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**Hydraulic Properties of Hanford
Waste Vitrification Project 39-4 Frit
Slurries**

G.P. Abrigo

March 1996

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

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

MASTER

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Pacific Northwest National Laboratory
Richland, Washington 99352

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SUMMARY

Pacific Northwest Laboratory (PNL) conducted this study for Fluor Daniel Inc. and Westinghouse Hanford Company. The purpose of the study was to assess the effect of solids loading on the hydraulic properties of frit slurries.

The effect of solids loading on the hydraulic properties of the frit slurries was evaluated by testing various concentrations of frit slurries in various sized schedule 40 stainless steel piping. The pressure drop in straight and 90-degree long radius elbow sections was measured as a function of flow-rate, pipe size, and solids concentration.

The results of testing yielded recommendations for predicting the pressure drop as a function of solids concentration, pipe size, and flow-rate. The contribution of a 90-degree long radius elbow to the pressure drop was measured and recommendations given. Observations were also made on solids settling in the lines, wear on the testing equipment, slurry properties, and measuring equipment performance. The equipment and procedures used for pumping the high solids concentration frit slurry were successful in completing the test.

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Jim Davis	Technical Consultation, Performing Test Procedures
Charles Freeman	Technical Support, Critical Thinking, Document Review
Steve Halstead	Technical Consultation, Performing Test Procedures
George Jensen	Document Review
Don Larson	Technical Consultation, Document Review
Rick McKay	Technical Support

ABBREVIATIONS LIST

DAS	Data Acquisition System
FST	Frit Slurry Test
HB	High-Bay in 324 Building, Hanford 300 Area
HWVP	Hanford Waste Vitrification Project
NPSH	Net Positive Suction Head
PNL	Pacific Northwest Laboratory
SIPT	Slurry Integrated Performance Testing
STL	Slurry Test Loop

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1.0 INTRODUCTION

This report satisfies the objectives for the Frit Slurry Testing addendum considered part of the Test Plan HWVP-91-1.2.2.03.03B, Rev. 1, "Test Plan Slurry Integrated Performance Testing (SIPT) Hanford Waste Vitrification Program." This addendum report covers the testing program for Frit Slurry Testing (FST).

Fluor Daniel Inc., as part of the Hanford Waste Vitrification Project (HWVP) preliminary design, estimated pipe-line sizes and pump head requirements for the HWVP process slurries. The pipe-line size estimates were based on requirements for maintaining flow rates of 3 to 10 ft/s. The pump head requirement estimates were based on published hydraulic correlations for pressure drop and published viscosities for glass frit slurries. The published viscosities were obtained from the Technical Data Package (TDP). These estimates indicated a requirement for pump discharge head capabilities beyond that which can be met by commercially available air-driven duplex diaphragm pumps. The foundation for this conclusion was based on Net Positive Suction Head (NPSH) requirements.

Based on the results of the estimates mentioned above, Fluor Daniel Inc. had indicated a need for obtaining more accurate hydraulic properties of frit slurries. In particular, a need for pressure drop versus flow rate data was specified. The FST provides a means for obtaining information pertaining to the frit slurry hydraulic properties. Specifically, the FST will provide data for flow rate versus pressure drop data for various flow rates, frit concentrations, and pipe sizes and fittings. The FST is intended to meet the requirements of Fluor Daniel Inc. Technical Need Items 1.8a and 1.8b (see appendix A for the full need statement). The testing covered by this report satisfies key milestone K-1018.

1.1 FRIT SLURRY DESCRIPTION

The various frit slurries characterized in this test consisted of the following components:

- Water, 324 Building process water
- 90 wt% Formic Acid
- Frit (HWVP 39-4, supplied by American Porcelain) with particle size ranges from the vendor specifications of 80 mesh (177 microns) to 200 mesh (74 microns) with less than 10 wt% solids smaller than 200 mesh. The frit composition was an alkali-boro-silicate. The exact composition of the frit used is included in section 4.1.1.

Various concentrations of frit slurry were prepared to measure the effect of solids loading on the pressure drop. Table 1.1 summarizes the physical properties of the various frit slurries tested in the slurry test loop. Water was also tested for acceptance of the slurry test loop instrumentation.

TABLE 1.1. Summary of Properties of the Frit Slurries Tested

<i>Target Frit Slurry Concentration (wt%)</i>	<i>Actual Frit Slurry Concentration (wt%)</i>	<i>Density (g/mL)</i>	<i>pH</i>
8	9.3 ± 0.2	$.99 \pm .01$	$4.0 \pm .1$
45	43.5 ± 1.2	$1.1 \pm .03$	$3.5 \pm .1$
60	55.5 ± 0.5	$1.4 \pm .05$	$3.3 \pm .02$

2.0 OBJECTIVES

The objectives of the FST are based on the Fluor Daniel Inc. Need Data Sheet, Item 1.8a and 1.8b. The Need Data Sheet is included in Appendix A for reference. These data needs were used to compile the following test objectives.

2.1 DETERMINE THE PRESSURE DROP AS A FUNCTION OF FLOW RATE

The pressure drop as a function of flow-rate was measured for the frit slurries at the following process conditions:

- flow rate (minimum range 3 to 10 ft/s)
- pipe diameter (schedule 40 stainless steel: 1/2 in., 1 in., 1 1/2 in., 2 in., 3 in.)
- frit concentration (0 wt%, 8 wt%, 45 wt%, 60 wt%)
- pipe configuration (straight and butt-welded long radius elbow)

No temperature control existed in the FST system. Therefore, the fluid temperature sensitivity was not evaluated. As a result, efforts were made to maintain a consistent temperature throughout testing.

The experimental pressure drop versus flow data was correlated and compared, if possible, to empirical and theoretical models.

2.2 EVALUATE THE PHYSICAL PROPERTIES OF THE DRY FRIT AND OF EACH FRIT SLURRY

The following physical properties of each frit slurry were evaluated:

- density (slurry, frit particle, and frit bulk)
- wt% solids of slurries
- pH
- settling rate

2.3 OBSERVE THE PUMPABILITY OF THE FRIT SLURRY

Observations on slurry pumpability and system wear were taken.

2.0 OBJECTIVES

The objectives of the FST are based on the Fluor Daniel Inc. Need Data Sheet, Item 1.8a and 1.8b. The Need Data Sheet is included in Appendix A for reference. These data needs were used to compile the following test objectives.

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2.3 OBSERVE THE PUMPABILITY OF THE FRIT SLURRY

Observations on slurry pumpability and system wear were taken.

2.4 EVALUATE THE EFFECTIVENESS OF MIXING AND OBSERVE SETTLING OF SOLIDS

Samples were taken at the inlet and outlet of the Slurry Test Loop (STL) and the frit concentrations of the samples were analyzed and compared to target concentrations.

An assessment of solids settling in the process lines as a function of flow rate (3 to 10 ft/s) was made by monitoring the pressure drop and flow-rate in the test-line as a function of time.

3.0 EQUIPMENT DESCRIPTION

The equipment used in the FST consisted of a slurry feed tank and an STL composed of five different line sizes (1/2 in., 1 in., 1 1/2 in., 2 in. and 3 in.) equipped with flow-meters, differential pressure transmitters, and control valves. This equipment was located in the 324 building/High Bay. Figures 3.1. and 3.2. show the equipment used in Frit Slurry Testing.

3.1 SLURRY FEED TANK (HB-34)

The frit slurry used in the FST was held in a tank, designated HB-34. The vessel is 5 ft. in diameter by 7 ft. 8 in. in height. It has a maximum capacity of 685 gallons and a normal operating capacity of 500 gallons. Penetrations support a center-mounted agitator, an internal coil, chemical addition lines, and water lines, as well as process monitoring instrumentation.

3.1.1 Transfer Pump (P-2011)

The frit slurry was pumped from the slurry feed tank through the STL by a Peerless feed pump, P-2011. This centrifugal pump had a 2 in. discharge and was driven via a 25 horsepower electrical motor. The pump was capable of supplying 150 gpm against 60 psi discharge pressure.

3.1.2 Variable Speed Agitator (AG-2006)

Tank HB-34 is equipped with a Sharpe agitator that has two impellers mounted on a single shaft. Both are 15 in. diameter axial flow impellers. The lower impeller was mounted 8 in. (20 cm.) above the bottom of the vessel on the bottom of the shaft and upper impeller was mounted 24 in. (61 cm.) from the bottom of the shaft. A 2 hp variable speed electric motor was coupled to a reduction gear that rotates the shaft at a maximum rate of 124 rpm. The agitator was operated at 80% of full power.

3.1.3 Thermocouple (TI-3400)

Tank HB-34 was also equipped with a thermowell in which a type J thermocouple, TI-3400, resides. The thermocouple measures the tank's temperature and is calibrated within a range of 0 to 750 °C.

FIGURE 3.1. Frit Slurry Test System
3rd Floor High Bay
324 Building

FIGURE 3.2. Frit Slurry Test System
2nd Floor High Bay
324 Building

3.2 HOLDING TANK (HB-15)

The Feed Preparation Test System test vessel (tank HB-15) was used as a holding tank while water flushing the frit slurry test loop. After testing a specific line, the test line was flushed forward and backward with water and air to HB-15.

The tank has a 12 ft. inside diameter, is 16-1/2-ft. tall, and has an operating capacity of 9,400 gal. The enclosed tank is constructed from Carpenter 20 Cb-3 steel, with the exception of the support structure which is fabricated from carbon steel. The overall vessel height, including the support structure, is 18 ft.

3.3 SLURRY TEST LOOP (STL)

The slurry test loop is composed of five line sizes (1/2 in., 1 in., 1 1/2 in., 2 in. and 3 in. diameter) of Schedule 40 stainless steel pipe. Each line size has a straight and long radius elbow section. The STL is equipped with a 1/2 in. line with air at 90 psi and a 1 in. line with water at 90 psi for flushing clean the lines. The flow rate in each specific pipeline is controlled by the downstream valve configuration and monitored by a magnetic flow-meter that is located so that the flow-rate in each test section can be measured. Differential pressure instruments measured the pressure drop across straight sections and long radius elbow sections of each line size. Valved ports were used to sample slurry at the inlet and outlet of the FSTL. A data acquisition system gathered measurements from the pressure and flow transmitters at 15 s intervals and stored it in a computer file.

3.3.1 Flow-meters

Endress and Hauser FTI-1943 Variomag magnetic flow-meters were located in the 1/2 in. (FI-0203), 1 in. (FI-0202), 1-1/2 in. (FI-0204), and the initial 3 in. (FI-0205) supply line to the STL. Using these flow-meters, the flow-rate through all lines in the STL can be measured. All of these flow-meters have Teflon liners. The 1/2 in. and 1 in. flow-meters have 316 stainless steel measuring electrodes while the 1 1/2 in. and 3 in. flow-meters have Hastelloy measuring electrodes.

3.3.2 Pressure Transmitters

The pressure drop in straight sections and long radius elbow sections of pipe was measured using:

- PIC W24 Type TF Flow Through Remote Seals (PI Instruments, Inc.)
- Rosemount 3051CD Smart Differential Pressure Transmitters

These pressure transmitters are located on all five line sizes tested. Table 3.1 summarizes the dimensions and locations of the pressure transmitters on the straight pipe sections. Table 3.2

summarizes the dimensions and locations of the remote seal pressure transmitters on the elbow pipe sections. The remote seal pressure units contained a recessed cavity in which a sealed diaphragm measures the fluid pressure. The remote seal units were designed specifically to separate the pressure instrument from the media while allowing the instrument to sense the process pressure. A diagram of a remote seal unit is shown in Figure 3.3.

TABLE 3.1. Dimensions of Straight Section Pressure Transmitters

Straight Test Section (I.D. #)	Length Between Pressure Transmitters	Minimum distance from Pipe Fittings (elbows)
3 in. (PI-0210)	17.4 ft.	8 ft.
2 in. (PI-0202)	22 ft.	7 ft.
1 1/2 in. (PI-0208)	18.4 ft.	5 ft.
1 in. (PI-0204)	25 ft.	4 ft.
1/2 in. (PI-0206)	25 ft.	2 ft.

TABLE 3.2. Dimensions of Elbow Section Remote Seal Pressure Transmitters

Elbow Test Section (I.D. #)	Pressure Transmitter Upstream from Long Radius Elbow	Pressure Transmitter Downstream from Long Radius Elbow
3 in. (PI-0209)	111 in.	91.5 in.
2 in. (PI-0201)	117 in.	81 in.
1 1/2 in. (PI-0207)	33.5 in.	59 in.
1 in. (PI-0203)	29 in.	47 in.
1/2 in. (PI-0205)	27.5 in.	24.4 in.

FIGURE 3.3. Remote Seal Unit

The results from water testing the elbow sections with remote seal instruments indicate that they were reading between 30 and 300% higher than expected literature results. Due to this discrepancy, 1/16 in. taps were drilled into the tops of the 1/2 in., 1 in., 1-1/2 in., and 2 in. elbow sections to verify the remote seal results. The pressure tap holes were cleaned of any burrs that might affect the pressure drop measurements. These taps were attached to a Rosemount 3051CD pressure transmitter (PI-0211) via 3/8 in. plastic tubing and Swagelok fittings. The 3/8 in. tubing was purged of air by filling the lines with water before any measurements. Water was periodically added to the differential pressure lines to fill and flush out any solids in the pressure tap holes. No problems with clogging of the water-filled pressure tap lines were observed. Subsequent water pressure drop testing with the taps indicated that the remote seals pressure units in the elbow section were reading much higher. The pressure drop data taken with taps corresponded better with expected literature values than remote seal data and was, therefore, used in the FST elbow pressure drop analysis. Elbow section remote seal data was used to confirm trends in the elbow contribution pressure drop between water and frit slurries. Table 3.3 indicates the locations of the elbow section 1/16 in. taps.

Remote seal units were originally chosen because of their ease of use in slurry systems. After installation, no regular maintenance is required. The 1/16 in. taps added to the elbow sections required that the lines be filled with water and periodically flushed to ensure that the taps were not clogged. The taps were drilled in the top of the pipe and no clogging problems were experienced during testing.

TABLE 3.3. Dimensions of Elbow Section 1/16 in. Taps

Elbow Test Section (I.D. #)	Pressure Tap Upstream from Long Radius Elbow	Pressure Tap Downstream from Long Radius Elbow
2 in.	4 in.	72.5 in.
1 1/2 in.	1.3 in.	51.5 in.
1 in.	1.1 in.	41.1 in.
1/2 in.	1 in.	19.3 in.

3.4 DATA ACQUISITION SYSTEM

Data during slurry test loop testing was acquired from instruments by a Hewlett Packard (HP)-3852 Scanning Voltmeter. The HP-3852 performed all engineering unit conversions on the data acquired from its internal Analog-Digital Converters (ADC). A processing unit - INTEL 80386-based AT-Architecture Computer converted the data from the HP-3852 and performed alarm range checking, displayed user-selected data values in both text and visual forms, and provided data archiving facilities. Data from tests were stored in binary format and converted into Microsoft Excel files.

4.0 TEST APPROACH

To satisfy the test objectives in the test plan, two test procedures: TP93-FST-01: "Acceptance Testing of Frit Slurry Test System with Water" and TP93-SIPT-01: "Frit Slurry Makeup and Frit Slurry Transfer Testing" were written and followed. Some modifications were made to the test procedures regarding flushing, sampling, and 1/16 in. tap measurements.

4.1 TEST PREPARATION

4.1.1 Frit Slurry Makeup

The frit slurry makeup consisted of combining and mixing the frit slurry components to produce a homogenous slurry. The components of the slurry were measured (by weight) and then combined in the Frit Slurry Feed Tank (FSFT), Tank HB-34. The process variables considered in this step were the following:

- Frit Concentration (0 wt%, 8 wt%, 45 wt%, and 60 wt%)
- 90 wt% Formic Acid Concentration (1% by weight of the Frit)

Calculations indicated that 450 gal. of frit slurry was adequate to fill all FST lines and maintain an appropriate level in the tank HB-34 for agitation. The frit slurry components necessary to provide 450 gal. of frit slurry are listed in Table 4.1.

TABLE 4.1. Amount of Materials Required in Different Concentrations of Frit Slurry Makeup

Concentration (wt%)	lb. of Water	lb. of Frit	lb. of 90% Formic Acid
0	3750 (450 gal)	0	0
8	3626 (435.4 gal)	315.6	3.5 (0.35 gal)
45	2481 (341.1 gal)	2346	26.1 (2.6 gal)
60	2358 (283.1 gal)	3596	40.0 (4.0 gal)

The components of the frit slurry listed in Table 4.1 consist of the following:

- Water, 324 Building process water

- 90 wt% Formic Acid
- Frit (39-4), comprised of the following:
 - 70 wt% Silica Dioxide, SiO_2
 - 14 wt% Boron Oxide, B_2O_3
 - 9 wt% Sodium Oxide, Na_2O
 - 5 wt% Lithium Oxide, Li_2O
 - 1 wt% Calcium Oxide, CaO
 - 1 wt% Magnesium Oxide, MgO

4.1.2 Homogeneity Assessment

The components were mixed until homogeneity was achieved. Pumping the frit slurry also helped mix the tank contents because the material was pumped from the bottom of the tank. Homogeneity was not assessed from samples taken from the tank. Instead, samples were taken from the sample ports at the inlet and outlet of the STL. Samples used to assess tank homogeneity were taken at high flow-rates through the slurry test loop to minimize the possibility of settling in the test line. These samples were analyzed for wt% solids and compared with the target slurry concentration.

4.2 PRESSURE DROP MEASUREMENT AND SETTLING ASSESSMENT

4.2.1 Pressure drop measurement

The pressure drop measurement portion of the test consisted of pumping the frit slurry through the STL per procedure TP-93-SIPT-01. Pressure drop and flow data were recorded using the Data Acquisition System (DAS). The process variables included are as follows:

- pipe size (stainless steel schedule 40: 1/2 in, 1in., 1-1/2 in., 2 in., 3 in.)
- pipe configuration (straight pipe, butt-welded long radius elbow)
- flow rate (minimum range 3 to 10 ft/s)
- frit concentration (0 wt%, 8 wt%, 45 wt%, and 60 wt% frit)
- temperature (ambient °C)

Separate pipe lines corresponding to each of the different pipe diameters have been included in the STL. The pipe size process variable was accommodated by pumping the frit slurry through the appropriate test line of the STL.

4.2.2 Settling Assessment

A settling assessment as a function of flow rate in the STL was originally to be made by comparing the frit concentration from samples taken at the STL inlet and the STL outlet sample ports. An assessment of the 8 wt% frit slurry was made by taking samples during the pressure drop versus flow test. Visually inspecting the samples for differences in solids content, it was clear that there was too much error in the sampling method to reach any conclusion on settling. Instead, settling in the lines was assessed by monitoring for increasing pressure drop and decreasing flow-rate as a function of time.

4.3 POST TEST ACTIVITY

The post test activities did not consider any process variables. The post test activity was as follows:

- **Flush frit slurry from lines**
After testing a specific line, it was immediately flushed. Two different flushing procedures were tried. During the 8 wt% test, at the conclusion of each line test, the return line to the tank was isolated and the frit slurry in the test line was water and air flushed down to a holding tank (HB-15) through the low point of the system. Then the test line was isolated and the return line to HB-34 was water and air flushed to the holding tank. This method, however, allowed time for the solids in one line to settle while the other line was being flushed. This might lead to plugging in the higher wt% solid frit slurries. Therefore, another method was used for the 45 and 60 wt% frit slurry tests. Immediately after line testing, the test line and return lines were immediately flushed back to HB-34 with air. After the test and return line were cleared, they were individually water and air flushed down to the holding tank. The amount of water required to flush the line was determined qualitatively. Usually the test line was hot due to friction from pumping frit slurry. Therefore, enough flush water was used until the operator could feel the temperature on the test pipe decrease. Flush air was turned on until air was heard flowing through the pipe at a maximum rate. This flushing method proved successful in preventing clogging or plugging in the lines for the highest frit slurry concentrations.

5.0 RESULTS

FST occurred from March 18, 1994 to April 25, 1994. During this time, 8 wt%, 45 wt%, and 60 wt% frit slurries were made-up and then pumped in the STL at varying velocities to obtain pressure drop versus flow curves. The magnetic flow-meters had difficulty measuring the flow-rate of high concentration frit slurries. The noise suppression and time constants were adjusted on some flow-meters to account for the noise fluctuations in the magnetic flow-meter, but this did not entirely solve the problem. Table 5.1 summarizes the actual concentrations, densities and pH of the frit slurries tested. Table 5.2 summarizes the average temperature of the test fluid in HB-34 during testing.

Due to difficulties measuring the velocity of high wt% slurries at high flow-rates (as will be discussed later), not all the tests could be completed over the flow-range and concentrations desired. The 3 in. test at 60 wt% frit slurry was canceled due to problems during the 45 wt% frit slurry test where settling at the low velocity range and problems measuring the velocity at high flow-rates occurred.

TABLE 5.1. Summary of Properties of Frit Slurries Tested

Target Frit Slurry Concentration (wt%)	Actual Frit Slurry Concentration (wt%)	Density (g/mL)	pH
8	9.3 ± 0.2	.99 ± .01	4.0 ± .1
45	43.5 ± 1.2	1.1 ± .03	3.5 ± .1
60	55.5 ± 0.5	1.4 ± .05	3.3 ± .02

TABLE 5.2. Summary of Average Fluid Temperatures during Testing

Test	1/2 in. Line	1 in. Line	1 1/2 in. Line	2 in. Line	3 in. Line
0% frit	38 °C	19.1 °C	34.1 °C	29.2 °C	25.8 °C
8% frit	39.6 °C	36.7 °C	30.3 °C	24.4 °C	25.0 °C
45% frit	33.1 °C	35.5 °C	31.8 °C	28.8 °C	40.2 °C
60% frit	36.0 °C	40.4 °C	44.3 °C	30.4 °C	N/A

5.1 DETERMINE THE PRESSURE DROP AS A FUNCTION OF FLOW-RATE

5.1.1 Acceptance Testing with Water (0 wt% Frit)

Straight Sections

Before the FST, the instruments in the test loop were tested with water to ensure correct readings. Water was pumped through the test loop over the specified flow range (3 to 10 ft/s). The results of the water testing (shown in Appendix B) indicated that the straight section differential pressures (measured using remote seals units) fell within expected values of smooth (roughness = 0 ft) and commercial (roughness = .00015 ft) Schedule 40 pipe. These differential pressures were nearer to the pressure drops expected in smooth pipe.

The expected pressure drop due to friction in the pipe was calculated by using the Fanning/Darcy equation (Sakiadis 1984):

$$\frac{\Delta P}{L} = \left(\frac{4f}{D} \right) \frac{V^2}{2g_c} \rho \quad (1)$$

Where

- $\Delta P/L$ is the pressure drop per length of pipe, psi/ft
- V is the velocity, ft/s
- f is the friction factor
- D is the pipe diameter, ft.
- ρ is the fluid density, lb/ft³
- g_c is the gravitational constant, 32.2 ft/s²

The friction factor, f , for water was calculated using the Colebrook equation (Sakiadis 1984):

$$\frac{1}{\sqrt{f}} = -4 \cdot \log \left(\frac{\epsilon}{3.7D} + \frac{1256}{Re\sqrt{f}} \right) \quad (2)$$

- ϵ is the roughness of the pipe, ft.
- Re is the Reynolds number = $\rho DV/\mu$, dimensionless, where
- μ is the fluid (water) viscosity, cp. To convert cp to lb/(ft sec) multiply cp by 6.7197 E -4.

$$\mu = -24.7 + 4.21E3/T + 4.53E-2T - 3.38E-5 T^2 [=] \text{ cp}, \quad (\text{Reid et. al. 1987) and}$$

T is the temperature in Kelvin

The Shacham correlation, shown below, was also used to calculate the f and is within 1% of the Colebrook equation. This was used in some calculations because it does not require an iterative solution.

Shacham Correlation (Olujic 1981):

$$f = \frac{1}{4} \left\{ -2 \log \left(\frac{\epsilon/D}{3.7} - \frac{5.02}{Re} \log \left(\frac{\epsilon/D}{3.7} + \frac{14.5}{Re} \right) \right) \right\}^{-2} \quad (3)$$

The straight section water pressure drop data was converted into a friction factors vs. Reynolds number plot. This data is shown in Figure 5.1. Using the Shacham equation to estimate the roughness of the pipes in the straight sections in the test loop, an average relative roughness, ϵ/D , of .00015 was found for the STL. This relative roughness relates closely to a smooth pipe in the flow-range tested. A curve fit ($y=ax^b$) of the friction factor data is also shown in Figure 5.1 which has an R^2 ^(a) of 0.86. All flow was observed to be turbulent based on a Reynolds number of greater than 4,000. The scatter in the data shown in Figure 5.1 was probably due to differences in the individual pipe roughnesses.

FIGURE 5.1. Friction factor vs. Reynolds Number for Water (3 to 10 ft/s)

^(a) The Pearson product moment correlation coefficient squared. This can be interpreted as the proportion of the variance in y due to the variance in x for a line curve-fit through known x and y data points.

90° Long Radius Elbows

The results of the remote seal measurements for elbow sections were mixed. Although the entire elbow section pressure drop fell within expected values for commercial and smooth pipe, the elbow-only pressure drops differed significantly from expected, especially for the smaller pipe sizes (1/2 in. and 1 in.). The pressure transmitters were located so that the elbow contribution to the elbow section pressure drop was ~20%. To calculate the experimental elbow-only pressure drop, the straight lengths in the elbow section were subtracted out from the elbow section pressure drop ($\Delta P_{\text{elbow only}} = \Delta P_{\text{elbow section}} - L_{\text{straight length in elbow section}} \cdot (\Delta P/L)_{\text{straight section}}$). The straight lengths in the equation were the measured lengths from the center of the pressure transmitter remote seal to the elbow weld. The pressure drop per length of the straight section ($\Delta P/L_{\text{straight section}}$) was calculated by dividing the measurement from the straight section differential pressure transmitters by the distance between the pressure transmitters. The expected elbow pressure drop was calculated by multiplying the expected pressure drop/length by the equivalent lengths of straight pipe due to the elbow. The expected pressure drop/length was calculated for both smooth and commercial pipe over the experimental flow-range using the Colebrook equation. Table 5.3. shows literature values for the equivalent length/diameter values used in calculating the expected elbow pressure drop. An uncertainty of 25% is associated with these literature values.

TABLE 5.3. Summary of Literature and Experimental Water L_e/D s at High Flow-Rates (>8 ft/s)Equivalent Straight Section Pressure Drop per Diameter (L_e/D)

<i>Test Section</i>	<i>Bend Radius / Diameter</i>	<i>Literature Value L_e/D*</i>	<i>1/16 in. Tap Data L_e/D</i>	<i>Remote Seal Data L_e/D</i>
1/2 in. (0.622 in. i.d.)	1.47	9.5	5	28
1 in. (1.049 in. i.d.)	1.45	14	18	24
1 1/2 in. (1.66 in. i.d.)	1.40	14	14	24
2 in. (2.067 in. i.d.)	1.43	14	6	14
3 in. (3.068 in. i.d.)	2.41	14	N/A	19

*Perry's Chemical Engineers' Handbook, sixth edition, pg. 5-39, Fig. 5-45.

*Perry's Chemical Engineers' Handbook, sixth edition, pg. 6-57, Table 6-15.

The pressure drop due to the elbow was also evaluated by calculating the ratio of equivalent lengths of straight pipe pressure drop to diameter (L_e/D) and comparing experimental results with that expected from literature. The location of the remote seal pressure units and 1/16 in. taps were located so that the elbow contribution to the elbow section pressure drop was significant. Table 5.4 summarizes the elbow contribution to the elbow section pressure drop in the flow-range tested for the 1/16 in. tap. The L_e/D was calculated using the following equation:

$$\frac{L_e}{D} = \frac{\Delta P_{\text{elbow_only}}}{(\Delta P / L)_{\text{straight_section}} (D)} \quad (4)$$

TABLE 5.4. Estimated Contribution of Elbow to Elbow Section Pressure Drop in the Flow-Range Tested

Test Section	Elbow Pressure Drop Contribution	
	~ 3 ft/s	~ 10 ft/s
2 in.	25%	20%
1 1/2 in.	50%	29%
1 in.	17%	22%
1/2 in.	17%	15%

The calculated L_e/D values at each flow-rate tested using the remote seal pressure sensors are shown in Figure 5.2. The calculated L_e/D using remote seal pressure data is between 35% and 300%

higher than that reported by the literature. The calculated L_e/D s were lower at the higher flow-rates and increased as the flow-rate was decreased. The 1/2 in. elbow section L_e/D value was much higher than reported by the literature and was not lower than the other lines as predicted by literature.

Calculated L_e/D values at each flow-rate tested for the 1/16 in. tap measurements are shown in Figure 5.3. The water tap data corresponded closer to literature values and agreed with the literature prediction that the 1/2 in. line has a lower L_e/D value than the other line sizes. Even though the average of the tap data was different from literature values, the literature values were hit for all but one case. The literature L_e/D values also seemed to be in the median of L_e/D values as measured by water taps. The 1/2 in. line, as predicted by literature has a lower L_e/D than the other elbow sections because it had a higher bend radius/diameter and was a less sharp bend than the other elbows.

Table 5.3. also summarizes the water fluid L_e/D values at high velocities (> 8 ft/s) as measured by the remote seal unit and direct pressure tap measurements. The remote seal units in the elbow sections measured higher pressure drops than expected literature values and water tap measurements. The 1/2 in. line in the direct tap pressure measurement resulted in a lower L_e/D than the other elbow sections (as predicted by literature) while the remote seal measurement of the same pressure drop was higher. Due to the discrepancies between remote seal data and expected results, the 1/16 in. tap data will be reported in this report for the 1/2 in., 1 in., 1-1/2 in. and 2 in. line sizes. No direct taps were added to the 3 in. elbow section so remote seal results will be presented for this elbow section.

FIGURE 5.2. Water Test: Elbow Section Pressure Drops as measured by Remote Seal Sensors

FIGURE 5.3. Water Test: Elbow Section Pressure Drop as measured by 1/16 in. Taps

The remote seal pressure units contained a recessed cavity in which a sealed diaphragm measured the fluid pressure (see Figure 3.3). The remote seal units were designed specifically for slurry systems which may plug pressure taps. It is believed that the recessed cavity in the remote seal unit may have induced turbulence in the fluid flow directly after the remote seal unit which increased the pressure drop in the pipe. The increased pressure drop due to the induced turbulence was small in comparison the total measured signal. This was apparent because the experimental straight and elbow section results were within the expected results of smooth and commercial pipe. However, when extracting the elbow only pressure drop (which is a small pressure drop) from the elbow section pressure drop, the relative contribution of the induced turbulence from the remote seal unit to the extracted elbow only pressure drop was large and resulted in a much higher pressure drop and L/D than expected. The 1/16 in. taps used for measuring the elbows were located either far downstream from the remote seal units or upstream from the remote seal units in an attempt to avoid any flow turbulence induced by the remote seal units. Use of remote seal units to measure pressure drops in a section of pipe was adequate and experimental results fell within expected results. However, the use of remote seal units to extract the contributions of fittings was limited due to its accuracy.

5.1.2 Frit Slurry Testing

Frit slurry testing was conducted per procedure TP93-SIPT-01; "Frit Slurry Makeup and Frit Slurry Transfer Testing." Some modifications were made to the procedure during the testing. The

flushing procedure was revised for the 45 wt% and 60 wt% frit slurries to minimize the amount of settling in the lines as described in Section 4.3.1. Also because taps were added into all but the 3-in. long radius elbow sections, the pressure transmitter lines from the tap to the pressure transmitter were water filled and purged of air. Periodically during the test, they were flushed to ensure that frit had not clogged the 1/16 in. taps.

Flow-meter Performance

The 3 to 10 ft/s flow-range was attempted for all frit concentrations and line sizes except the 3 in. line with the 60 wt% frit slurry. As the wt% solids in the frit slurry increased, the amount of noise in the 1 in., 1-1/2 in., and 3 in. flow-meter measurements increased. Only the 1/2 in. flow-meter did not exhibit the flow measurement fluctuations of the other lines. Also as the wt% solids in the frit slurry increased, there seemed to be a limit to the maximum flow a meter could read. This was realized during the 45 wt% frit slurry test. As the flow was increased past the flow-meter limits, the pressure drop increased (indicating a higher flow-rate), but the average of the flow-meter measurements did not increase, and sometimes decreased. The decrease in flow-rate and increase in pressure drop could not have been due to settling and clogging in the lines at these higher flow-rates. This can be seen in the plots of pressure drop versus flow in the straight sections shown in Appendix C.

Endress and Hauser, the flow-meter manufacturer, was contacted about the problems and they had two possible explanations which were tested. First, entrained air could have been trapped in the system resulting in erroneous readings. This theory was tested by sampling the frit slurry from the taps at the top of the elbow sections. Samples from the test loop were drawn through a tube into a slurry filled bucket. The tube was held below the liquid level in the bucket so that gas bubbles could be observed. However, no air bubbles were observed and, therefore, this theory was rejected. The second possible explanation was that the particles in the line were impacting the measuring electrodes in the magnetic flow-meters and causing noise. Particles striking the electrodes induce a higher measured voltage (which is converted into flow velocity). Indeed at high flow velocities, the 1-1/2 in. flow-meter kept displaying an over-range error, while the data logged on the DAS seemed to be lower than expected. Technical support from Endress and Hauser indicated that the 1/2 in. flow-meter did not exhibit the noise problem because its measuring electrodes were embedded in the side and not as exposed to the fluid. Therefore, to reduce the noise in the signal, the time constant and noise suppression on the 1-1/2 in. and 3 in. flow-meters were adjusted to steady the readings and minimize the noise. These adjustments did minimize the noise a bit, but still resulted in anomalous pressure drop versus flow curves at high flow-rates and solids concentrations. Final consultation with Endress and Hauser indicated that these flow-meters were recommended to be used with abrasives at a range of < 8 ft/s. It is suspected that the

amount of noise encountered increases with the velocity (increased momentum) and concentration of the solid particles. And after some combination of these two factors, the noise induced from particles striking the electrode overwhelm the actual measured signal resulting in false readings. This phenomena can be seen in the raw data results shown in Appendix C in which the pressure drop increases while the measured flow-rate decreases.

Due to this contradiction in readings, a subsequent test was conducted to verify the flow-meter readings below the upper flow-measurement limit. The frit slurry was run through just one line but two flow-meters: the 3 in. and 1-1/2 in. flow meters. The flow in the line was reduced until the 3 in. flow-meter and 1-1/2 in. flow-meters were reading essentially the same, both the instantaneous and totaled flow-measurements. This occurred at approximately 8 ft/s in the 1-1/2 in. line. Much more noise occurred in the 1-1/2 in. flow measurements than the 3 in. flow measurements because 8 ft/s in the 1-1/2 in. flow meter is a lower flow velocity for the 3 in. line. A final test was done in which part of tank HB-34 contents were transferred to another tank that was equipped with load cells to monitor the weight transferred. The amount of slurry transferred was measured by the 3 in. flow-meter, the 1-1/2 in. flow-meter, and the receiving tank load cells. The velocity in the line was set so that the 3 in. and 1-1/2 in. flow-meters corroborated with each other. Slurry was transferred from HB-34 to the other tank for approximately two minutes and the amount of slurry transferred was calculated using the measured total flow through the two flow-meters and the change in weight of the receiving tank. The conclusion of this test was that the amount transferred as measured by the flow-meter agreed with the change in weight of the receiving tank.

Because of the anomalies in the pressure drop versus flow measurements due to the flow-meter problem. Much of the data in the tests were not included in data analysis, especially at the higher flow-rates. The invalid points were deleted when the pressure drop increased and the flow-reading did not increase. A few points below this occurrence were also deleted from the data analysis. Appendix D shows the raw data taken during frit slurry testing and delineates the data used in frit slurry testing analysis (used in curve fit data).

Although the measured flows fluctuated during a steady state measurement, the measured pressure drops in the test line remained steady. In fact the pressure drop readings were a better indicator of the flow conditions during testing than the flow meters. Endress and Hauser suggested that electrodeless or DC magnetic flow-meters might be able to measure the flow of abrasive slurries better.

Straight Section

Several approaches were used to try to characterize the pressure drop of the various frit slurries and previous waste simulants. The Durand and Condolios correlation was investigated, unfortunately, this correlation requires the solid particle size and volume % solids in the mixture (Govier and Aziz 1982). Because previous waste simulants were heterogeneous mixtures, a distribution of solid particle sizes and the volume % solids was not easily obtainable. To keep the data analysis approach consistent, this approach was rejected. Another approach was to plot the friction factor of the frit slurry data versus the Reynolds number. The viscosity used in the Reynolds number was calculated using several viscosity correlations assuming a pseudo-homogeneous suspension (e.g. Thomas Equation and Guth and Simha Equation). However, these viscosity correlations did not improve the fit of the data versus using water viscosity, and at low velocities this assumption fails as concentration gradients form in the liquid.

Direct viscosity measurements of the frit slurries were not feasible due to the time dependent nature of the fluid. The solids in the mixture begin settling out immediately without agitation. Therefore, frit particles in the mixture would settle rapidly during a rheogram analysis, which requires measurements be taken under laminar flow. Because the characteristic time of the liquid (the fast settling time) is shorter than the experimental time required to attain an adequate rheology measurement, this was decided to be an inadequate method for measuring frit slurry viscosities. Even attaching an impeller onto a viscometer to keep the particles suspended, is limited because standards or correlations are not available for such systems.

Another approach to characterize the viscosity of the mixture is to calculate the friction factor from the pressure drop data and use a friction factor versus Reynolds number correlation such as the Colebrook equation. The published correlations of friction factor versus Reynolds numbers (e.g. Equation (2)) are valid for Newtonian fluids. The viscosity of Newtonian fluids should be constant as a function of shear rate (and therefore, velocity). Given a friction factor and assuming a relative roughness (ϵ/D) of .00015, the Reynolds number could be calculated from Equation (2). For a particular density, velocity, and pipe diameter, the viscosity of the mixture could be calculated. For this calculated viscosity value to be valid, the fluid must be Newtonian and the viscosity nearly constant at the various velocities (and shear rates). Calculations were done for the 1/2 inch pipe at the 8 wt% concentration. Using the above method to calculate the viscosity, the viscosity did not remain constant but increased with increasing velocities (shear rate). Because the friction factor versus Reynolds number correlation used is valid only for Newtonian fluids in which the viscosity remains constant with shear rate, this method of correlating the data was rejected.

Literature correlations of the pressure drop due to sand/water slurries essentially plot pressure drop versus velocity (Govier and Aziz 1982). Because the frit slurry test involved several line sizes, the dimensionless friction factor was used to correlate the pressure drop of the various sized lines to compare the effect of solids loading on the pressure drop. The Fanning friction factor (solve for f in Equation (1)) was calculated for the frit slurry testing data. Figure 5.4 shows a plot of friction factor versus velocity for the various frit concentrations. The friction factor was then curve fit as a function of velocity using a statistical analysis program called AXUM® by TRIMETRIX to a $f = aV^b$ formula. The results of this curve fit for the various concentrations are shown in Table 5.5.

FIGURE 5.4. Friction Factor vs. Velocity Plot of Various Frit Slurries (with standard deviations)

TABLE 5.5. Summary of $f = a (V)^b$ curve fits of various frit concentrations shown in Figure 5.4.

<i>Target Frit Concentration</i>	<i>Actual Frit Concentration</i>	<i>a</i>	<i>b</i>	<i>R²</i>
0 wt% (water)	0 wt%	$7.333\text{E-}3 \pm 3.36\text{E-}4$	-0.2143 ± 0.0225	0.71
8 wt%	9.3 wt%	$8.932\text{E-}3 \pm 5.30\text{E-}4$	-0.2882 ± 0.0323	0.71
45 wt%	43.5 wt%	$1.623\text{E-}2 \pm 8.52\text{E-}4$	-0.4637 ± 0.0299	0.86
60 wt%	55.6 wt%	$1.845\text{E-}2 \pm 1.59\text{E-}3$	-0.5451 ± 0.0500	0.82

As can be seen in Figure 5.4 as the frit concentration increased, the deviation of the frit slurry friction factor increased with respect to water. As the frit slurry concentration increased, the effective roughness of the fluid/pipe surface interface increased, thereby increasing the frictional losses, and consequently, the higher pressure drop. This can be seen in the curve fit intercept values (Table 5.5 column a), as the concentration increased so did the curve fit intercept values. At lower velocities, the deviation from water increases as concentration gradients form in the fluid increasing the resistance to flow and therefore the pressure drop. As the concentration increases higher velocities are required to keep the solids in the mixture suspended. Thus, the slope of the curve increases with increasing frit slurry concentration (Table 5.5 column b). Although the friction factor for the 43 and 55 wt% frit slurries are almost super-imposed in Figure 5.4, the pressure drop due to the 55 wt% frit slurry at the same velocity was actually higher because the 55 wt% frit slurry has a higher density.

A further correlation of the friction factor coefficients based on frit concentration was done using AXUM®. The coefficients a and b in Table 5.5 were plotted and correlated as a function of solids concentration. Figure 5.5 compares the actual friction factor coefficients versus the correlation of the coefficients. Shown below Equation (5) is an equation to predict the friction factor as a function of frit concentration and velocity.

$$f_{\text{frit slurry}} = [7.216\text{E-}3 + 2.042\text{E-}2 X] V^{[-0.2161 - 0.5847 X]} \quad (5)$$

Where X = the weight fraction solids, $0 < X < 0.60$

V = mixture velocity, 3 to 10 ft/s

FIGURE 5.5. Comparison of actual and correlated friction factor coefficients

Elbow Section

Due to the problems measuring the flow caused by the frit particles, the errors associated with the elbow sections results are large. Shown in the following figures (Figure 5.6 - Figure 5.8), however, are the calculated L_e/D s for the various frit slurries. The pressure drop (ΔP) versus flow-rate (Q) data of both the straight and elbow sections was curve fit to a $\Delta P = aQ^b$ equation using AXUM. The L_e/D values were calculated using Equation 4 and the curve fits of FST data.

Table 5.6 and Figures 5.6 through 5.8 summarize the results of testing with 1/16 in. taps. For the 1 in., 1-1/2 in., 2 in. and 3 in. elbows ($R/D = 1.4$), indicated essentially no change in L_e/D for frit slurry over water. A slight increase occurred in the 1/2 in. elbow ($R/D = 2.4$) L_e/D with increasing solids concentration. An unexpected result in the higher frit concentration slurries was that the L_e/D values decreased with decreasing velocity.

Table 5.6 summarizes the L_e/D values as measured by water taps for the various frit slurries flowing at high velocities. The 1 in., 1-1/2 in., and 2 in. lines, essentially, show no change in the L_e/D values throughout the various concentrations of frit slurry. The 1 in., 1-1/2 in., 2 in. and 3 in. elbows (Bend $R/D = 1.4$) had L_e/D values ranging from approximately 15 to 20 throughout most of the tests.

TABLE 5.6. L_0/D values at high velocities as measured by 1/16 in. taps.(~8 ft/s)

<i>Frit Concentration</i>	<i>1/2 in.</i>	<i>1 in.</i>	<i>1 1/2 in.</i>	<i>2 in.</i>	<i>3 in.*</i>
0 wt%	5	18	14	6	19
8 wt%	5 ± 3	19 ± 6	13 ± 16	15 ± 50	15 ± 40
45 wt%	10 ± 2	18 ± 20	16 ± 20	13 ± 20	0 ± 200
60 wt%	20 ± 7	20 ± 30	15 ± 50	15 ± 40	N/A

*Measured by Remote Seal Unit

FIGURE 5.6. 8 wt% Frit Slurry: L_0/D vs. Velocity as measured by 1/16 in. taps

FIGURE 5.7. 45 wt% Frit Slurry: L_p/D vs. Velocity as measured by 1/16 in. taps

FIGURE 5.8. 60 wt% Frit Slurry: L_p/D vs. Velocity as measured by 1/16 in. taps

Table 5.7 summarizes L_p/D values taken with remote seal units. They corroborate with the 1/16 in. tap data that, essentially, little change occurred in the L_p/D values with increasing concentrations.

TABLE 5.7. L_0/D values at high velocities as measured by remote seal units (6-8 ft/s)

<i>Frit Concentration</i>	<i>1/2 in.</i>	<i>1 in.</i>	<i>1 1/2 in.</i>	<i>2 in.</i>	<i>3 in.</i>
0 wt%	28	24	24	14	19
8 wt%	24 ± 3	26 ± 10	20 ± 20	14 ± 90	15 ± 40
45 wt%	29 ± 3	28 ± 40	19 ± 40	13 ± 20	0 ± 200
60 wt%	42 ± 16	30 ± 50	21 ± 70	13 ± 40	N/A

5.2 EVALUATE THE PHYSICAL PROPERTIES OF THE DRY FRIT AND OF EACH FRIT SLURRY

The bulk and particle density of HWVP 39-4 frit (80 to 200 mesh) were evaluated. Laboratory measurement of the bulk frit density was obtained by tarring a 25 mL graduated cylinder, filling the cylinder with a volume of frit, and weighing the filled cylinder. The particle density was obtained by adding water into a graduated plastic centrifugal tube and measuring the initial volume and weight of the water filled tube. Dry frit was then added into the tube, ensuring that no frit was on the sides of the tube. The volume and weight of the frit/water solution in the tube was measured. The density of the frit could be calculated by dividing the change in the weight by the change in the volume. The results of the bulk density and particle density measurements are shown in Table 5.8.

TABLE 5.8. Measured Bulk and Particle Density with Standard Deviations

Bulk Density (gm/mL)	Particle Density (gm/mL)
$1.16 \pm .05$	2.4 ± 0.2

The frit particle size ranges of the HWVP 39-4 frit used in testing came from American Porcelain specifications: 80 mesh (177 microns) to 200 mesh (74 microns) with less than 10 wt% solids smaller than 200 mesh.

The physical properties of each frit slurry was evaluated following makeup. These included the density, wt% solids, pH, and settling rate. All these are summarized in the Table 5.9. The wt% solids was determined by drying the frit slurry in an oven at 105 °C for 24 hours or firing the frit slurry in an oven at 1000 °C for 2 to 3 hours. The pH was measured using a Coming pH 240 meter. As the concentration of solids was increased, the pH of the mixture decreased (became more acidic) as formic

acid was added to equal 0.1% of the added frit weight. The settling rate was measured by pouring a frit slurry sample into a graduated cylinder, stirring the cylinder until the frit slurry was well mixed, and measuring the volume of solids settled on the volume and the time. The settling rate was obtained by performing a linear regression on the data. Figure 5.9 shows the settling rate data for the various frit slurries. As the solids concentration in the frit slurry increased, the settling rate (volume fraction settled per time) decreased. The settling rate decreased with increasing frit concentration because the number of particle collisions increased and hindered settling. Sample calculations for the settling rate calculation are shown in Appendix D.

TABLE 5.9. Summary of Frit Slurry Physical Properties

Target Frit Slurry Concentration (wt%)	Actual Frit Slurry Concentration (wt%)	Density (g/mL)	pH	Settling Rate (Vol.%/s)
8	9.3 ± 0.2	$.99 \pm .01$	$4.0 \pm .1$	10
45	43.5 ± 1.2	$1.1 \pm .03$	$3.5 \pm .1$	3
60	55.5 ± 0.5	$1.4 \pm .05$	$3.3 \pm .02$	2

FIGURE 5.9. Volume Fraction Settled vs. Time for Various Frit Slurry Concentrations

The rheological properties of the frit slurry were to be determined using a Haake viscometer and star rotor. The direct viscosity measurements of the mixture are impossible to obtain due to the time dependent nature of the fluid. The frit in the mixture begins settling out immediately without agitation or turbulent mixing. The frit solids in the mixture would be settling during a rheogram analysis which requires measurements be taken under laminar flow. Because the characteristic time of the liquid (the fast settling time) is shorter than the experimental time required to attain an adequate rheology measurement, no adequate method exists for measuring the viscosities of frit slurries. Brookfield was contacted about attaching an impeller to suspend the solids and measure the viscosity in their viscometers. Unfortunately there are currently no standards or correlations to measure fluid viscosity based on an impeller that agitates the fluid.

Most pressure drop versus flow correlations for liquid/solid mixtures cited in the literature (e.g. Govier and Aziz 1982) also do not include the mixture viscosity because of the time dependent nature of liquid/solid mixtures. Instead empirical fits of pressure drop data are based on the volume percent solids concentrations, particle sizes, and velocity. These empirical fits usually plot a function of pressure drop versus a function of flow.

5.3 OBSERVE THE PUMPABILITY OF THE FRIT SLURRY

The small scale feed preparation system worked well during frit slurry testing. The 25 horsepower peerless centrifugal pump attached to the HB-34 bottom drain was able to pump all the frit concentrations (including the 60 wt% frit slurry) through the STL without any plugging problems. Immediately flushing the lines with air and water after pumping kept the frit from settling and plugging the lines.

Erosion in the test loop pipes was noticed from frit slurry samples taken. There appeared to be a fine layer of steel particles in the samples. The amount seemed to increase as the test was run. The erosion in the pipes was verified by preliminary ultrasonic measurements which indicated wear on piping immediately after the HB-34 pump discharge. The amount of fine metal in the samples increases as the test progressed and the frit concentrations increased.

Two different flushing methods were used during frit slurry testing. Initially after running a test, the test lines were forward water and air flushed down to a holding tank (HB-15). Then, the return line was backward flushed with water and air down to the holding tank. The drawback to this method is that while the test line was being flushed, solids were settling in the return line. Another method used to flush

the system was, immediately after turning off the pump, to flush the frit slurry filled test lines back to HB-34 with air. This method reduced the amount of time the frit slurry was settling in the lines. After flushing the test lines up to HB-34, the test and return lines were forward and backward flushed with water and air to a holding tank.

5.4 EVALUATE THE EFFECTIVENESS OF MIXING AND OBSERVE SETTLING OF SOLIDS

Operating the agitator at 80% of full, there appeared to be good mixing in the tank. This was verified by the fact that samples taken from the slurry test loop were near the target values and did not contain much scatter (see Table 5.9.).

Settling in the lines, which could be due to fluid flowing below the critical velocity (the velocity at which particles begin to accumulate on the pipe bottom), was speculated to have observed only once during the test. In the 3-in. line during the 45 wt% solids test, the pressure drop in the straight section of pipe increased with time while the velocity decreased with time at approximately 3 ft/s. This is shown in Figure 5.10. If this condition were allowed to continue, plugging would likely occur. No tests were done in the 3-in. STL at 60 wt% frit slurry, but it is expected that the critical velocity would have been higher than in the 45 wt% frit slurry. The dotted line in Figure 5.10. indicates the approximate critical velocity at which settling was likely beginning.

Figure 5.10. also illustrates the problem measuring the velocity in the system. At the higher flow-rates, although much scatter exists in the velocity measurements, the measured pressure drop measurements were essentially constant indicating a steady flow-rate.

FIGURE 5.10. Straight Section Pressure Drop of 45 wt% frit slurry in the 3 in. test line

During 60 wt% frit slurry testing in the 1/2 in. line, the pressure drop versus flow diagram began to flatten out as a concentration gradient forms in the fluid (see Figure 5.11). The dotted line in Figure 5.11 indicates the critical velocity at which settling is likely beginning. At this fluid velocity and slightly below this would likely result in a moving bed of particles on the pipe floor (Govier and Aziz 1982). If the fluid velocity was further decreased sedimentation would form on the pipe bottom and pipe blockage could occur (Govier and Aziz 1982).

FIGURE 5.11. Straight Section pressure drop of 60 wt% frit slurry in the 1/2 in. test line

6.0 CONCLUSIONS

The straight section pressure drops for various frit slurry concentrations can be obtained from the curve-fit of the data shown in Figure 5.4. To estimate the frit slurry pressure drop, first the friction factor for frit slurry should be calculated for a particular velocity and frit concentration using Equation (6). The pressure drop per length can then be directly calculated for a particular fluid density, velocity, and pipe diameter using Equation (7).

$$f_{frit\ slurry} = [7.216E-3 + 2.042E-2 X] V^{[-0.2161 - 0.5847 X]} \quad (6)$$

Where X = the weight fraction solids, $0 < X < 0.6$
 V = the mixture velocity, $3 \text{ ft/s} < V < 10 \text{ ft/s}$

$$\frac{\Delta P}{L} = \left(\frac{4 f_{frit\ slurry}}{D} \right) \frac{V^2}{2 g_c} \rho \quad (7)$$

Where $\Delta P/L$ = the pressure drop per length of pipe, psi/ft
 D = the pipe diameter, ft.
 ρ = the fluid density, lb/ft^3
 g_c = the gravitational constant, 32.2 ft/s^2

The long radius elbow L_e/D values did not show a significant increase over water with increasing frit concentration. An L_e/D value of 20 should be used for the 1 in., 1-1/2 in., 2 in. and 3 in. long radius elbows (Bend $R/D = 1.4$). An L_e/D value of 10 should be used for the 1/2 in. long radius elbow (Bend $R/D = 2.4$). The 1/2 in. elbow has a lower L_e/D value because it has a higher bend radius/diameter and, therefore, is a less sharp bend than the other elbows. Table 6.1 summarizes recommended L_e/D values for the elbow sections.

TABLE 6.1. Summary of Recommended L_e/D Values for Design Purposes

Long Radius Elbow	Bend Radius / Diameter	Recommended L_e/D
1/2 in.	2.41	10
1 in.	1.43	20
1 1/2 in.	1.40	20
2 in.	1.45	20
3 in.	1.47	20

The estimated pressure drop due to frictional losses of frit slurry flowing in Schedule 40 stainless steel pipe and long radius elbows can be calculated as follows:

$$\Delta P = \left(\frac{\Delta P}{L} \right) \cdot \left(L_{st} + n \cdot \frac{L_e}{D} \cdot D \right) \quad (8)$$

Where

ΔP is the pressure drop in the a section of horizontal piping due to frictional losses.

$\Delta P/L$ is the pressure drop per length as calculated in the equation above using $f_{frit\ slurry}$

L_{st} is the length of straight section in the piping, ft.

n is the number of 90 degree long radius elbow bends

L_e/D is from Table 6.1.

D is the pipe diameter, ft.

7.0 REFERENCES

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APPENDIX A: FLUOR DANIEL TECHNOLOGY NEED DATA SHEET

FLUOR DANIEL TECHNOLOGY NEED DATA SHEET

Tech Need Item 1.8 a & b - Hydraulic Properties of Slurries ✓

Pipe-line sizes and pump head requirements for HWVP slurries were estimated during Preliminary Design using standard published hydraulic correlations for pressure drop. Viscosities for glass frit slurries were also based on published correlations. (Viscosities for waste oxide-frit mixtures were taken from the HWVP TDP).

Slurry lines must be sized to meet velocity limitations of 3-10 feet per second, per both the TDP and good engineering practice, to avoid settling of solids at low velocities and high erosion at high velocities. The slurry systems must also be designed within the discharge head capabilities and NPSH limitations of commercially available pumps. In both the frit slurry systems and the waste oxide/frit transfer systems, using pipe sizes which met the velocity criteria resulted in excessively high pressure drop.

The primary problem in the frit slurry system was with NPSH requirements. With the calculated pressure drop in the frit slurry pump suction line, using a line size which results in at least 3 ft/sec, it is not possible to meet the NPSH requirements of commercially available air-driven duplex diaphragm pumps. The calculated pressure drop in the frit slurry pump discharge lines is also high and may be a problem depending on the final piping layout.

The primary problem in the waste oxide/frit slurry systems is the high pressure drop calculated for the half-inch sample transfer lines. The high pressure drop is largely a result of using the viscosity data from the TDP, which is known to be conservatively high.

Data are required from the WHC prototype testing program to confirm or correct the calculated pressure drops and viscosities for the frit and waste oxide/frit systems. The attached table shows the data which are required. The table should be completed by filling in the pressure drop, velocity, and viscosity for each line item. The data may be obtained from bench scale experiments. The test liquid should duplicate exactly the HWVP frit slurry and waste oxide/frit slurry mixtures in all rheological properties.

FLUOR DANIEL TECHNOLOGY NEED DATA SHEET

Tech Need Item 1.8a & b - Hydraulic Properties of Slurries

FLUID TO BE ANALYZED	NOMINAL PIPE SIZE	PIPE SCHEDULE	FLOW (GPM)	FITTINGS	TEMP DEG F	dP PSI/100 FT	VEL FT/SEC
60% Frit Slurry	1/2"	80 40	7	Straight Pipe L.R Elbow	70		
60% Frit Slurry	1"	80 40	7	Straight Pipe L.R Elbow	70		
60% Frit Slurry	2"	40	40	Straight Pipe L.R Elbow	70		
60% Frit Slurry	3"	40	70	Straight Pipe L.R Elbow	70		
8% Frit Slurry	1/2"	80 40	3	Straight Pipe L.R Elbow	70		
8% Frit Slurry	1 1/2"	80 40	30	Straight Pipe L.R Elbow	70		
8% Frit Slurry	2"	40	85-100	Straight Pipe L.R Elbow	70		
Waste Oxide/Frit Mixture as in SME & MFT	1/2"	80 40	3	Straight Pipe L.R Elbow	125		
Waste Oxide/Frit Mixture as in SME & MFT	1"	40	8	Straight Pipe L.R Elbow	125		
Waste Oxide/Frit Mixture as in SME & MFT	2"	40	100	Straight Pipe L.R Elbow	125		

3-10
ft/sec

APPENDIX B: ACCEPTANCE TESTING WITH WATER RESULTS

STL Straight Sections**1/2" Straight Section**

Avg. Temp. = 36 C

1" Straight Section

Avg. Temp. = 18.1 C

1 1/2" Straight Section

Avg. Temp. = 34.1 C

2" Straight Section

Avg. Temp. = 29.2 C

STL Elbow Sections

1/2" El bow Section (Remote Seal s)

1/2" El bow Only (Remote Seal)

Avg. Temp. = 38.1 C, Le/D = 9.5

1 1/2" Elbow Section (Remote Seal)

Avg. Temp. = 34.1 C

1 1/2" Elbow Only (Remote Seal)

Avg. Temp. = 34.1 C, Le/D = 14

2" El bow Section (Remote Seal)

Avg. Temp. = 29.2 C

2" El bow Only (Remote Seal)

Avg. Temp. = 29.2 C, Le/D = 14

Elbow Sections (Water Taps)

1/2" Elbow Section (Water Tap)

Avg. Temp. = 38.1 C, Le/D = 9.5

1/2" Elbow Only (Water Tap)

Avg. Temp. = 38.06 C, Le/D = 9.5

1 1/2" Elbow Section (Water Tap)

Avg. Temp. = 34.1 C, Le/D = 14

1 1/2" Elbow Only (Water Tap)

Avg. Temp. = 34.1 C, Le/D = 14

2" El bow Section (Water Tap)

Avg. Temp. = 29.2 C, Le/D = 14

2" El bow Only (Water Tap)

Avg. Temp. = 29.2 C, Le/D = 14

**APPENDIX C: FRIT SLURRY PRESSURE DROP TESTING RAW DATA AND CURVE
FIT RESULTS**

8 wt% Frit Slurry

8 wt% Frit Slurry
1 1/2" Line 8 wt% Frit Slurry
2" Line

45 wt% Frit Slurry

60 wt% Frit Slurry

Summary of Pressure Drop vs. Flow

Curve Fits for FST Testing

$$\Delta P = a \cdot (\text{gpm})^b$$

Standard Error in a & b

$$a = a \pm c$$

$$b = b \pm d$$

Curve fits of ΔP and sigma ΔP were obtained

using AXUM software by TRIMETRIX

0 wt% Water

Line Size	dP Instrm.	a	b	R ²	c	d	Avg. Temp	Comments
3"	PI-0210	0.00137	1.77137	1	5.74E-05	0.00835	25.79	
	PI-0209	0.00011	2.27079	1	4.01E-06	0.00736		
2"	PI-0202	0.00722	1.87055	1	4.31E-05	0.00129	29.23	
	PI-0201	0.00864	1.80363	1	0.00012	0.00306		
	PI-0211	0.00472	1.73728	0.98	0.00027	0.01218		
1 1/2"	PI-0208	0.02345	1.80185	1	0.00023	0.00254	34.11	
	PI-0207	0.02069	1.70138	1	0.00087	0.01105		
	PI-0211	0.01607	1.63175	1	0.00082	0.0133		
1"	PI-0204	0.31973	1.71552	1	0.00298	0.00336	19.14	
	PI-0203	0.11508	1.69549	1	0.00146	0.00457		
	PI-0211	0.06018	1.74041	1	0.00147	0.0081		
1/2"	PI-0206	3.18339	1.78617	1	0.00753	0.00122	38.06	
	PI-0205	1.03624	1.62574	1	0.02447	0.01215		
	PI-0211	0.33771	1.65428	1	0.00691	0.01052		

8 wt% Frit Slurry

Line Size	dP Instrm.	a	b	R^2	c	d	Avg. Temp	Comments
3"	PI-0210	0.00361	1.58734	0.99	0.00026	0.01447	24.95	
	PI-0209	0.00048	1.99641	0.99	2.06E-05	0.00862		
2"	PI-0202	0.00799	1.86485	0.98	0.00094	0.02846	24.42	
	PI-0201	0.01399	1.71277	0.98	0.00154	0.02674		
	PI-0211	0.00078	2.16833	0.98	0.00013	0.04093		
1 1/2"	PI-0208	0.04647	1.66038	0.99	0.00185	0.0108	30.3	
	PI-0207	0.02723	1.65273	0.99	0.00115	0.01145		
	PI-0211	0.01137	1.73949	0.99	0.00063	0.01497		
1"	PI-0204	0.40946	1.63762	1	0.00698	0.00601	36.73	
	PI-0203	0.17981	1.56291	1	0.00322	0.00631		
	PI-0211	0.09401	1.60593	1	0.00189	0.00709		
1/2"	PI-0206	3.71145	1.73177	1	0.01581	0.0024	39.64	
	PI-0205	0.9363	1.67641	1	0.00701	0.00421		
	PI-0211	0.27639	1.75325	1	0.0075	0.01527		

45 wt% Frit Slurry

Line Size	dP Instrm.	a	b	R^2	c	d	Avg. Temp	Comments
3"	PI-0210	0.02447	1.27025	0.74	0.00947	0.08181	40.2 *	
	PI-0209	0.00142	1.8338	0.72	0.00077	0.11492		
2"	PI-0202	0.03069	1.63696	0.98	0.00138	0.01072	28.82	
	PI-0201	0.03999	1.54696	0.98	0.00174	0.01039		
	PI-0211	0.00553	1.8024	0.97	0.00038	0.01637		
1 1/2"	PI-0208	0.21745	1.3471	0.93	0.01741	0.02296	31.8 *	
	PI-0207	0.0661	1.49548	0.93	0.0052	0.02256		
	PI-0211	0.02776	1.59593	0.92	0.00225	0.02326		
1"	PI-0204	0.93031	1.4813	0.92	0.06673	0.02714	35.51 *	
	PI-0203	0.33639	1.472	0.92	0.02432	0.02735		
	PI-0211	0.17977	1.49579	0.91	0.01373	0.0289		

1/2"	PI-0206	7.44681	1.51856	1	0.06005	0.00462	33.11
	PI-0205	1.54942	1.56471	1	0.00549	0.00229	
	PI-0211	0.68758	1.49878	1	0.01048	0.00873	

60 wt% Frit Slurry

Line Size	dP Instrm.	a	b	R^2	c	d	Avg. Temp	Comments
3"	PI-0210							N/A
	PI-0209							
2"	PI-0202	0.07049	1.49113	0.91	0.00655	0.02269	30.38 *	
	PI-0201	0.07543	1.44321	0.91	0.0068	0.02167		
	PI-0211	0.01286	1.65491	0.9	0.00133	0.02482		
1 1/2"	PI-0208	0.30752	1.27328	0.87	0.04674	0.04562	44.33 *	
	PI-0207	0.12017	1.37598	0.87	0.01965	0.04906		
	PI-0211	0.04448	1.50415	0.87	0.00796	0.05368		
1"	PI-0204	2.51733	1.15385	0.9	0.25749	0.04328	40.38 *	
	PI-0203	0.76211	1.21557	0.9	0.80367	0.04462		
	PI-0211	0.51913	1.15944	0.88	0.06017	0.04904		
1/2"	PI-0206	12.6802	1.29337	0.98	0.52758	0.02359	35.95	
	PI-0205	2.02211	1.50964	1	0.0357	0.01001		
	PI-0211	0.87465	1.5029	1	0.01491	0.00967		

* Note not all the data points were included. See specific graph to see which data points were not included in data analysis

**APPENDIX D: RAW DATA AND CALCULATION OF PHYSICAL PROPERTIES OF
DRY FRIT AND FRIT SLURRY**

Wt% Solids Calculation

Target wt%	Avg. wt%	Stdev	Sample wt%	Sample Number	Lab Numbers
8%	9.31%	0.17%	9.14%	FST-8-3-210-U	716-94,a,b
			9.41%	FST-8-1 1/2-63-U	714-94,a
			9.19%	FST-8-1-27-U	715-94,a,b
			9.49%	FST-8-1/2-9-U	713-94,a,b
45%	43.53%	1.16%	42.20%	HB-34-3/28/94	744-94,a
			44.10%	HB-34-3/29/94	742-94,a
			44.30%	FST-45-3-MAX-Ua	743-94,a
60%	55.55%	0.52%	55.60%	HB-34-4/25/94-12:48	813-94
			56.04%	HB-34-4/25/94-14:17	814-94
			55%	HB-34-4/25/94-16:06	815-94

Density Calculation

Avg. Density g/mL	Stdev	Density	Sample Number	Lab Numbers
0.99	0.0050	0.98	FST-8-3-210-U	716-94,a,b
		0.99	FST-8-1 1/2-63-U	714-94,a
		0.99	FST-8-1-27-U	715-94,a,b
		0.99	FST-8-1/2-9-U	713-94,a,b
1.12	0.0252	1.10	HB-34-3/28/94	744-94,a
		1.15	HB-34-3/29/94	742-94,a
		1.12	FST-45-3-MAX-Ua	743-94,a
1.37	0.0458	1.32	HB-34-4/25/94-12:48	813-94
		1.41	HB-34-4/25/94-14:17	814-94
		1.38	HB-34-4/25/94-16:06	815-94

Correlation of f vs. VelocityCurve Fitting of a and b using AXUM software by TRIMETRIX

$$a = 0.007215911 + 0.0204233 X$$

$$b = -0.2160589 -$$

$$0.58467 X$$

X, wt% solids	a	a curve fit	b	b curve fit
0	0.007333	0.007216	-0.21434	-0.21606
9.31%	0.008933	0.009117	-0.28821	-0.27049
43.50%	0.016269	0.0161	-0.46372	-0.47039
55.55%	0.01845	0.018561	-0.54514	-0.54084

Frit Slurry Testing

pH Calculation as measured by Corning pH

240 meter

8 wt% frit	pH	avg pH	stdev pH
FST-8-1-1/2-58-U	3.99	4.00	0.11
FST-8-2-105-U	3.90		
FST-8-3-170-D	4.12		

45 wt% frit

HB-34B - 3/28/94	3.42	3.50	0.08
FST-45-1/2-MAX-UA	3.58		
FST-45-3-MAX-DB	3.50		

60 wt% frit

FRIT-60-1	3.29	3.28	0.02
HB-34d	3.26		

FST-DRY HWVP 39-4 FRIT DENSITY

BULK DENSITY

5/9/94

25 mL graduated cylinder

Added dry frit into a tared 25 mL graduated cylinder

Measured volume and weight to get density

cylinder wt	volume	cyln + frit	frit	density	
gm	mL	gm	gm	gm frit/mL	
59.57	14.80	76.44	16.87	1.14	
	13.20	74.67	15.10	1.14	
	10.80	72.86	13.29	1.23	
	6.20	66.52	6.95	<u>1.12</u>	
				1.16	Avg
				0.05	Stdev

FST-DRY HWVP 39-4 FRIT DENSITY

PARTICLE DENSITY

25 mL graduated plastic centrifuge tube

Added water into tube, measured weight and volume

Added dry frit into tube, measured weight and volume

Repeated adding frit to tube 3 times

	weight, gm	volume, mL	density (gm/mL)=dweight/dvolume	
initial	10.79	6.10		
add frit	12.00	6.60	2.43	
add frit	13.80	7.40	2.25	
add frit	15.82	8.30	2.24	
add frit	17.41	8.90	<u>2.64</u>	
			2.39	Avg
			0.19	Stdev

Settling Rate Calculation

	Tot V (mL)	Vol (mL)	time	Vol%	Linear Interpolation	Vol%/s	Vol% CF
8 wt%	8	2	5	0.25 slope	0.106419	10.64189	0.234797
SAMPLE		5	9	0.625 intercept	-0.2973		0.660473
FST-8-1-1/2-58-U		8	12	1 R^2	0.993243		0.97973
				steyx	0.043593		
45 wt%	46	2	2	0.043478 slope	0.034976	3.497617	0.026823
SAMPLE		5	4	0.108696 intercept	-0.04313		0.096776
HB-34B-3/28/94		10	7	0.217391 R^2	0.988906		0.201704
		12	10	0.26087 steyx	0.042146		0.306633
		20	15	0.434783			0.481513
		30	20	0.652174			0.656394
		40	24	0.869565			0.796299
		44	28	0.956522			0.936204
		46	31	1			1.041132
60 wt%	64	2	4	0.03125 slope	0.017173	1.717298	0.080558
SAMPLE		5	5	0.078125 intercept	0.011866		0.097731
FRIT-60-1		8	8	0.125 R^2	0.973206		0.14925
		10	9	0.15625 steyx	0.057553		0.166423
		14	12	0.21875			0.217942
		20	16	0.3125			0.286633
		22	20	0.34375			0.355325
		26	22	0.40625			0.389671
		30	26	0.46875			0.458363
		32	28	0.5			0.492709
		50	40	0.78125			0.698785
		58	48	0.90625			0.836169
		62	53	0.96875			0.922034
		64	66	1			1.145282

APPENDIX E: SAMPLE CALCULATIONS

Slurry Test Loop Straight and Elbow Section Lengths

Inside Diameters of Schedule 40 Pipe

$d0x5 := .622 \cdot \text{in}$
 $d1x0 := 1.049 \cdot \text{in}$
 $d1x5 := 1.66 \cdot \text{in}$
 $d2x0 := 2.067 \cdot \text{in}$
 $d3x0 := 3.068 \cdot \text{in}$

Elbow Dimensions from Perry's Chemical Engineers' Handbook Table pg. 6-57
Table 6-15: Butt-Welding Fittings

Bend Radius = bR = distance to center of pipe

$bR0x5 := 1.5 \cdot \text{in}$
 $bR1x0 := 1.5 \cdot \text{in}$
 $bR1x5 := 2.25 \cdot \text{in}$
 $bR2x0 := 3 \cdot \text{in}$
 $bR3x0 := 4.5 \cdot \text{in}$

Measured Straight Section Lengths of Remote Seal Units

$Ls3x0rs := (111 + 91.5) \cdot \text{in}$	$Ls3x0rs = 16.875 \cdot \text{ft}$
$Ls2x0rs := (117 + 81) \cdot \text{in}$	$Ls2x0rs = 16.5 \cdot \text{ft}$
$Ls1x5rs := (33.5 + 59) \cdot \text{in}$	$Ls1x5rs = 7.708 \cdot \text{ft}$
$Ls1x0rs := (29 + 47) \cdot \text{in}$	$Ls1x0rs = 6.333 \cdot \text{ft}$
$Ls0x5rs := \left(27.25 + 24 + \frac{3}{8}\right) \cdot \text{in}$	$Ls0x5rs = 4.302 \cdot \text{ft}$

Measured Straight Section Lengths of Pressure Water Taps

$Ls2x0wt := (4 + 72.5) \cdot \text{in}$	$Ls2x0wt = 6.375 \cdot \text{ft}$
$Ls1x5wt := (1.25 + 51.5) \cdot \text{in}$	$Ls1x5wt = 4.396 \cdot \text{ft}$
$Ls1x0wt := (1.125 + 41.125) \cdot \text{in}$	$Ls1x0wt = 3.521 \cdot \text{ft}$
$Ls0x5wt := (1 + 19.25) \cdot \text{in}$	$Ls0x5wt = 1.687 \cdot \text{ft}$

Lengths of Elbow Only

$Lel0x5 := \frac{1}{4} \cdot 2 \cdot \pi \cdot bR0x5$	$Lel2x0 := \frac{1}{4} \cdot 2 \cdot \pi \cdot bR2x0$
$Lel1x0 := \frac{1}{4} \cdot 2 \cdot \pi \cdot bR1x0$	$Lel3x0 := \frac{1}{4} \cdot 2 \cdot \pi \cdot bR3x0$
$Lel1x5 := \frac{1}{4} \cdot 2 \cdot \pi \cdot bR1x5$	

$Lel0x5 = 0.196 \cdot \text{ft}$
 $Lel1x0 = 0.196 \cdot \text{ft}$
 $Lel1x5 = 0.295 \cdot \text{ft}$
 $Lel2x0 = 0.393 \cdot \text{ft}$
 $Lel3x0 = 0.589 \cdot \text{ft}$

Remote Seal Elbow Section Lengths

$1/2'' \quad Lel0x5 + Ls0x5rs = 4.498 \cdot \text{ft}$
 $1'' \quad Lel1x0 + Ls1x0rs = 6.53 \cdot \text{ft}$
 $1 \ 1/2'' \quad Lel1x5 + Ls1x5rs = 8.003 \cdot \text{ft}$
 $2'' \quad Lel2x0 + Ls2x0rs = 16.893 \cdot \text{ft}$
 $3'' \quad Lel3x0 + Ls3x0rs = 17.464 \cdot \text{ft}$

Water Tap Elbow Section Lengths

$Lel0x5 + Ls0x5wt = 1.884 \cdot \text{ft}$
 $Lel1x0 + Ls1x0wt = 3.717 \cdot \text{ft}$
 $Lel1x5 + Ls1x5wt = 4.69 \cdot \text{ft}$
 $Lel2x0 + Ls2x0wt = 6.768 \cdot \text{ft}$

Sample Calculation of Friction Factor for Frit Slurries

1/2" Line Data

$$\rho := 0.99 \frac{\text{gm}}{\text{mL}} \quad \text{Frit Density for 8 wt\% frit slurry}$$

$$d := 0.622 \cdot \text{in} \quad d = 0.052 \cdot \text{ft}$$

$$L := 25 \cdot \text{ft} \quad \text{Length between Pressure transmitters}$$

Test conditions at one flow-rate, the straight section pressure drop was:

$$v := 10.188714 \cdot \frac{\text{ft}}{\text{sec}}$$

$$dP_1 := 176.25 \text{ in. H}_2\text{O}$$

$$dP := \frac{dP_1}{27.7276} \cdot \text{psi}$$

$$dP = 6.356 \cdot \text{psi}$$

Convert Water Pressure Drop to psi (68 F), From Crane pg. B-11, Equivalents of Pressure and Head

From Perry's Chemical Engineers' Handbook, pg. 5-24, eqn. (5-57), solving for f

$$f := \frac{dP \cdot 2 \cdot d}{(\rho \cdot 4 \cdot L \cdot v^2)} \quad f = 0.00476 \quad \text{Check}$$

Excel Calculation of f from in. H₂O / ft. dP/L:

To convert dP (in. H₂O/ft) to dP ((lb/sq. ft)/ft):

$$(\text{in. H}_2\text{O/ft}) \cdot ((\text{lb/in}^2)/27.7276 \text{ in H}_2\text{O}) \cdot (144 \text{ in}^2/\text{ft}^2)$$

$$dPoL := \frac{dP_1 \cdot \text{in} \cdot \left(\frac{\text{lb}}{\text{in}^2} \right)}{L \cdot 27.7276 \cdot \text{in}} \quad dPoL = 0.254 \cdot \frac{\text{lb}}{\text{in}^2 \cdot \text{ft}}$$

$$dPoL := dPoL \cdot \frac{(12 \cdot \text{in})^2}{1 \cdot \text{ft}^2} \quad dPoL = 36.613 \cdot \text{lb} \cdot \text{ft}^{-3}$$

$$f := dPoL \cdot \frac{\text{lb/ft}^3 \quad \text{ft} \quad 32.2 \text{ ft/sec}^2}{(2 \cdot v^2 \cdot \rho)} \quad f = 0.00476 \quad \text{Check}$$

ft/sec lb/ft³

Battelle

Pacific Northwest Laboratories

CALCULATION WORKSHEET

Calc. No. _____

Page 1 of 4

Sample Calculation for dP of water flowing through pipe w/
roughness $(\epsilon) = 0.7$ and $E = .00015$ ft.

$1/2"$ Straight Section:

$$D = 0.622 \text{ in} = .0518 \text{ ft}$$

$$L_{st} = 25 \text{ ft}$$

$$L_{eb} = 11.75 \text{ ft.}$$

$$Q_{wg} = 9.19 \text{ gpm}$$

$$dP_{st, meas} = 171.33 \text{ "H}_2\text{O}$$

$$dP_{st, meas} / 25 \text{ ft} = 6.85 \text{ "H}_2\text{O} / \text{ft.}$$

$$dP_{eb, meas} = 91.88 \text{ "H}_2\text{O} / \text{ft.}$$

$$Q \text{ } T = 38.9^\circ\text{C} = 312.05 \text{ K}$$

$$\rho_w = 61.97 \text{ lb} / \text{ft}^3 \quad (\text{Perry's. CH + 13})$$

$$\text{Velocity} = 9.09 \frac{\text{gal}}{\text{min}} \times \frac{35.313 \text{ L}}{264.17 \text{ gal}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{1}{\pi \left(\frac{0.622 \text{ in} \cdot \frac{1 \text{ ft}}{12 \text{ in}} \right)^2} = 9.6 \text{ ft/s}$$

$$\text{Viscosity: } \ln \eta = -2.47E1 + \frac{4.21E3}{312.05 \text{ K}} + (4.53E-2) 312.05 \text{ K} - (3.38E-5) (312.05 \text{ K})^2$$

$$\eta \text{ (cp)} = e^{-0.38266} = 0.682 \text{ cp}$$

from Reid, Prausnitz, Poling;
Properties of Gases & Liquids;
McGraw Hill; pg. 455.

$$\text{Re \#} : \text{Re \#} = \frac{50.6 Q \rho}{D \mu} \quad \text{from Crane; Flow of Fluids Tech Paper \#410; (Eqn 3-3)}$$

$$\text{Re \#} = \frac{(50.6)(9.19 \text{ gpm})(61.97 \text{ lb} / \text{ft}^3)}{(0.622 \text{ in})(0.682 \text{ cp})} \quad \begin{matrix} Q = \text{gpm}; \rho = \text{lb} / \text{cu. ft.} \\ d = \text{in. diameter}; \mu = \text{visc. (cp)} \end{matrix}$$

$$\text{Re \#} = 67,637$$

Calculation of f

$$\text{Smooth pipe } \begin{matrix} E = .00015 \text{ ft} & \text{commercial} \\ E = 0 & \text{smooth} \end{matrix}$$

$$\text{Colebrook Eqn} = \frac{1}{f} = -4 \log \left(\frac{E}{3.7D} + \frac{1.256}{\text{Re} \sqrt{f}} \right)$$

$$f \left(\frac{E = .00015 \text{ ft}}{\text{Re} = 67,637} \right) = .006953 \text{ solved by iteration}$$

$$f (RE=0, \text{Re}=67,637) = .004887 \text{ solved by iteration}$$

Title Calculation of Expected Pressure Drop for Water Project FWCT / CIPT / FCT

Prepared by: G.P. Alving / P.D. 11-100 Date: 11/3

Reviewed by: _____

Date: _____

Estimated Pressure Drop per Length ($\Delta P/L$) (from PERRY'S CHEM 5-24)
 eqn. 5-57

$$\frac{\Delta P}{L} = \frac{2f v^2}{D g_c} \times \rho = \frac{(lb/ft^3)}{ft}$$

$$\frac{\Delta P}{L} = \frac{2f v^2}{D g_c} \times \rho \times \frac{ft^2}{144 in^2} \times \frac{27.7276}{lb/in^2} \text{ in } H_2O = \text{in. } H_2O / ft.$$

f = friction factor

D = diameter = ft

ρ = lb/ft^3

v = $ft/sec.$

g_c = $32.2 ft/sec^2$

for Commercial Sch. 40 pipe: $\epsilon = .00015 ft.$

$$\frac{\Delta P}{L} \left(f(\epsilon = .00015 ft) = .006953 \right) = \frac{2(.006953)(9.5)^2}{(.622/12)(32.2)} \times 61.97 \times \frac{1}{144} \times 27.7276 = 9.15 \frac{H_2O}{ft.}$$

for Smooth Pipes, $\epsilon = 0$

$$\frac{\Delta P}{L} (f(\epsilon = 0) = .004887) = \frac{2(.004887)(9.59)^2}{(.622/12)(32.2)} \times 61.97 \times \frac{1}{144} \times 27.7276 = 6.44 \frac{H_2O}{ft.}$$

Experimental $\Delta P/L = 171.32 \text{ in } H_2O / 25 ft = 6.85 \frac{H_2O}{ft.}$

with expected for smooth & commercial roughness pipe.

Title Calculation of Expected Pressure Drop for Water

Project RWCT/SIPT/FST

Prepared by: GP Abrigo, LP Abrigo

Date
11/3

Reviewed by:

Date

Calculation of Pressure Drop in Long Radius Elbows

Pipe Diam. (in)	Long Radius Elbow Bend Radius (in)	Bend Radius/Diameter	L_e/D^A
0.622	1.5	2.41	9.5
1.049	1.5	1.43	14
1.61	2.25	1.40	14
2.067	3	1.45	14
3.068	4.5	1.47	14

* Perry's ChE HB p. 6-57, Table 6-15.

^ Perry's ChE HB Fig. 5-45 pg. 5-39

L_e = equiv. length of straight pipe.

D = diam. of pipe.

for 1/2" elbow only ΔP :

$$L_e = 9.5 \times \left(\frac{0.622}{12} \right) \text{ ft} = .492 \text{ ft}$$

for $E = .00015$

$$\Delta P_{el} = 9.15 \frac{\text{H}_2\text{O}}{\text{ft}} \times .492 \text{ ft} = 4.5 \text{ H}_2\text{O}$$

for $E = 0$

$$\Delta P_{el} = 6.85 \frac{\text{H}_2\text{O}}{\text{ft}} \times .492 \text{ ft} = 3.37 \text{ H}_2\text{O}$$

To get experimental elbow only ΔP

as measured by Remote Seal

$$\Delta P_{el} = \Delta P_{el, \text{exp}} - L_{el} \left(\frac{\Delta P}{L} \right)_{\text{straight, exp.}}$$

L_{el} = length of straight section pipe in elbow section (from ΔP transmitter to elbow welds).

$\left(\frac{\Delta P}{L} \right)_{\text{straight, exp.}}$ = measured experimental straight section $\Delta P/L$.

$$\Delta P_{el} = 91.88 \text{ H}_2\text{O} - 11.75 \text{ ft} \left(\frac{6.85 \text{ H}_2\text{O}}{\text{ft}} \right) = 11.4 \text{ H}_2\text{O}$$

Title Calculation of Expected Pressure Drop for Water Project RWCT/STL/FST

Prepared by: GP Abrego LP Obregon

Date: 11/3

Reviewed by: _____

Date: _____

To convert elbow only pressure drop to L_e/D :

$$L_e/D = \Delta P_{elb} \times \left(\frac{L}{\Delta P} \right)_{\text{straight, db}} \times \frac{1}{D}$$

$$L_e/D = 11.4 \cdot H_2O \times \left(\frac{ft}{6.85 \cdot H_2O} \right) \times \left(\frac{1}{.622/12 \cdot ft} \right) = 32$$

Remote seal $L_e/D = 32$ expected ~ 9.5 from Perry's Lit.

→ Radial test w/ water taps instead of remote seal units.

L_e/D with water taps ≈ 5 . Closer to Perry's.

Title Calculation of Expected Pressure Drop for Water

Project _____

Prepared by: GP Kierigo EP Abzigo

Date 11/13

Reviewed by: _____

Date _____

Calculation of Errors associated w/ L_e/D values for 90° Long Radius Elbows

$$\frac{L_e}{D} = \left(dP_{es} \cdot \frac{L_{st}}{dP_{st}} - L_{st,es} \right) \frac{1}{D}$$

L_e = equiv. lengths of straight section dP , ft.

D = diameter, ft.

dP_{es} = Elbow Section dP , in. H_2O w/ $G_{dP_{es}}$

L_{st} = Length of straight section, ft.

dP_{st} = Straight Section dP , in. H_2O w/ $G_{dP_{st}}$

$L_{st,es}$ = Length of straight pipe in elbow section (not including elbow), ft.

Find $G_{L_e/D}$

$$G_{L_e/D} = \sqrt{\left\{ \left(\frac{1}{dP_{es}} \left(\frac{L_e}{D} \right) \right) G_{dP_{es}} \right\}^2 + \left\{ \left(\frac{1}{dP_{st}} \left(\frac{L_e}{D} \right) \right) G_{dP_{st}} \right\}^2} \quad \text{HPC}$$

$$G_{L_e/D} = \sqrt{\left\{ \left(\frac{1}{dP_{es}} \left(\frac{L_e}{D} \right) \right) G_{dP_{es}} \right\}^2 + \left\{ \left(\frac{1}{dP_{st}} \left(\frac{L_e}{D} \right) \right) G_{dP_{st}} \right\}^2}$$

$$\frac{\partial}{\partial P_{es}} \frac{L_e}{D} = \frac{L_{st}}{D dP_{st}}$$

$$\frac{\partial}{\partial P_{st}} \frac{L_e}{D} = -\frac{dP_{es} L_{st}}{D} \cdot \frac{1}{dP_{st}^2}$$

$$G_{L_e/D} = \sqrt{\left\{ \frac{L_{st}}{D dP_{st}} G_{dP_{es}} \right\}^2 + \left\{ -\frac{dP_{es} L_{st}}{D dP_{st}^2} G_{dP_{st}} \right\}^2}$$

Note: $dP_{es} = f(V)$ V = fluid velocity
are curvefits
of data
generated by
AXUM
by TRIMETRIX
 $dP_{st} = f(V)$
 $G_{dP_{es}} = f(V)$
 $G_{dP_{st}} = f(V)$

Title Calculation of Errors Associated w/ L_e/D

Project Slur, Test Loop

Prepared by: G.P. Abrico

Date 5/11/94

Reviewed by:

Date

Calculation of σ_{dP} associated w/ dP

$dP = a Q^b$, where Q = flow rate (gpm) dP = pressure drop (in. H₂O)
data from FST testing & ~~rate~~ was fit to the above equation.
using AXUM by TRIMETRIX.

The software gave the standard errors on the regression coefficients a, b
 σ_a, σ_b

To find $\sigma_{dP} \Rightarrow$

$$\sigma_{dP} = \sqrt{\left(\frac{d}{da} dP \sigma_a\right)^2 + \left(\frac{d}{db} dP \sigma_b\right)^2}$$

$$\sigma_{dP} = \sqrt{(Q^b \sigma_a)^2 + (a x^{\frac{1}{b}} \ln(x) \sigma_b)^2}$$

note ~~$\sigma_a = f(Q)$~~ BPA $\sigma_{dP} = f(Q)$
 ~~$\sigma_b = f(Q)$~~

Title Uncertainty in error from power law fit

Project _____

Prepared by: Gerardo Alvarado

Date 3-11-93

Reviewed by: _____

Date _____

APPENDIX F: MEASURING AND TEST EQUIPMENT LIST

Measuring and Test Equipment List

Effective 11 JAN 1994

INSTRUMENT NUMBER	ASSOCIATED EQUIPMENT	LOCATION	DESCRIPTION	FUNCTION	MANUFACTURE	PART NUMBER	SERIAL NUMBER	RANGE	TRANSMITTER OUTPUT	% ERROR	CALIBRATING AGENT	CAL FREQ	CAL CALIB	DATE	CUSTODIAN	COMMENTS
AE 014	HB-14	HB-14	PH PROBE	ELEMENT	PHOENIX ELECT CO	PH0774730HB-04D-CW	NONE	0-14 pH	NA	N/A	USER	2	NA	NA	SD HALSTEAD	
AT 014	HB-14	HB-14	PH PROBE	TRANSMITTER	RADIOMETER AMERICA	PH4M5-2	82824002	0-14 pH	RS-232	N/A	USER	2	NA	NA	SD HALSTEAD	
AE 1001	HB-15	HB-15	PH PROBE	ELEMENT	PHOENIX ELECT CO	PH0774730HB-04D-CW	NONE	0-14 pH	NA	N/A	USER	2	NA	NA	SD HALSTEAD	
AT 1001	HB-15	HB-15	PH PROBE	TRANSMITTER	RADIOMETER AMERICA	PH4M5-2	82824003	0-14 pH	RS-232	N/A	USER	2	NA	NA	SD HALSTEAD	
FEFT 0202	STL	1" STL	PROCESS FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300EP	1943-08130582	0-30 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FEFT 0203	STL	1 1/2" STL	PROCESS FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194300TSSA1GP300EP	1943-081370582	0-15 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FEFT 0204	STL	1 1/2" STL	PROCESS FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194320TFFHCA1GP300NE	1943-081350493	0-100 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Mar-83	Mar-84	SD HALSTEAD
FEFT 0205	STL	3" STL	PROCESS FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TFFHCA1GP300NE	1943-0809368	0-220 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Jan-83	Jan-84	SD HALSTEAD
FE 801	CD-1000	PRC-3-01	CONDENSATE FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943190	0-13 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 801	CD-1000	RACK 2	CONDENSATE FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943190	0-13 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 802	TK-900	P-1-02	CHEM ADD TO HB-15	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077953190	0-53 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 802	TK-900	RACK 1	CHEM ADD TO HB-15	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077953190	0-53 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 803	P-801	CA-172-01	FORMIC ADD TO HB-15	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077953190	0-53 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 803	P-801	FLAME HOOD	FORMIC ADDITION FLOW	TRANSMITTER	ENDRESS & HAUSER	FT11941100TFFHCA1GP300NE	1943-077953190	0-53 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1001	E-1001/E-1002	PR5-4-01	STEAM SUPPLY	FLOW ELEMENT	FISCHER PORTER	FT11941100TFFHCA1GP300NE	1943-077953190	0-53 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1001	E-1001/E-1002	RACK 1	STEAM SUPPLY	TRANSMITTER	FISCHER PORTER	FT11941100TFFHCA1GP300NE	1943-077953190	0-53 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1002	CD-1000/HB-15	LPW-2-01	SUPPORT SERVICES	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-310 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1002	CD-1000/HB-15	RACK 2	SUPPORT SERVICES	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-310 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1003	E-1003	PSW-2-02	COOLING WATER FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1003	E-1003	RACK 1	COOLING WATER FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1010	P-1002	LWP-1 1/2-01	FLUSH WATER FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1010	P-1002	RACK 1	FLUSH WATER FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1011	HYDRAGARD	SAMPLER	HYDRAGARD FLUSH WATER	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1011	HYDRAGARD	SAMPLER	HYDRAGARD FLUSH WATER	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1013	HB-15	P-2-06	CHEM ADD FROM HB-13	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-170 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1013	HB-15	RACK 1	CHEM ADD FROM HB-13	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-170 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FEFT 1014	HB-13	HB-13	CONDENSATE FLOW TO 10 GPM LINE	TRANSMITTER	ENDRESS & HAUSER	FT11941100TFFHCA1GP300NE	1943-077943000	0-170 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FEFT 1015	HB-13	HB-13	CONDENSATE FLOW TO 10 GPM LINE	TRANSMITTER	ENDRESS & HAUSER	FT11941100TFFHCA1GP300NE	1943-077943000	0-170 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1021	P-1101	LPW-2-09	FLUSH WATER FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1021	P-1101	RACK 1	FLUSH WATER FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1022	HYDRAGARD	SAMPLER	HYDRAGARD FLUSH WATER	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1022	HYDRAGARD	SAMPLER	HYDRAGARD FLUSH WATER	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077973000	0-125 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1023	FEED NOZZLE	P-3V-01	HYDRAGARD FLUSH WATER	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-1037248R3	0-15 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Dec-83	Dec-84	SD HALSTEAD
FT 1023	FEED NOZZLE	EDL-102	FEED FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-1037248R3	0-15 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Dec-83	Dec-84	SD HALSTEAD
FE 1024	P-1101	P-2-03	TRANSFER LINE FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-1037248R3	0-15 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Dec-83	Dec-84	SD HALSTEAD
FT 1024	P-1101	RACK 1	TRANSFER LINE FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-1037248R3	0-15 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Dec-83	Dec-84	SD HALSTEAD
FE 1102	CD-1000	PRW-4-01	COOLING WATER FLOW	FLOW ELEMENT	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-310 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1102	CD-1000	PRW-4-01	COOLING WATER FLOW	TRANSMITTER	ENDRESS & HAUSER	FT1194301TSSA1GP300NE	1943-077943000	0-310 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1103	CD-1000	VOG-3-01	OFFGAS FLOW	FLOW ELEMENT	EG&G FLOW TECHNOLOGY	FT-48C1XA-GEA-3	480608	15-750 ACFM	NA	+/-1%	EG FLOW TECHNOLOGY	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1103	CD-1000	VOG-3-01	OFFGAS FLOW	TRANSMITTER	EG&G FLOW TECHNOLOGY	FT-48C1XA-GEA-3	480608	15-750 ACFM	NA	+/-1%	EG FLOW TECHNOLOGY	1	12	Aug-83	Aug-84	SD HALSTEAD
FE 1104	CD-1000	VOG-2-01	OFFGAS FLOW (AUXILIARY)	FLOW ELEMENT	FISCHER PORTER	FT1194301TSSA1GP300NE	1943-077943000	0-170 GPM	NA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FT 1104	CD-1000	VOG-2-01	OFFGAS FLOW (AUXILIARY)	TRANSMITTER	FISCHER PORTER	FT1194301TSSA1GP300NE	1943-077943000	0-170 GPM	4-20 MA	+/-1%	ENDRESS & HAUSER	1	12	Aug-83	Aug-84	SD HALSTEAD
FI 1053	HB-15	PL-1-08	AIR SUPPLY FLOW	FLOW INDICATOR	OMEGA ENGINEERING	PSK-8163	NONE	0-450 SCFM	NA	+/-1%	FISCHER & PORTER	1	12	Aug-83	Aug-84	SD HALSTEAD
FY 802	TK-900	RACK 1	CHEM ADD FROM TK-900	FLOW CONTROL	MOORE INDUSTRIES	IPT	830742	4-20 MA	3-15 PSI	N/A	N/A	3	NA	NA	SD HALSTEAD	REFERENCE ONLY
FY 1013	HB-15	RACK 1	CHEM ADD FROM HB-13	FLOW CONTROL	MOORE INDUSTRIES	IPT	830745	4-20 MA	3-15 PSI	N/A	N/A	3	NA	NA	SD HALSTEAD	IP CONVERTER
FY 1014	HB-15	RACK 1	HB-15 PURGE AIR CONTROL	FLOW CONTROL	MOORE INDUSTRIES	IPT	830748	4-20 MA	3-15 PSI	N/A	N/A	3	NA	NA	SD HALSTEAD	IP CONVERTER
LEAT 1400	HB-14	HB-14	LEVEL PROBE	LIQUID LEVEL	BAIDOCATOR	CL1301CB820	NONE	0-96 INCHES	4-20 MA	N/A	N/A	3	NA	NA	SD HALSTEAD	REFERENCE ONLY
PE 0201-1	STL	2" STL	2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1750 PSI	NA	+/-0.1%	WMC 452-80-02-029	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0201-2	STL	2" STL	2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1750 PSI	NA	+/-0.1%	WMC 452-80-02-029	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0201	STL	2" STL	2" ELBOW DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	88827	0-100 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-018	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0202-1	STL	2" STL	2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-018	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0202-2	STL	2" STL	2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-018	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0203	STL	2" STL	2" STRAIGHT DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	87609	0-150 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-018	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0203-1	STL	1" STL	1" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1250 PSI	NA	+/-0.1%	WMC 452-80-02-030	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0203-2	STL	1" STL	1" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1250 PSI	NA	+/-0.1%	WMC 452-80-02-030	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0204	STL	1" STL	1" ELBOW DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	88207	0-250 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-030	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0204-1	STL	1" STL	1" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-285 PSI	NA	+/-0.1%	WMC 452-80-02-077	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0204-2	STL	1" STL	1" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-285 PSI	NA	+/-0.1%	WMC 452-80-02-077	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0204	STL	1" STL	1" STRAIGHT DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	87609	0-150 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-018	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0205-1	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1250 PSI	NA	+/-0.1%	WMC 452-80-02-031	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0205-2	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-1250 PSI	NA	+/-0.1%	WMC 452-80-02-031	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0206	STL	1 1/2" STL	1 1/2" ELBOW DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	88203	0-100 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-031	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0206-1	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0206-2	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241F	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0207	STL	1 1/2" STL	1 1/2" STRAIGHT DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	88057	0-350 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0207-1	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0207-2	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ROSEMOUNT	W241T	NONE	0-275 PSI	NA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0207	STL	1 1/2" STL	1 1/2" ELBOW DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD3A22A1AS2M5B4	88057	0-350 IN/HQ	4-20 MA	+/-0.1%	WMC 452-80-02-078	1	12	Sep-83	Sep-84	SD HALSTEAD
PE 0208-1	STL	1 1/2" STL</														

WAIVER OF CALIBRATION

Pacific Northwest Laboratories

WAIVER OF CALIBRATION

INITIATOR RL Myers *RL Myers* 1/14/94 QA PLAN NUMBER WTC 006, Rev 7
Signature Date

M&TE NOMENCLATURE Feed Preparation Test System

M&TE CONTROL NUMBER FI-0204, FI-0205 CALIBRATION CATEGORY Level 1

LOCATION 300 Area, 324 Building, High Bay Addition

Reason for Waiver:

Each individual instrument was purchased with current calibrations in place and PNL QC reviewed and accepted all calibration documents supplied by the vendors. Neither of the instruments has been used with any material other than water during equipment checkout. Also, the additional downtime would further delay milestones associated with SIPT 3 (RWCT) and SIPT 4 (HTM-1) testing schedules. Due to the fact that the instruments have not been subjected to any adverse conditions it is believed that the calibrations will still be accurate. It is the purpose of this waiver to allow use of these instruments for a period of six months from the last calibration due dates.

Period of Waiver:

Six months beginning on calibration expiration dates. The waiver is good until September 1, 1994.

Remarks:

1. Instruments are for use in the HWVP Feed Preparation Test System.
2. FI-0204 1 1/2" STL Flowmeter, 0-100 gpm
FI-0205 3" STL Flowmeter, 0-220 gpm

QP REPRESENTATIVE

Signature

B.D. Slonecker
BD Slonecker

1/17/94
Date

COGNIZANT MGR./TASK LEADER

Signature

CJ Freeman
CJ Freeman

1/17/94
Date

Measuring and Test Equipment List

Effective 11 JAN 1994

INSTRUMENT NUMBER	ASSOCIATED EQUIPMENT	LOCATION	DESCRIPTION	FUNCTION	MANUFACTURE	PART NUMBER	SERIAL NUMBER	RANGE	TRANSMITTER OUTPUT	% ERROR	CALIBRATING AGENT	CAL LEVEL	CAL FREQ	LAST CALIB	DATE DUE	CUSTODIAN	COMMENTS
PE 0208-2	STL	1 1/2" STL	1 1/2" REMOTE SENSOR	ELEMENT	ITT CONOFLOW	300H7825	NONE	0-2500 PSI	N/A	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PT 0208	STL	1 1/2" STL	1 1/2" STRAIGHT DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD2A22A1AS2M5B4	147177	0-200 IN H2O	4-20 MA	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PE 0208-1	STL	3" STL	3" REMOTE SENSOR	ELEMENT	ITT CONOFLOW	300H7825	NONE	0-2500 PSI	N/A	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PE 0208-2	STL	3" STL	3" REMOTE SENSOR	ELEMENT	ITT CONOFLOW	300H7825	NONE	0-2500 PSI	N/A	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PT 0209	STL	3" STL	3" ELBOW DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD2A22A1AS2M5B4	141805	0-75 IN H2O	4-20 MA	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PE 0210-1	STL	3" STL	3" REMOTE SENSOR	ELEMENT	ITT CONOFLOW	300H7825	NONE	0-2500 PSI	N/A	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PE 0210-2	STL	3" STL	3" REMOTE SENSOR	ELEMENT	ITT CONOFLOW	300H7825	NONE	0-2500 PSI	N/A	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PT 0210	STL	3" STL	3" STRAIGHT DP TRANSMITTER	TRANSMITTER	ROSEMOUNT	3051CD2A22A1AS2M5B4	141807	0-75 IN H2O	4-20 MA	+/-0.1%	ROSEMOUNT	1	12	Oct-83	Oct-94	SD HALSTEAD	
PDE/PT 1002	HB-15	RACK 1	HOLLEDGE DETECTOR	DP TRANSMITTER	ROSEMOUNT	3051CD2A22A1AB4J2M5	19687	0-250 H2O	4-20 MA	+/-0.1%	WHC 147-80-02-001	1	12	Jun-83	Jun-94	SD HALSTEAD	
PDE/PT 1003	HB-15	RACK 1	HOLLEDGE DETECTOR	DP TRANSMITTER	ROSEMOUNT	3051CD2A22A1AB4J2M5	19688	0-250 H2O	4-20 MA	+/-0.1%	WHC 147-80-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
PDE/PT 1004	HB-15	RACK 1	HOLLEDGE DETECTOR	DP TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19772	-20-40 H2O	4-20 MA	+/-0.1%	WHC 147-80-02-003	1	12	Jun-83	Jun-94	SD HALSTEAD	
PDE/PT 1005	HB-15	RACK 2	HOLLEDGE DETECTOR	DP TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19773	0-250 H2O	4-20 MA	+/-0.1%	WHC 147-80-02-004	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1001	E-1001/E-1002	RACK 1	COIL STEAM SUPPLY	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19780	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-007	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1012	P-1002	SPL-1/2-02	SAMPLE PUMP DISCHARGE PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	51543	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-028	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1012	P-1002	SPL-1/2-02	SAMPLE PUMP DISCHARGE PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	51543	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-028	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1013	HYDRAGARD	LOCAL	HYDRAGARD SAMPLER DISCHARGE	TRANSMITTER	ROSEMOUNT	W247T	NONE	0-1250 PSI	N/A	+/-0.1%	WHC 452-80-02-028	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1013	HYDRAGARD	SPL-1/2-03	HYDRAGARD SAMPLER DISCHARGE	ELEMENT	ROSEMOUNT	3051CG2A22A1AB4J2M5	51544	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-015	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1020	P-1101	P-2-04	CROSSFLOW STRAINER	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	72102	0-1250 PSI	N/A	+/-0.1%	WHC 452-80-02-015	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1020	P-1101	P-2-04	CROSSFLOW STRAINER	ELEMENT	ROSEMOUNT	W247F	NONE	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-021	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1021	E-1001/E-1002	LOCAL	STEAM HEADER	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19381	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-018	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1022	E-1002	RACK 1	CONDENSATE OUT	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19382	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-010	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1023	E-1001	RACK 1	CONDENSATE OUT	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19383	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-009	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1024	E-1003	RACK 1	E-1003 COIL INLET PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	48608	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1025	E-1001	RACK 1	E-1003 COIL OUTLET PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	48609	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1031	P-1101	P-2-03	TRANS-FEED PUMP DISCH PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	48608	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1031	P-1101	P-2-03	TRANS-FEED PUMP DISCH PRESS	ELEMENT	ROSEMOUNT	3051CG2A22A1AB4J2M5	48608	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1032	P-1101	P-2-04	FEED RECYCLE LOOP RETURN PRESS	TRANSMITTER	ROSEMOUNT	W247F	NONE	0-70 PSI	N/A	+/-0.1%	WHC 452-80-02-020	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1032	P-1101	P-2-04	FEED RECYCLE LOOP RETURN PRESS	ELEMENT	ROSEMOUNT	3051CG2A22A1AB4J2M5	48605	0-70 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-017	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1033	P-1101	P-3/4-01	MELTER FEED LINE 3-WAY BK PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	47083	0-70 PSI	N/A	+/-0.1%	WHC 452-80-02-017	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1033	P-1101	P-3/4-01	MELTER FEED LINE 3-WAY BK PRESS	ELEMENT	ROSEMOUNT	W247T	NONE	0-70 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-022	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1034	P-1101	P-3/4-01	MELTER FEED NOZZLE BK PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	47088	0-70 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-014	1	12	Jun-83	Jun-94	SD HALSTEAD	
PE 1034	P-1101	P-3/4-01	MELTER FEED NOZZLE BK PRESS	ELEMENT	ROSEMOUNT	W247T	NONE	0-70 PSI	N/A	+/-0.1%	WHC 452-80-02-014	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1051	HB-15	RACK 1	AIR SUPPLY	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19384	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-003	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1051	CD-1000	RACK 2	COOLING WATER IN	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	19385	0-300 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-007	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1102	CD-1000	RACK 1	CONDENSER COOL H2O OUT PRES	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	48607	0-100 PSI	4-20 MA	+/-0.1%	WHC 452-80-02-011	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1103	CD-1000	RACK 2	CONDENSER PRESS	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	87309	-50-150 H2O	4-20 MA	+/-0.25%	WHC 452-80-02-025	1	12	Jun-83	Jun-94	SD HALSTEAD	
PT 1105	HB-15	RACK 1	TANK HEADSPACE	TRANSMITTER	ROSEMOUNT	3051CG2A22A1AB4J2M5	56435	-20-40 H2O	4-20 MA	+/-0.1%	WHC 452-80-02-001	1	12	Oct-81	N/A	SD HALSTEAD	NOT IN SERVICE
PV 1000	HB-15	RACK 1	OFFGAS VACUUM CONTROL	PRESS CONTROL	MOORE INDUSTRIES	IFT	839875	4-20 MA	3-15 PSI	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	MP CONVERTER
PV 1001	E-1001/E-1002	RACK 1	STEAM CONTROL	PRESS CONTROL	MOORE INDUSTRIES	IFT	834331	4-20 MA	3-15 PSI	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	MP CONVERTER
TE 0100	HB-15	RACK 1	HIGH BAY AMBIENT TEMPERATURE	THERMOCOUPLE	EUSTIS CO INC	4189	TE-0100	0-100 C	N/A	+/-2.2%	WHC 452-78-02-003	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 0100	HB-15	RACK 1	HIGH BAY AMBIENT TEMPERATURE	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	0359831	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-010	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1031	E-1003	PRW-2-02	COOLING WATER IN	RTD	ROSEMOUNT	0058C-1200-C01	0315519	0-100 C	N/A	+/-0.05%	WHC 452-78-03-007	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1031	E-1003	RACK 1	COOLING WATER IN	TRANSMITTER	ROSEMOUNT	3044A1B1M1	55022663	0-100 C	4-20 MA	+/-0.14%	WHC 452-80-01-003	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1032	E-1003	PRW-2-02	COOLING WATER OUT	RTD	ROSEMOUNT	0058C-1200-C01	0315520	0-100 C	N/A	+/-0.05%	WHC 452-78-03-004	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1032	E-1003	RACK 1	COOLING WATER OUT	TRANSMITTER	ROSEMOUNT	3044A1B1M1	55022664	0-100 C	4-20 MA	+/-0.14%	WHC 452-80-01-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1041	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-318	0-300 C	N/A	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1041	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359838	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-004	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1042	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-320	0-300 C	N/A	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1042	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359937	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-005	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1043	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-328	0-300 C	N/A	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1043	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359838	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-011	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1044	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-328	0-300 C	4-20 MA	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1044	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359838	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-007	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1045	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-318	0-300 C	N/A	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1045	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359840	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1046	HB-15	TEMP	HB-15 TEMP	THERMOCOUPLE	EUSTIS CO INC	4189	452-78-02-002-330	0-300 C	N/A	+/-2.2%	WHC 452-78-02-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1046	HB-15	RACK 1	HB-15 TEMP	TRANSMITTER	ROSEMOUNT	0444TJ1U1A2E5	480359841	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1047	E-1001/E-1002	RACK 1	STEAM SUPPLY	RTD	ROSEMOUNT	0058C-1200-C01	0315521	0-100 C	N/A	+/-0.05%	WHC 452-78-03-008	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1047	E-1001/E-1002	RACK 1	STEAM SUPPLY	TRANSMITTER	ROSEMOUNT	3044A1B1M1	55022665	0-200 C	4-20 MA	+/-0.14%	WHC 452-80-01-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1051	HB-15	FLA-1-03	AIR PURGE SUPPLY	RTD	ROSEMOUNT	0058C-1200-C01	0315522	0-100 C	N/A	+/-0.05%	WHC 452-78-03-003	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1051	HB-15	RACK 1	AIR PURGE SUPPLY	TRANSMITTER	ROSEMOUNT	3044A1B1M1	55022666	0-100 C	N/A	+/-0.14%	WHC 452-80-01-001	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1052	E-1001	PSC-1-01	CONDENSATE OUT	RTD	ROSEMOUNT	0058C-1200-C01	0315523	0-100 C	N/A	+/-0.05%	WHC 452-78-03-001	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1052	E-1001	RACK 1	CONDENSATE OUT	TRANSMITTER	ROSEMOUNT	3044A1B1M1	55022668	0-200 C	4-20 MA	+/-0.14%	WHC 452-80-01-001	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1053	E-1002	PSC-1-03	CONDENSATE OUT	RTD	ROSEMOUNT	0058C-1200-C01	0315523	0-100 C	N/A	+/-0.05%	WHC 452-78-03-002	1	12	Jun-83	Jun-94	SD HALSTEAD	
TT 1053	E-1002	RACK 1	CONDENSATE OUT	TRANSMITTER	ROSEMOUNT	3044A1B1M1	550034848	0-200 C	4-20 MA	+/-0.14%	WHC 452-80-01-004	1	12	Jun-83	Jun-94	SD HALSTEAD	
TE 1054	P-1101	P2-04-SST	FEED RECYCLE LOOP RETURN	THERMOCOUPLE	ROSEMOUNT	0444TJ1U1A2E5	0359833	0-300 C	4-20 MA	+/-0.2%	WHC 452-80-01-018	1	12	Jun-83	Jun-94	SD HALSTEAD	ON ORDER
TT 1054	P-1101	P2-															

Measuring and Test Equipment List

Effective 11 JAN 1994

INSTRUMENT NUMBER	ASSOCIATED EQUIPMENT	LOCATION	DESCRIPTION	FUNCTION	MANUFACTURE	PART NUMBER	SERIAL NUMBER	RANGE	TRANSMITTER OUTPUT	% ERROR	CALIBRATING AGENT	CAL LEVEL	CAL FREQ	LAST CALIB	DATE DUE	CUSTODIAN	COMMENTS
TE 1101	CD-1000	CD-1000	CONDENSER TEMP	RTD	ROSEMOUNT	0058C-1200-C01	0115524	0-100 C	N/A	+0.05%	WHC 452-79-03-011	1	12	Jun-93	Jun-94	SD HALSTEAD	
TT 1101	CD-1000	RACK 2	CONDENSER TEMP	TRANSMITTER	ROSEMOUNT	304A1811M1	55002268	0-100 C	-4-20 MA	+0.14%	WHC 452-80-01-012	1	12	Jun-93	Jun-94	SD HALSTEAD	
TE 1102	CD-1000	PRW-2-01	COOLING WATER OUT	RTD	ROSEMOUNT	0058C-1200-C01	0115525	0-100 C	N/A	+0.05%	WHC 452-79-03-008	1	12	Jun-93	Jun-94	SD HALSTEAD	
TT 1102	CD-1000	RACK 2	COOLING WATER OUT	TRANSMITTER	ROSEMOUNT	304A1811M1	55002268	0-100 C	-4-20 MA	+0.14%	WHC 452-80-01-018	1	12	Jun-93	Jun-94	SD HALSTEAD	
TE 1103	CD-1000	PRC-3-01	CONDENSATE OUT	RTD	ROSEMOUNT	0058C-1200-C01	0115526	0-100 C	N/A	+0.05%	WHC 452-79-03-005	1	12	Jun-93	Jun-94	SD HALSTEAD	
TT 1103	CD-1000	RACK 2	CONDENSATE OUT	TRANSMITTER	ROSEMOUNT	304A1811M1	55002267	0-100 C	-4-20 MA	+0.14%	WHC 452-80-01-014	1	12	Jun-93	Jun-94	SD HALSTEAD	
TE 1104	CD-1000	PSW-2-01	COOLING WATER IN	RTD	ROSEMOUNT	0058C-1200-C01	0115527	0-100 C	N/A	+0.05%	WHC 452-79-03-006	1	12	Jun-93	Jun-94	SD HALSTEAD	
TT 1104	CD-1000	RACK 2	COOLING WATER IN	TRANSMITTER	ROSEMOUNT	304A1811M1	55002267	0-100 C	-4-20 MA	+0.14%	WHC 452-80-01-015	1	12	Jun-93	Jun-94	SD HALSTEAD	
TE 1105	CD-1000	VOG-3-01	OFFGAS OUT	RTD	ROSEMOUNT	0058C-1200-C01	0115528	0-100 C	N/A	+0.05%	WHC 452-79-03-010	1	12	Jun-93	Jun-94	SD HALSTEAD	
TT 1105	CD-1000	RACK 2	OFFGAS OUT	TRANSMITTER	ROSEMOUNT	304A1811M1	55002267	0-100 C	-4-20 MA	+0.14%	WHC 452-80-01-013	1	12	Jun-93	Jun-94	SD HALSTEAD	
WE 901	TK-900	TK-900	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	D2-2000	4601	0-2000N	N/A	+0.07%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WE 902	TK-900	TK-900	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	D2-2000	4602	0-2000N	N/A	+0.07%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WE 903	TK-900	TK-900	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	D2-2000	4603	0-2000N	N/A	+0.07%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WT 900	TK-900	TK-900	TOTALIZER	TANK WEIGHT	KISTLER-MORSE	1020-X1	637	0-3500N	-4-20 MA	+0.05MA	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WE 1001	HB-18	HB-18	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	8105-X1	3487	0-50000N	N/A	+0.25%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WE 1002	HB-18	HB-18	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	8105-X1	3488	0-50000N	N/A	+0.25%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WE 1003	HB-18	HB-18	LOAD CELL	STRAIN GAGE	KISTLER-MORSE	8105-X1	3489	0-50000N	N/A	+0.25%	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
WT 1000	HB-18	HB-18	TOTALIZER	TANK WEIGHT	KISTLER-MORSE	1020-X1	638	0-95000N	-4-20 MA	+0.05MA	KISTLER-MORSE	3	N/A	N/A	N/A	SD HALSTEAD	REFERENCE ONLY
EY 1000	AQ-1000	AQ-1000	AGITATOR SPEED	INPUT	ELECTRO SENSORS	DISC10C	40773	0-200 RPM	0-10 VDC	+0.05	WHC 147-23-09-001	1	12	Aug-91	Apr-93	SD HALSTEAD	NOTES 1,2,3
HE 1000	AQ-1000	CONTROLLER	AGITATOR CURRENT	INPUT	ROCHESTER INST. INC.	CCCI1BC5E1XAF8020	R38431-323	0-150 AMP	-4-20 MA	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
HE 1000	AQ-1000	CONTROLLER	AGITATOR VOLTAGE	INPUT	RELUXANCE ELECTRIC	0-55325-B	NONE	0-410 VAC	0-10 VDC	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
EY 1010	P-1002	P-1002	PUMP SPEED	INPUT	ELECTRO SENSORS	DISC10C	33781-2	0-2000 RPM	0-10 VDC	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
HE 1010	P-1002	CONTROLLER	PUMP CURRENT	INPUT	ROCHESTER INST. INC.	CCCI1BC5E1XAF8020	R38431-320	0-50 AMP	-4-20 MA	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
IE 1010	P-1002	CONTROLLER	PUMP VOLTAGE	INPUT	RELUXANCE ELECTRIC	0-55325-B	NONE	0-410 VAC	0-10 VDC	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
EY 1020	P-1101	P-1101	PUMP SPEED	INPUT	ELECTRO SENSORS	DISC10C	31978-4	0-2000 RPM	0-10 VDC	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
IE 1020	P-1101	CONTROLLER	PUMP CURRENT	INPUT	ROCHESTER INST. INC.	CCCI1BC5E1XAF8020	R38431-319	0-50 AMP	-4-20 MA	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
IE 1020	P-1101	CONTROLLER	PUMP VOLTAGE	INPUT	RELUXANCE ELECTRIC	0-55325-B	NONE	0-440 VAC	0-10 VDC	N/A	N/A	3	N/A	N/A	N/A	SD HALSTEAD	
147-06-01-001	N/A	N/A	SCALE	SCALE	ARLYN	610C	3165	0-100 LBS	N/A	+0.1%	WHC 147-06-01-001	1	12	Jan-94	Jan-95	SD HALSTEAD	
147-06-01-002	N/A	N/A	SCALE	SCALE	ARLYN	310M	3164	0-1000 LBS	N/A	+0.1%	WHC 147-06-01-002	1	12	Jan-94	Jan-95	SD HALSTEAD	
NOTES:			1) Calibration extended from February 1, 1991 to February 1, 1992 by Walker of Calibration initiated on February 21, 1991 by DR. Jackson														
			2) Calibration extended from February 1, 1992 to January 1, 1993 by Walker of Calibration initiated on October 17, 1991 by DR. Jackson														
			3) Calibration extended from January 1, 1993 to April 1, 1994 by Walker of Calibration initiated on December 18, 1992 by JR. Gaydos														