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**FINAL REPORT:
LONG TERM TEST OF A GEAR-TYPE PUMP
FOR THE AM/CM PROJECT (U)**

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EXECUTIVE SUMMARY

At the request of the Immobilization Technology section, the Experimental Thermal Fluids group carried out a test to determine the operational characteristics of a gear-type pump. This pump was under consideration as a replacement for the air-lift melter feed pumping system of the Americium and Curium Project.

As part of an overall project to stabilize an existing radioactive solution which contains valuable substances of Americium and Curium, a melter system is being developed specifically to vitrify this material. Of the many processes in this system, one is the feeding of the solution from a melter feed tank to the melter proper. The overall system is being tested at TNX, but several parts are also being developed, and tested, at other locations; one being the Experimental Thermal Fluids laboratory.

The melter feed system was originally developed by the Experimental Thermal Fluids group on the request of the Design Authority in 1995. Since that request, the melter system has evolved, resulting in many design changes. Those changes had many impacts on existing equipment, like the melter feed system.

The major impact on the melter feed system, as the result of overall process changes, was the need to reduce the melter feed from 8 liters/hour to under 3 liters/hour. Because the entire stabilization process will operate in a radioactive environment, the original system was required to have no moving parts. An air-lift system was proposed, designed, and successfully tested. That system used air to lift the Americium/Curium solution to a constant head tank, which then fed solution to the melter by gravity. The solution flow rate into the melter was controlled with a properly sized orifice. After testing the air-lift melter feed system, it was delivered to TNX for incorporation into the overall melter system. However, as stated, further developments in the melter design required lower feed rates. Using lower feed rates with that initial feed system caused it to operate marginally, so modifications were necessary. Modifications were made to the air-lift system and the lower flow rates (i.e., 2 to 3 liters/hour) were attainable. Unfortunately, when starting the flow at or below 2.5 liters/hour, it was sometimes difficult to initiate flow because of the very small orifice needed to control the flow, i.e., 0.021 inch.

Because of the starting difficulties with the air-lift system at low flows, the Experimental Thermal Fluids group suggested a positive displacement pump as a more robust replacement. This pump would give better service at the low flow rates. While this type of pump does have moving parts, one was found with the proper materials that could withstand the expected radiation environment for the projected short life of the stabilization process, i.e., 4 to 6 months. However, to make sure that this pump would mechanically operate without failure for the entire campaign, e.g., gear damage, a long-term test was devised. The projected amount of liquid to be transferred was 1180 liters, with a density of 1.224 g/ml and 2.8 M in HNO_3 . The test would transfer the same amount of liquid, except a non-radioactive surrogate would be used that would have similar properties to the Americium/Curium feed, i.e., density, heavy elements. The test was run from January 20 to March 3, 1998.

The test results confirmed that the gear-type pump tested will operate satisfactorily for the entire Americium/Curium campaign. They are as follows:

- After pumping 1241 liters of surrogate Americium/Curium liquid at 50°C the pump gears experienced a 10% reduction in gear tooth volume and no damage. Any change in pump performance due to the wear was insignificant.
- Using an expected pumping cycle of two hours on, and one hour off, the pump cycling ran smoothly for 728 hours.
- The flow rate of this positive displacement gear pump was affected by changes in the pressure across the pump. That effect is approximately: ± 0.13 liters /hour per 30 inches of H₂O at 2.6 liters/hour.
- Vendor-supplied pump performance data differed significantly from actual pump performance. However, the pump will still provide the needed flow to the melter.
- Any reassembly of the pump will need a subsequent performance check to ensure it operates to expectations.

Based on the results, the following recommendations are made:

- This pump will last the entire Am/Cm campaign of transferring 1180 liters. It should be considered for a replacement to the air-lift system.
- This pump can be procured with all radiation hard materials.
- After a disassembly of the pump, all parts need a thorough cleaning before reassembly.

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NOMENCLATURE

This nomenclature only elaborates on the information in the main body of this report. The symbols used in Appendix D: Measurement Uncertainty Analysis are explained in that appendix.

Am	- Americium
Cm	- Curium
EDS	- Engineering Development Section
EES	- Engineered Equipment & Systems Department
ETF	- Experimental Thermal Fluids (group or laboratory)
ITS	- Immobilization Technology Section
Micropump	- Vendor of the pump being tested (Vancouver, Washington)
P	- Pressure
Q	- Volumetric Flow Rate
SRTC	- Savannah River Technology Center
SRS	- Savannah River Site
TNX	- Multipurpose Pilot Plant Facility Campus
WSRC	- Westinghouse Savannah River Company

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1.0 INTRODUCTION

As part of an overall project to stabilize an existing radioactive solution which contains valuable substances of Americium (Am) and Curium (Cm), a melter system is being developed to vitrify this solution. Of the many processes in this system, one transports the feed solution from a melter feed tank to the melter proper. This melter system is being designed specifically to process the Am/Cm solution and is being tested prior to deployment for radioactive operation. The overall system is being tested at TNX but the several parts are being developed and tested in several other locations; one being the Experimental Thermal Fluids (ETF) laboratory.

The melter feed system was originally developed by the ETF group [Refs. R1, R2, and R3] on the request of the Design Authority in 1995. Since that request, the melter system has evolved from a batch operation, to a continuous operation, and back to a batch operation again. That is, the original design requirements for the melter feed system have changed significantly which resulted in many design changes.

Changes to the melter system have caused the flow rate of the melter feed system to be reduced from 8 liters/hour to under 3 liters/hour, Ref. R4. Because the entire stabilization process will operate in a radioactive environment, the original system was required to have no moving parts. An air-lift system was proposed, designed, and successfully tested. This system used air to lift the Am/Cm solution to a constant head tank, which then fed solution to the melter by gravity, while the flow rate was controlled with a properly sized orifice. After testing, the feed system was delivered to TNX for incorporation in the overall melter system. However, further developments in the melter design required lower feed rates. Using lower feed rates with the delivered feed system caused it to operate marginally and further modifications were necessary. Several modifications were made, and a new test was carried out, Ref. R5. The lower flow (i.e., 2 to 3 liters/hour) was attainable, but starting the flow below approximately 2.5 liters/hour was sometimes difficult because of the very small orifice needed to control the flow, i.e., 0.021 inch.

Because of the starting difficulties with the air-lift system at low flows, the ETF group suggested a positive displacement pump as a more robust replacement. This pump would give better service at the low flow rates. While this type of pump does have moving parts, one was found with the proper materials that could withstand the expected radiation environment for the projected short life of the stabilization process, i.e., 4 to 6 months. However, to make sure that this pump would operate without failure for the entire campaign, e.g., gear damage, a long-term test was devised. The projected amount of liquid to be transferred was 1180 liters with a density of 1.224 g/ml and 2.8 M in HNO₃, Ref. R4. Therefore, the test would transfer the same amount of a surrogate mixture that had similar properties to the Am/Cm feed, i.e., density, heavy elements. The test was run from 1/20/98 to 3/2/98.

The question to be answered is:

How will the pump perform during the transfer of 1180 liters of Am/Cm solution?

2.0 EXPERIMENTAL SETUP

A general description of the test setup will be given and reference will be made to the figures in Appendix A.

2.1 Overall Test Apparatus

The purpose of this test was to run the chosen pump a sufficient amount of time to transfer at least 1180 liters of surrogate feed. Figure A1 shows the pump along with the supporting circulation system. The main features are the pump, flowmeter, mixer and tank, condenser and controlling valves. Each will be described separately.

2.2 Pump

There were several pumps that could carry out the task of transferring the feed solution but a positive displacement magnetic drive gear pump was chosen because of good experience in the past. A piston-type pump was initially considered. However, it was rejected because the lubrication needs of the piston create a leak path for the working fluid. The actual feed solution is not only radioactive, but it has many dissolved solids which can crystallized when exposed to air. This would eventually cause problems in the piston movement, not to mention the contamination caused by leakage.

Two magnetically driven gear pumps were procured from Micropump with a flow rate range to 3.6 liters/hour. (The specific pumps are, Model: 187-000-010, Serial Nos: 817727 and 814923. The former was tested and the latter was the control, to compare gear wear.) The best feature of this type pump is that it is driven magnetically from outside the fluid boundary. Both Fig. A2 and A3 show details of the pump. What is not shown is the driving magnet, which attaches to an appropriate drive motor. Once the magnet cup is sealed against the pump body the pump is ready to operate. The drive magnet, which is attached to a drive motor, is then placed on the outside of the magnet cup. The pump body is held to the drive motor by the drive housing. As the motor turns the drive magnet, the magnetic field drives the driven magnet which is housed within the magnet cup. Since there is no mechanical connection between the drive motor and the pump there is no bearing leak problem.

The pump itself is made of several parts which can be seen from Figs. A2, A3, and A4. The two parts to be investigated were the drive and driven gears. The drive gear is the central gear which is engaged to the driven magnet. That gear then drives the driven gear. Both gears are held in place by the suction shoe, under which they sit. Materials of the pump varied from 316 stainless steel for the body, shafts, and magnet housing; graphite for the gears and bushing; and polytetrafluoroethylene for the seals. Of course, for a pump to be used in a radiation field the PTFE material will have to be changed out for another. Micropump offers a material by Victrex called PEEK which holds up very well in radiation fields and will not be significantly affected by the solution's 9.54 Ci/liter (Ref. R4) during the 4 to 6 month period of the Am/Cm campaign. In fact, PEEK can withstand five orders of magnitude of gamma radiation better than PTFE before damage begins.

2.3 Piping and Valves

During operation, the system was closed loop, however, there was a vent to the atmosphere to prevent an pressure buildup in the event of an accident. The vent was the

vertical pipe which passed through the condenser shown in Fig. A1. During sampling, to measure flow rates, the system was opened which slightly changed the pressure drop across the pump due to the static head of the liquid. The length of piping and its several bends corresponded to the existing Am/Cm liquid feed system piping when this test began. Thus, the test setup had the same frictional resistance to flow that would be encountered in the actual system. All of the piping and valves were made of stainless steel.

The valves shown in Fig. A1 had the following functions:

Valve Function

V1	To isolate the mixing tank from the pump (to shut off flow).
V2	To isolate the upstream flow line from the pump (to remove pump).
V3	To isolate the downstream flow line from the pump (to remove pump).
V4	To vent the lines so the line could be evacuated of liquid.
V5	To isolate the return line from the mixing tank (so that sampling could be done).
V6	To take samples to measure the flow rate (V5 is closed when V6 is open).
V7	To allow water to flow through condenser.
V8	To allow water to rinse the mixing tank after line was connected to V9 fitting.
V9	To fill the mixing tank and replace samples taken, using valve V6.

2.4 Mixing Tank and Agitator

The mixing tank shown in Fig. A1, was approximately one foot in diameter and when it was approximately half filled after introducing the 34 liters of Am/Cm surrogate feed solution. The tank and fittings were made of stainless steel, except the cover, which was Plexiglas, to allow visual inspection of the liquid. An agitator was used to keep the liquid mixed and to help maintain the temperature constant. The agitator shaft penetrated the Plexiglas top and was sealed with a stainless steel bearing.

2.5 Heaters

Around the bottom outside perimeter of the mixing tank were eight surface heater, each capable of producing 200 watts of power. These were used to maintain the feed solution at 50°C. The feed temperature will be administratively controlled for the Am/Cm process. While the liquid itself is radioactive, the expected 25.4 watts/gallon of heat generation will have an insignificant effect on the liquid temperature with respect to the environmental conditions at the pump. Since the pump will reside in a controlled environment, it was important to have it at that temperature. Before testing began, a test was done to determine how the laboratory environment would affect the liquid temperature in the pump. Since the ambient temperature in the ETF laboratory fluctuated between 20°C and 25°C, the pump would experience a lower temperature than the Am/Cm environment. In fact, an 8°C drop was found to exist between the heated mixing tank and the pump. Therefore, another surface heater was placed on the pump housing. Throughout the test the liquid and pump temperatures were maintained at approximately 50°C. See the last two columns in Table B1 of Appendix B.

2.6 Feed Solution

The test solution was made to be similar in most aspects to the Am/Cm solution, except for the radioactive compounds. The density was measured to be 1.23 g/cc, had 2.8 M of HNO₃, and was made to have 100 g/liter in oxides. Further, in the pretreatment of the

Am/Cm solution, all insoluble solids are expected to be removed. The test solution did not have any insoluble solids. If more detail on either solution is needed, it can be found in Refs. R4, R6, and R7. Approximately, 34 liters of solution was received for the test and all of it was used.

2.7 Measurement Instruments

The important instruments used during the operation of this test measured the fluid temperature and flow rate. There were two thermocouples in the mixing tank to monitor and control the liquid temperature. However, only one was recorded, while the other served as a backup. There was one thermocouple on the inside of the pump housing to control the pump heater so that the fluid within the pump was close to 50°C. The flowmeter was a ball-in-tube rotameter. The initial main-purpose for the rotameter was to insure that the liquid was circulating. Since there were no pressure meters in the system, there needed to be a way to confirm fluid movement. That is, a blockage in a line would not prevent the pump from operating, so there would be no way to determine fluid movement without a flowmeter. As it turned out, during sampling the change in the pressure in the system due to a static head of liquid caused an effect on the flow rate. The rotameter was useful to pick up this difference and ultimately to correct the flow rates. This will be explained in detail in the results section. The specifics of each instrument is given in the next section.

3.0 INSTRUMENTATION

The output of the thermocouples (TC) was microvolts. However, all measurements were only recorded manually and logged in the task notebook.

Measurement	Location	Make	Model	Serial	Range	Tolerance	TR-	Notes
Temperature	Tank	Omega	EQSS-116G-12	NA	0-100°C	±1.7°C	3041	TC-typeE
Temperature	Tank	Omega	EQSS-116G-12	NA	0-100°C	±1.7°C	3044	TC-typeE
Temperature	Tank	Omega	EQSS-116G-12	NA	0-100°C	±1.7°C	3047	TC-typeE
Temperature	Pump Housing	Omega	EQSS-116G-16	NA	0-100°C	±1.7°C	1815	TC-typeE
Pressure	Pump Suction	WIKA	NA	NA	0-30inHg	±1 inHg	NA	
Pressure	Pump Discharge	Ashcroft	NA	NA	0-30psid	±2 psi	NA	
Weight	NA	OHAUS	CT600-S	08881	0-600g	±0.5g	2501	
Flow	Pump Discharge	Brooks	1350EMA7CFF1A	9411HC090541	0-6 L/h	±0.1 L/h	NA	Water
RPM	Pump Magnet	Cole Parmer	08199-41	NA	10 kRPM	±0.5%typ	NA	±1RPM resolution
Volume	NA	Pyrex (flask)	0.15	NA	99.01-105.92 ml	±0.15 ml	NA	Flow Rate, Density
Time*	NA	Thomas Sci	8788-T52	86199	NA	±694µsec/sec	3467	Stopwatch

* The tolerance is for the device itself, i.e., not for the reaction time of the technician which is assumed to create an error of approximately ±0.5 second.

There were two operations to obtain the periodic flow rate and density measurements:

Collection After valve V6 [Fig. A1] was opened to take a timed sample, a 100 ml calibrated flask was used to collect the liquid.

Measurement A stopwatch was used to time the collected sample (to determine flow rate) and a scale was used to weigh the sample to determine density.

4.0 GENERAL TEST OPERATION

Details of the test procedure will not be given here but can be found in the Ref. R8. However, a general outline is given below to illustrate how data were obtained. Refer to Fig. A1.

Test Procedure Steps

1. With all valves closed, open valve V9 and fill the mixing tank with the surrogate Am/Cm solution, then close V9.
2. Turn on the agitator and the tank heaters
3. After the liquid reaches 50°C, open valves V1, V2, V3, Flowmeter valve, V5, and turn on the pump to full speed (20 mA); remove air from the tubes.
4. Turn on the pump heater and adjust the power to obtain 50°C.
5. Close valve V5 and open V6 to take a timed sample. Continue taking samples until a flow rate of 2.7 L/h is obtained. The flow is adjusted by the pump speed.
6. Make appropriate adjustments to the temperature and flow rates to allow the system to run at steady state with the liquid being at 50°C and the flow rate at 2.7 L/h.
7. Set the computer to run the pump for a two-hour period then to shut it down for one hour. This cycle repeats over and over until a system check is needed.
8. On a daily basis, note the flow rate with the rotameter, the pump current, and the liquid and pump temperatures.
9. At the end of approximately a seven-day period the pump and its heater are shut off so that the pump can be removed from the flow loop.
10. Immediately before shutting down the pump, the flow rate and liquid density are measured.
11. After disconnecting the pump it is flushed with water and dismantled to remove the two gears.
12. Under a power 10 magnifier the gears are inspected for any obvious damage.
13. Repeat steps 5 to 12 until the amount of liquid circulated is equivalent to the expected volume of entire Am/Cm campaign (≈ 1180 liters).
14. End of a test.

5.0 DISCUSSION OF RESULTS

The results are broken into three section, in order of importance: Gear Wear, Overall Pump Operation, and Anomalies. The overall result was that the pump generally operated satisfactory and will withstand the entire 4- to 6-month campaign to stabilize the Am/Cm solution. Note, that while the campaign will last 4 to 6 months, the actual pump cycle time will be only long enough to transport all the Am/Cm solution. For this test, the pump was continuously cycled until an equivalent amount of surrogate solution was pumped. With a few delays for pump inspections, and other reasons, the test lasted only 40 days. This will be explained further in this section. What follows are the observations concerning the pump operation to enable better planning in the event the campaign runs longer than projected or if the pump is utilized in another application.

5.1 Gear Wear [Gear Material: Carbon Graphite]

Summary: Wear had no significant impact on the pump performance.

Many pictures were taken of the pump gears under magnification to quantify the amount of wear that occurred during the test. All the picture numbers are included in the reference section. However, for the purpose of this report, only a few pictures were chosen to best illustrate the gears' state. Columns F and L of Table C1 in Appendix C show that during the 40 days of testing, the pump ran 490 hours, and pumped 1241 liters of surrogate Am/Cm feed solution. This volume is 61 liters more than is expected to be transferred during processing of the Am/Cm solution. The pump time is less than 40 days because it ran on a two-hours-on and one-hour-off cycle to mock the best estimate of its actual operation with the melter system. Further, on a weekly basis the pump was dismantled to inspect the pump and its gears for damage. The gears had no failure during the entire test.

As shown in Figs. A2 and A3 there are two gears in the pump tested: The drive (or driving) gear and the driven (or follow) gear. The gears in the pump tested are called "old" and those in the untested (control) pump are called "new". The drive and driven gears are identical, except that the drive gear has holes to allow the fingers of the driven magnet to be attached. Figure B1 (a) and (b) show those holes. Figs B1 and B2 show the gears magnified 6 times and there is a scale under the gears with 1/32-inch divisions. Their actual size is 8.5 mm (0.334 inch) in diameter and 1.5 mm (0.060 inch) thick.

From Figs. B1 and B2 it is hard to see any detail, but wear on the face of the old gears [Figs. B1 (a) and B2 (a)] is evident. There is some small amount of wear on the new gears because the untested pump was used for a couple of hours to obtain some flow data. However, the evident face wear appears to be insignificant and had no apparent impact on the pump's operation. Because of the small size of the gears the actual worn thickness could not be measured.

A close look at the same figures shows that the teeth of the old gears appear to be slightly thinner than the new gear teeth, but a larger magnification was necessary to quantify the difference. [Note: Some damage (chips removed) is apparent on one side of one of the new gears, Fig. B1 (b). It is not known how that damage occurred or if it were present on the gear when the pumps were purchased. However, this information has no significance to this test.]

A slight difference is noticeable between the old and the new gear teeth from the pictures taken with the electron microscope [Figs. B3 and B4] at a 60x magnification. A good one-to-one comparison is difficult to make because of the angle the pictures were taken. However, comparing the old gears [Fig. B3 (a) and B4 (a)] with the new gears [Figs. B3 (b) and B4 (b)], it is apparent that the top and the bottom of the old gear teeth are somewhat thinner. In an attempt to quantify the tooth wear, dimensions of an old and a new gear tooth were measured from the photographs and superimposed on one another [Fig. B5]. From Fig. B5 the old gear tooth lost approximately 10% of its volume. As will be seen in the following section there was no noticeable degradation in the pump's performance, therefore, this amount of wear is not deemed significant.

5.2 Overall Pump Operation

Summary: Performed satisfactorily in pumping required volume of surrogate feed solution.

5.2.1 Surrogate Feed Transferred

The goal of transferring 1180 liters of feed solution was accomplished [Column L; Table C1] over a 40-day period, about 952 hours. During that period the pump ran for 490 hours [Column F; Table C1] and was idle for the remaining 462 hours. Of the 462 hours, for 238 hours the pump was idle because of the method of cycling the pump, i.e., 2 hour on and 1 hour off, continuously. The remaining 224 hours of idle time were either from the planned weekly stoppage to evaluate the pump, a short power outage period, or from the evaluation period during which the pump operation produced some anomalies which will be explained in the next section.

The pump could be operated either manually or remotely. Since around-the-clock operation was required, it was operated remotely by inputting a 4 to 20 mA signal. As seen in Column G of Table C1 the current was predominantly set between 15 and 16 mA. This current was to produce a pump flow of $2.6 \text{ L/h} \pm 0.2 \text{ L/h}$ [Column I; Table C1]. As it turned out, the pump flow was actually $2.5 \text{ L/h} \pm 0.2 \text{ L/h}$ [Column J; Table C1]. This difference in flow rates was the result of how the flow rate was checked and does not impact the pump operation. This difference will be explained in the next subsection.

As shown in Fig. C1, despite some fluctuations in the flow rate, which is explained in section 5.3 [top curve; the corrected flow rate], the pump continued to operate satisfactorily until the target liquid volume to be pumped was accomplished [bottom curve]. Fig. C1 only show those hours that the pump was actually running; not the idle or evaluation times. The times between groups of data points correspond to the weekends, when the pump ran but no data were taken. On Fig. C1, the accumulated volume of liquid transferred was normalized to the goal volume of 1180 liters. This enabled placing on the same graph both the accumulated volume and the measured flow rate.

Table C2 was included in Appendix C to see the equations used in Table C1. The origin of some of the columns in Table C1, like the Corrected Flow Rate; column J, is not obvious.

5.2.2 Pressure Effect on Flow Rate

Near the latter part of the experiment it was noticed that when a sample was taken to measure the flow rate and density (going from a closed to an open flow system) the height of the ball in the rotameter, measuring the flow, increased. Not checking this fact before testing began was an oversight. The effect of pressure was not overlooked, but simply thought insignificant. From the misnomer of calling a gear pump "positive displacement," to believing in the performance curves from the vendor, led to the assumption that the expected 20 to 30 inches of water ($\approx 1 \text{ psi}$) difference from the open to close system would not affect measurable flow rates. It is not exactly clear when an actual pump can be classified as positive displacing, but theoretically, changes in flow-line pressure should not affect flow. The vendor-supplied performance curves indicated that $\Delta Q / \Delta P \approx 0.007$ (liters/hour) / psi, therefore, not more than a 0.01 liters/hour variation was expected. However, subsequent testing (the subject of the next subsection) found the variation to be more than an order of magnitude higher, that is, 0.13 liters/hour.

To quantify the pressure effect on flow rate a test was done at the end of the experiment in order to calibrate the rotameter against flow rate, with the pump flow system open and closed. Those test data, along with corresponding data from Table C1, were used to form Table C3. Figure C2 show the open and closed system results. With this information the

bottom curve (for the open system) can be used to correct the data shown on the top curve (for the closed system). While the effect is not large, the correction reduces the pump flow rates by approximately 4%. The average pump flow rate shown in column I of Table C1, of 2.6 liters/hour, was reduced to 2.5 liters/hour. The concern of this pressure effect was not so much about correcting the experimental data (both 2.6 and 2.5 liters/hour were acceptable test flow rates) as it was to fully understand how the pump would react to larger pressure fluctuations. At the termination of the test, the pump system was set up to measure the pump pressure drop versus flow rate of water. With this information a comparison could be made to the vendor's pump performance curves.

5.2.3 Pump Performance with Water

As mentioned above, the effect of pressure on flow rate led to a subsequent test to quantify that effect. Table C4 contains the results of that test and Fig. C3 compares the vendor's information with those test results. While the test apparatus for the original test was used, Fig. A1, it was slightly modified to install pressure gauges near the upstream and downstream valves of the pump, i.e., V2 and V3. Also, the pump housing was modified to create a window for a visual inspection of the drive magnet. The drive magnet was marked so that the speed of the pump could be measured, i.e., rpm. Measuring the pump speed during the actual test was not possible because the pump housing had to be heated to maintain the surrogate Am/Cm solution at 50°C. Since the vendor data are for water at room temperature, this test was carried out under the same conditions. The instruments used for this extra test are also listed in section 3 of this report, with their measurement uncertainties.

Figure C3 shows the pump performance of total head versus flow rate. The vendor information was given at five pump speeds: 500, 1450, 1725, 2850, and 3450 rpm. This test was done at four pump speeds, approximately: 945, 2000, 3040, and 4070 rpm. However, at all speed the results are similar. That is, the slopes of the vendor data range approximately 160 to 60 psi / (liters/hour) [an average of 123 psi / (liters/hour) or 3,400 in.H₂O / (liters/hour)] and for this test data the range is approximately 10 to 7 psi / (liters/hour) [an average of 7.9 psi / (liters/hour) or 219 in.H₂O / (liters/hour)]. There is an order of magnitude between the two sets of data.

While this test was done with water, the slope of the pump curve for the surrogate feed solution is similar. This was verified in the previous subsection and is repeated here. Consider when the pump system was opened to take a sample. The height of the liquid above the sampling port opening (connected to valve V6 as shown in Fig. A1) was approximately 22 inches. For the surrogate feed solution with a density of 1.23 g/cc (column M of Table C1), the extra back pressure on the pump was approximately $22 \times 1.23 = 27$ inches of H₂O, or approximately 1 psi. This extra pressure will cause a change in flow rate of $1 \text{ psi} / [7.9 \text{ psi} / (\text{liters/hour})] = 0.13 \text{ liters/hour}$. This is exactly the vertical height between the two curves in Fig. C2.

5.3 Anomalies

Summary: Pump performance may change when disassembly and assembly occurs.

As shown on Fig. C1, after three weeks of uneventful pump operation the flow rate suddenly dropped from 2.6 liters/hour to 2 liters/hour. This occurred on 2/12/98 just after the weekly evaluation and just before a long weekend. There was not gradual change. Just before dismantling the pump it was running fine. After the evaluation and reassembly, the

pump would not return to the same flow rate at the same driving current that had been used for the past three weeks, i.e., 15.45 mA. Several possible causes were investigated immediately, like air in the system, blockage, or gear damage, but to no avail. Because of the late hour that day the pump was allowed to operate over that weekend at the lower flow rate. On 2/17/98 and 2/18/98 a series of test were conducted to evaluate the lowered flow rate. The unused control pump, that had been sent to TNX [Ser. No.: 814923], was retrieve to assist in the evaluation.

Over a two-day period, four different tests were carried out, as well as baselining the then current status of both the non-used 'new' pump and the used 'old' pump. The many data sets are not given in this report but are highlighted in Fig. C4 (the data can be found in the task notebook). The results of all the testing did not elicit a satisfactory reason for the change in pump operation, however, they eliminated many of the possible reasons why the change occurred. A summary of that testing is now given, along with a possible cause for the unexpected pump fluctuations which is consistent with all the data obtained.

Before beginning to evaluate the pump, some baseline data were obtained. From the vendor literature, a Q vs. RPM curve (valid for water at room temperature) was obtained [the top line on Fig. C4]. Subsequently, the same information was obtained for the new pump (from TNX) by doing a test with water at room temperature [the open circles on Fig. C4]. The then current status of the old pump was obtained which showed a significant difference from the preceding data [the closed circles on Fig. C4]. Under the same flow conditions the following changes were made to the old pump, and for each a data set was obtained in an attempt to discover the anomaly: 1. The old drive magnet and motor were replaced with the new [the open triangles on Fig. C4]. 2. The old drive magnet and motor were reinstalled and then the old gears were replaced with the new [the closed triangles on Fig. C4]. 3. The old gears were reinstalled and then the old pump (driven) magnet was replaced with new [the open squares on Fig. C4]. 4. Leaving in the new pump magnet, the old drive magnet was replaced with the new [the closed squares on Fig. C4].

Figure C4 shows that all that testing produced practically the same data set. After a thorough check of the gears no evidence of significant wear or damage was apparent. The old pump was put back in its original condition and the pump test continued; further delays did not seem reasonable. However, the pump current was increased to bring the flow rate back to 2.7 liters/hour. The pump ran stably for eight more days after which it was dismantled for its weekly evaluation. Surprising, on reassembling the pump and returning it to service on 2/26/98, the current had to be lowered to its original level that was used prior to 2/12/98 in order to obtain a flow rate of 2.7 liters/hour. Whatever was causing the problem left the same way it came, suddenly. Therefore, on completing the overall test, another data set, with water at room temperature, was obtained to see how it compared to previous data on Fig. C4. Those data are the 'plus' symbols, and for convenience a curve fit is shown to more easily see the trend. It appears that the performance of the old pump matched that of the new pump, implying that it returned to its original level of performance.

Since all the old pump evaluations were done with water, and the pump was disconnected from the test apparatus, then the test apparatus was not the source of the problem. It could only have been caused by something inside the pump. It is believed that some foreign particle was attached to bottom of the suction shoe [see Figs. A2 and A3] which prevented it from seating properly, causing a secondary leak path. The unseating could be easily missed because of the size of the parts and because the suction shoe is only held in place with a small spring. The gears are only 1.5 mm in height, so a particle that has a diameter on the order of a couple of hairs could cause a significant flow bypass. From Fig. C4 the

data at low flow rates were always the same, however at the higher flow rate the data diverge. With the suction shoe slightly unseated, a bypass for flow would occur and the result would be a slightly lower flow rate. Furthermore, as the flow rate increase the bypass would cause a more pronounced reduced flow. This is exactly what the data in Fig. C4 imply.

The overall test required that the pump to be disassemble frequently. In normal usage, a pump would not be disassembled, only checked for proper operation. It would be expected to function properly until damage occurs. The results of the anomaly noticed during this test imply that before a new pump is put into service it should be checked for expected operation. Once in service it should perform satisfactorily.

6.0 CONCLUSIONS

The general conclusion is: model 187 gear pump, from Micropump, is expected to perform satisfactorily for the entire Am/Cm campaign. The following statements are based on the results in Appendices B and C, and as discussed in the previous section.

- 6.1** After pumping 1241 liters of surrogate Am/Cm liquid at 50°C the pump gears experienced a 10% reduction in gear tooth volume and no damage. Any change in pump performance due to the wear was insignificant.
- 6.2** Pump Overall Performance
 - 6.2.1** Pump cycling of two hours on and one hour off for 728 hours ran smoothly.
 - 6.2.2** The flow rate of this positive displacement gear pump was affected by changes in the pressure across the pump. That effect is approximately: ± 0.13 liters /hour per 30 inches of H₂O at 2.6 liters/hour.
 - 6.2.3** Vendor-supplied pump performance data may significantly differ from actual pump performance. However, the pump will still provide the needed flow to the melter.
- 6.3** Any reassembly of the pump will need a subsequent performance check to ensure it operates to expectations.

7. RECOMMENDATIONS

- 7.1** This pump will last the entire Am/Cm campaign of transferring 1180 liters. It should be considered for a replacement to the air-lift system.
- 7.2** Pump can be procured with all radiation hard materials.
- 7.3** After a disassembly of the pump all parts need a thorough cleaning before reassembly.

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- R3. Spatz, T. L., "Air Lift Demonstration Task Technical and QA Plan," WSRC No. SRT-ETF-TT-96-004-0, September 12, 1996.
- R4. Choi, A. S., "Preliminary Design Basis Material Balance For Am/Cm Vitrification Flowsheet," Inter-Office Memorandum No. SRT-AMC-97-0001, January 20, 1997.
- R5. Hargett, S. T., "Testing and Development of a Feed system for the Americium/ Curium (Am/Cm) Vitrification Program (U)," Technical Report No. WSRC-TR-97-0179, July, 1997.
- R6. Duignan, M. R., *Environmental Evaluation Checklist*, No.TC-A-97-030, 12/11/97.
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- R8. Duignan, M. R., "Am/Cm Long Term Melter Feed Pump Test," Test Procedure No. FP-749, Rev.0, 1/15/98.
- R9. Mandel, John, *The Statistical Analysis of Experimental Data*, Dover Pub,NY, 1964.

Photographic References

P1. Microphotographs of pump gears: Photographers: James C. Piercy and Tony Curtis
Numbers are from the WSRC Bldg 723-A Metallurgical Laboratory Reference Log

Sequence #	# photos	Description	Magnification	Camera
54640	2	Drive Gears: new/old; front/back	6x	mp4
54641	2	Driven Gears: new/old; front/back	6x	mp4
54642	4	Driven Gears: new/old; front/back	16x	mp4
54643	5	Drive Gears: new/old; front/back	16x	mp4
54645	5	Drive,n Gears: new/old; front/back	30x	mp4
54646	9	Drive,n Gears: new/old; front/back	30x, 60x	SEM

mp4 = standard 35 mm camera with magnification lenses

SEM = Scanning Electron Microscope

Note: All photographs were taken in March 1998

APPENDIX A

EXPERIMENTAL APPARATUS AND PUMP DETAIL

Fig. A1. Schematic of the Overall Experimental Test Apparatus

Fig. A2. Enlargement of MicroPump Internals: Model 187

Service Instructions

FOR MOD. 181/183/184/185/186/187/1830/1840

Fig. A3. Overall Detail Schematic of MicroPump: Model 187

Fig. A4. Pertinent Dimensions of MicroPump: Model 187

APPENDIX B

PHOTOGRAPHS AND SCHEMATIC OF PUMP GEARS

Figure B1. 35-mm Photograph of Drive Gear: (a) Old, (b) New; Enlargement 6X,
[bottom scale: 1/32 inch divisions]

Figure B2. 35-mm Photograph of Driven Gear: (a) Old, (b) New; Enlargement 6X,
[bottom scale: 1/32 inch divisions]

(a)

(b)

Figure B3. SEM Photograph of Drive Gear: (a) Old, (b) New; Enlargement 60X

(a)

(b)

Figure B4. SEM Photograph of Driven Gear: (a) Old, (b) New; Enlargement 60X

Fig. B5. Schematic of Superimposing of a Old Gear Tooth On New

APPENDIX C

EXPERIMENTAL DATA

MICRO-PUMP PERFORMANCE (MODEL 187)

Fig. C1. Overall Test Data

Am/Cm Long Term Meller Feed Pump Test Data

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Test Date	Test Period hours:min	Test Run Time minutes	Test Run Time Days	Pump Time minutes	Pump Time hours	Pump Current mA	Rotameter ball height	Flow Rate liters/hour	Flow Rate (Corrected) liters/hour	Difference %	Volume Pumped liters	Density grams/cc	Liquid Temp °C	Pump Housing Temp °C
1	2/1/98	16:40	0	0	0.0		25	2.65	2.48	-6%	0.0	1.225	52	
2	2/1/98	16:40	0	0	0.0		25	2.65	2.48	-6%	0.0	1.225	52	
3	2/1/98	16:40	0	0	0.0		25	2.65	2.48	-6%	0.0	1.225	52	
4	2/2/98	7:50	910	1	895	14.9	15.45	2.65	2.54	-6%	37.0	1.225	46.6	42.3
5	2/2/98	10:50	1030	1	975	16.3	15.45	2.65	2.54	-6%	40.4	1.225	47.5	42
6	2/2/98	16:00	1340	1	1182	19.7	15.45	2.65	2.48	-7%	48.9	1.23	50.8	49.3
7	2/2/98	17:00	1340	1	1182	19.7	15.45	2.65	2.54	-6%	48.9	1.23	50.8	49.3
8	2/2/98	17:00	1340	1	1182	19.7	15.45	2.65	2.54	-6%	48.9	1.23	50.8	49.3
9	2/2/98	17:00	1340	1	1182	19.7	15.45	2.65	2.54	-6%	48.9	1.23	50.8	49.3
10	2/3/98	8:08	2248	2	1787	28.8	15.45	2.65	2.54	-6%	74.6	1.225	51.5	47.1
11	2/3/98	15:45	2705	2	2092	34.9	15.45	2.65	2.54	-6%	87.5	1.225	49.8	48.7
12	2/3/98	7:45	6545	5	4652	77.5	15.45	2.65	2.54	-6%	195.6	1.225	49.7	49.7
13	2/3/98	17:15	7115	5	5032	83.9	15.45	2.65	2.54	-6%	211.7	1.225	49.4	48.4
14	2/3/98	7:02	7942	6	5583	93.1	15.45	2.65	2.54	-6%	233.5	1.225	49.9	49.2
15	2/4/98	7:07	9387	7	6546	109.1	15.45	2.65	2.54	-4%	276.1	1.225	50.2	49.3
16	2/4/98	16:45	9965	7	6932	115.6	15.45	2.65	2.54	-4%	292.7	1.225	49.8	48.6
17	2/4/98	7:00	10820	8	7502	125.0	15.45	2.65	2.54	-4%	317.3	1.225	50.6	49.4
18	2/5/98	15:05	11305	8	7825	130.4	15.45	2.63	2.48	-6%	330.7	1.225		
19	2/5/98	15:27	11305	8	7825	130.4	15.45	2.63	2.48	-6%	330.7	1.225		
20	2/5/98	16:55	11393	8	7884	131.4	15.45	2.63	2.59	-2%	333.2	1.225	49.5	49
21	2/6/98	7:55	12293	9	8484	141.4	15.45	2.63	2.59	-2%	359.1	1.225	50.6	49.8
22	2/6/98	16:12	12790	9	8815	146.9	15.45	2.63	2.59	-2%	373.4	1.225	49.6	48.4
23	2/9/98	10:16	16754	12	11458	191.0	15.45	2.63	2.59	-2%	487.5	1.225	50.3	48.7
24	2/9/98	16:00	17038	12	11687	194.8	15.45	2.63	2.59	-2%	497.4	1.225	50.1	48.6
25	2/10/98	7:36	18034	13	12311	205.2	15.45	2.63	2.46	-6%	523.2	1.225	50.4	49.2
26	2/10/98	17:00	18598	13	12687	211.6	15.45	2.63	2.54	-4%	539.1	1.225	49.5	49.3
27	2/11/98	7:40	19478	14	13274	221.2	15.45	2.63	2.59	-2%	564.4	1.225	50.1	49.3
28	2/11/98	17:05	20043	14	13650	227.5	15.45	2.63	2.59	-2%	580.6	1.225	50.2	50.4
29	2/12/98	7:42	20920	15	14235	237.3	15.45	2.63	2.59	-2%	605.8	1.225	50.3	49.4
30	2/12/98	15:55	21413	15	14564	247.7	15.45	2.746	2.59	-6%	620.0	1.224	49.7	49.9
31	2/13/98	16:51	21413	15	14564	247.7	15.45	2.128	2.01	-6%	620.0	1.231		
32	2/13/98	9:20	22402	16	15223	253.7	15.45	2.128	2.01	-6%	641.5	1.231	50.3	49.2
33	2/13/98	16:20	22822	16	15503	258.4	15.45	2.128	1.95	-8%	650.6	1.231	50.7	46.8
34	2/16/98	8:15	26657	19	18060	301.0	15.45	2.128	2.11	-1%	740.6	1.231	50.6	48.3
35	2/16/98	12:00	26882	19	18210	303.5	15.45	2.128	2.11	-1%	745.8	1.231	50	49.4
36	2/16/98	17:05	27187	19	18413	308.9	15.45	2.128	2.11	-1%	753.0	1.231	50.5	48
37	2/17/98	7:30	28052	19	18990	316.5	15.45	2.128	2.11	-1%	773.3	1.231	50.7	46
38	2/17/98	9:10	28152	20	19056	317.6	15.45	2.128	2.11	-1%	775.6	1.231	50.2	50.1
39	2/17/98	9:40	28182	20	19076	317.9	15.45	2.39	2.27	-5%	776.4	1.231	50.9	48.5
40	2/18/98	9:45	29187	20	19746	329.1	15.45	2.39	2.22	-7%	801.2	1.231		
41	2/19/98	17:00	29187	20	19746	329.1	15.45	2.65	2.54	-4%	801.2	1.229		
42	2/20/98	10:00	30207	21	20426	340.4	19.5	2.65	2.54	-4%	830.0	1.229	50.1	48.7
43	2/23/98	7:45	34272	24	23136	385.6	19.5	2.65	2.54	-4%	968.4	1.229	50.1	50.7
44	2/23/98	8:30	34272	24	23136	385.6	17.75	2.65	2.54	-4%	968.4	1.229	50	49.6
45	2/23/98	11:30	34452	24	23256	387.6	17.75	2.65	2.48	-6%	973.3	1.229	49.7	47.8
46	2/23/98	14:08	34610	24	23362	389.4	18	2.65	2.54	-4%	977.8	1.229	49.5	46
47	2/23/98	15:00	34662	24	23396	389.9	18	2.65	2.54	-4%	979.2	1.229	49.5	48.5
48	2/24/98	7:45	35247	24	23786	395.4	18	2.65	2.54	-4%	995.8	1.229	49.5	43.1
49	2/24/98	12:22	35524	25	23971	399.5	18	2.65	2.54	-4%	1003.8	1.229	48.8	49.3
50	2/24/98	15:08	35690	25	24082	401.4	17.75	2.65	2.54	-4%	1008.5	1.229	49.2	49.5
51	2/25/98	14:18	37078	26	25007	416.9	17.75	2.65	2.59	-2%	1048.4	1.229	49.1	47.8
52	2/25/98	17:12	37254	26	25124	416.7	17.75	2.65	2.59	-2%	1053.5	1.229	49.7	47.6
53	2/26/98	9:00	38202	27	25756	429.3	17.75	2.65	2.59	-2%	1080.7	1.229	49.3	49
54	2/26/98	10:32	38284	27	25818	430.3	17.75	2.92	2.89	-6%	1083.5	1.229	48.5	49.5
55	2/26/98	14:35	38294	27	25818	430.3	15.75	2.65	2.54	-4%	1083.5	1.229	48.5	49.2
56	2/26/98	16:25	38404	27	25891	431.5	15.75	2.65	2.54	-4%	1086.6	1.229	48.5	49.6
57	2/27/98	9:48	39447	27	26588	443.1	15.75	2.65	2.54	-4%	1116.0	1.229	49.8	49.8
58	3/2/98	8:47	43706	30	29426	490.4	15.75	2.85	2.84	-7%	1240.9	1.229	49.2	48.7
59														
60														
61														

Table C1. Overall Test Data

Table C2. Overall Test Data (Equations Used)

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Test Period	Test Run Time	Test Run Time	Test Run Time	Pump Run Time	Pump Time	Pump Current	Rotameter	Flow Rate	Flow Rate	Difference	Volume Pumped	Density	Liquid Temp	Pump Housing Temp
Date	hours:min	minutes	Days	minutes	Hours	mA	ball height	liters/hour	liters/hour	%	liters	grams/cc	°C	°C
34354	0.6944444444444445	0	=C3/60/24	0	=E3/60		26	2.65	=H3*0.10583-0.16352	=J3-13/13	=L3*F3	1.225	52	
34355	0.3263888888888889	=15*60+10	=C4/60/24	=E4=(1-60/180)*C4	=E4/60			2.85	=H3*0.10583-0.16352	=J4-14/14	=L3*J4*(F4-F3)		46.6	42.3
34355	0.4513888888888889	=C4*3*60+80	=C4/60/24	=E4=(1-60/180)*C4	=E4/60	15.45	25.5	2.7	=H5*0.10583-0.16352	=J5-15/15	=L4*J5*(F5-F4)		47.5	42.3
34355	0.6866666666666667	=C5*5*60+10	=C6/60/24	=E6=(1-60/180)*C6	=E6/60	15.45	25	2.67	=H6*0.10583-0.16352	=J6-16/16	=L5*J6*(F6-F5)	1.23		
34362	0.7063333333333333	1340	=C7/60/24	=E8=(1-60/180)*C7	=E7/60	15.45	25.5	2.695	=H7*0.10583-0.16352	=J7-17/17	=L6*J7*(F7-F6)	1.23	50.8	49.3
34362	0.7361111111111111	=C7+40	=C8/60/24	=E7=(1-60/180)*C8	=E8/60	15.45		2.695	=H7*0.10583-0.16352	=J8-18/18	=L7*J8*(F8-F7)			
34383	0.3368888888888889	=C8+14*60+20+8	=C9/60/24	=E8=(1-60/180)*C9	=E9/60	15.45		2.695	=H7*0.10583-0.16352	=J9-19/19	=L8*J9*(F9-F8)		51.5	47.1
34363	0.65625	=C9*7*60+45+8	=C10/60/24	=E9=(1-60/180)*C10	=E10/60	15.45		2.695	=H7*0.10583-0.16352	=J10-110/110	=L9*J10*(F10-F9)		49.8	49.7
34386	0.3229166666666667	=C10+64*60	=C11/60/24	=E10=(1-60/180)*C11	=E11/60	15.45	25.5	2.695	=H12*0.10583-0.16352	=J11-11/11	=L10*J11*(F11-F10)		49.7	49.7
34366	0.71875	=C11+9*60+30	=C12/60/24	=E11=(1-60/180)*C12	=E12/60	15.45		2.695	=H12*0.10583-0.16352	=J12-112/112	=L11*J12*(F12-F11)		49.4	48.4
34367	0.2930555555555556	=C13+14*60+13	=C13/60/24	=E12=(1-60/180)*C13	=E13/60	15.45	25	2.695	=H13*0.10583-0.16352	=J13-13/13	=L12*J13*(F13-F12)		49.9	49.2
34368	0.2952577777777778	=C13+24*60+5	=C14/60/24	=E13=(1-60/180)*C14	=E14/60	15.45	25	2.695	=H16*0.10583-0.16352	=J14-114/114	=L13*J14*(F14-F13)		50.2	49.3
34368	0.6979166666666667	=C14+9*60+46+7	=C15/60/24	=E14=(1-60/180)*C15	=E15/60	15.45	26	2.695	=H16*0.10583-0.16352	=J15-115/115	=L14*J15*(F15-F14)		49.8	48.6
34369	0.2916666666666667	=C15+18*60+45	=C16/60/24	=E15=(1-60/180)*C16	=E16/60	15.45	26	2.695	=H16*0.10583-0.16352	=J16-116/116	=L15*J16*(F16-F15)		50.8	49.4
34369	0.6204722222222222	=C16+8*60+5	=C17/60/24	=E16=(1-60/180)*C17	=E17/60	15.45	25	2.63	=H17*0.10583-0.16352	=J17-117/117	=L16*J17*(F17-F16)	1.225		
34369	0.64375	11305	=C18/60/24	=E17=(1-60/180)*C18	=E18/60	15.45		2.63	=H17*0.10583-0.16352	=J18-118/118	=L17*J18*(F18-F17)			
34369	0.7048611111111111	=C18+1*60+28	=C19/60/24	=E18=(1-60/180)*C19	=E19/60	15.45	28	2.63	=H19*0.10583-0.16352	=J19-119/119	=L18*J19*(F19-F18)		49.5	49
34370	0.3298611111111111	=C19+15*60	=C20/60/24	=E19=(1-60/180)*C20	=E20/60	15.45	28	2.63	=H19*0.10583-0.16352	=J20-120/120	=L19*J20*(F20-F19)		50.6	48.8
34370	0.875	=C20+6*60+12+5	=C21/60/24	=E20=(1-60/180)*C21	=E21/60	15.45	48	2.63	=H19*0.10583-0.16352	=J21-121/121	=L20*J21*(F21-F20)		50.8	48
34373	0.4277777777777778	=C21+6*60+4	=C22/60/24	=E21=(1-60/180)*C22	=E22/60	15.45		2.63	=H19*0.10583-0.16352	=J22-122/122	=L21*J22*(F22-F21)		50.3	48.7
34373	0.6866666666666667	=C22*5*60+18	=C23/60/24	=E22=(1-60/180)*C23	=E23/60	15.45		2.63	=H19*0.10583-0.16352	=J23-123/123	=L22*J23*(F23-F22)		50.1	48.6
34374	0.3166666666666667	=C23+15*60+36	=C24/60/24	=E23=(1-60/180)*C24	=E24/60	15.45	25	2.63	=H24*0.10583-0.16352	=J24-124/124	=L23*J24*(F24-F23)		49.4	49.2
34374	0.7083333333333333	=C24+10*60+39	=C25/60/24	=E24=(1-60/180)*C25	=E25/60	15.45	25.5	2.63	=H25*0.10583-0.16352	=J25-125/125	=L24*J25*(F25-F24)		49.5	49.3
34375	0.3194444444444444	=C25+14*60+40	=C26/60/24	=E25=(1-60/180)*C26	=E26/60	15.45	29	2.63	=H26*0.10583-0.16352	=J26-126/126	=L25*J26*(F26-F25)		50.1	49.3
34376	0.7180555555555555	=C26+10*60+35	=C27/60/24	=E26=(1-60/180)*C27	=E27/60	15.45	29	2.63	=H27*0.10583-0.16352	=J27-127/127	=L26*J27*(F27-F26)		50.2	50.4
34376	0.3208333333333333	=C27+1*60+37	=C28/60/24	=E27=(1-60/180)*C28	=E28/60	15.45	26	2.63	=H28*0.10583-0.16352	=J28-128/128	=L27*J28*(F28-F27)		50.3	49.4
34376	0.6631944444444444	=C28+6*60+13	=C29/60/24	=E28=(1-60/180)*C29	=E29/60	15.45	26	2.746	=H29*0.10583-0.16352	=J29-129/129	=L28*J29*(F29-F28)	1.224	49.7	49.9
34376	0.7026833333333333	21413	=C30/60/24	=E29=(1-60/180)*C30	=E30/60	15.45	20.5	2.128	=H30*0.10583-0.16352	=J30-130/130	=L29*J30*(F30-F29)	1.231		
34377	0.3868888888888889	=C30+16*60+29	=C31/60/24	=E30=(1-60/180)*C31	=E31/60	15.45	20	2.128	=H31*0.10583-0.16352	=J31-131/131	=L30*J31*(F31-F30)		50.3	49.2
34377	0.6055555555555556	=C31+7*60	=C32/60/24	=E31=(1-60/180)*C32	=E32/60	15.45	20	2.128	=H31*0.10583-0.16352	=J32-132/132	=L31*J32*(F32-F31)		50.7	48.6
34380	0.34375	=C32+64*60+5	=C33/60/24	=E32=(1-60/180)*C33	=E33/60	15.45	21.5	2.128	=H33*0.10583-0.16352	=J33-133/133	=L32*J33*(F33-F32)		50.6	48.3
34380	0.5	=C33+4*60+15	=C34/60/24	=E33=(1-60/180)*C34	=E34/60	15.45	21.5	2.128	=H34*0.10583-0.16352	=J34-134/134	=L33*J34*(F34-F33)		50	49.4
34380	0.7180555555555555	=C34+5*60+5	=C35/60/24	=E34=(1-60/180)*C35	=E35/60	15.45	21.5	2.128	=H35*0.10583-0.16352	=J35-135/135	=L34*J35*(F35-F34)		50.5	48
34381	0.3125	=C35+14*60+25	=C36/60/24	=E35=(1-60/180)*C36	=E36/60	15.45	21	2.128	=H35*0.10583-0.16352	=J36-136/136	=L35*J36*(F36-F35)		50.7	48
34381	0.3819444444444444	=C36+2*60+20	=C37/60/24	=E36=(1-60/180)*C37	=E37/60	15.45	21.5	2.128	=H37*0.10583-0.16352	=J37-137/137	=L36*J37*(F37-F36)		50.2	50.1
34381	0.4027777777777778	=C37+30	=C38/60/24	=E37=(1-60/180)*C38	=E38/60	15.45	23	2.39	=H38*0.10583-0.16352	=J38-138/138	=L37*J38*(F38-F37)			
34381	0.7083333333333333	28182	=C39/60/24	=E38=(1-60/180)*C39	=E39/60	15.45	22.5	2.39	=H39*0.10583-0.16352	=J39-139/139	=L38*J39*(F39-F38)		50.9	48.5
34382	0.40825	=C39+18*60+45	=C40/60/24	=E39=(1-60/180)*C40	=E40/60	15.45	23	2.39	=H39*0.10583-0.16352	=J40-140/140	=L39*J40*(F40-F39)			
34383	0.7083333333333333	29187	=C41/60/24	=E40=(1-60/180)*C41	=E41/60	19.5	25.5	2.65	=H41*0.10583-0.16352	=J41-141/141	=L40*J41*(F41-F40)	1.229		
34384	0.4166666666666667	=C41+17*60	=C42/60/24	=E41=(1-60/180)*C42	=E42/60	19.5		2.65	=H41*0.10583-0.16352	=J42-142/142	=L41*J42*(F42-F41)		50.1	48.7
34387	0.3229166666666667	=C42+67*60+45	=C43/60/24	=E42=(1-60/180)*C43	=E43/60	19.5	30.5	2.65	=H43*0.10583-0.16352	=J43-143/143	=L42*J43*(F43-F42)		50.1	50.7
34387	0.3541666666666667	=C43+6*60+48	=C44/60/24	=E43=(1-60/180)*C44	=E44/60	17.75	25.5	2.65	=H44*0.10583-0.16352	=J44-144/144	=L43*J44*(F44-F43)		49.7	47.8
34387	0.4791666666666667	=C44+3*60	=C45/60/24	=E44=(1-60/180)*C45	=E45/60	17.75	25	2.65	=H45*0.10583-0.16352	=J45-145/145	=L44*J45*(F45-F44)		49.7	47.8
34387	0.5068888888888889	=C45+2*60+38	=C46/60/24	=E45=(1-60/180)*C46	=E46/60	18	25.5	2.65	=H46*0.10583-0.16352	=J46-146/146	=L45*J46*(F46-F45)		49.5	48.5
34387	0.825	=C46+1*60+8	=C47/60/24	=E46=(1-60/180)*C47	=E47/60	18	25.5	2.65	=H47*0.10583-0.16352	=J47-147/147	=L46*J47*(F47-F46)		49	48.5
34388	0.3229166666666667	=C47+9*60+45	=C48/60/24	=E47=(1-60/180)*C48	=E48/60	18		2.65	=H47*0.10583-0.16352	=J48-148/148	=L47*J48*(F48-F47)		49.5	43.1
34388	0.5152777777777778	=C48+5*60+23	=C49/60/24	=E48=(1-60/180)*C49	=E49/60	18	26.3	2.65	=H49*0.10583-0.16352	=J49-149/149	=L48*J49*(F49-F48)		48.3	49.3
503488	0.9305555555555556	=C49+2*60+18	=C50/60/24	=E49=(1-60/180)*C50	=E50/60	17.75	25.5	2.65	=H50*0.10583-0.16352	=J50-150/150	=L49*J50*(F50-F49)		49.2	49.5
34389	0.4944444444444444	=C50+23*60+8	=C51/60/24	=E50=(1-60/180)*C51	=E51/60	17.75	26	2.65	=H51*0.10583-0.16352	=J51-151/151	=L50*J51*(F51-F50)		49.1	47.8
523489	0.7166666666666667	=C51+13*60+4	=C52/60/24	=E51=(1-60/180)*C52	=E52/60	17.75	26	2.65	=H52*0.10583-0.16352	=J52-152/152	=L51*J52*(F52-F51)		49.7	47.6
34390	0.375	=C52+15*60+48	=C53/60/24	=E52=(1-60/180)*C53	=E53/60	17.75	26	2.65	=H53*0.10583-0.16352	=J53-153/153	=L52*J53*(F53-F52)		49.3	49
543390	0.4368888888888889	=C53+1*60+32	=C54/60/24	=E53=(1-60/180)*C54	=E54/60	17.75	27	2.92	=H54*0.10583-0.16352	=J54-154/154	=L53*J54*(F54-F53)		48.5	49.5
543390	0.6793666666666667	38294	=C55/60/24	=E54=(1-60/180)*C55	=E55/60	17.75	25.5	2.65	=H55*0.10583-0.16352	=J55-155/155	=L54*J55*(F55-F54)			
543390	0.6640277777777778	=C55+2*60+10	=C56/60/24	=E55=(1-60/180)*C56	=E56/60	17.75	25.5	2.65	=H56*0.10583-0.16352	=J56-156/156	=L55*J56*(F56-F55)		49.5	49.2
573491	0.4083333333333333	=C56+17*60+23	=C57/60/24	=E56=(1-60/180)*C57	=E57/60	15.75	25.5	2.65	=H57*0.10583-0.16352	=J57-157/157	=L56*J57*(F57-F56)		48.8	49.6
543394	0.3659722222222222	=C57+17*60+1	=C58/60/24	=E57=(1-60/180)*C58	=E58/60	15.75	26.5	2.85	=H58*0.10583-0.16352	=J58-158/158	=L57*J58*(F58-F57)		49.2	48.7
59														
60														
61														
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EFFECT OF OPENING SAMPLING VALVE ON FLOW RATE

Fig. C2. Effect of Pressure on Pump During Test

Table C3. Effect of Pressure on Pump During Test

	A	B	C	D	E	F	G	H	I
1	Measurement	Liquid Temp	Pump Current	Rotameter Reading	Rotameter Reading	Sample Volume	Sample Time	Flow Rate	Flow Rate
2	Date	°C	mA	millimeter	millimeter	milliliter	seconds	ml/minute	liters/hour
3				closed system*	open system**				
4	1/21/98	52.0	15.28	25.0	na	100.01	137.00	43.80	2.63
5	1/22/98	40.0	15.45	25.0	na	100.89	136.00	44.51	2.67
6	1/22/98	50.6	15.45	25.5	na	101.96	136.20	44.92	2.70
7	2/5/98	50.6	15.45	25.0	na	102.02	139.86	43.77	2.63
8	2/12/98	49.7	15.45	26.0	na	101.01	132.40	45.77	2.75
9	2/12/98	na	15.45	20.5	na	100.20	169.53	35.46	2.13
10	2/17/98	50.2	15.45	23.0	na	100.78	151.79	39.84	2.39
11	2/19/98	na	20	28.0	na	103.36	128.12	48.40	2.90
12	2/19/98	na	16	19.5	na	100.78	182.23	33.18	1.99
13	2/19/98	na	14	15.0	na	103.25	244.71	25.31	1.52
14	2/19/98	na	10	7.5	na	100.43	593.91	10.15	0.61
15	2/19/98	na	18.51	25.5	na	102.58	139.56	44.10	2.65
16	2/26/98	48.5	17.76	27.0	29	103.02	126.82	48.74	2.92
17	3/2/98	49.2	15.76	26.5	27.5	104.96	132.55	47.51	2.85
18	3/2/98	49.2	8	8	9.5	101.46	493.46	12.34	0.74
19	3/2/98	49.2	12.01	17.5	18.5	101.19	198.2	30.63	1.84
20	3/2/98	49.2	16.01	27.5	28.5	103.92	128.34	48.58	2.92
21	3/2/98	49.2	20	39	40	103.36	94.47	65.65	3.94
22	3/2/98	49.2	8.02	7.5	9	101.35	499.08	12.18	0.73
23	3/2/98	49.2	12.01	17.5	18.5	103.7	205.3	30.31	1.82
24	3/2/98	49.2	16.01	27	28	102.02	126.85	48.26	2.90
25	3/2/98	49.2	20	38.5	39.5	102.8	93.68	65.84	3.95
26									
27	* A closed system was when the system operated normally, that is, with the liquid completing a closed circuit.								
28	** An open system was when a sample was taken to independently measure the flow rate. From Fig. A1,								
29	valve V5 would be closed and valve V6 would be opened.

Fig. C3. MicroPump Performance with Water at Room Temperature

Table C4. MicroPump Performance with Water at Room Temperature

[illegible]

AM/CM PUMP FLOW DEVIATION

Fig. C4. Pump Deviation During Testing

APPENDIX D

MEASUREMENT UNCERTAINTY ANALYSIS

EXPERIMENTAL MEASUREMENT UNCERTAINTY

As always, any measurement made has an attributed error which must be known before a level of confidence can be attained for the results obtained. This error may come from one or all of the following: the measurement instrument, the way an instrument is set up to make a measurement in relation to the experimental phenomenon to be measured, and the person using the instrument. It is not the purpose of this section to exhaust all possible avenues of measurement uncertainty, but rather to illustrate the level of measurement uncertainty in the results presented in Appendix C. In general, the measurement uncertainties present here are systematic. However, some random errors may be included, i.e., a persons reaction time when using a stop watch, parallax reading of a volume, etc.

Most of the data listed in Appendix C are instrument data and not calculated. Therefore, the uncertainties are listed in section 3.0 for each instrument. There are two calculated which are address here: Flow rate = Volume / time, and Density = Mass / Volume. The general method to determine the uncertainties of this calculated items is by the Law of Propagation of Errors, (section 4.7 of Ref. R9). The derivation will not be given here and the following is just one example for one type of relation, albeit a common relation.

For example, a calculated entity A has an uncertainty of ΔA . The entity A is a function of three measured quantities: B, C, and D by the following relationship: $A = B \times C / D$ and these quantities have measurement uncertainties of ΔB , ΔC , and ΔD , respectively. In this case the relative uncertainty of A will be:

$$\Delta A/A = [(\Delta B/B)^2 + (\Delta C/C)^2 + (\Delta D/D)^2]^{1/2}.$$

D1.0 Volumetric Flow Rate: (Column I of Table C1)

This uncertainty is from the combination of the two measurement devices to make the calculation: Volume and Time.

Instrument Uncertainty (Section 3.0): Volume = ± 0.15 milliliter
 Time = ± 0.5 second (reaction time)

Example: Line 4 of Table C3:

Flow Rate = 100.01 milliliters / 137 seconds = 0.73 ml/s = 2.628 liters/hour

Therefore, $[(0.15 / 100.01)^2 + (0.5 / 137)^2]^{(1/2)} \times 100\% = \pm 0.4\%$ (0.011 liter/hour)

In subsection 5.2.2, it was explained that the flow rate needed to be corrected because the pressure effect. Therefore, the column containing the corrected flow rate, i.e., column J of Table C1, has the added uncertainty of the correction. That uncertainty is tied to the variability of the data point around the best fit line shown in C2. The details of the variability is not discussed here, but it will be noted that the correction amount is approximately 0.13 liters/hour, and a standard deviation on that variability is 0.04 liters/hour. Therefore, the overall uncertainty will be set at:

$[(0.011 / 2.628)^2 + (0.04 / 2.628)^2]^{(1/2)} \times 100\% = \pm 1.6\%$ (0.041 liters/hour)

D2.0 Density: (Column M of Table C1)

This uncertainty is from the combination of the two measurement devices to make the calculation: Volume and Time.

Instrument Uncertainty (Section 3.0): Mass = ± 0.5 grams
Volume = ± 0.15 milliliter

Example: Line 3 of Table C

This density was obtained from a weight measurement of 123.7 grams and a volume measurement of 101.01 milliliters

$$\rho = 123.7 \text{ grams} / 100.01 \text{ milliliters} = 1.225 \text{ grams} / \text{liter}$$

$$\text{Therefore, } [(0.5 / 123.7)^2 + (0.15 / 101.01)^2]^{(1/2)} \times 100\% = \pm 0.43\% \text{ (0.005 g/ml)}$$