erratic and the data could not be analyzed for this case. Test 12 did not include the operation of the PP and was conducted to check the reconfiguration of the MicroMotion® System.

Test 15 provides an example of the system response observed when the discharge check valve of the PP becomes fouled. This can occur if material becomes lodged in the valve or the ball of the check valve becomes coated with material and begins to stick. Under such circumstances, the back-flush capability of the system can and was successfully employed to alleviate the problem. The measurements for the mass flow rate, the specific gravity, and the discharge pressure obtained in response to the fouled discharge valve during Test 15 are presented in Figures 4.6 and 4.7. The periodic measurement for the specific gravity and the negative mass flow rates are observed in Figure 4.6. The specific gravity decreases during the discharge portion of the cycle in response to the air being passed into the retrieval line. The density increases at the completion of the discharge portion of the cycle due to the air rising out of the flow passage in the MicroMotion® System. Negative gage pressures at the exit of the PP are shown in Figure 4.7, which indicate that the check valve is not closing properly.

To evaluate the effect of particles larger than those of the kaolin clay on the PP, sands of two different particle size distributions were used. The measured particle size distributions for the sands are presented in Table 3.2. At the completion of Test 17, the specific gravity of the kaolin clay slurry was measured at 1.2. The fine sand (particle size 0.3 - 1 mm) was added to the slurry to create a mixture with a specific gravity of 1.3, which was used for Test 18.

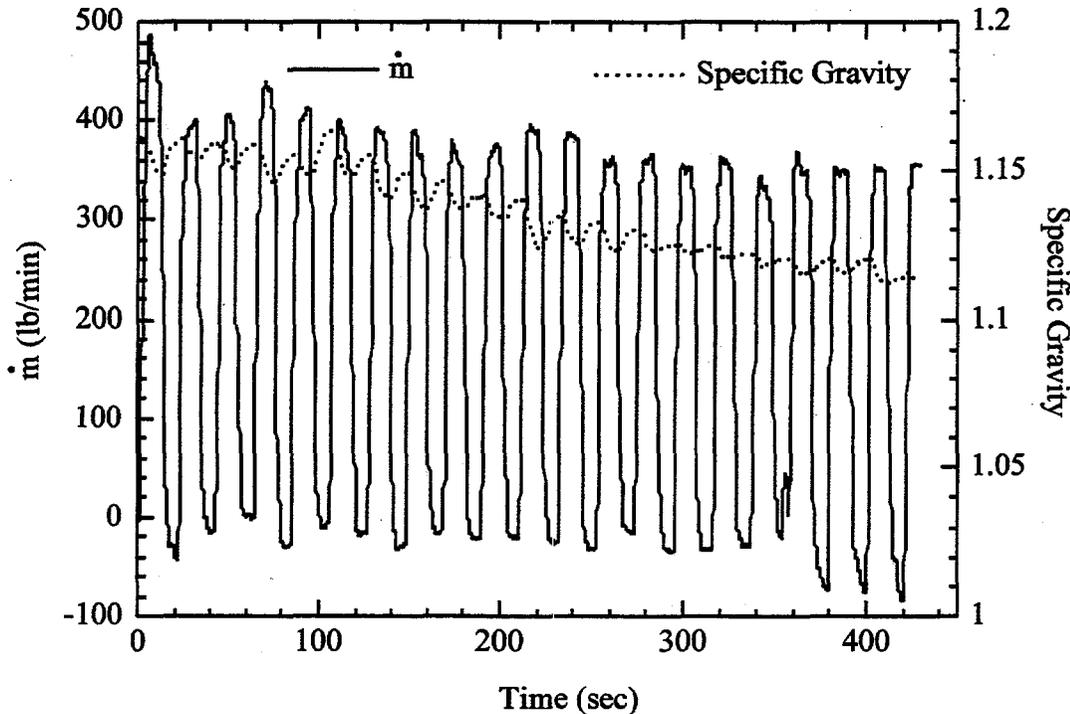


Figure 4.5 Mass Flow Rate and Specific Gravity as a Function of Time for Drawdown of Test Tank conducted during Test 16.

The time-averaged measurements of the vacuum and supply pressures for Test 18 were 74 kPa-absolute (10.8 psia) and 305 kPa-gage (44.3 psig), respectively, and the cycle duration was 20 seconds. The average of the readings for the specific gravity from the MicroMotion® system was 1.37 compared to bottle sample measurements of 1.32, 1.36, and 1.38. The response of the system was erratic and negative values were obtained for the PP exit pressure. The PP was pumping the sand; however, the length of the test was not long enough to determine if hold-up of the sand was occurring in the retrieval line. Because of the erratic measurements obtained for the mass flow rate along with the possibility of sand hold-up in the system, time-averaged values of the mass flow rates for the cases tested with sand are not reported.

At the completion of Test 18, the PP was back flushed and fine sand was added to the test slurry to create a mixture of kaolin clay, fine sand, and water that had a specific gravity of 1.4. Problems with the compressor resulted in an insufficient vacuum source so that no fluid was pumped during Test 19. Test 20 was conducted with the same simulant that was used in Test 19. During Test 20, the time averaged vacuum and air supply line pressures were 74 kPa absolute (10.7 psia) and 307 kPa gage (44.6 psig), respectively, and the cycle duration was 20 seconds.

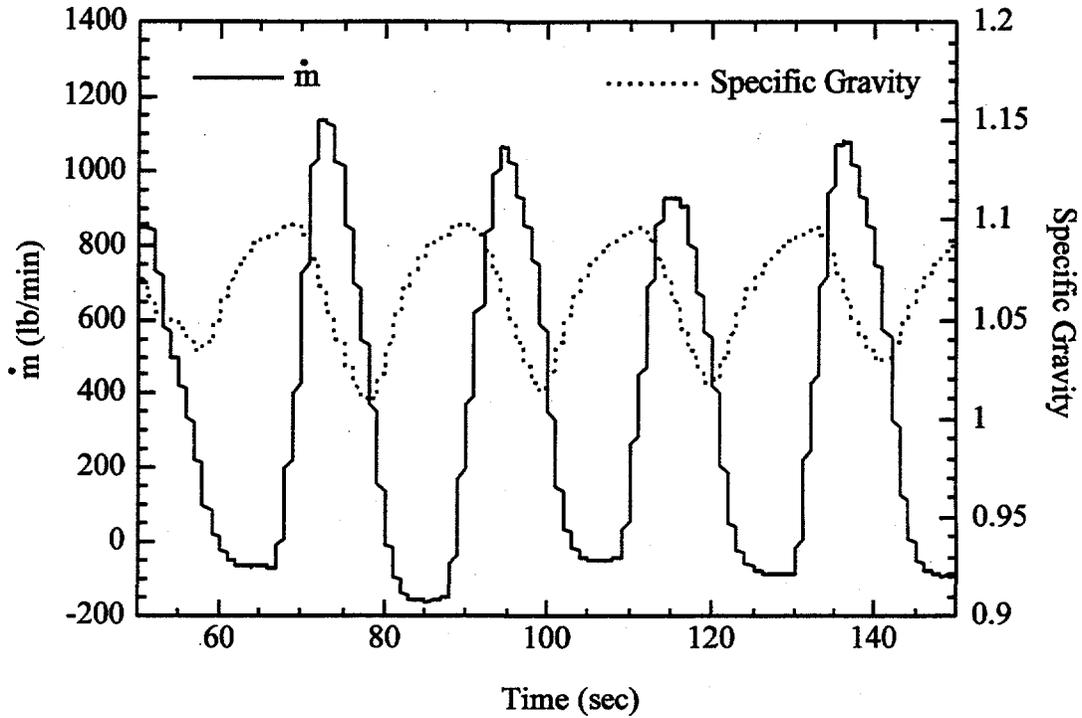


Figure 4.6 Mass Flow Rate and Specific Gravity as a Function of Time for a Portion of Test 15.

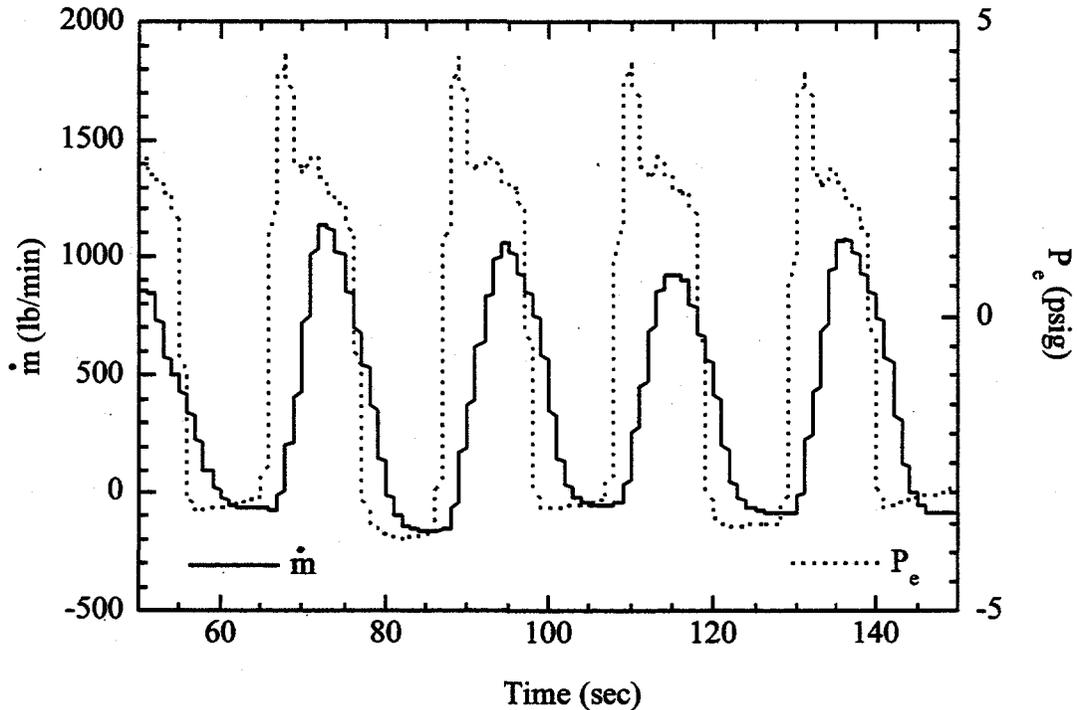


Figure 4.7 Mass Flow Rate and Retrieval Line Pressure at the Exit of Pulsating Pump as a Function of Time for Test 15.

The mass flow rate and specific gravity as a function of time for Test 20 are given in Figure 4.8. The negative flow rates (shown in Figure 4.8) along with the negative discharge pressures confirm that the discharge valve was not closing during the fill portion of the pump cycle. Figure 4.8 displays an apparent increase in the specific gravity over time. The rise in the specific gravity means that the solids concentration in the retrieval line is increasing (indicates that hold-up is occurring). Bottle samples taken from the return line yielded values for specific gravity of 1.21 and 1.20 which is less than that obtained from the MicroMotion® System (refer to Figure 4.8). This difference also points to the possibility of hold-up occurring in the retrieval line.

Test 21 was a continuation of Test 20. Shortly after the start of the Test 21 data file, the flow through the retrieval line ceased. Back-flush operations were carried out without success. The MicroMotion® System's sensor had become plugged with a large quantity of fine sand.

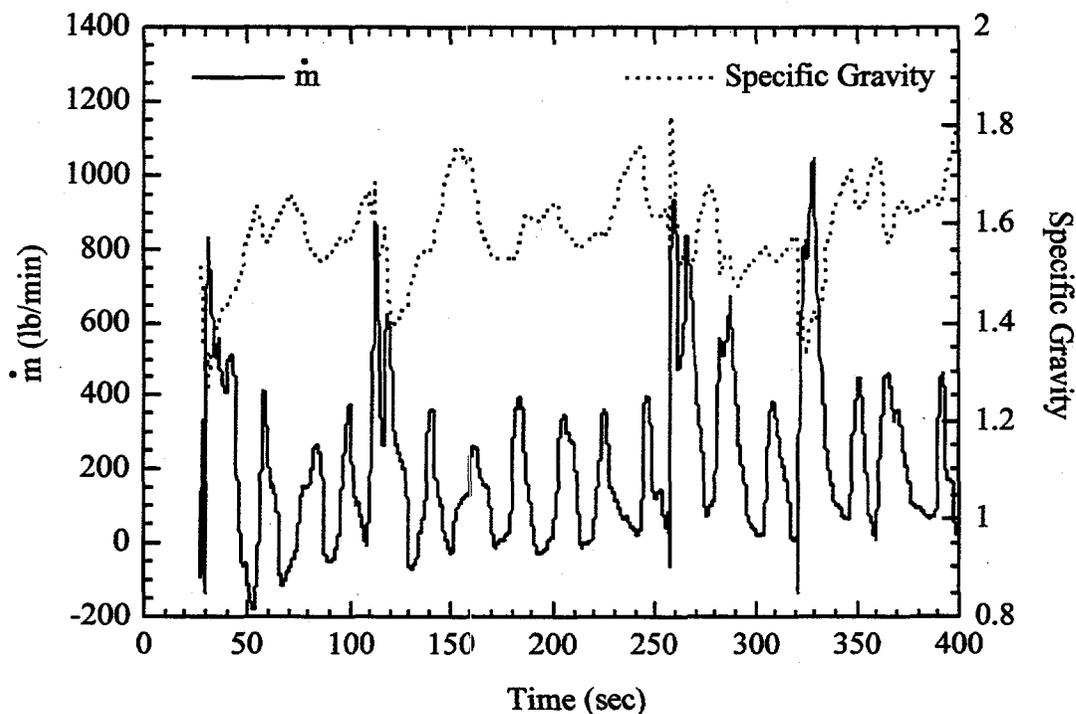


Figure 4.8 Mass Flow Rate and Specific Gravity as a Function of Time for Test 20.

Test 22 was performed to check the performance of the MicroMotion® System following the unplugging of the sensor channels. Test 22 did not involve the PP.

Tests 23 and 24 were conducted with the medium sand being added to the slurry. For Tests 23 and 24, the cycle time was 20 seconds and the average vacuum and air supply line pressures were 75 kPa absolute (10.9 psia) and 378 kPa gage (54.8 psig), respectively. During Tests 23 and 24 negligible amounts of fluid were observed at the return line except when back-flush operations were conducted during Test 23. The upper check valve on the PP appeared to be malfunctioning or plugging repeatedly during the tests. Test 24 was terminated when the

discharge valve plugged and was not quickly cleared by back flushing. Repeated attempts to back flush eventually cleared the valve.

Bottle samples taken during Tests 23 and 24 yielded specific gravity measurements of 1.03, 1.54, and 1.08. The second sample was taken at the start of a back flush and contained a large quantity of fine sand. The lower values for specific gravity obtained from the first and third samples are the result of dilution in the retrieval line due to repeated backflushing. The bottle samples contained some fine sand; however, no medium sand was observed in the captured samples. Readings, obtained from the MicroMotion® System during Tests 23 and 24, yielded specific gravity measurements at the minimum limit (less than 1) for the set configuration. This indicates that at times a large amount of air was present in the sensor.

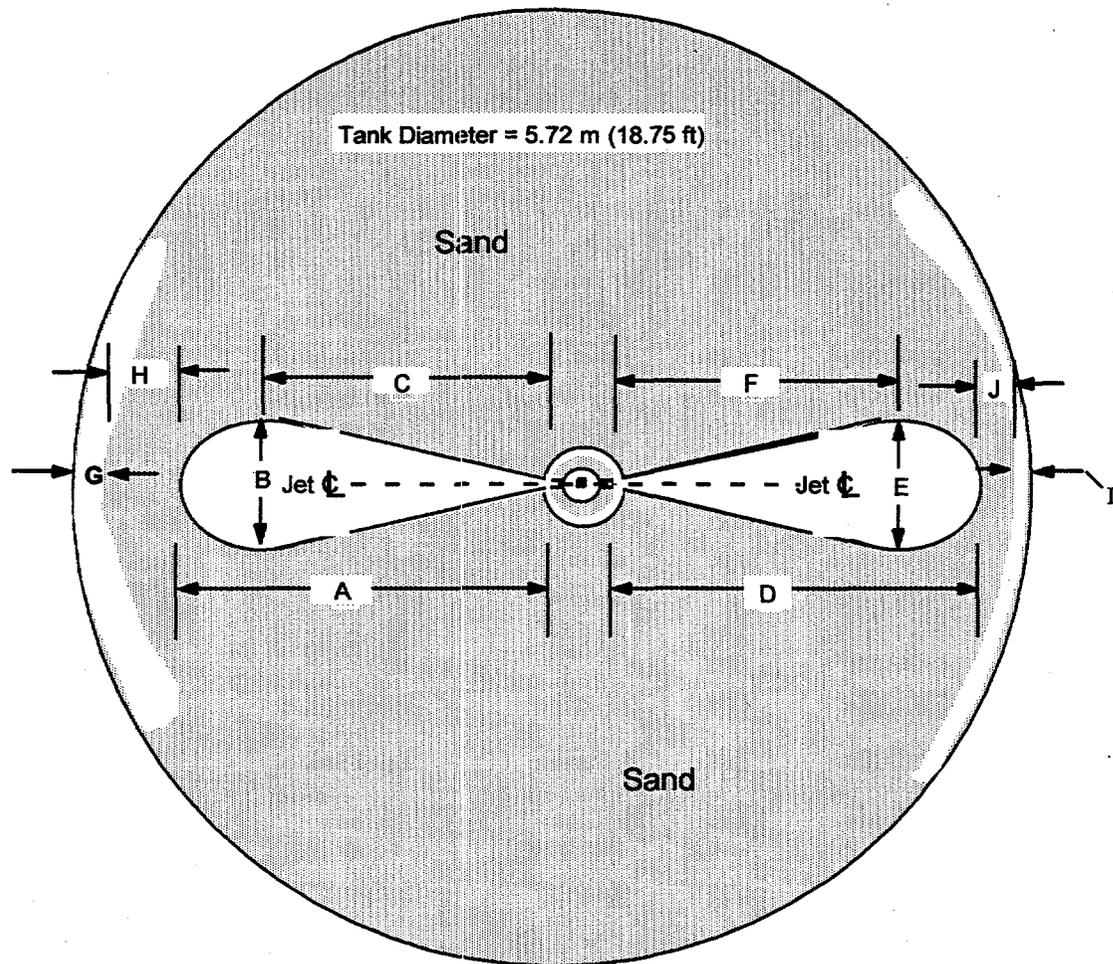
The inability of the PP to transport the medium sand and the limited time available resulted in the conclusion of the PP testing.

4.2. Data Measurements for PM

The PM was demonstrated using the entire 1/4 Scale DST. Four data sets were collected during the demonstration. The first two data sets were collected with 0.41 m (16 in.) of water in the tank. Tests 3 and 4 for the PM contained the washed medium sand spread over the bottom of the tank floor. The vacuum and supply line pressures were the only two on line measurements recorded by the DAS during the PM tests. The tests with water provided operational experience for the PNNL personnel.

The tests with medium sand in the tank were conducted in two phases and allowed the influence of the mixing jets on the bottom of the tank to be observed. In both phases of testing, the PM remained stationary. Prior to the sand tests, the floor of the tank was covered with a thin layer of the sand whose thickness was approximately 1 to 2 particle diameters. The nozzles were oriented in a north-south direction along the bottom of the tank. Perpendicular to the axis of the nozzles (east-west direction) on the west side of the PM a 38 - 63 mm (1.5 - 2.5 in.) thick layer of the sand was placed.

Test 3 was conducted with the nozzles oriented in a north-south direction. During Test 3 the period was 21 seconds and the vacuum and supply pressures were 77 kPa absolute (11.1 psia) and 557 kPa gage (80.7 psig) respectively. For both Test 3 and Test 4, the log of the data file was started prior to starting the operation of the PM. The PM was run for 9 minutes and then the cleared area on the tank floor (referred to as the footprint of the jet) was measured. The footprint of the jets on the bottom of the tank is dimensioned in Figure 4.9. The PM was not located in the exact center of the tank.



Test 3 Results

Dimension	m	in.	Dimension	m	in.
A	2.34	92	F	1.6 - 1.7	63-66
B	0.79 - .81	31-32	G	0.20	8
C	1.57 - 1.60	62-63	H	0.25	10
D	2.59	102	I	0.08	3
E	0.76 - 0.79	30-31	J	0.08	3

Test 4 Results

Dimension	m	in.	Dimension	m	in.
A	2.51	99	H	3	0.08
B	0.60	24	G	3	0.08
C	1.78 - 1.83	70-72			

Figure 4.9 Diagram and Dimensions of Jet Footprint created by Pulsating Monitor on Tank Floor.

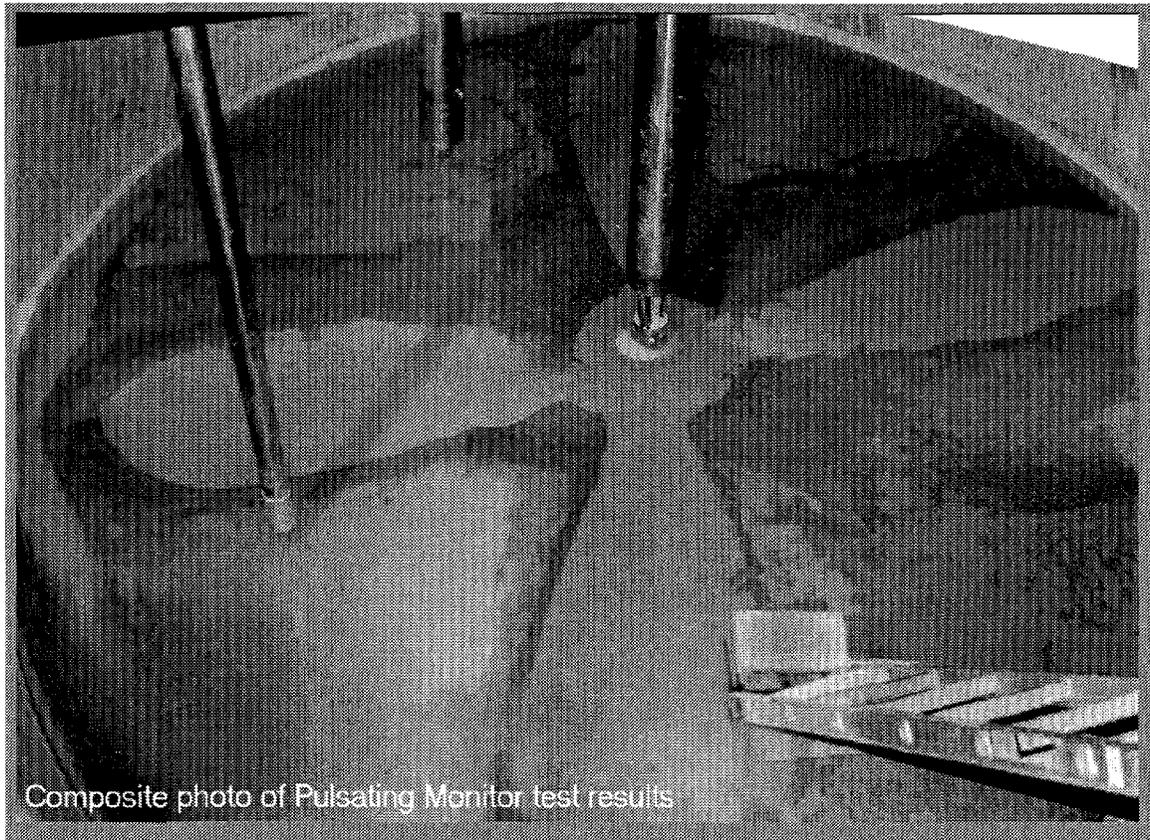


Figure 4.10 Composite Photograph of Flow Pattern Created in Sand by Pulsating Monitor at Completion of Testing.

Observations were made from the equipment bridge above the 1/4 Scale DST. The first jet pulse cleared the floor of sand out to a distance of approximately 1.5 m (5 ft) and on the second pulse to about 1.8 m (6 ft). After the first four pulses, the growth of the footprint slowed considerably. After nine minutes of run time the jets were still moving sand on the bottom of the tank causing the foot print to grow at a slow rate.

For Test 4, the PM was rotated 90° so that one of the nozzles would erode the thick layer of sand. The pulse rate was maintained at 21 seconds, and the time average pressures were 78 kPa absolute (11.4 psia) and 80.7 kPa gage (556 psig) for the vacuum and supply pressure, respectively. Test 4 was run for approximately four minutes. The dimensions for the footprint of the jet created to the west of the PM (i.e., through the thick layer of sand) are presented in Figure 4.9. The footprint of the jet created to the east of the PM was not measured because the ladder and other test equipment at the tank wall interfered with the flow. A composite photograph of the bottom of the 1/4 Scale DST was taken at the completion of Test 4 and is displayed in Figure 4.10. The photograph was taken from the East Side of the tank (i.e., north is to the right of the picture).

4.3. Calculated Results

The time-averaged results reported in Table 4.1 that were used to perform a dimensional analysis of the PP system. The physical properties of the sludge influence the performance of the PP. The density of the slurry provides a relationship for the hydrostatic pressures imposed by the height of the liquid in the tank, in the PP, and in the discharge pipe. The resistance of the slurry to flow is a function of the viscosity and shear stress. Experimental measurements suggest that the rheological behavior of the kaolin-based slurry (between 0.04 and 0.25 mass fraction) can be approximated by the Bingham plastic model. Therefore, the plastic viscosity and the yield stress are used as input parameters. In this situation, the mass flow rate can be mathematically described as a function of the system variables, thus

$$\dot{m} = F(P_s, P_v, P_e, \rho, \mu, \tau_o)$$

where,

\dot{m} = Mass flow rate

P_e = Exit pressure

ρ = Slurry density

τ_o = Bingham yield stress

P_s = Supply pressure

P_v = Vacuum pressure

μ = Plastic viscosity

The vacuum pressure and period or frequency of operation were considered; however, due to the interdependence between the period and the vacuum and supply pressures, redundant nondimensional parameters were obtained. In the current system, a single rotary valve controls the length of time the vacuum and supply air is opened to the pump chamber. In the configuration tested the ratio of the application time of the vacuum to that of the supply air was approximately 1.2. The objective for operating the pump is to draw in the same volume of fluid with the vacuum pressure as is discharged with the supply pressure. Therefore, the supply and vacuum line pressure parameters are dependent on each other.

The pressure difference between the supply pressure and the pump discharge was used because it is this pressure difference that is applied to the fluid column in the pump. The supply pressure must be set high enough to overcome the backpressure on the system during discharge. Furthermore, once the supply pressure is acting on the system, the difference between the supply and exit pressure determines the work performed on moving the sludge. Thus, the functional relationship can be rewritten as

$$\dot{m} = F(P_s - P_e, P_v, \rho, \mu, \tau_o)$$

Three dimensionless groups can be derived from the above relationship, namely

$$G_1 = \frac{\dot{m}\sqrt{\rho\tau_o}}{\mu^2}, G_2 = \frac{P_s - P_e}{\tau_o}, G_3 = \frac{P_s - P_e}{P_v}$$

To obtain estimates for the viscosity and yield stress, data from previous rheological characterization of kaolin clay slurries was utilized. Table 4.4 contains measured values of the yield stress and viscosity for various mass fractions of kaolin clay/water slurries.

TABLE 4.4 Experimental data for Rheological Measurements of Kaolin Clay Slurries.

Kaolin Mass Fraction	μ (cP)	τ_o (Pa)
0.1105	3.0	0.200
0.1322	4.0	0.300
0.1454	4.3	0.400
0.0378	2.0	0.025
0.0838	2.0	0.070
0.2230	12.0	6.000
0.1225	4.5	0.400

These data yield the following empirical relationships for the viscosity and yield stress

$$\mu = 1.12 + 415.85 \omega^{2.433}$$

$$\tau_o = 0.007181 e^{29.644 \omega}$$

where ω is the mass fraction of kaolin, the viscosity is given in cP (the correlation coefficient, R , of the viscosity fit is 0.989), and the yield stress in Pa ($R = 0.999$ for the yield stress fit). Data and correlation for viscosity and yield stress are shown in Figure 4.11 and Figure 4.12, respectively.

Applying the data obtained from these tests to a multidimensional regression analysis reveals that the dimensionless group G_3 does not contribute to the establishment of a functional relationship among the dimensionless groups. In other words, for the range of conditions tested, the mass flow rate appeared to be independent of G_3 . This may not be the case if the range of operation were extended or if the period of a cycle for P_s and P_v could be set independent of one another. From this regression analysis the following equation is obtained, which yields $R = 0.97$. Figure 4.13 shows a comparison between the data, in dimensionless form, and the correlation. This correlation can be used to predict the required supply pressure necessary to deliver a specified flow rate, provided the slurry parameters and system pressure drops are known.

$$\frac{\dot{m} \sqrt{\rho \tau_o}}{\mu^2} = 43375 \left(\frac{P_s - P_e}{\tau_o} \right)^{0.267}$$

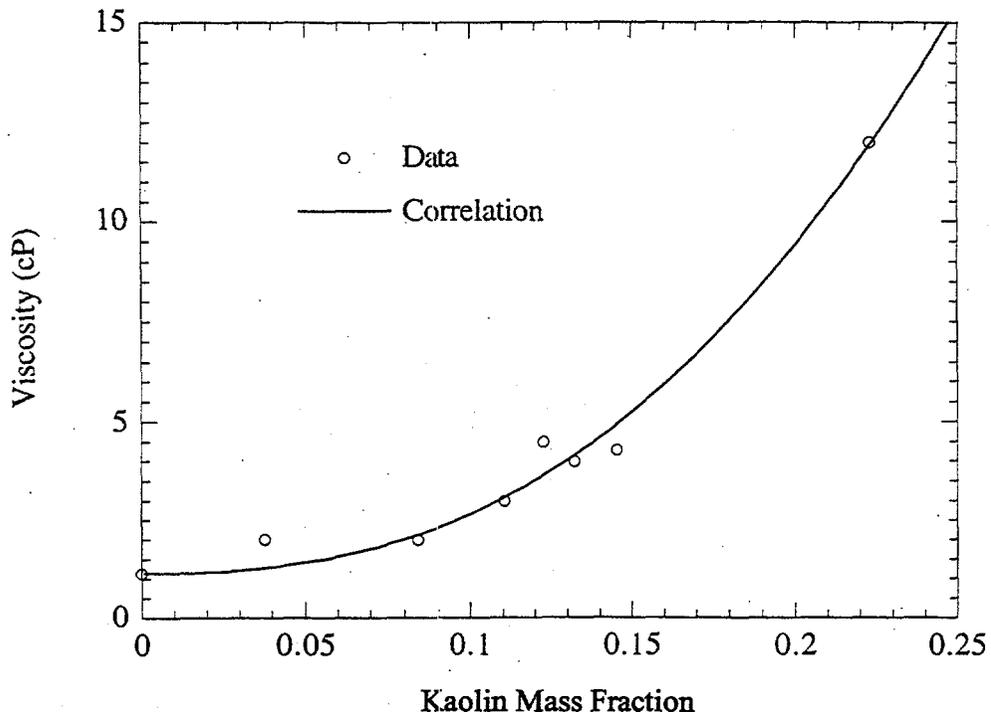


Figure 4.11 Correlation and Experimental Data of Viscosity versus Kaolin Clay Mass Fraction.

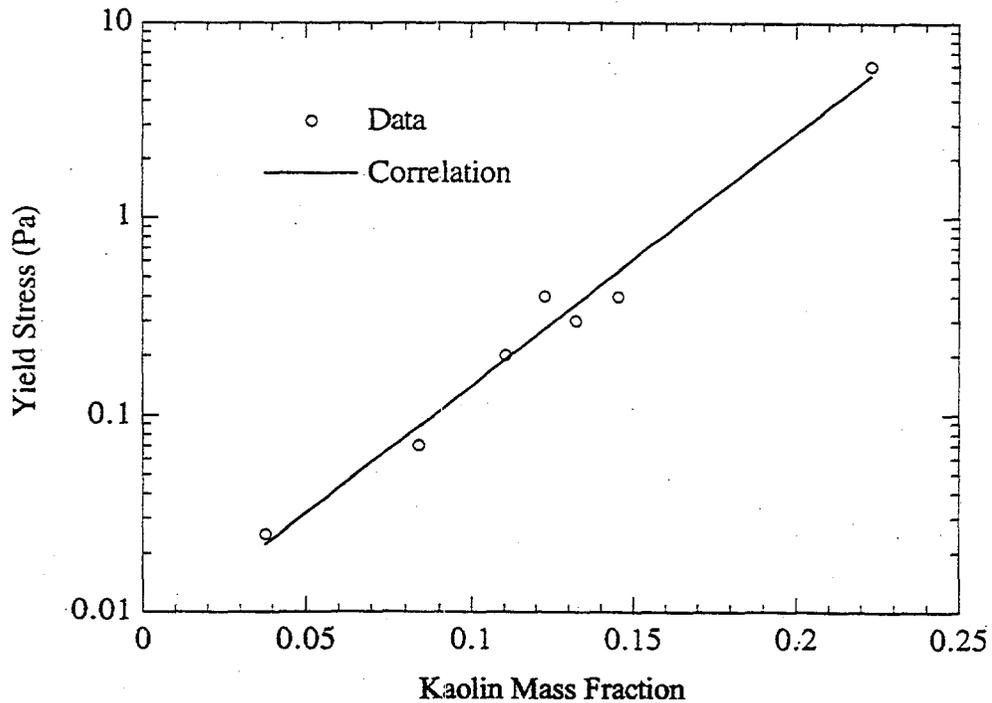


Figure 4.12. Correlation and Experimental Data of Yield Stress versus Kaolin Clay Mass Fraction.

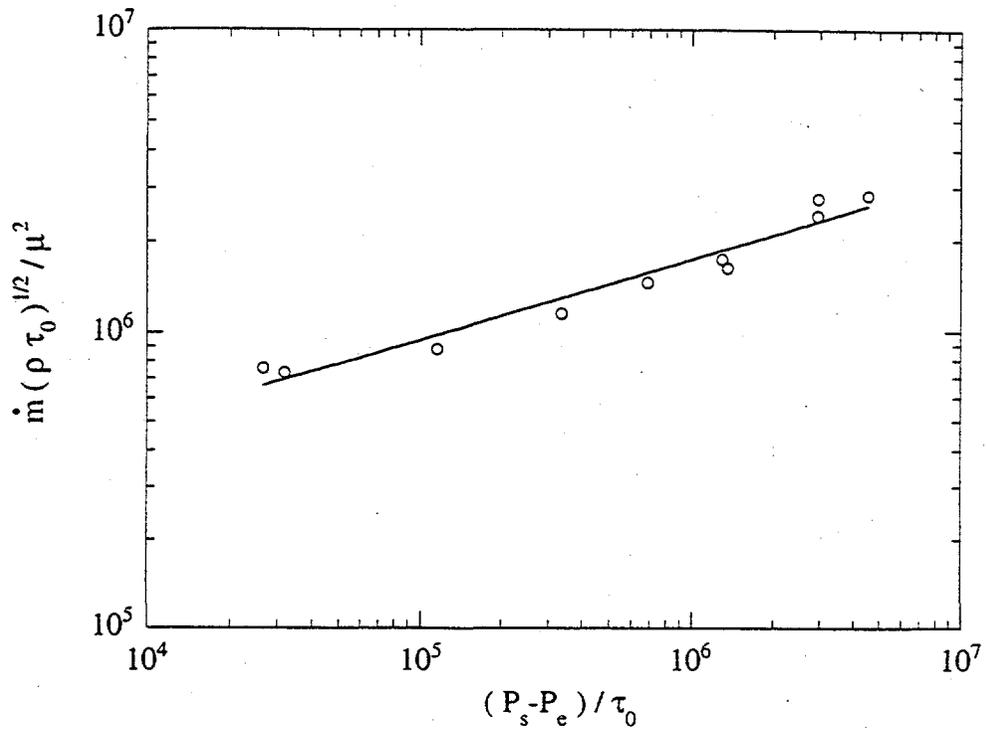


Figure 4.13. Correlation for Operation of Pulsating Pump Developed from Multi-Dimensional Regression Analysis using Time-Averaged Steady State Data for Kaolin Clay Slurry Tests.

5.0 Discussion and Observations

This section discusses the results presented in Section 4.0 and includes the qualitative observations from the test program. The purpose of this section is to provide an explanation for the recommendations presented in Section 6.0 based on the results and observations of the test program.

The measurements taken during the operation of the Pulsating Pump (PP) under steady state operating conditions yielded periodic results. For the purpose of conducting the initial analysis, time averages were calculated for the measured parameters of the various tests when periodic data were obtained. The time averages of these data were presented in Table 4.1. The calculated values for the average volume flow rate of slurry pumped by the PP were also presented. The average volume flow rate obtained for all of the kaolin clay tests varied from 4.4 to 5.1 m³/hr (19.5 to 22.7 gpm); a variation of 0.7 m³/hr (3 gpm) or 15 %.

Test 4, 5, and 6 were done for the purpose of investigating the relationship between the cycle duration (period) and the flow rate. A slight increase in the flow rate is observed with the decrease of the cycle time. However, when the pressure drop across the pump inlet is evaluated, the results are seen to be inconclusive. The pressure drop across the pump inlet was estimated using the volume of sludge pumped per cycle (estimated from the time averaged flow rate and the cycle period) and the time averaged values of the vacuum line pressure. The estimate applies to the period just prior to the end of the fill portion of the cycle when the fluid reaches a maximum height in the pump. The pressure drop across the pump inlet is directly related to the speed at which the pump reservoir will fill. The estimated pressure drop for Test 4 was approximately twice that of Tests 5 and 6. Very few tests were conducted for a specific condition to rely on a statistical analysis for evaluating the effect of a single parameter on the system.

In an ideal system, the period of operation should not be a factor in determining the flow rate. A high-frequency operation delivering a small volume per cycle will be as effective as a low-frequency operation pumping a large volume per cycle. In an actual system, there are losses associated with the fluid flow and the opening and closing of the valves. There are also losses associated with pressurizing and evacuating the pump or monitor reservoir. For the current tests, the estimated percent of the reservoir volume used was 25 - 40%. If the reservoir was completely filled with liquid during a cycle, then the initiation of the supply air results in the fluid being ejected without having to first pressurize a rarefied volume of the reservoir. Using only a fraction of the reservoir volume results in a large volume of air being conveyed without supplying any work to the system.

The effect of slurries containing large particles (those with settling velocity of the same order of magnitude as the fluid velocities within the system) must be considered when optimizing the system. Large particles will have velocities that differ from those of the liquid phase and there are additional losses resulting from accelerating the particles with each pulse.

Several long pulses will be more efficient at transferring particles out of a tank through a vertical retrieval line compared to a higher frequency pulse rate. The inlet velocity must also be high enough to entrain and convey the particles upward into the pump reservoir. If the diameter of the pump reservoir is overly large, the reduction in the upward fluid velocity in the reservoir compared to the velocity through the inlet valve may result in the bulk of the particles being separated from the fluid. The particle concentration in the bottom of the reservoir may become very high and cause problems during the discharge phase of the cycle.

Fluid entering the pump/monitor will experience the highest velocity at the initiation of the fill portion of the pumping cycle, after which it will continue to decrease as the fluid level within the reservoir increases. This is due to the change in hydrostatic head resulting from the difference between the fluid levels inside and outside of the reservoir. Therefore, fill time can be reduced by maximizing the ratio of reservoir volume to liquid elevation. This can be accomplished by increasing the ratio of the reservoir diameter to the reservoir height or by reclining the reservoir. The size and shape of the reservoir should be optimized so that a majority of the volume is utilized for the pumping process. Fill time can also be reduced by reducing the pressure drop across the inlet check valve.

A difficulty in testing the system was the reliance on manual control to adjust the system under changing operating conditions and the inability to adjust phase durations (i.e., vary the relative lengths of rarefaction and pressurization periods). The system operation relies on the fill and evacuation phases of the pump cycle being balanced with regards to the flow rate. What is drawn into the reservoir must be discharged. If the system is out of balance, then the volume of fluid in the reservoir will either incrementally decrease, eventually resulting in the discharging of air to the retrieval line, or incrementally increase, resulting in fluid being drawn into the vacuum line. This will not occur in cases where the height of the vacuum line is higher than the limit of the hydrostatic head achievable with a given slurry and vacuum line pressure.

Under steady state operating conditions, the PP and PM require minimal control. However, if changes do occur in the operating conditions (e.g., changes in the height of the tank fluid, in the concentration of the pumped slurry, fouling of the check valves or hold-up in the retrieval line) then adjustments must be made to rebalance the system. If the changes are a continual occurrence, continual or periodic action will be required.

During testing, any changes in the operating conditions required operator interpretation of the data acquisition system (DAS) output and manual adjustment of the control parameters (e.g., vacuum and supply pressure and cycle duration). Several instances occurred where the PP experienced a forced shut down because of large volumes of air in the retrieval line (creating unstable slug flows) or system plugging. The manual response to the changing conditions was not fast enough to compensate for the changes. Compounding the problem was the fact that this is a periodic system, which operates at a low frequency. The effects of manual adjustments take time to evaluate.

The results presented in Section 4.0 indicate the system is easily monitored and problems can be uniquely identified. The exit pressure and flow rates are indicators of the status of the

system. These indicators, together with the other parameters measured, are needed to predict changes in performance and implement required adjustments accordingly. Additional instrumentation such as level indicators or detectors could be incorporated into the reservoir designs to simplify the control of the system. A control strategy can and must be developed so that the system maintains stable operation under changing conditions and can be operated remotely.

The Flow Control Unit is unnecessarily consolidated and difficult to service (especially the valves). For field operation, redundancy of pulsation control should be provided. This could be accomplished with electronic control circuitry and solenoid or automated valves. Routing backflush and waste delivery through the control unit requires extra hose or pipe and contaminates a piece of topside equipment that would otherwise remain relatively clean (except for aerosols drawn through the vacuum system). Parallel control valves could be employed to allow for servicing while maintaining uninterrupted operation of the equipment, or at least to allow for continued operation to an organized shut down of the system.

During operation, the check valves and the rotary control valve experienced problems due to particulate. The rotary control valve required disassembly during the test program, at which time, simulant particulate and Teflon flakes were discovered in between the valve faces. The particulate was entrained in the vacuum air stream and the Teflon flakes were shaved off the interfacing disks of the rotary valve by the entrained grit. The continual rotating operation of the rotary control valve creates a high potential for wear and thus system failure. Quick action solenoid valves, or other alternative, should be used throughout the system. The valves should allow for remote operation and independent control of the supply and vacuum line pressures.

The rotary control valve also limits an advantageous feature of fluidic devices that operate by varying the pressure or volume of a pump chamber. The suction and discharge requirements of such devices are independent. These devices can discharge fluids at high pressures while requiring minimum net positive suction heads which means fluids can be retrieved when liquid levels are low without entraining air or affecting the discharge pressure. The rotary control valve causes the ratio of the time of rarefaction to the time of pressurization for the reservoir to be constant. Using independent valves would eliminate the interdependence between the period of the vacuum and supply pressures and would take full advantage of the design concept.

Forward flushing of the PP is easy and effective; however, volumetric control is needed to limit the volume of backflush water used and interlock with the vacuum system control valves to prevent accidental flooding of the pump with liquid to the point that it is aspirated by the vacuum system. The backflush system has several limitations. If the inlet check valve is operating normally and the discharge check valve requires flushing, the amount of fluid that can be used is limited unless venting and isolation valves are added to the system. The additional valves would allow either check valve to be isolated and back flushed.

The rarefaction for the vacuum line was created using an eductor. The working gas passing through the PP and PM comes in direct contact with the slurry. Therefore, the expelled

air cannot be discharged directly to the atmosphere. Fine particulate was observed and collected at the exit of the eductor during testing. No separation or filtration was provided in the test system. Nominally, with the vacuum set at a maximum pressure below that required to lift a given density of waste to the top of the riser, sludge waste should not be transported into the vacuum system. However, if the waste has any tendency to foam or produce aerosols as it is drawn into the reservoir through the foot valve, some waste will be drawn through the vacuum system and ejected. Backflushing operations, with the current configuration, can also inadvertently introduce waste and flush water into the rotary valve and working gas supply line.

The filtering and conditioning of the exit gas stream from the system could be simplified if the eductor could be placed inside of the waste tank during operations, thus utilizing the tank ventilation system. Two options exist with the eductor in the tank. Clean air could be passed through a compressor to provide supply air and power the eductor. Because the tanks are maintained at a negative pressure, one issue is whether the tank ventilation can accommodate the increased air supply or if supplemental ventilation and filtering would be required. A second scenario would consist of recirculating the tank air through the system. This would result in contamination of the compressor. A combination of the two scenarios should also be considered. If high pressures are required for the supply air (e.g., significant elevation change in discharge line, high viscosity fluid, or settling particulate are present), the eductor could be run with recirculating air since it will require the larger volume flow rate, and a clean, high-pressure source could provide air for the PP supply line. Other options for air handling include the use of a vacuum pump vented to the tank or the use of a modified blower to provide both supply air and rarefaction.

The operation of the PP check valves was compromised when granular materials were added to the kaolin simulant. The large seat area of the check valves provided the opportunity for grit to obstruct the valves preventing their closure. This resulted in the reservoir contents draining back to the tank through the inlet valve during the pressure phase of the pump cycle or being drawn in from the retrieval line during the fill portion of the cycle (which is indicated by negative values for the discharge flow rate). Erratic measurements of the flow rate, density, and discharge pressure were obtained when sand and gravel were included in the simulant. The control unit manifold had difficulties handling the grit, making backflushing difficult. The operators were able to clear all the valves with the backflushing system during testing, but this resulted in lengthy interruptions.

A dimensional analysis of the time-averaged data for the PP was presented in Section 4.3, which produced a physically meaningful correlation for describing the operation of the system. Testing over a wider range of conditions with independent control for the vacuum and supply line pressures could be used to expand the correlation for application to full size waste tanks.

The purpose of the PM is to mix; therefore, a number of the problems associated with pumping particle-laden mixtures can be avoided by keeping the larger particles out of the PM. Screens and/or lower inlet velocities could be used to avoid drawing particles into the reservoir

of the PM. It is not necessary for particles to pass through the PM in order to be mixed or mobilized.

Section 4.2 described the testing performed with the PM. Included in the results were measurements of the radial distance the PM jets cleared sand from the tank floor, which is referred to as the effective cleaning radius (ECR). It is important to keep in mind that the ECR is not the only indicator of mixer pump performance. Mixer pumps have been used for two specific functions. One function is for mobilizing or breaking up waste. The other function is to mix the waste or maintain a suspension. While one mode of operation of a mixer pump may be ideal for waste mobilization it is not necessarily the most efficient way to mix or maintain a homogeneous suspension.

The PM used for testing did not have the capability to rotate. In most tank applications, a rotating mixer would be desired. The PM also creates a pulsating jet rather than the continual flow of conventional jet mixer pumps. Comparing the PM to a conventional jet-mixing pump via only the ECR may not provide a thorough evaluation. The power required to maintain a specific suspension should also be considered.

Testing was conducted at vacuum and supply pressures of approximately 76 kPa-absolute (11 psia) and 414 kPa-gage (60 psig), respectively. The application of such a small range of pressures and the interdependence of the pressures created by the rotary control valve resulted in a fraction of the range of capability of the PP and PM being tested. An improvement in the control system would provide the PP and PM with the ability to operate over a wide range of steady and transient conditions.

6.0 Conclusions and Recommendations

Tests for the Russian Retrieval Equipment were conducted over a five-day period. In that time, only a limited range of the potential operating conditions was tested. The Pulsating Pump (PP) successfully pumped kaolin clay/water slurries with densities as high as 1300 kg/m^3 (81.2 lbm/ft^3), which is equivalent to 37 wt % solids, and reduced bulk densities (due to air entrainment in the simulant) as high as 1200 kg/m^3 (74.9 lbm/ft^3). Tests of the PP performed by the Integrated Mining Chemical Company (IMCC) in Russia were reported to have pumped a kaolin clay mixture with a density of 1400 kg/m^3 (86.5 lbm/ft^3), which is equivalent to 46 wt % solids. For the tests conducted at PNNL, the maximum slurry viscosity and yield stress were approximately 40 cP and 0.5 kPa (0.072 psi), respectively. The mass and volume of the flow rates achieved with the PP ranged between 1.3 to 1.6 kg/s (172 - 209 lbm/min) and 4.4 to 5.1 m^3/hr (19.4 - 22.7 gpm).

Additional tests were conducted using sand whose average size particles were larger than those for kaolin clay; namely, fine (300 to 1000 μm) and medium (1 to 2.4 mm) grain sand particulate. The fine sand was added to the kaolin clay slurry to produce a different simulant. The PP was able to pump the simulant; however, the grit caused operational problems for the check valves resulting in erratic flow rates and the introduction of air into the discharge line. Bottle samples taken from the discharge line contained mixtures of 13-27 wt % sand. A periodic response of the system (which occurs during steady state operating condition) was not obtained with fine sand present in the slurry. Partial plugging of the flow meter occurred during the tests with the fine sand. The potential for plugging existed due to a double channel 180° configuration of the flow path through the mass flow meter. The backflush capabilities of the PP system worked to alleviate plugging except during Test 21. The medium size sand was added to the test mixture of clay, fine sand, and water. The PP was unable to transport the medium size sand through the pump to the discharge line.

Dimensional and multiparameter regression analyses of the PP were performed using the time averages for the periodic data obtained from tests with the kaolin clay. From the results of the analysis, a correlation was developed which can be used to predict the pump operating pressure required to produce a given flow rate provided the slurry properties of density, viscosity, and yield stress are known as well as the static back pressure of the retrieval system. The correlation has a correlation coefficient equal to 0.97. The data used to develop the correlation covers a small range of possible operating conditions and additional testing is required to extend its applicability to full-scale conditions.

A demonstration of the Pulsating Monitor (PM) was conducted in the Quarter-Scale DST using water and the medium size sand, which had the fines removed to maintain a clear test solution. The purpose of adding the medium sand to the tank was to allow for the influence of the flow of the jets on the tank bottom to be viewed and measured. It was observed that the jets cleared the medium sand from the tank floor along the centerline of the nozzles to within approximately 0.3-m (1-ft) of the edge of the tank.

The PP and PM are integrated into a single retrieval system that allows for the two pieces of equipment to be operated simultaneously. However, in the present test program these components were tested separately and all conclusions apply to the PP and PM operating as individual systems.

The low-frequency operation of the PP and PM results in steady state operating conditions that yield time periodic data. Careful reduction and assessment of the data was necessary to select purely periodic data (data indicative of proper pump operation) from which time-averaged parameters were calculated. The detailed assessment of the data allowed for the development of a physically meaningful correlation for the operation of the PP. In addition, the review of the data provided a comprehensive understanding of the equipment operation and how their performance departs from ideal behavior. Observations of these departures can aid in improving the efficiency and reliability of the systems. A thorough understanding of the equipment performance is also essential for developing a proper monitoring and control system necessary for remote operations.

The operation of the systems under steady state test conditions required no intervention or adjustment. However, changes in the operating conditions of the tests, such as increasing or decreasing slurry density and changes in the test tank level, resulted in deviations from the periodic response of the PP. The control of the PP during changing conditions was labor intensive due to the manual operation of the PP and the test facility equipment. The feedback control for the system consisted of operators observing gage readings or the conditioned signal on the data acquisition system (DAS). The periodic nature of the measured parameters along with the reliance on manual adjustments based on operator experience and intuition made for a slow response of the Pulsating Pump System to changing operating conditions. In general, manual control of the operation is not sufficiently fast to adequately respond to changing operating conditions which can result in a forced system shutdown. An automated feedback control system would allow the Pulsating Pump System to respond rapidly to changing operating conditions resulting in the desired operation without system shutdown.

The PP and PM as individual units proved to be durable and reliable pieces of equipment capable of withstanding the rigors of testing. The advantages of using the PP and PM for retrieving waste from underground storage tanks are:

- The PP and PM are robust devices that are simple and inexpensive with minimal moving parts in the tank or in the entire system (in-tank hardware has no powered moving parts).
- The PP has the ability to pump a wide range of fluid densities and viscosities.
- The equipment is inexpensive, lightweight, and can be easily adapted to various tank inlets.

- The operation of the systems is uncomplicated, they operate via imposed pressure differentials, which can be monitored and regulated with a simple control strategy.
- There are no concerns associated with water addition to the waste as a result of failed seals.

The limits of operation are:

- The particle size that can be transported. The capability of the PP to handle larger size particles can be improved. The pulsating flow of the pump will require additional investigation when designing/planning for the transport of particulate beyond that employed for steady flow pumps to address settling within the pump reservoir and discharge line.
- Atmospheric and supply air pressures. Vacuum line pressure, slurry density, viscosity, yield stress, and the height of the liquid waste in the tank dictate how fast the pump chamber will fill. The pump flow rate will be limited by the fact that the only operator controlled parameters dictating the PP fill and discharge rates are the vacuum, which is limited to one atmosphere, and the available air supply pressures.

The following recommendations are given for improving the integrated system comprised of the PP and PM.

- Develop a feedback control and monitoring system utilizing commercially available software and instrumentation. The control system needs to be capable of remote monitoring and control, provide system response to transient operating conditions, and allow for the employment of countermeasures to off-normal events such as plugging of the discharge line or the pump inlet.
- Replace the current check valve design with one capable of operating with particles larger than those of the kaolin clay slurry.
- Increase the flexibility of the valve configuration for the system to provide independent control for the application of the supply and vacuum line pressures. Use quick-acting response actuated valves throughout the system. Provide valves in series for backup manual control where necessary.
- Expand and improve the backflush capability of the system including the capability for decontaminating all wetted parts.
- Provide screen/guard at the inlet to the PP to eliminate clogging problems associated with tank debris.

- Consider controlling the operation cycle using level sensors or detectors incorporated into the reservoir design.
- Ensure the reservoir designs for the PP and PM are optimized to accommodate the expected operating conditions and cycle times.

The following recommendations are given for future work to be performed for development of the PP and PM System.

- Perform analyses to determine the maximum particle size for a given pump and discharge line configuration that can be accommodated as a function of the particle and liquid densities and the slurry rheology (viscosity and yield stress).
- Test the PP and PM over a wider range of operating conditions to extend the range of applicability of the obtained correlation. Perform tests of design improvements made for the handling of particles.
- Determine options and limitations for placing the eductor, used to provide rarefaction, inside of the waste tank to alleviate the problem of contaminated aerosols, or consider alternatives for providing rarefaction.
- Explore the relationships for mixing and mobilization between pulsating and steady state jets.

The PP and PM have potential for retrieval applications within the DOE complex. The concept of operation is straightforward and has been demonstrated for the PP using simulants with physical properties that lie within the range of that predicted/measured for some waste tank mixtures. However, there are a number of design and operational issues to be investigated before the PP and PM are ready for deployment. Additional work should concentrate on developing a remote feedback monitoring and control system, improving the current designs for remote operations, improving the ability of the PP to transport particulate, and testing of the system over a wide range of conditions for both operational parameters and waste properties.

This work offered the opportunity for technical exchange and collaboration between Russian and U.S. researchers. This collaboration was viewed as a productive and worthwhile endeavor by those involved at PNNL. This work is an example of what can be accomplished through international cooperation on technical issues.

5.0 Discussion and Observations

This section discusses the results presented in Section 4.0 and includes the qualitative observations from the test program. The purpose of this section is to provide an explanation for the recommendations presented in Section 6.0 based on the results and observations of the test program.

The measurements taken during the operation of the Pulsating Pump (PP) under steady state operating conditions yielded periodic results. For the purpose of conducting the initial analysis, time averages were calculated for the measured parameters of the various tests when periodic data were obtained. The time averages of these data were presented in Table 4.1. The calculated values for the average volume flow rate of slurry pumped by the PP were also presented. The average volume flow rate obtained for all of the kaolin clay tests varied from 4.4 to 5.1 m³/hr (19.5 to 22.7 gpm); a variation of 0.7 m³/hr (3 gpm) or 15 %.

Test 4, 5, and 6 were done for the purpose of investigating the relationship between the cycle duration (period) and the flow rate. A slight increase in the flow rate is observed with the decrease of the cycle time. However, when the pressure drop across the pump inlet is evaluated, the results are seen to be inconclusive. The pressure drop across the pump inlet was estimated using the volume of sludge pumped per cycle (estimated from the time averaged flow rate and the cycle period) and the time averaged values of the vacuum line pressure. The estimate applies to the period just prior to the end of the fill portion of the cycle when the fluid reaches a maximum height in the pump. The pressure drop across the pump inlet is directly related to the speed at which the pump reservoir will fill. The estimated pressure drop for Test 4 was approximately twice that of Tests 5 and 6. Very few tests were conducted for a specific condition to rely on a statistical analysis for evaluating the effect of a single parameter on the system.

In an ideal system, the period of operation should not be a factor in determining the flow rate. A high-frequency operation delivering a small volume per cycle will be as effective as a low-frequency operation pumping a large volume per cycle. In an actual system, there are losses associated with the fluid flow and the opening and closing of the valves. There are also losses associated with pressurizing and evacuating the pump or monitor reservoir. For the current tests, the estimated percent of the reservoir volume used was 25 - 40%. If the reservoir was completely filled with liquid during a cycle, then the initiation of the supply air results in the fluid being ejected without having to first pressurize a rarefied volume of the reservoir. Using only a fraction of the reservoir volume results in a large volume of air being conveyed without supplying any work to the system.

The effect of slurries containing large particles (those with settling velocity of the same order of magnitude as the fluid velocities within the system) must be considered when optimizing the system. Large particles will have velocities that differ from those of the liquid phase and there are additional losses resulting from accelerating the particles with each pulse.

Several long pulses will be more efficient at transferring particles out of a tank through a vertical retrieval line compared to a higher frequency pulse rate. The inlet velocity must also be high enough to entrain and convey the particles upward into the pump reservoir. If the diameter of the pump reservoir is overly large, the reduction in the upward fluid velocity in the reservoir compared to the velocity through the inlet valve may result in the bulk of the particles being separated from the fluid. The particle concentration in the bottom of the reservoir may become very high and cause problems during the discharge phase of the cycle.

Fluid entering the pump/monitor will experience the highest velocity at the initiation of the fill portion of the pumping cycle, after which it will continue to decrease as the fluid level within the reservoir increases. This is due to the change in hydrostatic head resulting from the difference between the fluid levels inside and outside of the reservoir. Therefore, fill time can be reduced by maximizing the ratio of reservoir volume to liquid elevation. This can be accomplished by increasing the ratio of the reservoir diameter to the reservoir height or by reclining the reservoir. The size and shape of the reservoir should be optimized so that a majority of the volume is utilized for the pumping process. Fill time can also be reduced by reducing the pressure drop across the inlet check valve.

A difficulty in testing the system was the reliance on manual control to adjust the system under changing operating conditions and the inability to adjust phase durations (i.e., vary the relative lengths of rarefaction and pressurization periods). The system operation relies on the fill and evacuation phases of the pump cycle being balanced with regards to the flow rate. What is drawn into the reservoir must be discharged. If the system is out of balance, then the volume of fluid in the reservoir will either incrementally decrease, eventually resulting in the discharging of air to the retrieval line, or incrementally increase, resulting in fluid being drawn into the vacuum line. This will not occur in cases where the height of the vacuum line is higher than the limit of the hydrostatic head achievable with a given slurry and vacuum line pressure.

Under steady state operating conditions, the PP and PM require minimal control. However, if changes do occur in the operating conditions (e.g., changes in the height of the tank fluid, in the concentration of the pumped slurry, fouling of the check valves or hold-up in the retrieval line) then adjustments must be made to rebalance the system. If the changes are a continual occurrence, continual or periodic action will be required.

During testing, any changes in the operating conditions required operator interpretation of the data acquisition system (DAS) output and manual adjustment of the control parameters (e.g., vacuum and supply pressure and cycle duration). Several instances occurred where the PP experienced a forced shut down because of large volumes of air in the retrieval line (creating unstable slug flows) or system plugging. The manual response to the changing conditions was not fast enough to compensate for the changes. Compounding the problem was the fact that this is a periodic system, which operates at a low frequency. The effects of manual adjustments take time to evaluate.

The results presented in Section 4.0 indicate the system is easily monitored and problems can be uniquely identified. The exit pressure and flow rates are indicators of the status of the

system. These indicators, together with the other parameters measured, are needed to predict changes in performance and implement required adjustments accordingly. Additional instrumentation such as level indicators or detectors could be incorporated into the reservoir designs to simplify the control of the system. A control strategy can and must be developed so that the system maintains stable operation under changing conditions and can be operated remotely.

The Flow Control Unit is unnecessarily consolidated and difficult to service (especially the valves). For field operation, redundancy of pulsation control should be provided. This could be accomplished with electronic control circuitry and solenoid or automated valves. Routing backflush and waste delivery through the control unit requires extra hose or pipe and contaminates a piece of topside equipment that would otherwise remain relatively clean (except for aerosols drawn through the vacuum system). Parallel control valves could be employed to allow for servicing while maintaining uninterrupted operation of the equipment, or at least to allow for continued operation to an organized shut down of the system.

During operation, the check valves and the rotary control valve experienced problems due to particulate. The rotary control valve required disassembly during the test program, at which time, simulant particulate and Teflon flakes were discovered in between the valve faces. The particulate was entrained in the vacuum air stream and the Teflon flakes were shaved off the interfacing disks of the rotary valve by the entrained grit. The continual rotating operation of the rotary control valve creates a high potential for wear and thus system failure. Quick action solenoid valves, or other alternative, should be used throughout the system. The valves should allow for remote operation and independent control of the supply and vacuum line pressures.

The rotary control valve also limits an advantageous feature of fluidic devices that operate by varying the pressure or volume of a pump chamber. The suction and discharge requirements of such devices are independent. These devices can discharge fluids at high pressures while requiring minimum net positive suction heads which means fluids can be retrieved when liquid levels are low without entraining air or affecting the discharge pressure. The rotary control valve causes the ratio of the time of rarefaction to the time of pressurization for the reservoir to be constant. Using independent valves would eliminate the interdependence between the period of the vacuum and supply pressures and would take full advantage of the design concept.

Forward flushing of the PP is easy and effective; however, volumetric control is needed to limit the volume of backflush water used and interlock with the vacuum system control valves to prevent accidental flooding of the pump with liquid to the point that it is aspirated by the vacuum system. The backflush system has several limitations. If the inlet check valve is operating normally and the discharge check valve requires flushing, the amount of fluid that can be used is limited unless venting and isolation valves are added to the system. The additional valves would allow either check valve to be isolated and back flushed.

The rarefaction for the vacuum line was created using an eductor. The working gas passing through the PP and PM comes in direct contact with the slurry. Therefore, the expelled

air cannot be discharged directly to the atmosphere. Fine particulate was observed and collected at the exit of the eductor during testing. No separation or filtration was provided in the test system. Nominally, with the vacuum set at a maximum pressure below that required to lift a given density of waste to the top of the riser, sludge waste should not be transported into the vacuum system. However, if the waste has any tendency to foam or produce aerosols as it is drawn into the reservoir through the foot valve, some waste will be drawn through the vacuum system and ejected. Backflushing operations, with the current configuration, can also inadvertently introduce waste and flush water into the rotary valve and working gas supply line.

The filtering and conditioning of the exit gas stream from the system could be simplified if the eductor could be placed inside of the waste tank during operations, thus utilizing the tank ventilation system. Two options exist with the eductor in the tank. Clean air could be passed through a compressor to provide supply air and power the eductor. Because the tanks are maintained at a negative pressure, one issue is whether the tank ventilation can accommodate the increased air supply or if supplemental ventilation and filtering would be required. A second scenario would consist of recirculating the tank air through the system. This would result in contamination of the compressor. A combination of the two scenarios should also be considered. If high pressures are required for the supply air (e.g., significant elevation change in discharge line, high viscosity fluid, or settling particulate are present), the eductor could be run with recirculating air since it will require the larger volume flow rate, and a clean, high-pressure source could provide air for the PP supply line. Other options for air handling include the use of a vacuum pump vented to the tank or the use of a modified blower to provide both supply air and rarefaction.

The operation of the PP check valves was compromised when granular materials were added to the kaolin simulant. The large seat area of the check valves provided the opportunity for grit to obstruct the valves preventing their closure. This resulted in the reservoir contents draining back to the tank through the inlet valve during the pressure phase of the pump cycle or being drawn in from the retrieval line during the fill portion of the cycle (which is indicated by negative values for the discharge flow rate). Erratic measurements of the flow rate, density, and discharge pressure were obtained when sand and gravel were included in the simulant. The control unit manifold had difficulties handling the grit, making backflushing difficult. The operators were able to clear all the valves with the backflushing system during testing, but this resulted in lengthy interruptions.

A dimensional analysis of the time-averaged data for the PP was presented in Section 4.3, which produced a physically meaningful correlation for describing the operation of the system. Testing over a wider range of conditions with independent control for the vacuum and supply line pressures could be used to expand the correlation for application to full size waste tanks.

The purpose of the PM is to mix; therefore, a number of the problems associated with pumping particle-laden mixtures can be avoided by keeping the larger particles out of the PM. Screens and/or lower inlet velocities could be used to avoid drawing particles into the reservoir

of the PM. It is not necessary for particles to pass through the PM in order to be mixed or mobilized.

Section 4.2 described the testing performed with the PM. Included in the results were measurements of the radial distance the PM jets cleared sand from the tank floor, which is referred to as the effective cleaning radius (ECR). It is important to keep in mind that the ECR is not the only indicator of mixer pump performance. Mixer pumps have been used for two specific functions. One function is for mobilizing or breaking up waste. The other function is to mix the waste or maintain a suspension. While one mode of operation of a mixer pump may be ideal for waste mobilization it is not necessarily the most efficient way to mix or maintain a homogeneous suspension.

The PM used for testing did not have the capability to rotate. In most tank applications, a rotating mixer would be desired. The PM also creates a pulsating jet rather than the continual flow of conventional jet mixer pumps. Comparing the PM to a conventional jet-mixing pump via only the ECR may not provide a thorough evaluation. The power required to maintain a specific suspension should also be considered.

Testing was conducted at vacuum and supply pressures of approximately 76 kPa-absolute (11 psia) and 414 kPa-gage (60 psig), respectively. The application of such a small range of pressures and the interdependence of the pressures created by the rotary control valve resulted in a fraction of the range of capability of the PP and PM being tested. An improvement in the control system would provide the PP and PM with the ability to operate over a wide range of steady and transient conditions.

6.0 Conclusions and Recommendations

Tests for the Russian Retrieval Equipment were conducted over a five-day period. In that time, only a limited range of the potential operating conditions was tested. The Pulsating Pump (PP) successfully pumped kaolin clay/water slurries with densities as high as 1300 kg/m^3 (81.2 lbm/ft^3), which is equivalent to 37 wt % solids, and reduced bulk densities (due to air entrainment in the simulant) as high as 1200 kg/m^3 (74.9 lbm/ft^3). Tests of the PP performed by the Integrated Mining Chemical Company (IMCC) in Russia were reported to have pumped a kaolin clay mixture with a density of 1400 kg/m^3 (86.5 lbm/ft^3), which is equivalent to 46 wt % solids. For the tests conducted at PNNL, the maximum slurry viscosity and yield stress were approximately 40 cP and 0.5 kPa (0.072 psi), respectively. The mass and volume of the flow rates achieved with the PP ranged between 1.3 to 1.6 kg/s (172 - 209 lbm/min) and 4.4 to 5.1 m^3/hr (19.4 - 22.7 gpm).

Additional tests were conducted using sand whose average size particles were larger than those for kaolin clay; namely, fine (300 to 1000 μm) and medium (1 to 2.4 mm) grain sand particulate. The fine sand was added to the kaolin clay slurry to produce a different simulant. The PP was able to pump the simulant; however, the grit caused operational problems for the check valves resulting in erratic flow rates and the introduction of air into the discharge line. Bottle samples taken from the discharge line contained mixtures of 13-27 wt % sand. A periodic response of the system (which occurs during steady state operating condition) was not obtained with fine sand present in the slurry. Partial plugging of the flow meter occurred during the tests with the fine sand. The potential for plugging existed due to a double channel 180° configuration of the flow path through the mass flow meter. The backflush capabilities of the PP system worked to alleviate plugging except during Test 21. The medium size sand was added to the test mixture of clay, fine sand, and water. The PP was unable to transport the medium size sand through the pump to the discharge line.

Dimensional and multiparameter regression analyses of the PP were performed using the time averages for the periodic data obtained from tests with the kaolin clay. From the results of the analysis, a correlation was developed which can be used to predict the pump operating pressure required to produce a given flow rate provided the slurry properties of density, viscosity, and yield stress are known as well as the static back pressure of the retrieval system. The correlation has a correlation coefficient equal to 0.97. The data used to develop the correlation covers a small range of possible operating conditions and additional testing is required to extend its applicability to full-scale conditions.

A demonstration of the Pulsating Monitor (PM) was conducted in the Quarter-Scale DST using water and the medium size sand, which had the fines removed to maintain a clear test solution. The purpose of adding the medium sand to the tank was to allow for the influence of the flow of the jets on the tank bottom to be viewed and measured. It was observed that the jets cleared the medium sand from the tank floor along the centerline of the nozzles to within approximately 0.3-m (1-ft) of the edge of the tank.

The PP and PM are integrated into a single retrieval system that allows for the two pieces of equipment to be operated simultaneously. However, in the present test program these components were tested separately and all conclusions apply to the PP and PM operating as individual systems.

The low-frequency operation of the PP and PM results in steady state operating conditions that yield time periodic data. Careful reduction and assessment of the data was necessary to select purely periodic data (data indicative of proper pump operation) from which time-averaged parameters were calculated. The detailed assessment of the data allowed for the development of a physically meaningful correlation for the operation of the PP. In addition, the review of the data provided a comprehensive understanding of the equipment operation and how their performance departs from ideal behavior. Observations of these departures can aid in improving the efficiency and reliability of the systems. A thorough understanding of the equipment performance is also essential for developing a proper monitoring and control system necessary for remote operations.

The operation of the systems under steady state test conditions required no intervention or adjustment. However, changes in the operating conditions of the tests, such as increasing or decreasing slurry density and changes in the test tank level, resulted in deviations from the periodic response of the PP. The control of the PP during changing conditions was labor intensive due to the manual operation of the PP and the test facility equipment. The feedback control for the system consisted of operators observing gage readings or the conditioned signal on the data acquisition system (DAS). The periodic nature of the measured parameters along with the reliance on manual adjustments based on operator experience and intuition made for a slow response of the Pulsating Pump System to changing operating conditions. In general, manual control of the operation is not sufficiently fast to adequately respond to changing operating conditions which can result in a forced system shutdown. An automated feedback control system would allow the Pulsating Pump System to respond rapidly to changing operating conditions resulting in the desired operation without system shutdown.

The PP and PM as individual units proved to be durable and reliable pieces of equipment capable of withstanding the rigors of testing. The advantages of using the PP and PM for retrieving waste from underground storage tanks are:

- The PP and PM are robust devices that are simple and inexpensive with minimal moving parts in the tank or in the entire system (in-tank hardware has no powered moving parts).
- The PP has the ability to pump a wide range of fluid densities and viscosities.
- The equipment is inexpensive, lightweight, and can be easily adapted to various tank inlets.

- The operation of the systems is uncomplicated, they operate via imposed pressure differentials, which can be monitored and regulated with a simple control strategy.
- There are no concerns associated with water addition to the waste as a result of failed seals.

The limits of operation are:

- The particle size that can be transported. The capability of the PP to handle larger size particles can be improved. The pulsating flow of the pump will require additional investigation when designing/planning for the transport of particulate beyond that employed for steady flow pumps to address settling within the pump reservoir and discharge line.
- Atmospheric and supply air pressures. Vacuum line pressure, slurry density, viscosity, yield stress, and the height of the liquid waste in the tank dictate how fast the pump chamber will fill. The pump flow rate will be limited by the fact that the only operator controlled parameters dictating the PP fill and discharge rates are the vacuum, which is limited to one atmosphere, and the available air supply pressures.

The following recommendations are given for improving the integrated system comprised of the PP and PM.

- Develop a feedback control and monitoring system utilizing commercially available software and instrumentation. The control system needs to be capable of remote monitoring and control, provide system response to transient operating conditions, and allow for the employment of countermeasures to off-normal events such as plugging of the discharge line or the pump inlet.
- Replace the current check valve design with one capable of operating with particles larger than those of the kaolin clay slurry.
- Increase the flexibility of the valve configuration for the system to provide independent control for the application of the supply and vacuum line pressures. Use quick-acting response actuated valves throughout the system. Provide valves in series for backup manual control where necessary.
- Expand and improve the backflush capability of the system including the capability for decontaminating all wetted parts.
- Provide screen/guard at the inlet to the PP to eliminate clogging problems associated with tank debris.

- Consider controlling the operation cycle using level sensors or detectors incorporated into the reservoir design.
- Ensure the reservoir designs for the PP and PM are optimized to accommodate the expected operating conditions and cycle times.

The following recommendations are given for future work to be performed for development of the PP and PM System.

- Perform analyses to determine the maximum particle size for a given pump and discharge line configuration that can be accommodated as a function of the particle and liquid densities and the slurry rheology (viscosity and yield stress).
- Test the PP and PM over a wider range of operating conditions to extend the range of applicability of the obtained correlation. Perform tests of design improvements made for the handling of particles.
- Determine options and limitations for placing the eductor, used to provide rarefaction, inside of the waste tank to alleviate the problem of contaminated aerosols, or consider alternatives for providing rarefaction.
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