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UC-721

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Performance Evaluation of the PITBULL™ Pump for the Removal of Hazardous Waste

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Executive Summary

One objective of the Waste Removal Project at the Department of Energy's Savannah River Site (SRS) is to explore methods to successfully remove waste heels that will remain in the high-level waste tanks after bulk waste removal has been completed. A PITBULL™ pump, manufactured by the Chicago Industrial Pump Company (CIPC), is being considered by SRS to retrieval sludge type waste from Tank 19. In the past, a diaphragm pump has been used in this application, but has experienced problems caused by ingestion of gravel-like material. Through funding provided by the DOE Tanks Focus Area, the Retrieval Process Development and Enhancements Project (RPD&E) has tested a PITBULL™ pump for debris tolerance, lift, and performance in conditions in which there is minimal liquid in the tank. These conditions are present after bulk retrieval methods have removed the majority of the waste.

Tests were conducted to measure the expected operating performance of the pump under a variety of conditions and to determine the likelihood of failure in extreme situations. No attempt was made to determine the average reliability of the pump, as such an undertaking would require information that is not available (such as the exact nature of debris in the tank) and a large number of long-duration tests to be statistically valid. However, the data presented here, along with operational experience and an understanding of the tank contents, will guide the decision to deploy the pump in Tank 19.

The PITBULL™ is comprised of a pump chamber, airlines, and control panel. The pump uses two distinct strokes, fill and discharge, to perform its pumping action. During the fill cycle, vacuum is applied to the pump chamber, which draws liquid into the pump. When the liquid level inside the chamber reaches a sensing tube, the chamber is pressurized with compressed air to discharge the liquid out of the pump chamber. Check-valves are used at the pump chamber inlet and exit to control the direction of flow. An air-powered vacuum pump at the control panel generates a vacuum in the airline. Maximum air pressure and discharge time are set at the control panel and can be adjusted, depending on the liquid being pumped and discharge conditions.

Based on this testing program, the PITBULL™ pump is a reliable, robust, and easy-to-operate pump that is well suited for the remote tank environment. The PITBULL™ has a unique set of advantages, including 1) the ability to discharge at a constant rate, regardless of pumping demand, 2) the ability to self-prim, 3) the ability to ingest air without losing prime, and 4) a moderate degree of debris tolerance.

Based on tests at a discharge head of 13.1 meters (43 ft), the PITBULL™ can transfer water and light slurry with a specific gravity of 1 at 266 liters per minute. Heavier slurries, up to a specific gravity of 1.2, can be transferred at 204 liters per minute. Heavier slurry with a specific gravity of 1.5 were encountered for brief periods during the program, and although

steady state performance is unavailable for these tests, the pump operated without problems. These flow rates are somewhat less than the 378 liters per minute anticipated by CIPC.

At the conclusion of these baseline tests, fine sand, coarse sand, and gravel were successively added to the final batch of slurry to determine the effect of larger particles on pump performance. The addition of fine or coarse sand did not affect the performance of the PITBULL™. The addition of pea gravel significantly degraded average pump performance in terms of average mass flow or volumetric flow. The presence of pea gravel caused the discharge check-valve to eventually stick open, which caused most of the pumped material to flow back into the chamber during the fill cycle. The vendor was contacted and recommended an alternative seal material for the check-valve.

Several attempts were made to create blockages in the system that might occur by ingesting a large amount of solid materials or by a flow interruption in which solids are allowed to settle in the pump chamber and discharge line. Solids settling in the chamber prevented the inlet valve from opening. Solid accumulation in the discharge line was never a problem, although several blockages were created to test the flushing system. Flushing with water or compressed air through the air pressure line and discharge line was helpful in dispersing solids in the chamber and discharge line and, to some extent, clearing the check-valves.

The pump appears to be well suited for remote operation and can transfer slurry with a range of specific gravity and solid loading without any adjustments. The unit has few moving parts, is easy to control, and operates entirely on compressed air. When problems did occur, the cause was usually easy to identify. The ability to monitor discharge flow rate, chamber pressure, and slurry specific gravity was very helpful in diagnosing problems that were encountered.

At the conclusion of this report, recommendations are provided for improving the PITBULL™ system and preparing for deployment.

Acronyms

CIPC	Chicago Industrial Pump Company
DAS	Data Acquisition System
DOE	Department of Energy
ESP	Extended Sludge Processing Facility
GPM	Gallon per minute
RPD&E	Retrieval Process Development and Enhancements
SCFM	Standard Cubic Feet Per Minute
SRS	Savannah River Site
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

One objective of the Waste Removal Project at the Department of Energy's Savannah River Site (SRS) is to explore methods to successfully remove waste heels that will remain in the high-level waste tanks after bulk waste removal has been completed. Tank closure is not possible unless this residue is removed. For example, Tank 19 contains an estimated 94,600 liter (25,000 gallons) residual zeolite heel which prevents immediate closure activities. The tanks are 3,785,000 liters (1 million gallon) nominal capacity with a diameter of 22.9 m to 25.9 m (75 to 85 ft) depending on the type of tank. Conventional waste removal techniques utilizing slurry pumps and transfer jets/pumps do not suspend and remove heel waste. As much as 151,000 liters (40,000 gallons) of residue can remain after a conventional waste removal campaign. The waste heels can be comprised of sludge, zeolite, and silica. The heels are generally hardened or compacted insoluble particulate with relatively rapid settling velocities. Tank access is largely limited to 61 cm (2 ft) diameter openings for the tank tops; however, the newer tanks have larger openings. The heel material must be removed in such a manner to leave minimal waste in the source tank and be transferred ultimately to the Extended Sludge Processing (ESP) Facility.

A PITBULL™ pump is being considered by SRS to retrieve sludge-type waste from Tank 19. In the past, a diaphragm pump has been used in this application, but has experienced problems caused by ingestion of gravel-like material. Through funding provided by the DOE Tanks Focus Area, the Retrieval Process Development and Enhancements Project (RPD&E) has tested a PITBULL™ pump for debris tolerance, lift, and performance in conditions in which there is minimal liquid in the tank. These conditions are present after bulk retrieval methods have removed the majority of the waste. Sections 1 through 4 of this report present the scope and objectives of the test program, describe the principles of operation of the PITBULL™, and present the test approach, set-up, and instrumentation. Test results, including pumping rates with water and slurry, are provided in Section 5, along with considerations for remote operation. Conclusions and recommendations are provided in Section 6.

2.0 Scope and Objectives

Work described herein was performed as part of the Retrieval Process Development and Enhancements Project 21355 - SRS Heel Removal Sub-task. This task procured and tested a PITBULL™ pump for pumping rate, debris tolerance, and performance in a low-head retrieval situation. Tests were conducted to measure the expected operating performance of the pump under a variety of conditions and to determine the likelihood of failure in extreme situations. No attempt was made to determine the average reliability of the pump, as such an undertaking would require information that is not available (such as the exact nature of debris in the tank) and a large number of long-duration tests to be statistically valid. Funding available for this task could not support this type of undertaking. However, the data presented here, along with operational experience and an understanding of the tank contents, will guide the decision to deploy the pump in Tank 19.

Instrumentation was installed to measure pumping cycle time, air pressure, discharge pressure, instantaneous flow rate, and average flow rate. The tests involved pumping of water, slurry, and debris to determine pumping rate, debris tolerance, lift, and final level of liquid remaining. In addition to measuring baseline performance, the tests were used to optimize pump operation and reveal shortcomings in the design that should be addressed prior to deploying the pump in a tank. Table 2.1 provides the objectives of the tests in terms of data requirement that were fulfilled and the type of data that was collected.

Table 2.1 Test Objectives

	Data Requirement	Data Type
A	**Pumping Rate**	
	Determine pumping rate over range of slurry specific gravity and particle size and concentration.	Test data
	Determine the effect of discharge pulse duration on pump performance.	Test data
	Determine the need to change discharge pulse duration due to: • changes in slurry height. • air ingestion. • check-valve fouling. • solids hold-up in retrieval line.	Test data Operator logs
B	**Pumping Solids**	
	Determine reliability of check-valves subjected to large particles.	Operator logs
	Monitor settling of particles in the pump chamber, vertical hose section, and horizontal pipeline.	Operator logs
	Determine the maximum particle size that can be pumped.	Operator logs Video record

	Data Requirement	Data Type
	Determine the need to inject water into the pump chamber to pump slurry with high solids content.	Operator logs
	Evaluate the potential for solids to accumulate around the pump inlet and choke flow.	Operator logs
C	**Pumping In Low Head Conditions**	
	Evaluate the ability of the pump to draw-down slurry/solids.	Test data Operator logs Video record
	Measure the minimum level achievable with water, water/sand, slurry/sand/rock.	Test data Operator logs Video record
	Determine the liquid level that must be maintained to effectively entrain solids.	Test data Operator logs Video record
	Evaluate techniques to entrain solids into the suction line, such as using a slurry jet, employing a water flush near the suction, or repositioning the pump.	Test data Operator logs Video record
	Determine the effect of ingesting air on cycle time and mist and/or foam with entrained particulate exiting vacuum.	Test data Operator logs Video record
D	**Remote Operations**	
	Evaluate effective monitoring and control systems for remote operation: • Nominal performance • Plugging of discharge line • Proper discharge duration cycle	Operator logs
	Determine the effectiveness of forward-flush and back-flush for dislodging blockage.	Operator logs
	Monitor foaming and aerosols discharge from vacuum line.	Operator logs Video record
	Monitor level in the pump to ensure complete discharge.	Test data
	Evaluate the need to monitor solids accumulation inside pump chamber.	Test data Operator logs Video record
	Potential for waste delivery through lines of pump during back and forward flushing.	Operator logs
	Potential for pump to topple over due to fluid surging.	Operator logs
	Measure flow rate of air that must be handled by the tanks ventilation system.	Test data Operator logs

3.0 Equipment Description

The PITBULL™ is comprised of a pump chamber, airlines, and control panel. The pump uses two distinct strokes, fill and discharge, to perform its pumping action. During the fill cycle, vacuum is applied to the pump chamber, which draws liquid into the pump. When the liquid level inside the chamber reaches a sensing tube, the chamber is pressurized with compressed air to discharge the liquid out of the pump chamber. Check-valves are used at the pump chamber inlet and exit to control the direction of flow. A vacuum pump powered by compressed air at the control panel generates a vacuum in the air line. Maximum air pressure and discharge time are set at the control panel and can be adjusted, depending on the liquid being pumped and discharge conditions.

The SRS Waste Removal Project evaluated many pump technologies for the Tank 19 heel retrieval application and selected the PITBULL™ for futher evaluation. The primary advantages of the PITBULL™ over other types of pumps are 1) the ability to discharge at a constant rate, regardless of pumping demand[1], 2) the ability to self-prime, 3) the ability to ingest air without losing prime, and 4) a moderate degree of debris tolerance. SRS has worked with the Chicago Industrial Pump Company (CIPC) to develop a unique version of the PITBULL™ pump (model 4814PC/6X2/ID/SP). The chamber of this custom pump is cylindrical in shape to facilitate insertion through a tank riser and is 35.6 cm (14 in.) in diameter and 124 cm (49 in.) tall. The inlet to the pump is through a 12.7 cm (5 in.) check-valve located on the bottom of the pump. A 5.08 cm (2 in.) discharge valve is located above the pump chamber. The pump is designed to sit on the bottom of the tank and draw sludge through a 2.54 cm (1 in.) gap between the tank bottom and inlet. A schematic of the pump exterior is provided in Figure 3.1. The discharge check-valve has a horizontal orientation to prevent solids from settling into the valve.

The air requirement for the pump depends on the discharge head and desired flow rate. Based on vendor calculations, 378 liters (100 gallons) per minute flow rate at 12.2 m (40 ft) and 30.5 m (100 ft) discharge head will require 906 and 1640 standard liters per minute (32 and 58 SCFM), respectively. The inlet air pressure must be regulated between 414 - 758 kPa (60-110 psi).

The pump is designed to pump sludge with a specific gravity of 1.2-1.3 at a rate of 378 liters per minute (100 gpm) with a total discharge head of 30.5 m (100 ft) of water. To operate in Tank 19 will require a 12.2 m (40 ft) equivalent discharge head. The piping system designed by SRS includes a forward- and back-flush capability. The discharge line includes 45.7 m (150 ft) of horizontal 7.62 cm (3 in.) line to direct flow to an adjacent tank.

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[1]The flow rate and pressure are relatively constant during the discharge cycle, which maintains velocity. In between discharge cycles, particles may settle, especially in horizontal pipe lines.

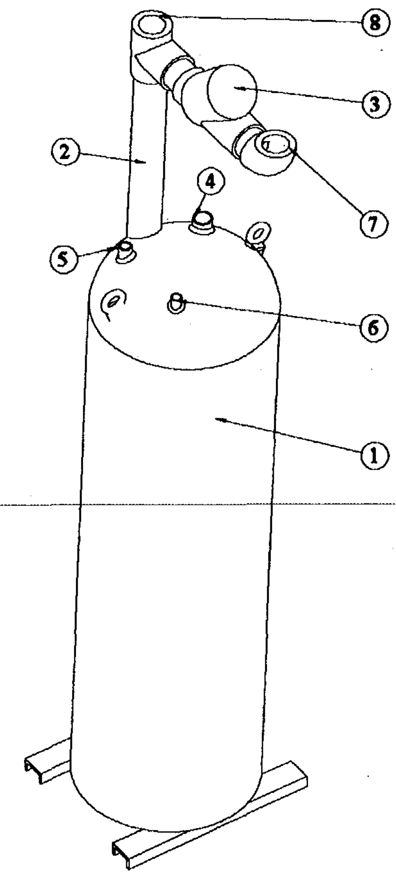


Figure 3.1 Schematic of the PITBULL™ Pump

4.0 Approach

The pump was installed in the Pacific Northwest National Laboratory's (PNNL) Fluid Dynamics Laboratory, located in the 336 Building at the Hanford Site. The pump was tested with water and slurry simulants. To evaluate the effects of large particles, sand and debris were added to the slurry. The test matrix included closed loop, steady state tests to evaluate pumping rate and draw-down tests to evaluate the effect of low liquid levels. The pump and discharge lines were flushed as required with water and compressed air to clean internal pipe surfaces, dislodge blockages, and clear check-valves. The test set-up, equipment, instrumentation, and simulants are discussed in the following sections.

4.1 Test Setup

The pump was placed at the bottom of a "12th-scale" tank, as shown in Figure 4.1. A 5.08 cm (2 in.) diameter pump discharge hose was routed 13.1 m (43 ft) vertically to an instrumented 7.62 cm (3 in.) diameter pipeline, which contains a Micromotion™ mass flow meter. The pipeline discharged into a funnel (to eliminate syphon effects) connected to a 15.2 cm diameter polyflex hose. Slurry was recycled into the 1/12th-scale tank or pumped to another tank, depending on the situation. The discharge line included connections to allow back and forward flushing. Flushing water or air could be introduced prior to the discharge check-valve, through the air pressure line, and at the end of the pipeline. The pump control panel and air supply instrumentation are shown in Figure 4.2. A piping and instrumentation drawing of the test setup is provided in Figure 4.3.

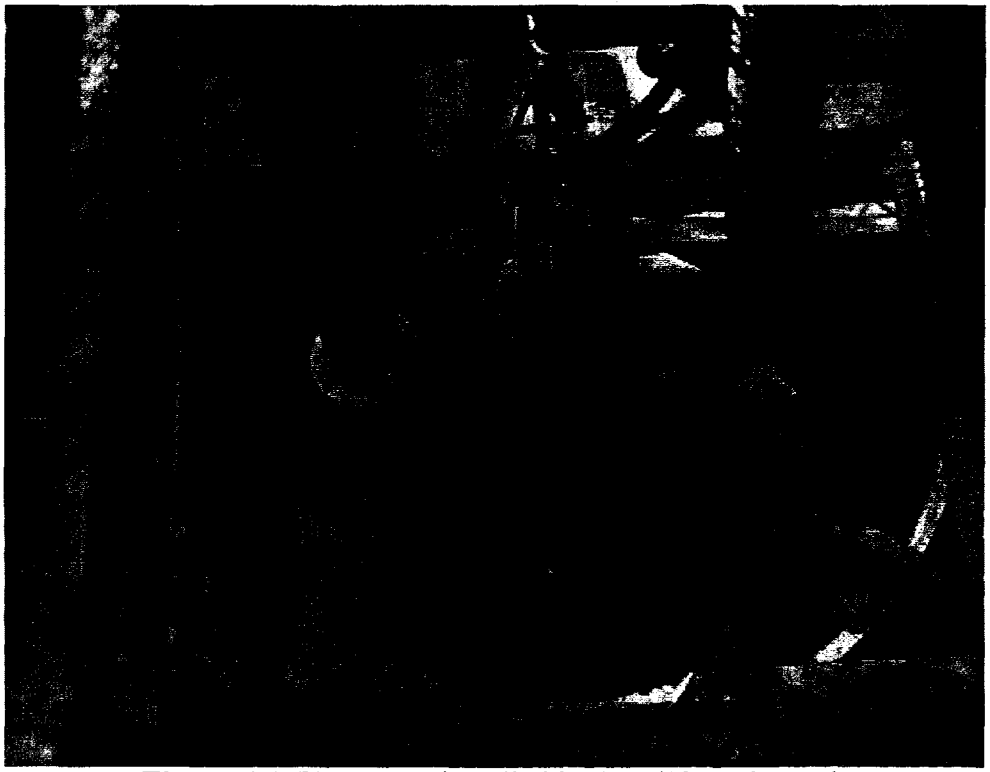


Figure 4.1 PITBULL installed in the 1/12 Scale Tank

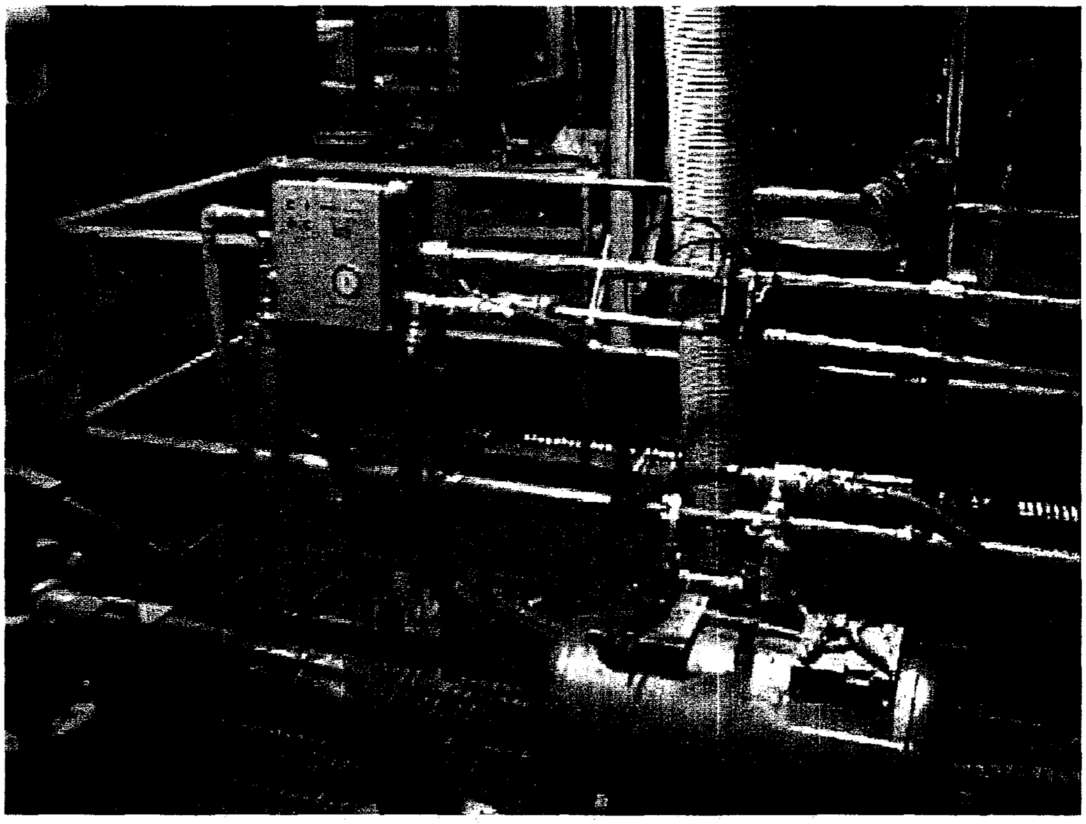


Figure 4.2 Pump Control Panel and Air Supply Instrumentation

4.2 Test Equipment and Instrumentation

The following sections describes the equipment and instrumentation used in the test program.

4.2.1 Equipment

- 1/12-Scale Tank: This cylindrical tank is 190.5 cm (75 in.) in diameter, 105.4 cm (41.5 in.) deep, and has a maximum capacity of 3,000 liters (794 gallons). When the pump was in the tank, the tank capacity was reduced by 106 liters (28 gallons). The bottom of the tank is 2.9 meters (9.5 ft) below the level of the first floor.

- Slurry Receipt Tank: A large, cone bottomed receipt tank was used to receive slurry during draw-down tests.

- Hoses: A 5.08 cm (2 in.) diameter hose was used to connect the pump discharge to the slurry test pipeline. The hose included a clear section near the discharge check-valve to monitor solids accumulation. At the end of slurry pipeline, the slurry was discharged into a large funnel to eliminate syphoning effects. The funnel was connected to a 15.2 cm hose return line.

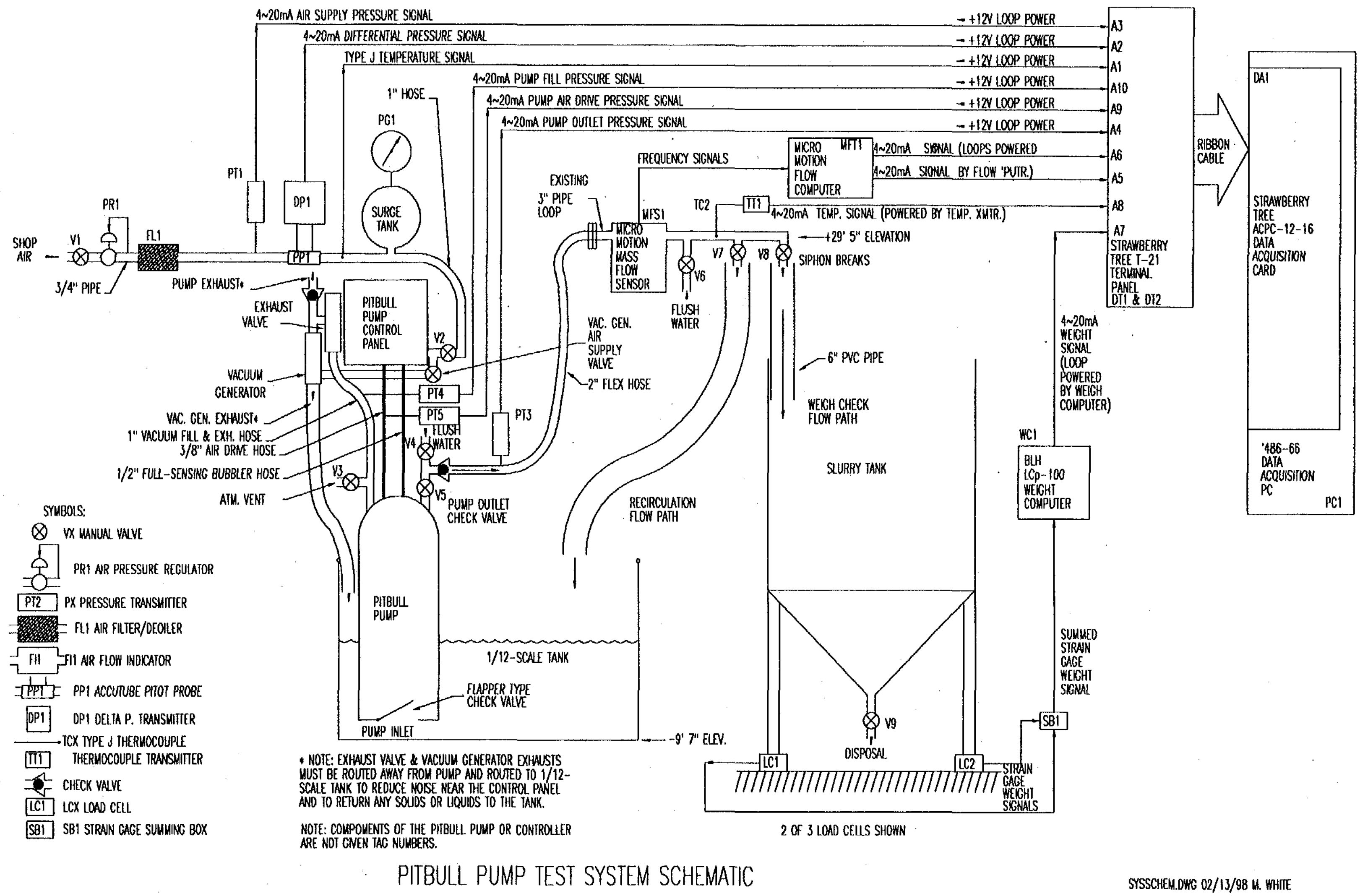


Figure 4.3 Piping and Instrumentation Diagram

- Slurry Test Pipeline: A horizontal 7.62 cm (3 in.) diameter pipeline was installed earlier in the test facility by the Hanford W320 Project to perform instrument calibration. The instrumented pipeline was located 13.1 meters (43 ft) above the bottom of the 1/12-scale tank.

4.2.2 Instrumentation

A Measurement and Test Equipment list is provided in Appendix A. The instrumentation is briefly described below. Calibration record of all instruments used to generate reported data are maintained in the project files.

- Data Acquisition System (DAS): The DAS consists of a Gateway 486-DX2-66E PC with a Strawberry Tree ACPC-12-16 analog input card and a T-21 terminal panel. The data acquisition software was Stawberry Tree Work Bench PC DOS^{R}, version 2.4.0. 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 raw data was averaged and converted to engineering units for real-time display by the DAS system.

- Supply Air Pressure Transmitter: Ametek model 88F, with a range of 0-827 kPa (0-120 psig) $\pm$ 0.25% of calibrated span with 4-20 mA output.

- Drive Air Pressure Sensor/Transmitter: Ametek model 88F, with a range of 48-827 kPa (7-120 psia) $\pm$ 0.25% of calibrated span with 4-20 mA output.

- Drive Air Flow Rate: An Accutube flow sensor and dual range differential pressure transmitter was installed in the air line to measure compressed air consumption and vacuum pump air flow.

- Discharge Pressure Transmitter: Ametek model 88F, with a range of 0-827 kPa (0-120 psig) $\pm$ 0.25% of calibrated span with 4-20 mA output.

- MicroMotion Coriolis Mass Flow Measurement System: The systems consists of a coriolis sensor and an accompanying transmitter. The sensor was MicroMotion model DS300S15SU, and the transmitter was model RFT9739. The sensor/ transmitter system has a minimum flow range of 0-159 kg/min (0-350 lbm/min) and a maximum flow range of 0-3177 (0 to 7000 lbm/min). The zero stability of the system is 0.32 kg/min (0.70 lbm/min). The accuracy of measurements for flow rate and density are $\pm$ 0.2% of flow rate $\pm$ the zero stability and $\pm$ 0.001 g/cm^3, 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 4-20 mA signals to the DAS. The signal averaging of the sensor was set to one second. The density range was maintained at a specific gravity of 1 to 2 throughout the test program. The density output was compared to the results of the density measurement from actual slurry samples.

- Slurry Tank Load Cells: The slurry receipt tank is mounted to three load cells, which were used to calculate mass flow rate during draw-down tests. This data was compared to the mass flow output from the MicroMotion sensor.

4.3 Simulant Development

The Tank 19 zeolite was reportedly added to the tank as 20 to 50 mesh particles (0.3 to 0.9 mm). However, it is possible that the zeolite may have undergone some consolidation and/or reactions that may yield larger particles during retrieval. The heel also contains some fraction of sludge particles, although it is unlikely that there will be sufficient quantity of sludge to give the slurry an appreciable yield stress. During heel retrieval of SRS Tank 19, a sluicing jet will be used to dislodge, mobilize, and dilute the heel layer. If deployed, the pump will be used to transfer slurry containing sludge and zeolite particles from the bottom of the tank to the tank surface. It is anticipated that the specific gravity of the slurry during retrieval will be 1.1 to 1.2. The composition of the slurries tested with the PITBULL™ were selected to provide a range of both specific gravity and particle size that will envelope the anticipated operating conditions.

Water containing silica and kaolin was pumped to determine the effect of specific gravity on pump performance. Water was used during check-out tests to provide a direct comparison with manufacturer's data. Silica (Min-U-Sil) was added to the water to increase the specific gravity to approximately 1.1. Silica was chosen for two reasons: 1) silica's fine particle size reduces the rate of settling and 2) silica added to water will create a low viscosity slurry, which will reduce the likelihood of air retention. Pump recirculation and air lances were used to suspend the silica from the tank bottom. As the specific gravity of the slurry was increased to 1.2, it was necessary to add a small amount of kaolin to reduce the hardness of the settled heel and the settling rate of the silica. Table 4.1 summarizes the slurries tested. The specific gravity of the mixture is a calculated value; in reality, some of the solids inevitably settled out, which resulted in a lower specific gravity. Samples of the slurry taken at the syphon break were tested to determine the actual specific gravity of the slurry.

Testing the pump with hard, fast-settling solids is probably the most challenging for the pump, as the solids will tend to jam the check-valves or create blockages in the discharge line. To determine the ability of the PITBULL™ to handle solids, approximately 35 liters of fine sand, coarse sand, and gravel were successively added to the final batch of water/silica/kaolin slurry. The size of the fine sand was 0.3-0.9 mm and is the most similar to un-reacted zeolite. The size of the coarse sand ranged from 1-2 mm, while the size of pea gravel ranged from 3-8 mm. Prior to pump tests, the solids were dumped in small piles on both sides of the pump inlet, submerged under a layer of slurry, and then introduced into the pump with air spargers during pump operation.

Table 4.1 Simulants Tested to Vary Specific Gravity

Slurry	Slurry Composition	Component Specific Gravity	Component Weight %	Mixture Specific Gravity	Batch Size liters
1	Water	1.00	100%	1	1313
2	Water	1.00	85.4%	1.1	1397
	Silica	2.65	14.6%		
3	Water	1.00	70.5%	1.225	1523
	Silica	2.65	25.8%		
	Kaolin	2.64	3.7%		

4.4 Testing Phases

This section presents the test phases conducted during the testing program. Individual test instructions can be found in the test plan. A total of 39 data sets were collected during the test program to measure the expected operating performance of the pump under a variety of conditions and to determine the likelihood of failure in extreme situations. A test summary log containing test parameters, data file names, and observations, is provided in Appendix B. The testing phases were as follows:

Check-out Test — These tests were conducted to verify the operation of the systems and data acquisition system.

Pumping Rate — Continuous pumping and draw-down tests were conducted with water and water containing silica and kaolin to determine optimum systems settings and to measure pumping rates, cycle times, and flow rates as a function of liquid level and slurry specific gravity.

Pumping Solids — Pumping tests were conducted with slurry containing sand and pea gravel to determine the effect of solids on pump performance and reliability. These tests also examined techniques to entrain rapidly settling solids into the pump and flushing techniques to eliminate blockages in the pumping system.

5.0 Test Results

This section provides the results of the PITBULL™ pumping tests. Pumping rates for water and slurries containing silica and kaolin during continuous pumping and draw-down tests are presented in Section 5.1. Pump performance during tests involving sand and pea gravel are presented in Section 5.2. Finally, observations collected during testing concerning the remote operation of the PITBULL™ pump are provided in Section 5.3.

5.1 Pumping Rate

This section provides PITBULL™ test results during continuous closed-loop and draw-down tests and discusses the effect of equipment settings and slurry specific gravity and liquid level on pump performance.

5.1.1 Vacuum Generator Optimization

This section describes a series of experiments that were conducted to determine the optimum configuration of the vacuum pump. A venturi-type air-powered vacuum pump (Vaccon Model VDF750) generates vacuum during the fill cycle of the PITBULL™ pump. Air is continuously supplied to the vacuum pump; the exhaust valve is opened during the fill cycle and closed during the discharge cycle. The performance of the VDF750 can be increased by increasing the annular gap between the venturi nozzle and the diffuser. Rotating the diffuser section counter-clockwise will increase the opening, allowing more supply air to flow through the unit and increasing both the vacuum flow and vacuum level. Since the generator is supplied with air continuously and the fill time is a large fraction of the overall pump cycle time, it was desirable to determine the relationship between diffuser position and vacuum flow, vacuum level, and air consumption. Diffuser setting was quantified by counting the number of rotations the diffuser had been turned from the fully closed position. Note that the vendor recommended a setting of 1.25 turns as an optimum setting for most applications and this value was used for the initial tests described in Section 5.1.2.

To measure supply air consumption, vacuum air flow, and vacuum level, the VDF750 was inserted into an instrumented piping circuit. For this set of experiments, the air pressure, temperature, and flow instrumentation were removed from the pump inlet line and installed into the piping circuit. By using an array of valves and parallel lines, this instrumentation could be used to alternatively measure air consumption and vacuum air flow and pressure.

The performance of the vacuum pump will depend on the supply air pressure and the diffuser position. For the first set of experiments, supply air pressure was held constant at 586 kPa, and the number of diffuser turns was varied from 0 to 3. Figure 5.1 provides air consumption and vacuum air flow versus number of diffuser turns, while Figure 5.2 provides vacuum pressure versus number of turns. The maximum vacuum flow of 1400 liters/min at standard temperature and pressure occurred at 2 turns and required 2200 liters/min of supply air. At one diffuser turn, however, the vacuum flow was only 4% less (1340 liters/min), but required 40% less supply air. The maximum vacuum pressure of -30 kPa occurred at 2 turns. Vacuum pressure was not considered a critical factor, since the pump chamber is exhausted under positive pressure for most of the fill cycle, and only a small vacuum (-15 kPa) is required to fill the chamber when the pump is immersed. Based on these tests, a diffuser setting of "one turn" was selected as the best compromise between air consumption and vacuum air flow and was used for all subsequent tests.

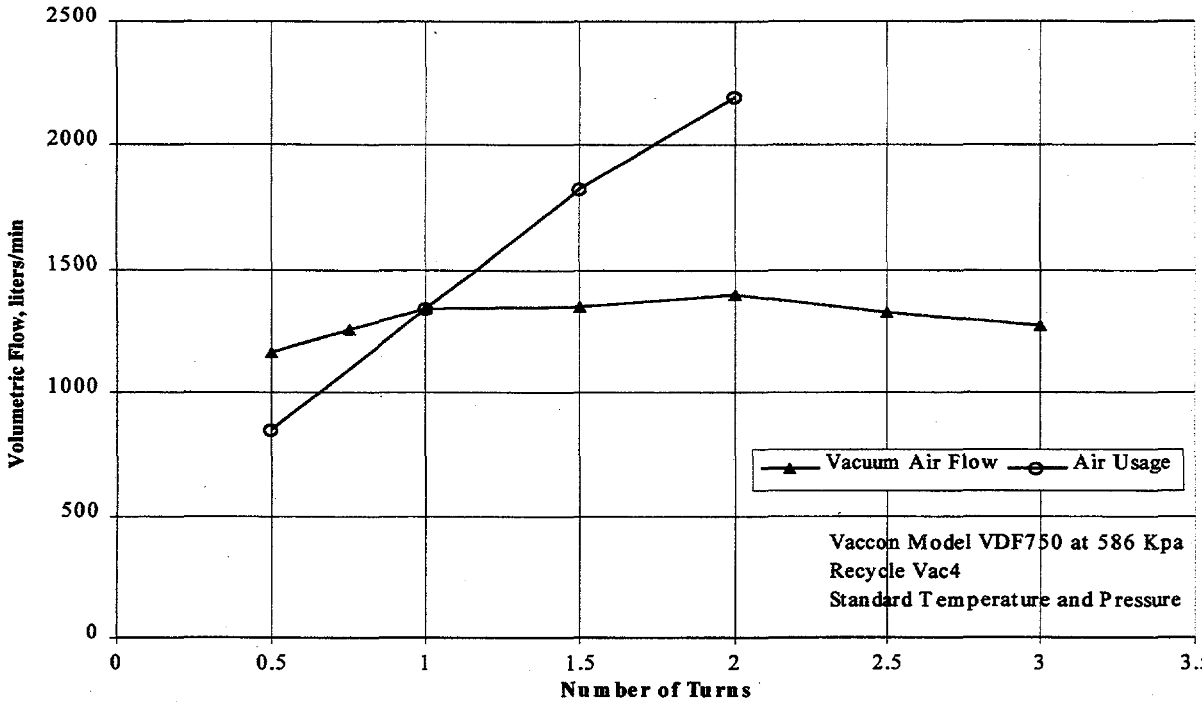


Figure 5.1 Vaccon™ Model VDF750 Vacuum Air Flow and Air Usage versus Diffuser Setting

For the second set of experiments, the diffuser position was held constant at one turn, and the supply pressure was varied from 400 to 650 kPa. Figure 5.3 provides air consumption and vacuum air flow versus supply pressure, while Figure 5.4 provides vacuum pressure versus supply pressure. Maximum vacuum flow occurred at a supply pressure of 620 kPa. Vacuum flow was found to be a weak function of supply pressure, and varied by only 10% for the range of pressures tested. During the pumping tests, the supply air pressure varied from 570 to 670 kPa and thus was in the appropriate range for maximum performance.

5.1.2 Effect of Discharge Pressure and Discharge Pulse Duration

The only settings that can be controlled on the PITBULL™ are discharge pressure and discharge cycle duration. According to the operating manual, the discharge pressure on the control panel should be set to 100 kPa above the calculated dynamic head required for the application. The test set-up includes a 13.1 meter lift through a combination of approximately 13 meters of hose (5.1 cm ID) and 8.5 meters of steel pipe (7.62 cm ID). The required dynamic head was calculated to be 214 kPa, assuming that the entire circuit is 5.1 cm hose and the pump discharges at twice the average flow rate of 266 liters/min. The recommended panel setting should be 214 +100 kPa, or 314 kPa. The vendor recommends the use of a relatively low panel setting to avoid unnecessary check-valve wear. Once the pressure is selected with the pressure regulator below the control panel, the discharge cycle duration is adjusted by turning a knob located on the inside of the control panel.

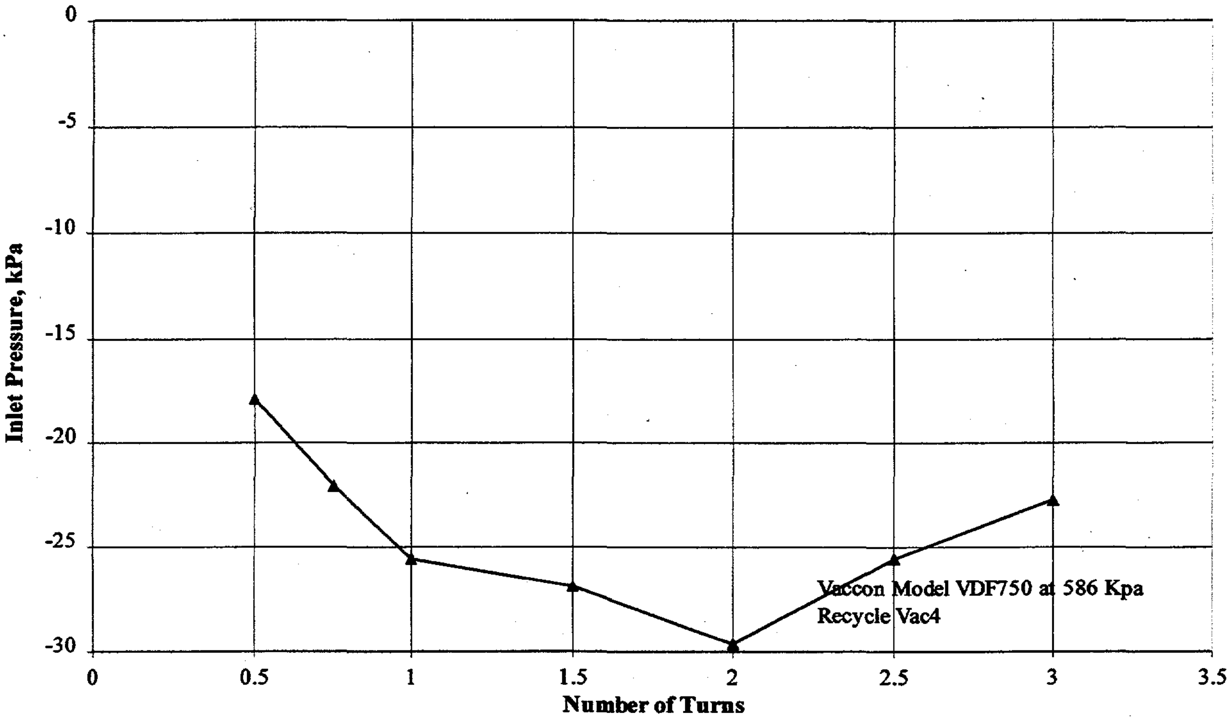


Figure 5.2 Vaccon™ Model VDF750 Vacuum Pressure versus Diffuser Setting

A series of tests were conducted to determine the effect of the discharge pressure setting on the pump performance. For each pressure setting, the discharge time required to completely exhaust the pump chamber was determined as follows. The discharge time was increased until air entered the discharge line, which was evident by a rapid increase in the instantaneous discharge flow rate at the end of the discharge cycle. The discharge time was shortened incrementally until a smooth discharge flow profile was obtained. The average and maximum discharge flow rates measured during these steady state conditions are provided in Figure 5.5, while the maximum chamber pressure is provided in Figure 5.6. The maximum mass flow increased with pressure setting although the average mass flow was not significantly affected. The data indicates a modest improvement in average flow rate if the panel pressure setting was set to at least 380 kPa, and this value was used for subsequent tests. Note that this is slightly higher than the vendor's recommended pressure setting of 314 kPa.

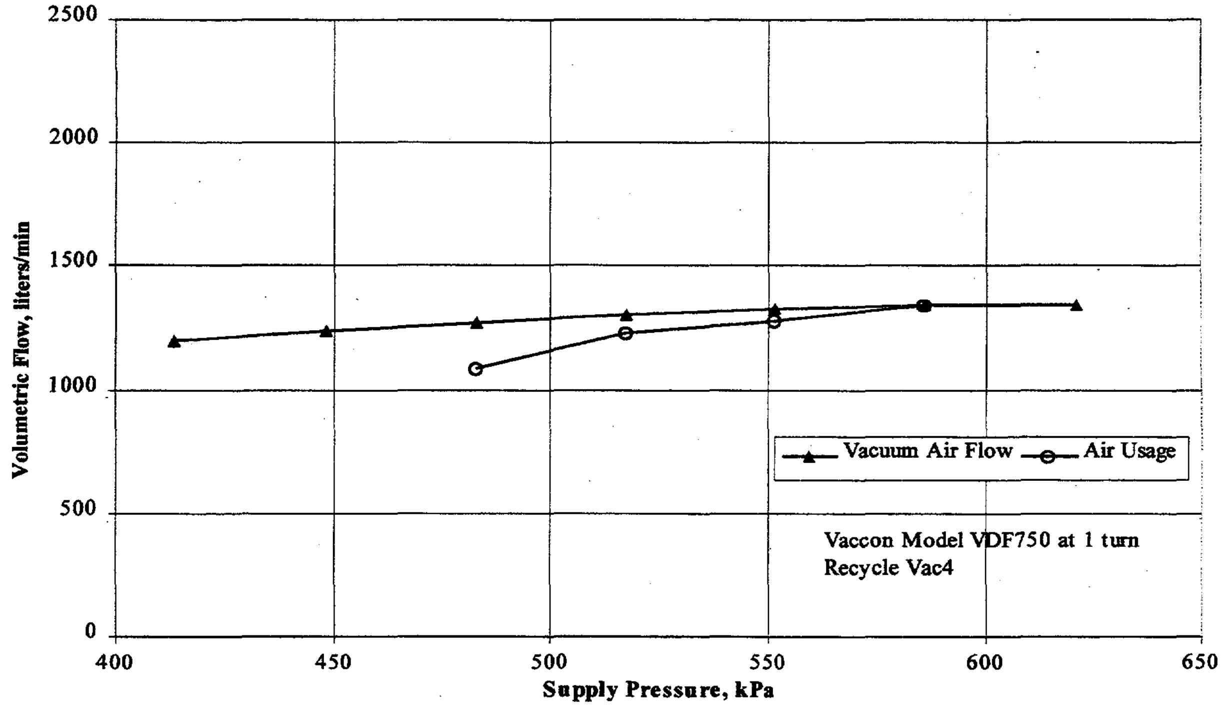


Figure 5.3 Vaccon™ Model VDF750 Vacuum Air Flow and Air Usage versus Supply Pressure

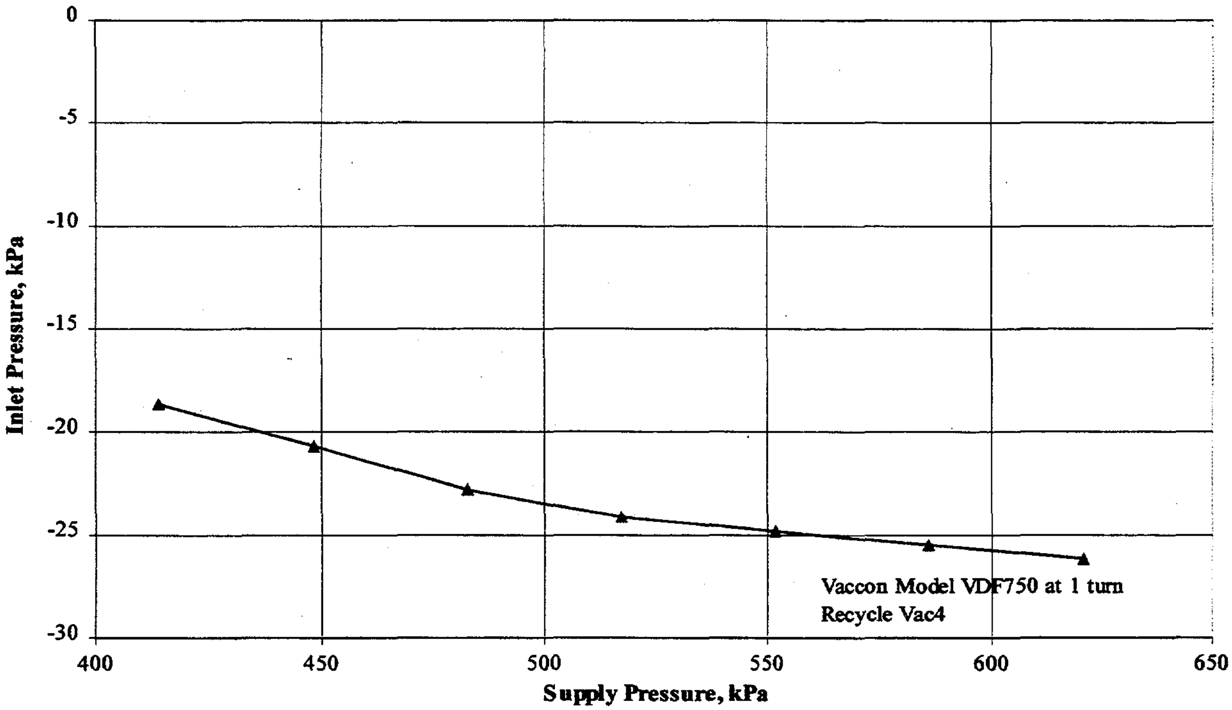


Figure 5.4 Vaccon™ Model VDF750 Vacuum Pressure versus Supply Pressure

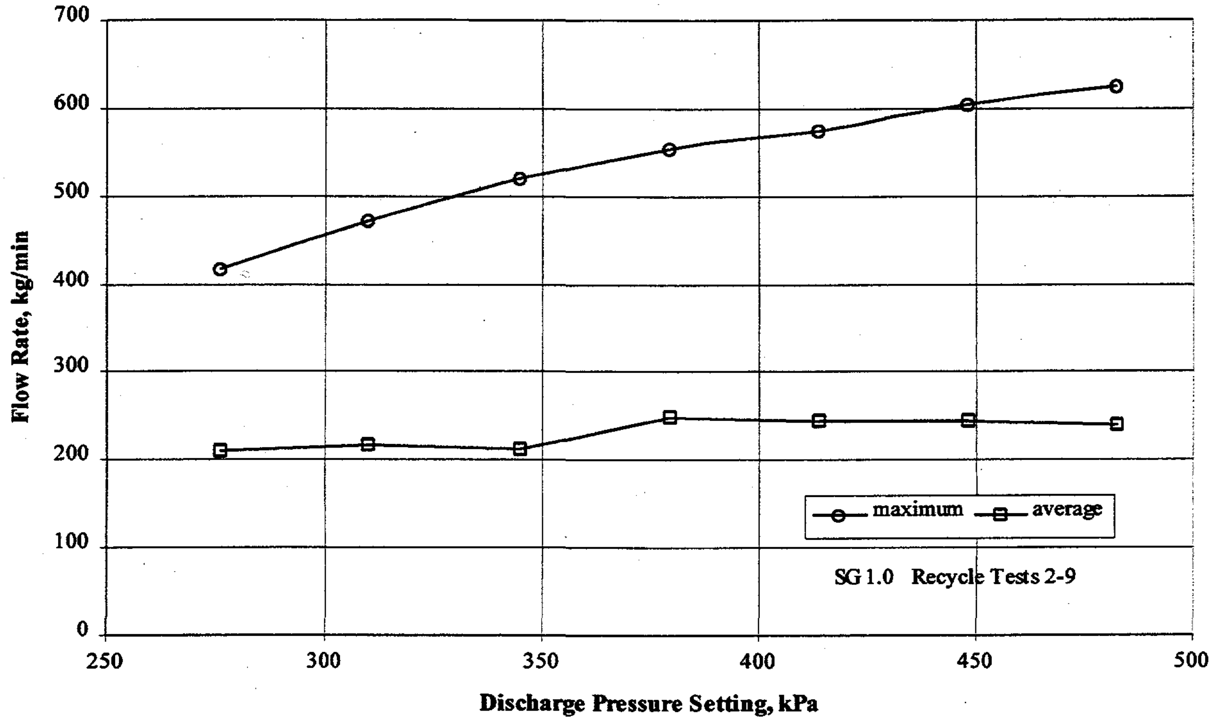


Figure 5.5 Discharge Flow Rate versus Panel Pressure Setting with Water

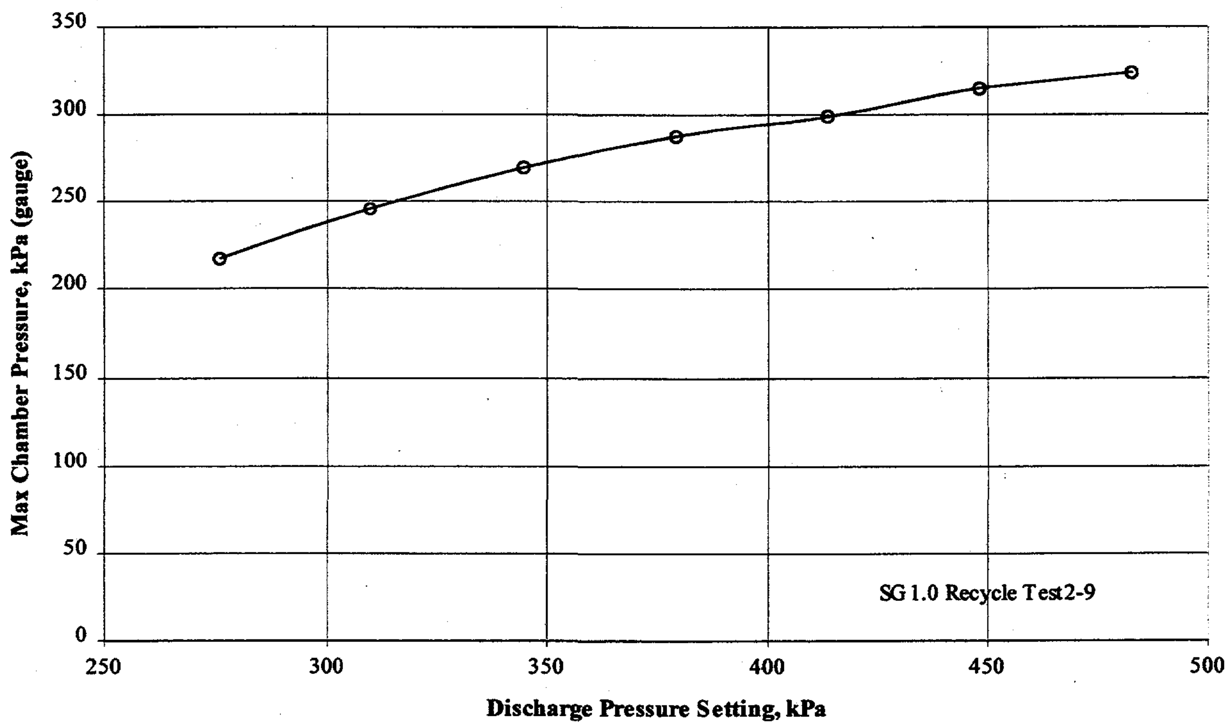


Figure 5.6 Pump Driving Pressure versus Panel Pressure Setting with Water

For a 380 kPa panel pressure, the discharge time panel setting required to completely discharge the chamber was found to be 25, which corresponded to 5.1 seconds for water. For the rest of the test program, the panel pressure and discharge time was set to 380 kPa and 25, respectively. Occasionally the discharge time was increased slightly to determine if the chamber was being completely discharged, but each time this resulted in air ingestion and the discharge time was reduced. Although the panel setting was set to 25, the actual discharge time measured during the tests varied from 5 to 8 seconds.

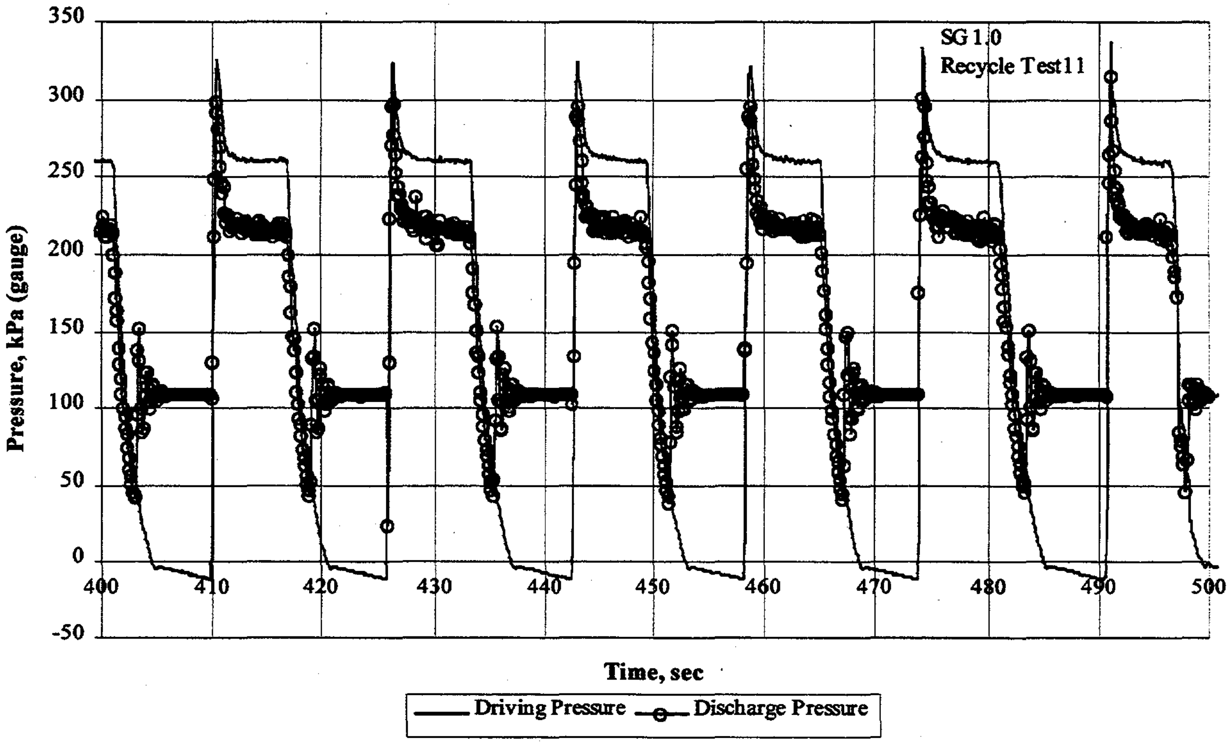


Figure 5.7 Pump Driving and Discharge Pressure versus Time with Water

5.1.3 Effect of Specific Gravity

Continuous closed-loop pump tests were conducted to determine the effect of specific gravity on pump performance. Figure 5.7 provides the pump chamber pressure (PT2) and discharge pressure (PT3) for a 100-second period during pumping of water. Figure 5.8 provides the dynamic discharge mass flow during the same 100-second period. Pump performance data plots for other slurries tests are provided in Appendix C. Table 5.1 provides average pump performance data during steady state conditions for water (S.G. 1); water and silica (S.G. 1.08); and water, silica, and kaolin (S.G. 1.18). The same discharge time (25) and discharge pressure (379 kPa) was used for all these tests. As shown in Figure 5.9, the average mass flow rate was identical for slurry with a specific gravity of 1.0 and 1.08, but decreased slightly for the heaviest slurry, probably because this simulant contained a small amount of kaolin which increased the viscosity of the slurry slightly. The volumetric flow of slurry decreased with increasing specific gravity as expected (Figure 5.9).

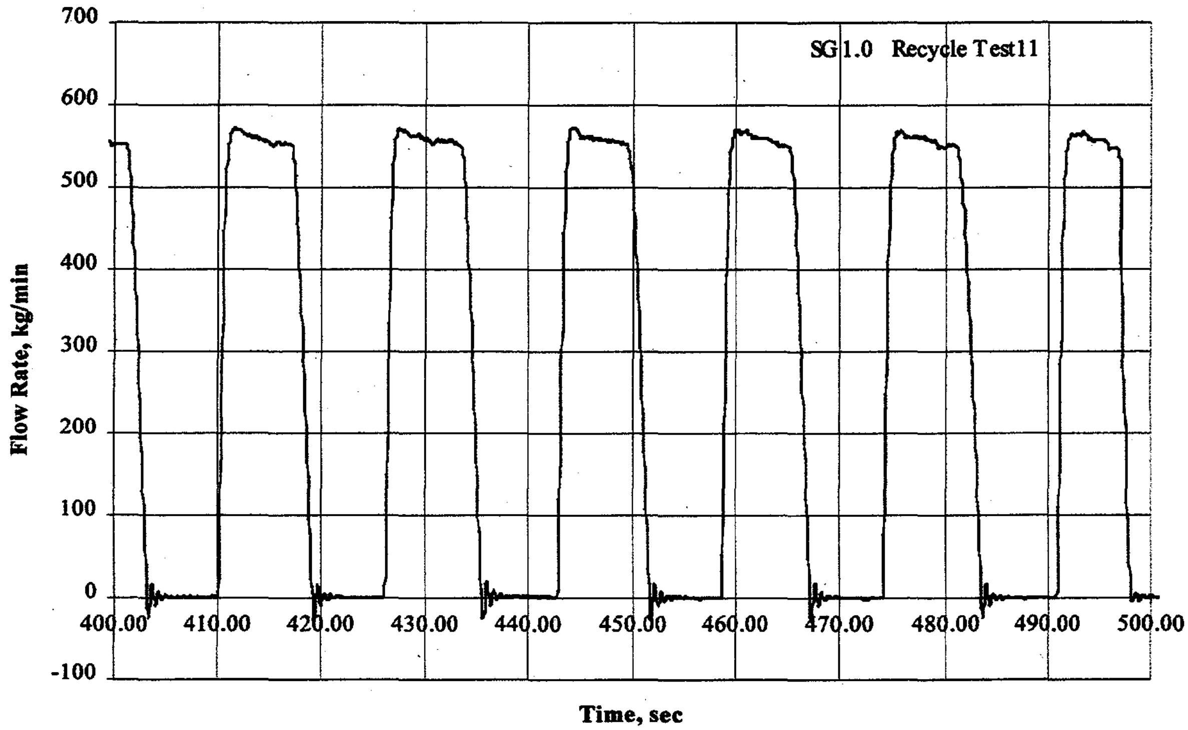


Figure 5.8 Discharge Flow Rate versus Time with Water

5.1.4 Effect of Liquid Level

Pump draw-down tests were conducted to determine the effect of liquid level in the tank on pump performance and the minimal achievable liquid level. The initial liquid level was approximately 45 cm for each test, and the pump was allowed to operate until pumping ceased, at which time the liquid level in the tank was measured. Three different slurries were tested, with specific gravity ranging from 1 to 1.18. Figure 5.10 provides the average mass flow rate of the pump versus liquid level. This data indicates that 1) pump performance decreases rapidly for tank liquid levels below 5 cm due to air ingestion and 2) high liquid levels did not improve tank performance.[1] The final liquid level was approximately 2.5 cm for each slurry. Since the pump will be operated with minimal liquid level for significant periods of time during the sluicing operation, it is important to note that vortexing of liquid at the pump inlet and air ingestion will decrease pump performance at low liquid levels.

[1] It was initially believed that high liquid levels would increase flow of slurry into the pump chamber. Apparently, the benefit is minor.

5.2 Pumping Solid Materials

This section provides PITBULL™ test results with slurry containing solids of various sizes. Operating the pump with hard, fast-settling solids is probably the most challenging for the pump, as the solids will tend to jam the check-valves or create blockages in the discharge line. To determine the ability of the PITBULL™ to handle solids, approximately 35 liters of fine sand, coarse sand, and gravel were successively added to the final batch of water/silica/kaolin slurry. Prior to pump tests, the solids were dumped in small piles on both sides of the pump inlet, submerged under a layer of slurry, and then introduced into the pump with air spargers during pump operation. The solids were circulated along with the slurry back into the tank, but rapidly settled into low-velocity zones. Air sparaging was not effective in resuspending the solids, so as pumping continued, more and more solids would settle out. The addition of solids also tended to make the silica and kaolin fall out of suspension, which resulted in a low specific gravity. Efforts were made to insure that the solids were passing through the pump, including monitoring the syphon break at the end of the slurry pipeline for solids and drawing the tank contents down periodically to insure that all the solids placed at the pump inlet were dispersed. Although it was not possible to control the rate of solids being introduced into the pump, these tests provided a quantitative measure of the problems that might be encountered during retrieval of hard, fast-settling solids.

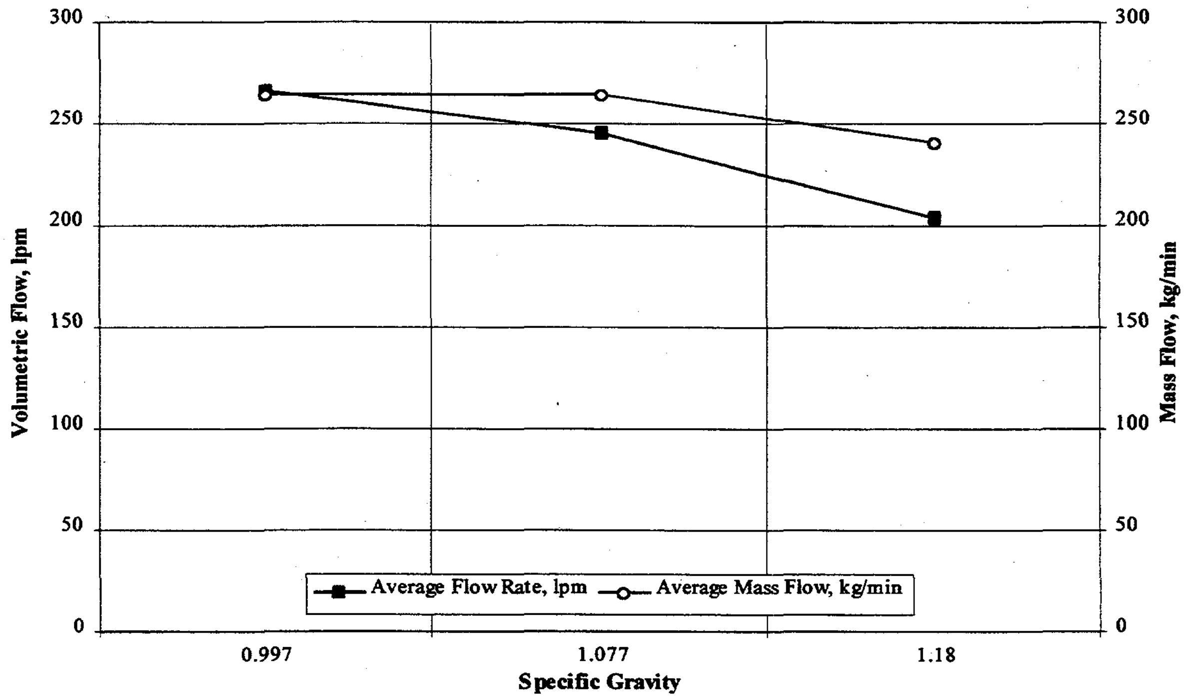


Figure 5.9 Average Pump Flow Rate versus Specific Gravity

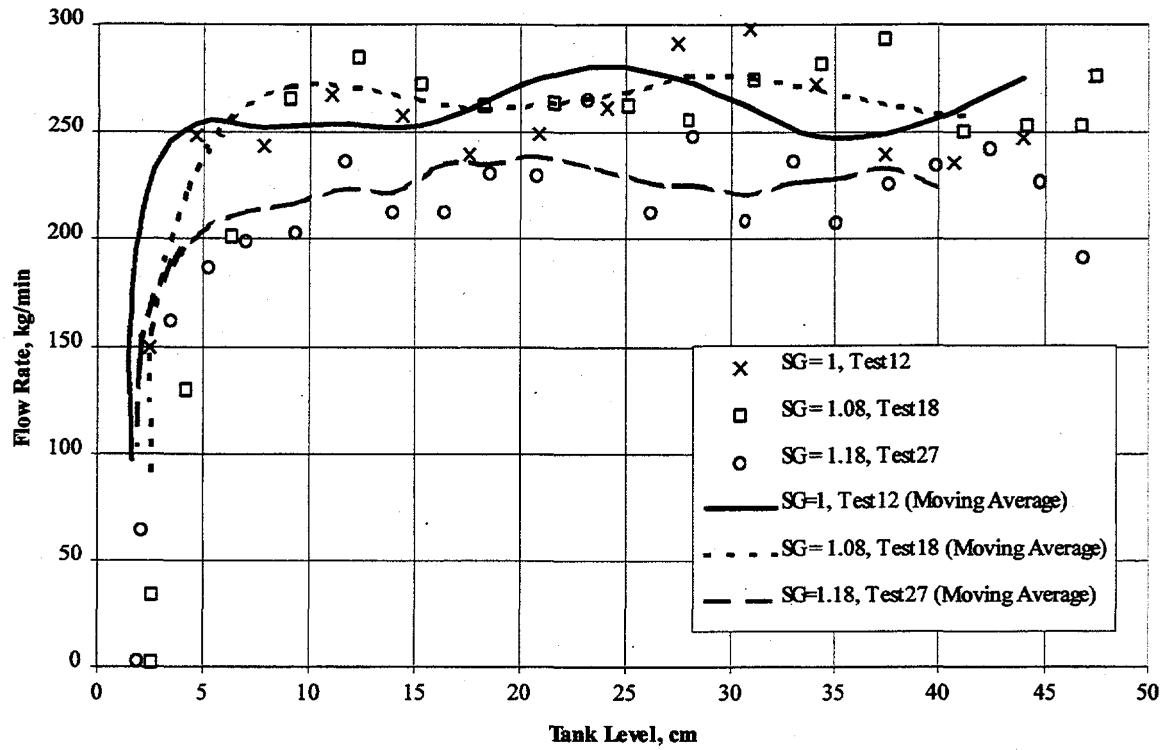


Figure 5.10 Average Flow versus Tank Level

5.2.1 Pump Recycle Tests with Solids

Addition of fine sand to the slurry did not affect pump performance, as the results were almost identical to the water/silica/kaolin tests. Average pumping results with coarse sand and pea gravel are provided in Table 5.1 and plots of chamber pressure, discharge pressure, and mass flow rate as a function of time are provided in Appendix C.

The addition of coarse sand did not degrade average pump performance in terms of average mass flow or volumetric flow, when compared to the results the water/silica/kaolin tests (Table 5.1). The presence of coarse sand did cause the discharge check-valve to take longer to close and to audibly chatter. This occurrence is evident by the large spikes in the discharge flow rate as the pump transitioned from the discharge to the fill cycle (Appendix C-Test Part 3). During these transient periods, slurry did flow from the discharge line back into the chamber as evidenced by the negative flow. Although the amount of back-flow was small and did not affect pump performance, the check-valve chatter did raise a concern for long-term reliability. Following the pump performance test with coarse sand, a 4-hour endurance test was conducted. During this test, check-valve chatter was initially evident, then subsided as the sand was flushed from the valve. Pump performance remained nominal during the test, although several hose fittings had to be tightened to eliminate leaks. Apparently, vibrations from the check-valve tend to loosen fittings.

The addition of pea gravel significantly degraded average pump performance in terms of average mass flow or volumetric flow, when compared to the results of the water/silica/kaolin tests (Table 5.1, right column). The presence of pea gravel caused the discharge check-valve to oscillate during the fill cycle, which resulted in significant slurry back-flow. This occurrence is evidenced by the large spikes in the discharge flow rate as the pump transitioned from the discharge to the fill cycle (Appendix C-Test Sluice1). Check-valve blockage also caused fluctuations in the discharge flow rate. Significant back-flow introduced air into the discharge line and resulted in spikes during the discharge cycle. During the test, the pump was stopped and attempts were made to flush the outlet check-valve by adding water to the air pressure line and by flushing water through the discharge line upstream of the check-valve. The pump was then restarted, although the discharge flow was still erratic. It should be noted that under these conditions, erratic mass flow and the presence of air in the discharge line may result in inaccurate mass flow measurement. The flow rate observed from the recycle line was observed to be very low. The pump was stopped again to examine the check-valve, and the contents of the discharge line drained back into the pump chamber, indicating that the check-valve was blocked open.

The outlet check-valve was disassembled and inspected. The sealing surface of the valve flapper is a nitrile rubber disk and is not bonded to the metal portion of the flapper. Upon inspection, sand was found between the rubber disk and the metal flapper, which caused the rubber disk to deform into a ripple shape. The prevented the valve from closing properly. To prevent this occurrence, the rubber disk should be bonded to the metal flapper. The valve was cleaned to remove sand from the rubber disk and pea gravel from around the flapper circumference, lubricated, and then reassembled, although the rubber disk was still partially deformed. When the pump was restarted, the discharge flow rate was nominal, although there was still quite a bit of back flow.

Following the pump performance test with pea gravel, an endurance test was attempted to determine if the pump can reliably pump pea gravel for long periods. After 2 minutes of testing, the pumping rate reduced significantly. Pea gravel was manually removed from the discharge check-valve, and pumping was resumed. After 6 additional minutes, the check-valve malfunctioned again and the test was terminated. In conclusion, the pump in its tested configuration did not reliably pump slurry containing pea gravel, and flushing with water was not a useful method for clearing the check-valve of pea gravel. The vendor was contacted and recommended an alternative seal material for the check-valve. The standard material is rubber (which was tested); urethane or aluminum sealing surfaces were recommended for pumping of slurries containing harder materials.

During these pumping tests, the sight glass in the 7.62 cm diameter pipeline was monitored for accumulations of solid materials, and none were noted. In addition, the vertical leg was drained after each test; the initial surge of material from the hose appeared to have a greater concentration of solids, but plugging never occurred.

5.2.2 De-plugging Tests

Once the slurry enters the pump chamber, the flow can be obstructed by solids accumulating in low-velocity areas inside the pump chamber, at elbows, and around check-valves. The extent of solids accumulation in the pumping system can be amplified by 1) ingesting a large amount of solid materials, such as when the pump is started inside a tank with settled solids or if solids are intentionally pushed into the pump inlet, and 2) flow interruption during a planned or unplanned stoppage. Both of these situations were examined during the test program.

To simulate the effect of starting the pump on an initially settled tank, the pump was allowed to completely fill its chamber, and the pump was stopped before the discharge cycle. The solids in the tank and pump chamber were allowed to settle for 12 hours and then restarted. This test was conducted on a number of occasions, and usually the pump operated without any problems. On two occasions, however, the solids inside the pump chamber prevented the inlet check-valve from opening. To clear the check-valve, an air lance was inserted into the pump's discharge pipe through valve V2 and compressed air was introduced into the bottom of the pump chamber, which quickly freed the valve and allowed the pump to operate. Rapid solids ingestion was also investigated during the pump recycle tests with sand and gravel. During early stages of these tests, the specific gravity of the slurry approached 1.5 without any pumping interruptions.

During any outage, slurry will always flow into the chamber by the force of gravity. This may be undesirable if the pump will not be operated for long periods of time, due to the likelihood of solids settling inside the discharge line and pump chamber. The discharge line was drained at the conclusion of each day using valve V10 to prevent blockage. In addition to this precaution, the capability to pressurize the chamber with compressed air was added to the test set-up to purge the pump at the end of each day and prevent slurry from entering the chamber.

Pipe plugging did not occur during any of the tests. To verify the operation of the flushing system, a flushing test was conducted in which coarse sand was intentionally placed into locations where settling could be a problem. Specifically, 11 liters of coarse sand were poured in the vertical section of the discharge line, and 7.5 liters of coarse sand were poured into the pump chamber through the discharge line. During this test, the tank had approximately 67 cm of dilute slurry. Upon start-up, the pump discharged erratically but, after a few cycles, the plugs were cleared and performance returned to nominal levels. After this test, the discharge check-valve was chattering excessively. The pump was stopped and flushed with water through manual valve V2. The pump was restarted, and the check-valve chattering was significantly reduced.

During pumping of slurries with sand, it was evident that the pump has a minimal ability to draw solids into the inlet from remote locations of the tank, and at times the heel of solids left un-suspended in the bottom of the tank approached 5 cm. Although the inlet itself would remain clear, solids would tend to accumulate into piles around the inlet. The flow of slurry into the chamber was sufficient to keep the inlet clear of solids. Two techniques were used to push the solids to the pump inlet: sluicing at low pressure and manual placement using shovels. It should be noted that these techniques are in no way prototypical of the retrieval methods for SRS Tank 19, but were attempted to enhance the amount of solid material entering the pump. Sluicing with 550 kPa water was effective in pushing solids near the inlet if the water level in the tank was low, but the momentum from the small jet was not sufficient to push material beyond 30 cm. Shovels were used to place material near the inlet, and sluicing water was used to slurry the solids and push the material into the inlet. Under these circumstances, solids were effectively pumped at high rates but occasionally blocked the inlet valve, which was evident by slurry exiting the inlet valve during the discharge cycle. To flush the inlet valve, the pump was stopped and process water was added to the chamber through the discharge line. This cleared the inlet valve and allowed the pump to operate nominally.

5.3 Considerations for Remote Operation

This section contains general observations collected during testing concerning the remote operation of the PITBULL™ pump, including the potential for discharge valve freezing and pump tipping, and the presence of liquid carry-over in the pump exhaust. A troubleshooting guide is provided at the end of the section to diagnose problems and recommend possible solutions.

During initial tests with water/silica slurries, icing of the pump exhaust valve was a problem. Water vapor would condense and freeze in the valve. As icing occurred, the time required to fill the chamber increased, while the average flow rate decreased. The pump vendor was contacted, and recommended that the original stainless steel exhaust valve (model EXVS75) be replaced with a larger aluminum valve (EXV200) which is much less likely to freeze, due to better heat transfer. After this valve was installed, no further icing occurred. During operation of this valve, water vapor from the exhaust jetted from joints between the valve body and flange connections. Rubber seals were fabricated for these joints to prevent leakage.

During most of the pump tests, the pump chamber was secured to the tank with straps to prevent it from moving or tipping. For one test, the straps were removed to determine if the pump would tend to topple during operation due to surging of material into the discharge line. The pump was operated for 10 minutes and showed no tendency to move or tip over.

The pump chamber exhaust was routed through the exhaust valve, vacuum generator, and through a long hose (to attenuate sound) and directed back into the tank. During pumping, the exhaust contained up to 2.5 liters per minute of water. Silica was found inside the exhaust valve, indicating that solids are present in the aerosols as well. The amount of aerosols appeared to increase with discharge pressure. Although aerosols in the exhaust is not a concern for the SRS application because the exhaust line will be directed back into the tank, aerosol discharge from the exhaust line should be considered for other applications.

The pump was lifted from the test tank twice during the testing program to inspect the pump chamber for solids accumulation: after the conclusion of the tests with water, silica, and kaolin slurries and at the conclusion of the tests with sand and pea gravel. In both cases, a layer of solids was found on the bottom of the chamber. The volume of material was approximately 5 liters during the first inspection and consisted of compacted silica and kaolin. The volume of material was approximately 1.5 liters during the second inspection and consisted of pea gravel, silica, and kaolin. Since the discharge line inside the chamber is approximately 6.35 cm from the bottom of the chamber, some solids accumulation is inevitable. It is unknown whether the solids filled the void between the inlet and the tank bottom and remained, or if the solids cycled through on a continuous basis. Heavy particles may accumulate inside the pump chamber, which could lead to higher radiation levels or, potentially, a criticality, if the pump is used to retrieve high-level waste.

The length of air supply and exhaust lines may affect pump performance. The control panel was installed approximately 3 meters from the pump for these tests, but during remote operations the control panel may be installed a considerable distance form the pump. For example, if the panel is placed at the tank dome of Tank 19, the air lines will have to be extended 12 meters. This will effectively increase the pump chamber by 10%, and will reduce pump performance to some extent.

Flushing with water and compressed air through the air pressure line and discharge line was helpful in dispersing solids in the chamber and to some extent clearing the check-valves. The flush water was isolated by valves to prevent the flow of water or slurry through the controls panel.

To aid the remove operation of the pump, a troubleshooting guide for problems encountered in this test program is provided in Table 5.2 and will augment information provided by the supplier. The ability to monitor discharge flow rate, chamber pressure, and slurry specific gravity was very helpful in diagnosing the problems that were encountered.

Table 5.1 Average Pump Performance Data During Steady State Operating Conditions

Data		Test11	Test17	Test26	Part3	Sluice1
Simulant		Water	Water Silica	Water Silica Kaolin	Water Silica Kaolin Fine sand Coarse sand	Water Silica Kaolin Fine sand Coarse sand Pea gravel
Specific Gravity	Ave	0.997	1.077	1.180	1.177	1.041
Diffuser	Setting	1 turn	1 turn	1 turn	1 turn	1 turn
Discharge Time	Setting	25	25	25	25	25
Max Panel Pressure Setting	kPa (psi) gauge	379 (55)	379 (55)	379 (55)	379 (55)	379 (55)
Supply Air Pressure (gauge)	Max, kPa (psi)	662 (96.0)	647 (93.9)	667 (96.7)	649 (94.1)	654 (94.9)
	Min, kPa (psi)	581 (84.2)	581 (84.3)	612 (88.7)	577 (83.7)	586 (85.0)
	Ave, kPa (psi)	629 (91.3)	616 (89.3)	642 (93.1)	615 (89.2)	629 (91.2)
Air Flow	Max, liter/min (SCFM)	NA	2914 (102.9)	3115 (110)	3098 (109.4)	3531 (124.7)
	Min, liter/min (SCFM)	NA	1320 (46.6)	1410 (49.8)	1328 (46.9)	1339 (47.3)
	Ave, liter/min (SCFM)	NA	2035 (71.9)	2055 (72.6)	2005 (70.8)	1964 (69.4)
Period	Ave, sec	9.1	15.3	12.2	12.3	17.5
Fill Time	Ave, sec	4.0	7.1	6.1	5.9	11.5
Discharge Time	Ave, sec	5.1	8.1	6.1	6.3	6.0
Mass Flow	Ave, kg/min (lb/min)	265 (583)	265.0 (583.8)	240.6 (530.1)	247 (544.2)	145 (319.5)
Volumetric Flow	Ave, liters /min (gpm)	266 (70.2)	245.9 (65.0)	203.9 (53.9)	210 (55.5)	139 (36.8)

Table 5.2 Troubleshooting Guide for Problems Encountered During Test Program

Problem / Symptom	Root Cause	Solution
• Liquid discharge from exhaust line at beginning of discharge stroke • Low flow rate	Missing O-ring in the exhaust valve as received from vendor	After O-ring was installed, unit functioned nominally
• Erratic mass flow, spikes • Specific gravity erratic, and decreases	Compressed air entering discharge line cause by excessively long discharge stroke	Decrease discharge time
• Pump will not cycle • No flow rate • High vacuum pressure in chamber	Inlet valve is blocked or stuck closed	Purge the chamber with air or water through inlet discharge line
• Progressively longer chamber fill times •Progressively lower flow rate	Icing of air exhaust valve	Replace or heat exhaust valve to prevent freezing Reduce discharge pressure
• Erratic mass flow, spikes • Specific gravity erratic, and decreases • Discharge line empties after pump is turned off	Discharge check-valve not closing properly.	Flush or repair discharge charge valve.

6.0 Conclusions and Recommendations

Based on this testing program, the PITBULL™ pump is a reliable, robust, and easy-to-operate pump that is well suited for the remote tank environment. The PITBULL™ has a unique set of advantages, including 1) the ability to discharge at a constant rate, regardless of pumping demand, 2) the ability to self-prime, 3) the ability to ingest air without losing prime, and 4) a moderate degree of debris tolerance.

Based on tests at a discharge head of 13.1 meters (43 ft) , the PITBULL™ can transfer water and light slurry with a specific gravity of 1 at 266 liters per minute. Heavier slurries, up to a specific gravity of 1.2, can be transferred at 204 liters per minute. Slurry with a specific gravity of 1.5 was encountered for brief periods during the program; and although steady state performance is unavailable for these tests, the pump operated without problems. These flow rates are somewhat less than the 378 liters per minute anticipated by CIPC.

At the conclusion of these baseline tests, fine sand, coarse sand, and gravel were successively added to the final batch of slurry to determine the affect of larger particles on pump performance. The size of the fine sand was 0.3-0.9 mm and is the most similar to un-reacted zeolite. The size of the coarse sand ranged from 1-2 mm, while the size of pea gravel ranged from 3-8 mm. The addition of fine sand did not effect the performance of the PITBULL™. The addition of coarse sand did not degrade average pump performance in terms of average mass flow or volumetric flow, when compared to the results the water/silica/kaolin tests. The presence of coarse sand did cause the discharge check-valve to take longer to close and to audibly chatter, which raised a concern for long-term reliability. The addition of pea gravel significantly degraded average pump performance in terms of average mass flow or volumetric flow. The presence of pea gravel caused the discharge check-valve to eventually stick open, which caused most of the pumped material to flow back into the chamber during the fill cycle. The pea gravel became wedged between the flapper and the valve body. The vendor was contacted and recommended an alternative seal material for the check-valve. The standard material is nitrile rubber (which was tested); aluminum sealing surfaces were recommended for pumping of slurries containing harder materials.

Several attempts were made to create blockages in the system that might occur by ingesting a large amount of solid materials or by a flow interruption in which solids are allowed to settle in the pump chamber and discharge line. Solids settling in the chamber prevented the inlet valve from opening. Solid accumulation in the discharge line was never a problem, although several blockages were created to test the flushing system. Flushing with water or compressed air through the air pressure line and discharge line was helpful in dispersing solids in the chamber and discharge line and to some extent clearing the check-valves.

The pump appears to be well suited for remote operation and can transfer slurry with a range of specific gravity and solid loadings without any adjustments. The unit has few moving parts, is easy to control, and operates entirely on compressed air. When problems did occur, the cause was usually easy to identify. The ability to monitor discharge flow rate, chamber pressure, and slurry specific gravity was very helpful in diagnosing problems that were encountered.

The following recommendations are given for improving the PITBULL™ system and preparing for deployment.

- It is recommended that the original stainless steel exhaust valve (model EXVS75) be replaced with a larger aluminum valve (EXV200) to reduce the likelihood of icing. Consider adding gaskets between the valve body and mating flanges.

- Improvements to the check-valve should be made to improve the ability to pump slurries containing hard solids.

- The discharge cycle is terminated by a timer, and not by a level sensor. In situations where the pump is operated for long periods without surveillance, it appears likely that the pump will inject air into the discharge line, which could result in water hammer effects. If this is undesirable, a low-level bubbler could be added to the pump for more reliability.

- The vendor recommends aluminum sealing surfaces, rather than nitrile used on the pump specified for SRS, for pumping of slurries containing harder materials.

- To reduce the solids accumulation in the pump chamber, consideration should be given to reducing the gap between the discharge pipe and the chamber bottom. The current gap is 6.35 cm. Alternatively, air nozzles could be incorporated into the chamber to suspend solids.

7.0 References

PITBULL™ Pump Installation and Instrumentation Manual, Chicago Industrial Pump Company

Enderlin, C.W., O.D. Mullen, and G. Terrones. 1997. *Performance Evaluation of the Quarter-Scale Russian Retrieval Equipment for the Removal of Hazardous Waste.* PNNL-11740, Pacific Northwest Laboratory, Richland, Washington.

Reynolds, B.A., E.A. Daymo, J.G.H. Geeting, and J. Zhang. 1996. *Instrument Validation Project*. PNNL-11221, Pacific Northwest Laboratory, Richland, Washington.

Vacuum Pumps, Manifolds, Cubs, and Accessories Catalogue, Vaccon Company, Inc. (http://www.vaccon.com).

APPENDIX A

Measuring and Test Equipment

Table A-1 Measuring Test Equipment

Measured Parameter	Range Units	Tag No.#	Sensor	Sensor Uncert.	Signal Conditioning	Sig. Cond. Uncert.	Data Acq. Uncert	Channel Uncert.	Notes
Supply Air Pressure	0~120 PSIG	PT1	Ametek 88F005A2CSSM Pressure Transmitter	±0.25%	N/A, in transmitter	N/A	±0.3%	±0.4%	Logged to data acq.
Supply Air Pressure	0~120 PSIG	PG1	4", 160 PSIG Bourdon tube Pressure Gage	±2%	None	N/A	N/A	±2%	Visual indication
Supply Air Flow	0~60 SCFM	FI1	Omega FL7990 Air Flow Indicator	±4%	None	N/A	N/A	±4%	Visual indication
Pump Drive Air Temp.	0~100°F	TT1	1/16", shrouded, ungrounded Type J T/C	±4°F	Data Acquisition	±2.2°F	0	±4.6°F	Logged to data acq.
Pump Drive Air Pressure	0~120 PSIG	PT2	Ametek 88F005A2CSSM Pressure Transmitter	±0.25%	None, in transmitter	N/A	±0.3%	±0.4%	Logged to data acq.
Pump Drive Air Flow	0~60 SCFM	PP1	Meriam Series 10A0007F Accutube	±0.3%	Rosemount 1151 DP 3EZZB2 AP transmitter	±0.1%	±0.3%	±0.3%	D.P. Log'd to data acq., flow calc'd. by data acq.
Pump Output Pressure	0~120 PSIG	PT2	Ametek 88F005A2CSSM Pressure Transmitter	±0.25%	N/A, in transmitter	N/A	±0.3%	±0.4%	Logged to data acq.
Pump Output Flow	0 ~+1000 Lb/min	MFS1/M FT1	MicroMotion CMF300 Coriolis Flow Sensor	±0.15%	MicroMotion RFT9739 Xmtr	Inclu. w/sensor	±0.3%	±0.4%	Logged to data acq.
Pumped Slurry Density	1.0~1.5 kg/l	MFS1/M FT1	MicroMotion CMF300 Coriolis Flow Sensor	±.001g/cc	MicroMotion RFT9739 Xmtr.	Inclu. w/sensor	±0.3%	±0.3%	Logged to data acq.
Pumped Slurry Temp.	0~100°F	TT1	1/16, shrouded, ungrounded Type J T/C	±0.4°F	Data Acquisition	±2.2%	0	±4.6%F	Logged to data acq.
Slurry Tank Weight	0~300 klbs.	LC1~3/S B1/WC1	BLH Z-Block Load Cells / BLH 306 J-Box	±0.25%	BLH LCp-100 Wt. Computer	±0.11	±0.3%	±0.4%	Logged to data acq.
Data Acq.			Strawberry Tree T-21 Term. Panel		S. T. ACPC-12-16 ISA Card		N/A	- - -	Voltage Signals
Data Acq. Timing					'486-66 PC	±0.04%	N/A	- - -	PC clock

APPENDIX B

Test Summary Log

Table B-1 Test Summary Log

Date	Procedure Parameters	Data File	Page LRB	Comments
12/19/97	Pump Check-out Depth of water: 35.6 cm Simulant: water	NA	1	Liquid discharge from exhaust line at beginning of discharge stroke, low flow rate (110 lpm) traced to missing O-ring in the exhaust valve. After O-ring was installed, unit functioned nominally.
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 275.8kPa (40 psi)	Test2	3	
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 310.3kPa (45 psi)	Test3	3	
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 344.7kPa (50 psi)	Test4	3	
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 379.2kPa (55 psi)	Test5	3	
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 413.7kPa (60 psi)	Test6	3	
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 448.2kPa (65 psi)	Test7	3	Discharge time too long, air in discharge line

Date	Procedure Parameters	Data File	Page LRB	Comments
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 448.2kPa (65 psi)	Test8	3	Retest, Discharge time reduced
12/22/97	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 482.6kPa (70 psi)	Test9	3	
12/22/97	Pump Check-out - Draw-down Depth of water: 35.6 cm Simulant: water Panel pressure setting: 379.2kPa (55 psi)	Test10	3	Final liquid depth = 2.5 cm
1/2/98	Vacuum Generator Test #Vacuum Flow vs number turns	Vac2	6	DP sensor saturated. Higher range sensor installed.
1/2/98	Vacuum Generator Test To check out pressure sensor	Vac3	6	
1/2/98	Vacuum Generator Test Vacuum flow vs number of turns, line pressure Air consumption vs number of turns, line pressure	Vac4	7	Test to optimize the vacuum generator operating parameters
1/6/98	Pump Check-out - Recycle Depth of water: 35.6 cm Simulant: water Panel pressure setting: 379.2kPa (55 psi) Flow rate vs number of turns on the vacuum generator	Test11	11	Air consumption is unavailable. DP sensor was saturated.

Date	Procedure Parameters	Data File	Page LRB	Comments
1/6/98	Pump Check-out - Draw-down Depth of water: 57.2 cm Simulant: water Panel pressure setting: 379.2kPa (55 psi) Flow rate vs number of turns on the vacuum generator	Test12	11	Air consumption is unavailable. DP sensor was saturated. Final depth 1.6 cm
1/7/98	Pump Recycle Test, SG = 1.04 Depth of water: 50.8 cm Simulant: water/silica SG=1.04 Panel pressure setting: 379.2kPa (55 psi) Flow rate vs number of turns on the vacuum generator	Test13	12	Test conducted to measure the air consumption of the vacuum generator and the slurry flow rate versus line pressure. Calibration factor for this test need to be adjusted
1/7/98	Vacuum Generator Test Air consumption vs line pressure	Test14	12	Test to validate prior data
1/8/98	Pump Recycle Test, SG = 1.06 Depth of water: 50.8 cm Simulant: water/silica SG=1.06 Supply pressure 565.4-627.4 kPa (82-91 psi) wide open	Test15	13	Measuring air flow and pressure to the vacuum generator during pumping
1/8/98	Pump Recycle Test, SG = 1.06 Depth of water: 50.8 cm Simulant: water/silica SG=1.06 Supply pressure 413.7-517.1 kPa (60-75 psi)	Test16	13	Measuring air flow and pressure to the vacuum generator during pumping
1/8/98	Pump Recycle Test, SG = 1.08 Depth of water: 50.8 cm Simulant: water/silica SG=1.08 Panel pressure setting: 379.2kPa (55 psi)	Test17	13	One turn on diffuser, data for SG = 1.1. SG sample taken.
1/8/98	Pump Draw-down Test, SG = 1.08 Depth of water: 50.8 cm Simulant: water/silica SG=1.08 Panel pressure setting: 379.2kPa (55 psi)	Test18	14	One turn on diffuser, data for SG = 1.1, final liquid level 2.5 cm.

Date	Procedure Parameters	Data File	Page LRB	Comments
1/13/98	Pump Recycle Test, SG = 1.19 Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.19 Panel pressure setting: 379.2kPa (55 psi)	Test20	16	One turn on diffuser. Pump takes progressively longer to fill - prelude to valve freezing problems.
1/13/98	Pump Recycle Test, SG = 1.18 Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.18 Panel pressure setting: 379.2kPa (55 psi)	Test21	17	One turn on diffuser. Pump takes progressively longer to fill - prelude to valve freezing problems. Discharge pressure transducer was plugged and cleaned. SG sample taken.
1/13/98	Pump Draw-down Test, SG = 1.18 Depth of water 55.9 cm Simulant: water/silica/kaolin SG=1.18 Panel pressure setting: 379.2kPa (55 psi)	Test22	18	0.75 turns on diffuser, test terminated due to long fill time, slow pumping.
1/13/98	Pump Draw-down Test, SG = 1.18 Depth of water 55.9 cm Simulant: water/silica/kaolin SG=1.18 Panel pressure setting: 379.2kPa (55 psi)	Test23	18	Pumping using manual exhaust valve to isolate problems with freezing of exhaust valve
1/15/98	Condensate separator installed on the exhaust line. Pump removed from tank and inspected.			5 cm of sludge remained in the pump
1/15/98	System leak test. Chamber was filled with compressed air and checked for leaks.			T=0 p=193 kPa (28 psi) T=5 min p=141 kPa (20.5 psi) Adequate seal
1/15/98	Pump Recycle Test, SG = 1.08 (unmixed) Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.08 Panel pressure setting: 379.2kPa (55 psi)	Test24	19	Test to determine if the exhaust valve will freeze again. It did. During test, vacuum generator setting reduce to 0.75 turns. Valve freezing still a problem.
1/15/98	Pump Recycle Test, SG = 1.16 Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.16 Panel pressure setting: 379.2kPa (55 psi)	Test25	21	Test to determine if the exhaust valve will freeze again. It did. Valve freezing still a problem.

Date	Procedure Parameters	Data File	Page LRB	Comments
1/16/98	Pump Recycle Test, SG = 1.18 Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.18 Panel pressure setting: 358.5kPa (52 psi)	Test26		Test run with S.G. ~1.18. Discharge pressure reduced, heat gun heating to prevent discharge valve freeze-up. Later in test, discharge pressure increased to 379.2kPa (55 psi), 1 turn on diffuser. This is recycle data for SG=1.18
1/16/98	Pump Draw-down Test, SG = 1.18 Depth of water: 55.9 cm Simulant: water/silica/kaolin SG=1.18 Panel pressure setting: 379.2kPa (55 psi)	Test27		Test run with S.G. ~1.18. Heat gun heating to prevent discharge valve freeze-up. This is draw-down data for SG=1.18. 1.9 cm (.75 inch) slurry final depth. Heal is 4.5 cm (1.75 inch) at perimeter of tank due to settling.
1/16/98	Pump was used without tie-down straps to check for tipping tendency			Pump had no tendency to tip over
1/16/98	Pump stopped on full chamber for 41 minutes			Pump did not restart. Chamber pressure -48.3 kPa (-7 psi). Air sparaging cleared the inlet valve immediately.
1/20/98	Pump Recycle Test, SG = 1.19 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine sand SG=1.19 Panel pressure setting: 379.2kPa (55 psi)	Part1	23	35 liters fine sand added to the slurry.
1/20/98	Pump Recycle/Draw-down Test, SG = 1.5-1.14 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine sand Panel pressure setting: 379.2kPa (55 psi) Include draw-down	Part2	23	Sludge allowed to settle for over 1 one, 1 hr 7 minutes. Pump restarted without assistance after vacuum pressure in chamber was 45.5kPa (-6.6 psi). Include recycle and draw-down. Final liquid level. 1.9 cm (.75 inch) slurry final depth. Heal is 2.5 cm (1.0 inch) at perimeter of tank due to settling.
1/20/98	Pump Recycle Test, SG = 1.18 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine/sand/ coarse sand Panel pressure setting: 379.2kPa (55 psi)	Part3	25	At beginning of test, tank contents fully mixed. Pump stopped and 35 liters of coarse sand added to the pump inlet. Pump then started. Outlet check-valve chatter started.

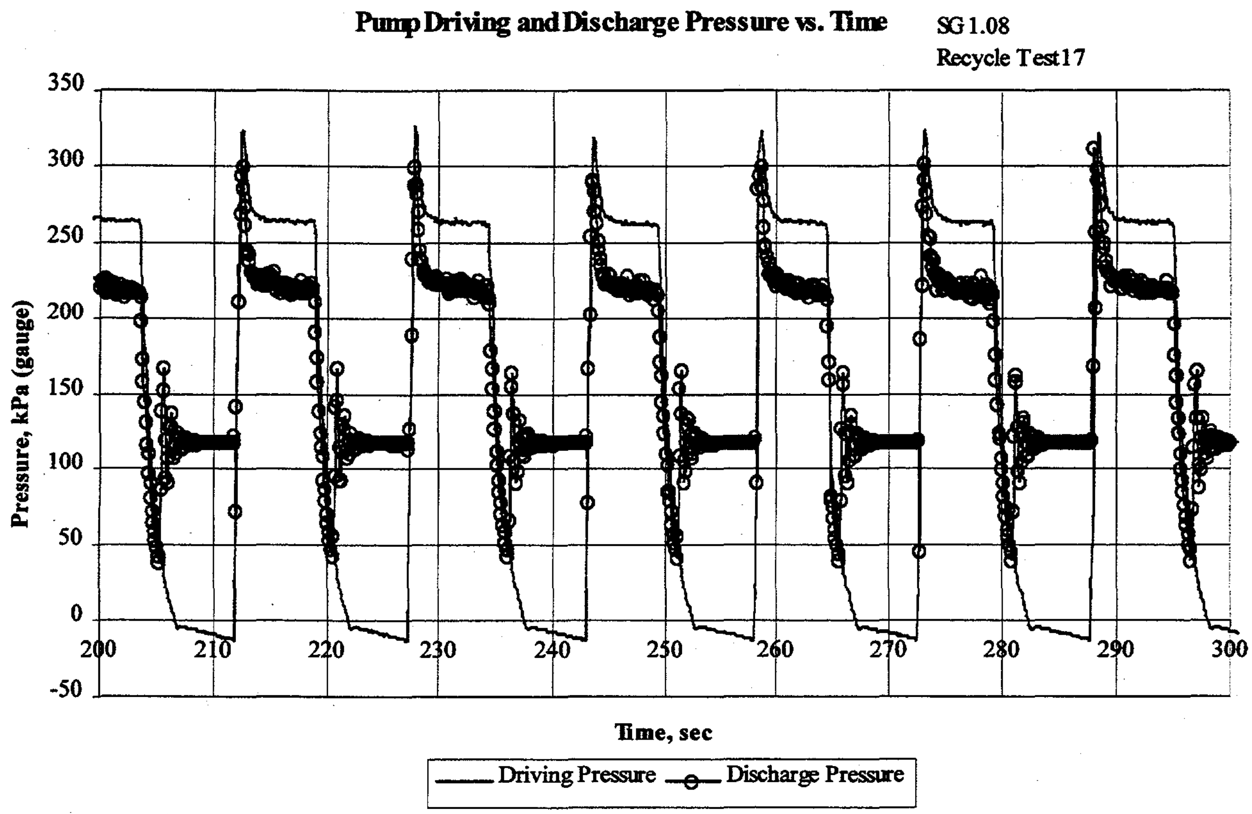
Date	Procedure Parameters	Data File	Page LRB	Comments
1/20/98	Pump Draw-down Test, SG = 1.18 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine sand/coarse sand Panel pressure setting: 379.2kPa (55 psi)	Part4	25	At the conclusion of draw-down, hose nozzle was used to push solids into the inlet. Worked fairly well. Shovel was used to push solids to the inlet as well. At the end of test, chamber became filled with solids and inlet check-valve stopped working on the discharge stroke. Sludge was seen squirting our of the inlet.
1/20/98	Pump Draw-down Test, SG = 1.25-1.14 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine-coarse sand Panel pressure setting: 379.2kPa (55 psi)	Part5	25	Test to determine if chamber can be flushed without refilling the tank. Chattering of check-valve apparent on almost every stroke. Stopped pump for 30 minutes to allow settling and restarted with no problem.
				New aluminum exhaust valve received and installed. Valve had to be modified to include gaskets between matting surfaces on valve body to eliminate leaks.
1/21/98	Pump Recycle Test, SG = 1.3 Depth of water: 55.9 cm Simulant: water/silica/kaolin/fine-coarse sand Panel pressure setting: 379.2kPa (55 psi)	Part6	28	Tank and chamber contents have settled overnight. Pump started up properly with no plugging.
1/22/98	Pump Endurance Test, SG 1.7-1.1 Depth of water: 67.3 cm Simulant: water/silica/kaolin/fine-coarse sand Panel pressure setting: 379.2kPa (55 psi)	Endur1a, Endur1b	28	4 hour, 20 minute endurance test. Started-up on settled tank. Initially, pump did not function. After drawing vacuum for 6 seconds and -41 kPa vacuum reached, pump restarted. Discharge check-valve chattered initially, then subsided after 40 minutes. No freezing occured. Had to tighten hose fittings periodically. Check-valve tends to loosen the fittings. Condensate from exhaust line flow rate measured to be 2.5 lpm.
1/22/98	De-plugging tests	Flush1	29	11 liters of coarse sand was poured into the vertical leg of discharge line. 7.5 liters coarse of sand was distributed into the pump chamber. Started pump. After a few strokes, plugs were cleared. Check-valve is chattering quite a bit. The pump was flushed with water through the discharge line and air pressure line. Both worked fine and cleared the chamber and check-valve.

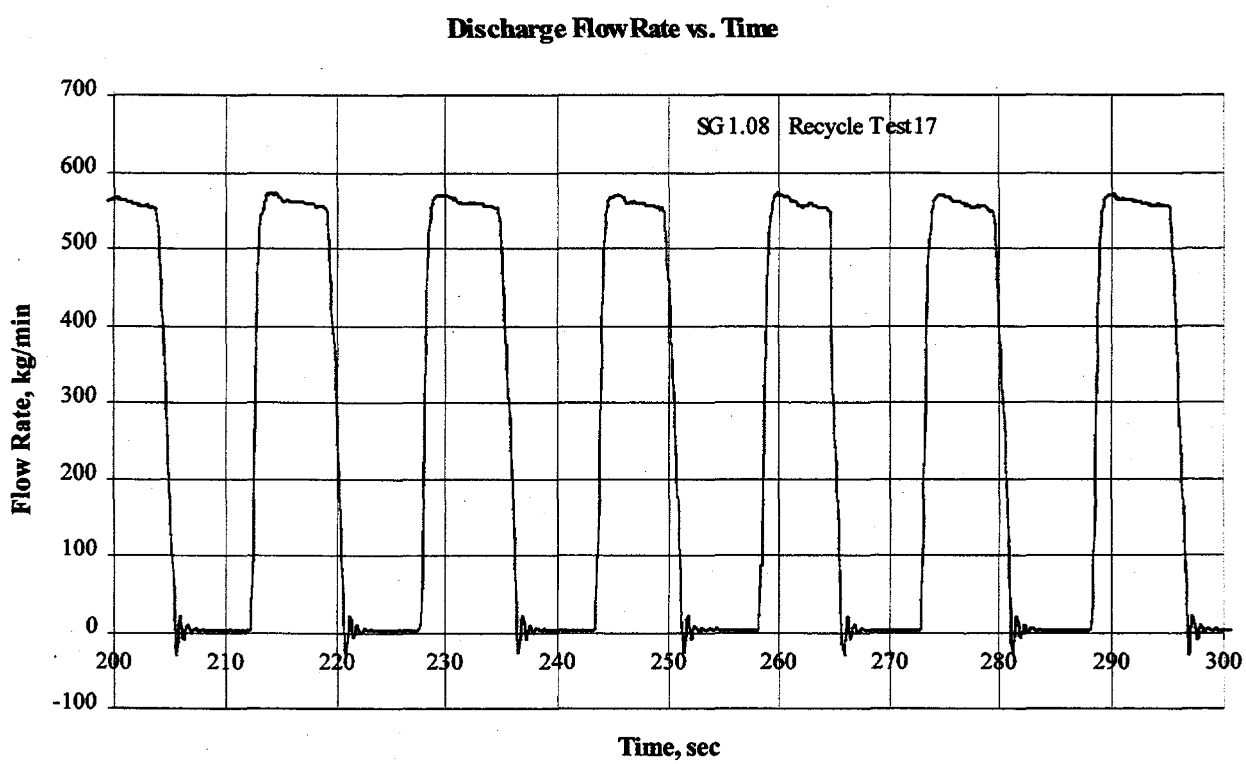
Date	Procedure Parameters	Data File	Page LRB	Comments
1/22/98	Pump Draw-down Test, SG = 1.12 Simulant: water/silica/kaolin/fine-coarse sand/pea gravel Panel pressure setting: 379.2kPa (55 psi)	Sluice1	25	Draw down on at settle tank. At 14:36:38, 35 liters of pea gravel was added to the both sides of the inlet. Very erratic flow. Back flow seen at the sight tube, indicating exhaust check-valve not fully functional. Attempted to flush chamber through the air pressure line, during which water flowed out of the inlet. After draw-down, sluicing nozzle used to push material into the inlet. Insufficient water pressure to penetrate compacted sludge. On shut down of pump, water flowed back from the discharge line, indicating it is stuck open. Pump restarted, average flow rate very low. High excursions, indicating air ingestion. Flushed water through the discharge line. Water initially flowed slowly, then flow increased. Started pump again, low flow rate still. Check-valve disassembled and examined. Valve cleaned to remove sand and gravel, lubricated, and put into service. Pump was restarted. Discharge flow is high, but there is still quite a bit of back flow.
1/22/98	Pump Recycle Test, SG = 1.06 Simulant: water/silica/kaolin/fine sand/coarse sand/pea gravel Panel pressure setting: 379.2kPa (55 psi)	Test28	32	Discharge check-valve chatter still. Good average flow rate, no air ingestion.
1/30/98	Pump Endurance Test, SG 1.2 Depth of water: 10 cm Simulant: water/silica/kaolin/fine sand/coarse sand/pea gravel Panel pressure setting: 379.2kPa (55 psi)	Endur2	32	Endurance test at low liquid level. Slurry pumped down to 10 cm level, then recycled. 2 minutes into the test, pumping rate was low, air apparent in discharge line. Pea gravel removed from check-valve and test resumed. After 6 minutes, check-valve malfunctioned again.
2/12/98	Post test pump inspection			1.5 liters of sludge and pea gravel removed from the pump chamber. Most of the material was pea gravel. Pea gravel found in check-valve.

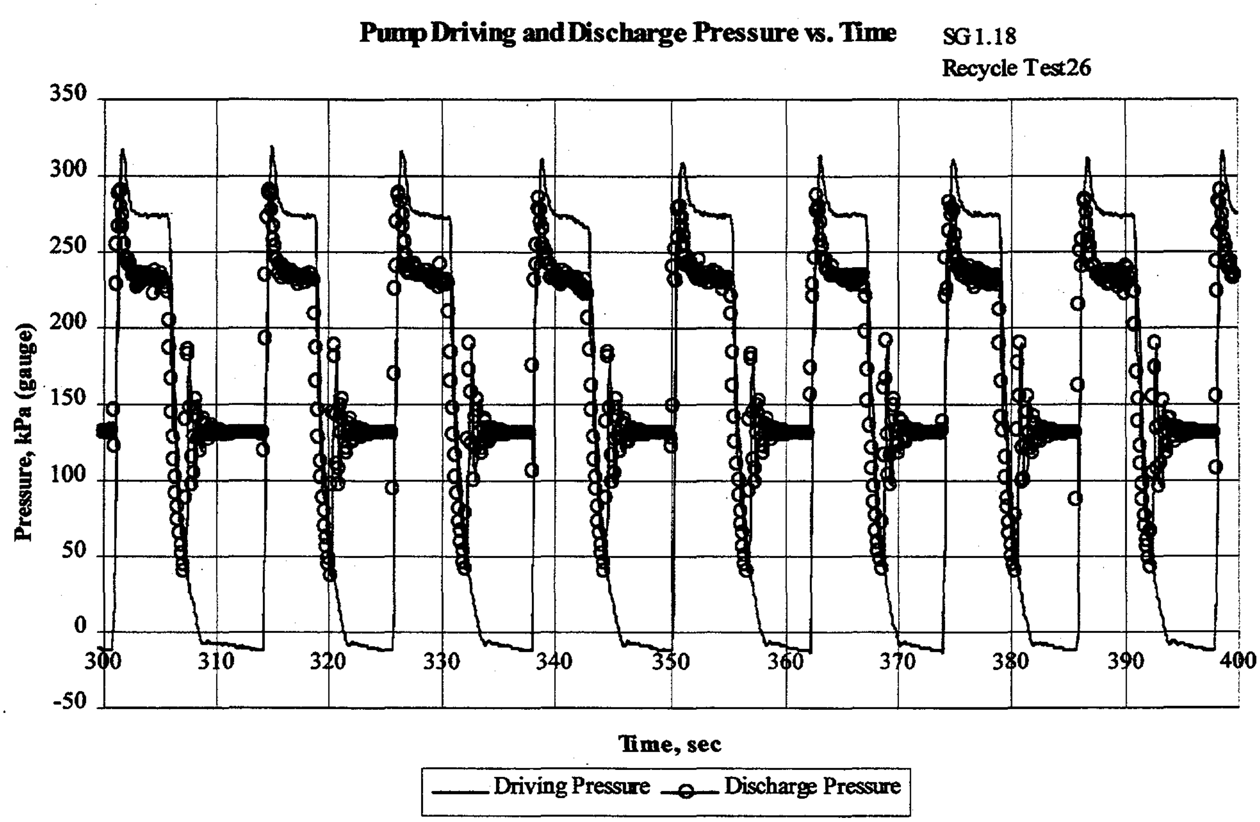
APPENDIX C

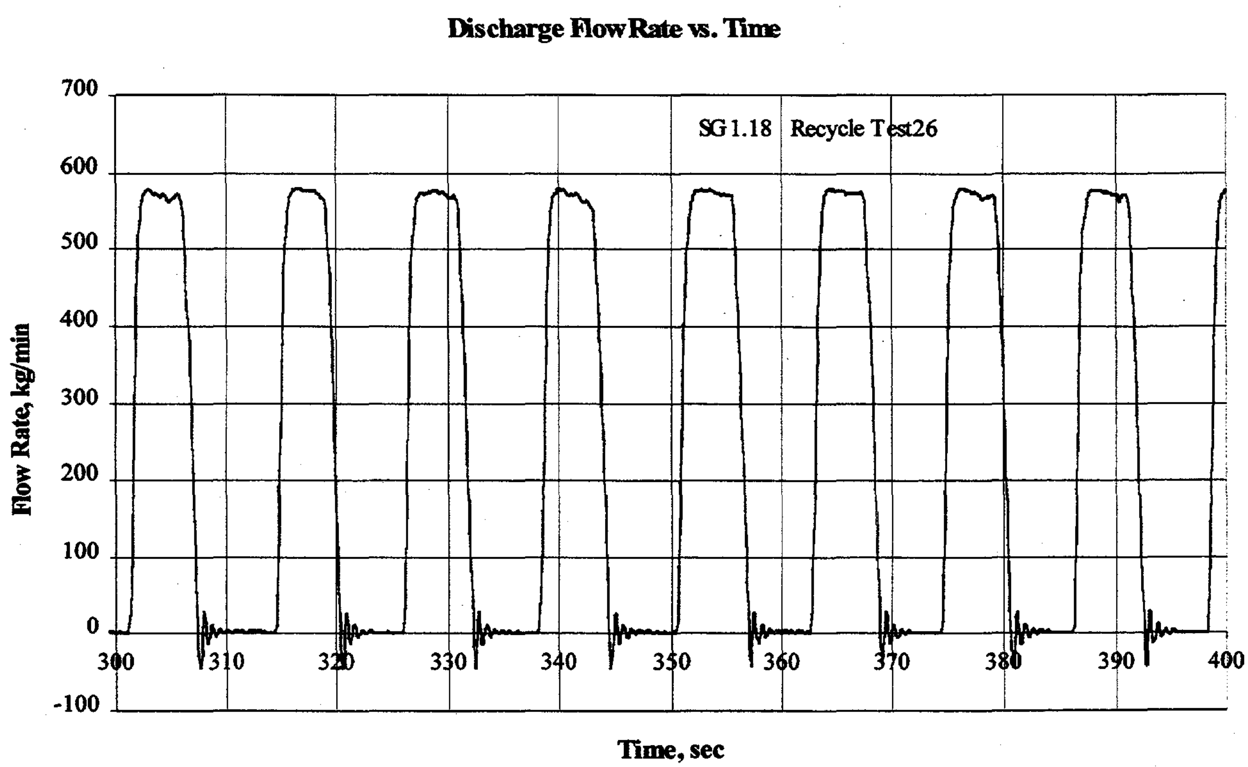
Pump Performance Data Plots

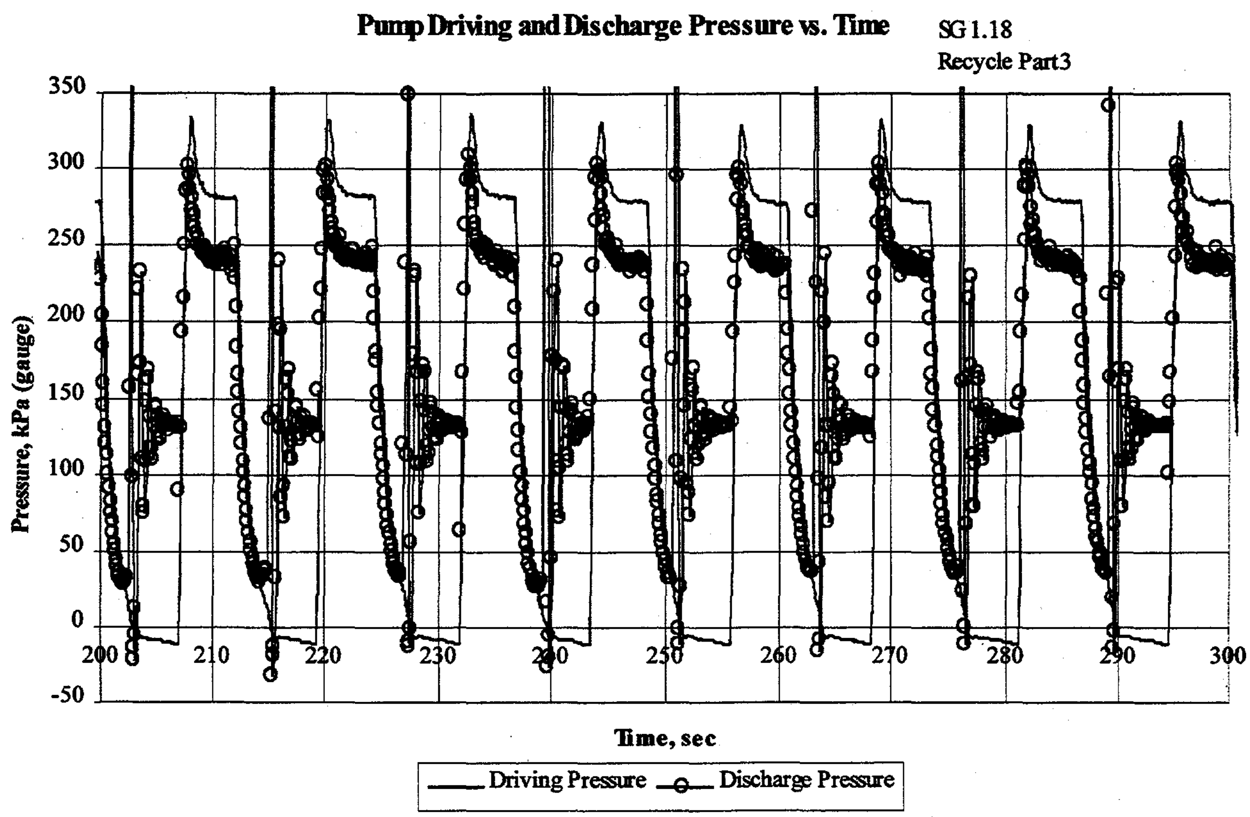
Test17	**Water, Silica**
Test26	**Water, Silica, and Kaolin**
Part3	**Water, Silica, Kaolin, Fine and Coarse Sand**
Sluice1	**Water, Silica, Kaolin, Fine and Coarse Sand, and Pea Gravel**

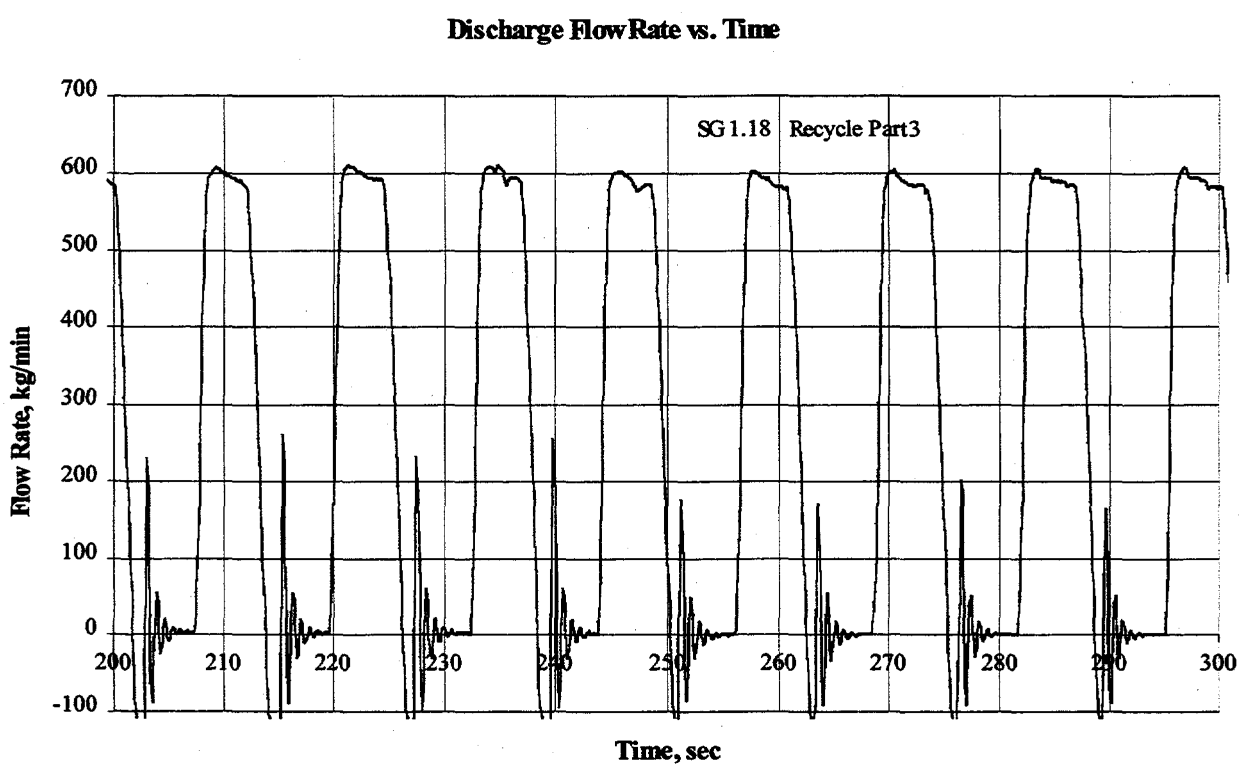

Pump Driving and Discharge Pressure vs. Time
SG 1.08
Recycle Test 17
Pressure, kPa (gauge)
350
300
250
200
150
100
50
0
-50
200
210
220
230
240
250
260
270
280
290
300
Time, sec
Driving Pressure
Discharge Pressure

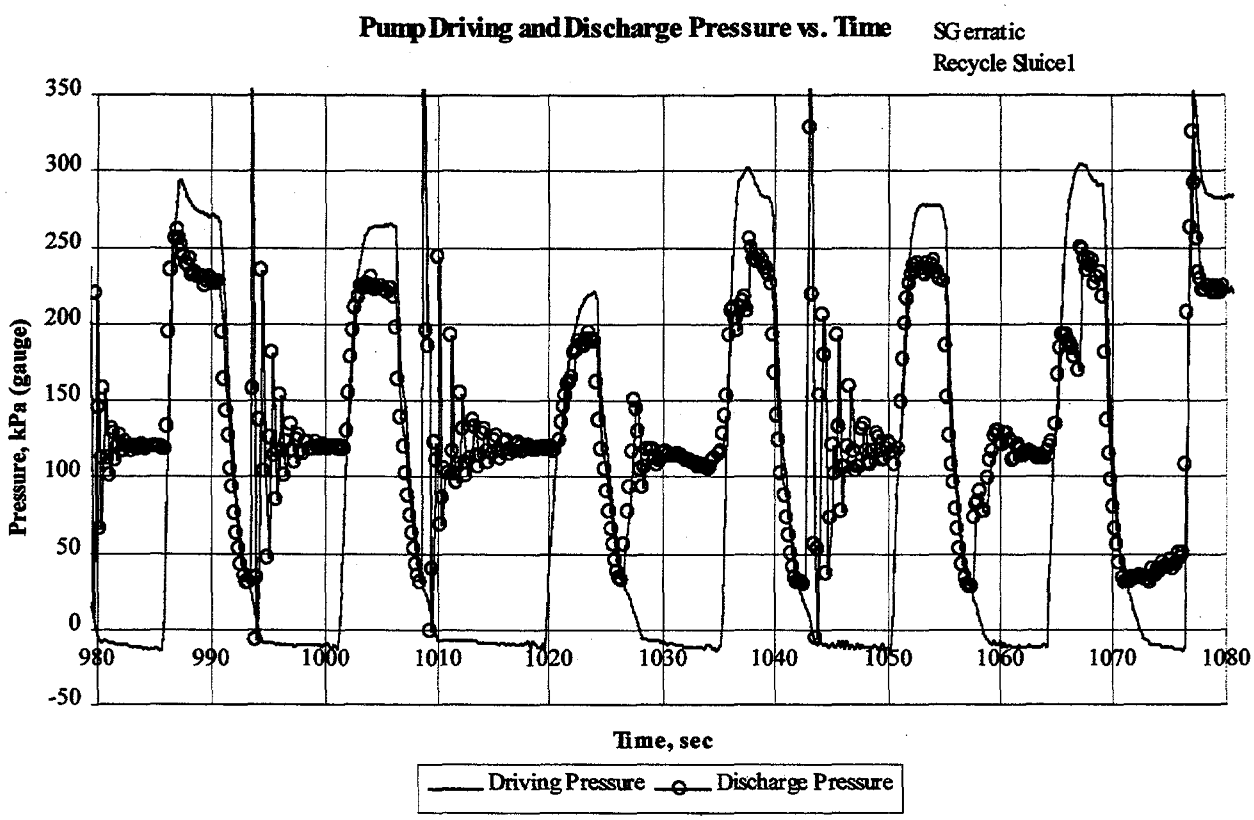

Discharge Flow Rate vs. Time
SG 1.08
Recycle Test 17
Flow Rate, kg/min
700
600
500
400
300
200
100
0
-100
200
210
220
230
240
250
260
270
280
290
300
Time, sec

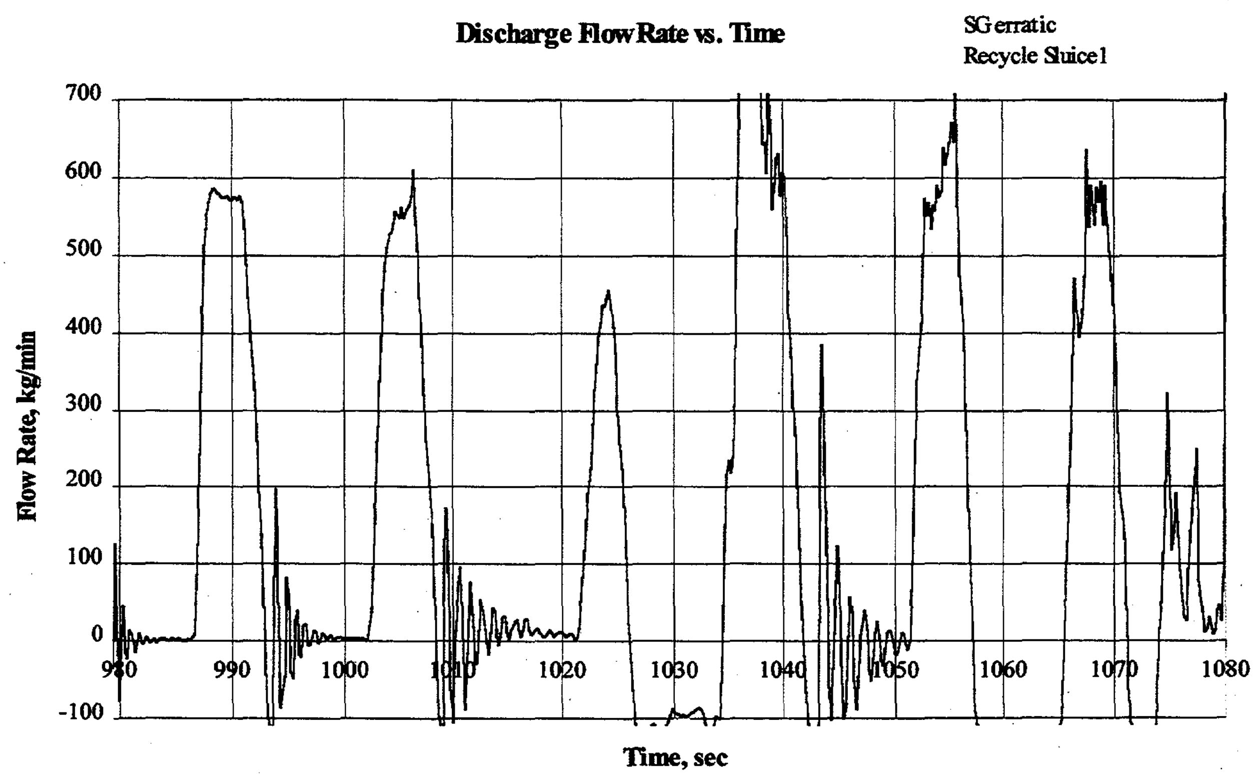

Pump Driving and Discharge Pressure vs. Time
SG 1.18
Recycle Test26
Pressure, kPa (gauge)
350
300
250
200
150
100
50
0
-50
300
310
320
330
340
350
360
370
380
390
400
Time, sec
Driving Pressure
Discharge Pressure


Discharge Flow Rate vs. Time
SG 1.18
Recycle Test26
Flow Rate, kg/min
700
600
500
400
300
200
100
0
-100
300
310
320
330
340
350
360
370
380
390
400
Time, sec


Pump Driving and Discharge Pressure vs. Time
SG 1.18
Recycle Part3
Pressure, kPa (gauge)
350
300
250
200
150
100
50
0
-50
200
210
220
230
240
250
260
270
280
290
300
Time, sec
Driving Pressure
Discharge Pressure


Discharge Flow Rate vs. Time
SG 1.18
Recycle Part3
Flow Rate, kg/min
700
600
500
400
300
200
100
0
-100
200
210
220
230
240
250
260
270
280
290
300
Time, sec


Pump Driving and Discharge Pressure vs. Time
SG erratic
Recycle Sluice1
Pressure, kPa (gauge)
350
300
250
200
150
100
50
0
-50
980
990
1000
1010
1020
1030
1040
1050
1060
1070
1080
Time, sec
Driving Pressure
Discharge Pressure


Discharge Flow Rate vs. Time
SG erratic
Recycle Sluice1
Flow Rate, kg/min
700
600
500
400
300
200
100
0
-100
980
990
1000
1010
1020
1030
1040
1050
1060
1070
1080
Time, sec

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