Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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Rheology and Flow Evaluation of Neutralized Sodium Reactor Experiment Fuel with Manganous Nitrate

J. M. Pareizs

October 2020

SRNL-STI-2020-00299, Revision 0

SRNL.DOE.GOV

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Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords: *Rheology, SRE, H-Canyon, neutralization*

Retention: *Permanent*

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REVIEWS AND APPROVALS

AUTHORS:

J. M. Pareizs, Chemical Flowsheet Development Date

TECHNICAL REVIEW:

E. K. Hansen, Chemical Flowsheet Development Date

APPROVAL:

G. A. Morgan, Manager Date
Manager, Chemical Flowsheet Development

S. D. Fink, Manager Date
Manager, Chemical Processing Sciences

T. E. Smith, H Canyon Outside Facilities and Tech Support Date

ACKNOWLEDGEMENTS

The author would like to acknowledge the support of the Shielded Cells technicians and management.

EXECUTIVE SUMMARY

H-Canyon is preparing the Sodium Reactor Experiment (SRE) solutions in Tanks 16.3 and 16.4 for discard to the Savannah River Site (SRS) High Level Waste (HLW) Tanks into Sludge Batch (SB) 10. To meet HLW's criticality requirements, manganese will be added to the SRE solutions. The addition of manganese to the existing thorium and uranium (i.e. insoluble solids) in the SRE solution have raised concerns with the ability of this neutralized material to flow as it is discharged from H -Canyon through the gravity drain system to the H-Area Pump Pit (HPP). A rheology study was completed as part of the SRE discard flowsheet development in 2012.[a] However, the initial rheology study did not include the addition of manganous nitrate as a poison. Therefore, H-Canyon engineering requested Savannah River National Laboratory (SRNL) to determine if the neutralized, Mn-adjusted SRE solutions will flow through the waste header to the HPP.

SRNL received samples of Tanks 16.3 and 16.4 from H-Canyon and added manganous nitrate to obtain an 80 to 1 Mn to U-235 equivalent mass ratio. At the time this work was initiated, a final decision on the ratio had not been made on the planned ratio. The H-Canyon TTR[b], specified a target of 80 to 1 to bound the uncertainty in Mn target. Parallel studies were being performed to ensure that freshly precipitated Mn did not have a solubility that would result in challenging the DWPF WAC requirements of 70 to 1. The material was then neutralized. The amount of NaOH for neutralization was calculated using methods found in H-Canyon procedure 221-H-4871-SW-28, Draft C, 4/20/20. The rheological properties of the resulting slurries were measured and used to calculate flow in the H-Canyon gravity drain system.

Based on the physical property results of the neutralized SRE products from Tanks 16.3 and 16.4, the material, maximum flow rates were calculated. Maximum flow rates of the neutralized 16.3 and 16.4 material were calculated and compared to the steam jet supplied flow rate into the waste system. Based on this comparison, potential exists for waste to backup into the 10-inch diameter header.

Another concern is the transport of the precipitated solids. The precipitated waste streams made by SRNL would result in settling of the larger solids, in both the 3-inch and 10-inch diameter lines. It is expected that the highly turbulent and slow caustic addition in Tank 8.4 will yield a much smaller particle size distribution (since SRNL poured caustic into the acidic solution instead of a slow addition). The smaller particles would result in slower settling solids and more viscous fluid.

This analysis did not account for steam jet dilution in transferring the material from Tank 8.4 to the 10-inch diameter waste header. This dilution would improve flow.

SRNL recommends processing the Tank 16.3 and 16.4 material to target a 5 wt% undissolved solids (UDS) slurry (including the dilution from the Tank 8.4 transfer steam jet). SRNL calculated that an additional 21,000 L of water needs to be added to the projected 77,000 L of neutralized Tank 16.3, and additional 21,000 L of water needs to be added to the projected 40,000 L of neutralized Tank 16.4 to obtain this target. This volume does not include any added water from the steam jet, which could be subtracted from this addition. Though the fluids would be slightly non-Newtonian, the yield stress would assist in the transport of the solids in the both the 10-inch diameter header and 3-inch diameter lines. While material may backup into the header, pausing flow by temporarily turning off the steam jet and allowing the line to partially drain before restarting per current procedure would overcome this issue.

[a] Daniel, W. E., Hansen, E. K. and Shehee, T. C. *Flowsheet Evaluation for the Dissolving and Neutralization of Sodium Reactor Experiment Used Nuclear Fuel*; SRNL-STI-2012-00279, Rev. 2; 2015.
[b] Smith, T. E. *Technical Task Request: Complete Rheology Study for SRE Solution Mixed with Manganese*; NMMD-HTS-2019-3453, Rev. 3; Savannah River Nuclear Solutions: Aiken, SC, 2020.

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LIST OF ABBREVIATIONS

ABD	Accelerated Basin Deinventory
BP	Bingham Plastic
ft	foot (or feet)
gpm	gallons per minute
HDPE	high density polyethylene
HLW	High Level Waste
HPP	H-Area Pump Pit
N	Newtonian
PSD	particle size distribution
s	second
SB	Sludge Batch
SG	specific gravity
SRE	Sodium Reactor Experiment
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TTQAP	Task Technical and Quality Assurance Plan
TTR	Technical Task Request
UDS	undissolved solids
WH	Waste Header
wt.%	weight percent

1.0 Introduction

H-Canyon is preparing the Sodium Reactor Experiment (SRE) solutions in Tanks 16.3 and 16.4 for discard to the Savannah River Site (SRS) High Level Waste (HLW) Tanks into Sludge Batch (SB) 10. To meet HLW's criticality requirements, manganese will be added to the SRE solutions. The addition of manganese to the existing thorium and uranium in the SRE solution raised concerns with the flow of this neutralized material as it is discharged from H-Canyon through the gravity drain system to the H-Area Pump Pit (HPP). A neutralized Mn adjusted SRE stream will produce primarily Mn, Th, and U solids that can deter transfer. A 2012 rheology study was completed as part of the flowsheet development.[1] However, the initial rheology study did not include the addition of manganous nitrate as a poison. Therefore, H-Canyon Engineering requested Savannah River National Laboratory (SRNL) to determine if the neutralized, Mn-adjusted SRE solutions will flow through the waste header to the HPP.[2]

The H-Canyon Technical Task Request (TTR)[2] specified a target of 80 to 1 to bound the uncertainty in Mn target. Parallel studies were being performed to ensure that freshly precipitated Mn did not have a solubility that would result in challenging the DWPF WAC requirements of 70 to 1.

This task was requested via a TTR and is governed by a Task Technical and Quality Assurance Plan (TTQAP).[2, 3]

2.0 Experimental Procedure

2.1 Preparation of Neutralized 16.3 and 16.4 Material

SRE samples were received from Tanks 16.3 and 16.4. Tank samples were analyzed independently. Existing analyses of the tank contents[4] were utilized to calculate the addition of manganous nitrate, and sodium hydroxide. The addition of water was based on reducing the final density to 1.33 g/mL;[4] which is the maximum density of tank contents in H-Canyon prior to steam jet transfer. The calculation was based on volume additivity and starting densities of the liquids. One hundred mL of neutralized, Mn-adjusted Tank 16.3 and 16.4 were prepared. Only enough material was prepared for rheology, weight percent (wt.%) solids, and density measurement. SRNL added the "bounding case" amount of Mn: a ratio of 80 g Mn per 1 g of U-235 equivalents specified by H-Canyon. Note that the U-235 equivalents was calculated per the DWPF Waste Acceptance Criteria document:[5] $\text{U-235}_{equ} = \text{U-235} + 1.4 \times \text{U-233}$. A more representative ratio will be used in SB10 qualification testing. The larger the Mn/U ratio, the more undissolved solids (UDS), resulting in an increase of the rheological properties.

The liquids were added to a clear-graduated 250 mL centrifuge tube, which facilitated observing the addition sequence and mixing. The tank samples were first placed into the centrifuge tube. Liquid 50.5 wt.% manganous nitrate, 50 wt.% NaOH, and water were then added in that order. The materials were poured in, not added slowly, and the vessels were not mixed until after additions were made. The amount of manganous nitrate added was an 80:1 mass ratio of Mn to U-235 equivalents. Sodium hydroxide and water were then added targeting an excess of 1.86 M free hydroxide (during planning for this task, H Canyon was targeting 1.86 M excess hydroxide[4]; current plans target 1.2 M excess free hydroxide[6]), and density of 1.33 g/mL respectively. Note that the required excess hydroxide is 1.1 M[7], and H-Canyon typically targets greater than 1.2 M excess hydroxide. A draft of H-Canyon procedure 221-H-4871-SW-28[8] was used to calculate 50wt.% NaOH amount. Amounts of H-Canyon material, manganous nitrate, sodium hydroxide, and water are given in Table 2-1.

After all the liquids were added, the centrifuge bottle was capped and the neutralized samples were mixed for approximately two minutes using a vortex mixer and allowed to settle overnight. The samples were then re-mixed and material transferred to high density polyethylene (HDPE) bottles.

Table 2-1. Batching of Mn-Adjusted Neutralized SRE Tanks 16.3 and 16.4 Samples

Material	Tank 16.3	Tank 16.4
SRE (g)	36.63	31.84
50.5 wt.% manganous nitrate solution (g)	28.26	32.92
50 wt.% NaOH solution (g)	45.84	42.36
Water (g)	22.27	25.80

2.2 Physical Properties Measurements

The measured physical properties were wt.% total solids in the slurry and supernate, density, rheology, and particle size distribution. Each of these measurements or calculations is discussed below.

2.2.1 *Weight Fraction Solids and Density*

The measured properties for solids analyses include the wt.% total solids in the slurry and the wt.% total solids in the supernate (or soluble solids in the supernate). These properties were determined using Equation 1 and 2. The supernate samples were obtained by filtering a portion of the slurries through a 0.45µm filter.

$$\boldsymbol{wt\%_{ts} = \frac{m_{dried\ slurry}}{m_{slurry}} \times 100} \quad (1)$$

$$\boldsymbol{wt\%_{sss} = \frac{m_{dried\ supernate}}{m_{supernate}} \times 100} \quad (2)$$

where:

$m_{slurry} = mass\ of\ slurry\ sample\ (g)$,
$m_{dried\ slurry} = mass\ of\ dried\ slury\ at\ 115\ °C\ (g)$,
$m_{supernate} = mass\ of\ supernate\ sample\ (g)$,
$m_{dried\ supernate} = mass\ of\ dried\ supernate\ at\ 115\ °C\ (g)$,
$wt\%_{ts} = weight\ percent\ \ of\ total\ solids\ in\ slurry$, and
$wt\%_{sss} = weitght\ percent\ of\ solids\ in\ supernate$.

Approximately 3 gram aliquots were placed into glass beakers and then placed into a forced convection oven at 115 °C. The mass of the beaker and the mass of the beaker plus sub-sample were measured prior to placing it into the oven. The beakers/samples were periodically weighed until a constant weight (difference of less than 0.005 g in subsequent weighing) was reached or until weights began increasing. Minimum weights were used in the wt.% solids calculations. Quadruplicate samples of the slurry and supernate were measured and analyzed.

The weight% of undissolved solids in the slurry ($wt\%_{uds}$) was calculated using Equation 3.

$$wt\%_{uds} = \frac{wt_{ts} - wt_{sss}}{100 - wt_{sss}} \times 100 \quad 3$$

Slurry density was determined by weighing slurry samples in vessels of known volume. Supernate density was determined by weighing samples in 10 mL volumetric flasks.

2.2.2 *Particle Size Distribution*

The particle size distribution (PSD) was determined using the Microtrac S3500. The Microtrac S3500. particle size analyzer uses a wet sample delivery controller (recirculator) to disperse the sample uniformly in a fluid and deliver the sample to the analyzer. This wet sample delivery controller in its basic form consists of a reservoir where the sample is introduced, a fluid pump, a valve to the drain system, and the necessary tubing connections to the analyzer. The flow through the analyzer sample cell is always from the bottom to the top. A laser beam is projected through a transparent quartz cell containing a stream of moving particles suspended in simulated supernate. Light from the laser strikes the particles and is scattered through various angles. The scattering angles and intensities of the scattered light are measured by two photodiode arrays producing electronic signals proportional to the measured light flux. The Microtrac proprietary mathematical software processes the signals to obtain a particle size distribution. Upon completion of the analysis, the Microtrac generates a report containing the tabular data, a histogram plot of the data, and various instrument parameters.

The volumetric particle size distribution is used. The 90 percentile particle sizes are used to support the various calculations below. It is assumed that the densities of the various precipitated particles are the same when using the PSD data for calculations, though in reality this is mostly not the case, but it is impractical (or impossible) to measure the individual flocculated materials or compounds and identify their densities.

The slurry samples were diluted using a simple simulant salt solution, primarily sodium hydroxide, aluminum nitrate, and sodium nitrate, to match the supernate composition of the slurries. The simulant salt solution is required to dilute the sample for the PSD measurement and to minimize any effect of dissolution with the undissolved solids in the radioactive wastes. The bottle containing the neutralized sludge samples were shaken to suspend the solids, the cap opened, and a slurry pipette inserted (location was random) and approximately 6.6 g for Tank 16.3 and 4 g for Tank 16.4 were removed to a beaker. The simulated supernate was then added to the 50 mL mark. Solids were allowed to settle and the resulting supernate was removed to leave 10 mL in the beaker. Contents of the beaker (undissolved solids and now diluted supernate) were poured into a green shielded bottle and submitted for PSD. The masses of slurry were chosen to provide approximately 0.2 g of solids for PSD, and the dilution was performed to reduce dose.

The neutralization process at the 221-H occurs in an mechanically agitated vessel containing two sets of flat blade impellers, the temperature of the solution during neutralization is controlled between 45 – 60 ^{o}C,[9-12] and the addition rate of caustic solution occurs over a period of hours.[13] The flat blade design is highly turbulent, and provides high shearing and dispersion of the caustic fluid during the neutralization process which was not utilized during the SRNL preparation. In the SRNL preparation, the SRE was added first, then the manganous nitrate solution, then the caustic, and finally the water. During these additions, the addition rate was not controlled, and no active mixing occurred. The mixture was shaken after all additions. As stated above, the Genie mixer was used after all the fluids were added and the bottle capped. The caustic addition rate and applied shear rate can reduce the resulting flocculated particle size distribution.[13] Extensive work in simulant sludge preparation for DWPF simulants have shown that there are multiple variables that can impact the PSD during the neutralization process, such as mixer speed, changes in pH, caustic addition rate, and scaling.[14-16] In these studies, the effect of particles less than 1 micron in diameter seem to have the most drastic impact on rheology. The particle size distributions of the fluids processed at SRNL are expected to be larger than those of the fluids produced in 221-H.

2.2.3 *Rheology*

The rheological properties of the neutralized SRE solutions were measured using a Haake RV20/M5 roto-viscometer. Visual inspection of the samples showed they contained precipitated solids and the solution was viscous in nature. For sludge, the MV1 bob/cup configuration is utilized to perform the measurements. The MV1 bob/cup configuration is a concentric cylinder, where the inner cylinder rotates, and the outer cylinder is fixed. The RV20 controls the rotational speed and measures both the rotational speed and measured torque on the rotating cylinder. The Haake software calculates the measured shear stress and shear rates given the M5 capabilities and the MV1/bob/cup geometry. The shear rates are those for Newtonian fluids and will not be corrected if the fluid has non-Newtonian characteristics. Non-Newtonian fluids at SRS are shear thinning; hence corrections to the shear rate for non-Newtonian behavior increases the shear rate for any given point, resulting in the decrease in the plastic viscosity. This non-correction is conservative relative to pressure drop in piping, yielding a higher pressure drop. The sludge flow curve profile listed in Table 2-2 was used. A National Institute of Standards and Testing (NIST) traceable Newtonian viscosity standard was used to verify the operability of the RV20/M5 roto-viscometer on a daily basis of use, where the calculated viscosity to the flow curve is within ±20% of the NIST oil standard viscosity at 25 °C. Measurements of the mixtures in this task were performed at 25 °C. Samples were prepared by vigorously shaking the bottle, swirling to assist in removing entrained air, loading into the cup, raising into to heating/cooling bath jacket, trimming excess fluid and starting the measurement using the sludge flow curve profile.

Table 2-2. Sludge Flow Curve Profile Using the MV1 Geometry

Shear rate and time of measurement		
Up Curve	Hold	Down Curve
0 to 600 s^{-1} linearly in 5 min	600 s^{-1} for 1 min	600 to 0 s^{-1} linearly in 5 min

The resulting up and down flow curves were linearly regressed using the following rheological models:

$$\text{Bingham Plastic: } \boldsymbol{\tau} = \boldsymbol{\tau_o} + \boldsymbol{\eta_\infty}\dot{\boldsymbol{\gamma}} \qquad 4$$

where:

$\tau = measured\ shear\ stress\ (Pa)$,
$\tau_o = Bingham\ Plastic\ Yield\ Stres\ (Pa)$,
$\eta_\infty = plastic\ viscosity\ (Pa \cdot \text{s})$, and
$\dot{\gamma} = shear\ rate\ (1/s)$.

The average apparent viscosity at the maximum shear rate was defined as:

$$\text{Apparent Viscosity at maximum shear rate: } \boldsymbol{\eta_{600\ s^{-1}}} = \left(\frac{\boldsymbol{\tau}}{\dot{\boldsymbol{\gamma}}}\right)_{\mathbf{600s^{-1}}} \qquad 5$$

The apparent viscosity is used when modeling the fluids as Newtonian.

2.3 Evaluation of Flow

The flows of neutralized Tanks 16.3 and 16.4 were modeled as non-Newtonian Bingham plastics and as Newtonian fluids.

The flow rate in the gravity waste transfer lines was determined using the energy Equation 6.[17] This energy equation assumes the flow is turbulent and this assumption was verified.

$$\frac{P_1}{g\rho_1} + z_1 + \frac{V_1^2}{2g} = \frac{P_2}{g\rho_2} + z_2 + \frac{V_2^2}{2g} + h_L \qquad 6$$

where:

$P_i = pressure\ (\frac{lbf}{ft^2})$,
$\rho_i = fluid\ density\ (\frac{lbm}{ft^3})$,
$z_i = elevation\ above\ a\ datum\ (ft)$,
$V_i = average\ fluid\ velocity\ (\frac{ft}{s})$,
$g = gravitational\ acceleration\ (\frac{ft}{s^2})$,
$h_L = head\ losses(ft)$, and
$i = any\ two\ points\ in\ the\ hydraulic\ system\ (1\ or\ 2)$.

The average fluid velocity and hydraulic radius are given as Equations 7 and 8, respectively. Calculation of the hydraulic radius is given below for partially full pipe. Hydraulic radius in a full pipe is equal to the pipe diameter divided by four.

$$V = \frac{\dot{Q}}{A} \qquad 7$$

$$R = \frac{A}{P_w} \qquad 8$$

where:

$R = hydraulic\ radius\ (ft)$,
$A = cross - sectional\ area\ of\ flow\ (ft^2)$,
$P_w = wetted\ perimeter\ (ft)$, and
$\dot{Q} = volumemetric\ flow\ rate\ (\frac{ft^3}{s})$.

The head losses associated with the waste lines include entrance, piping, elbows, and exit losses. These losses are determined using the following Equations 9, 10, 11, and 12.[17, 18]

Entrance: $$h_{entrance} = K_{entrance}\frac{V^2}{2g} = 0.5\frac{V^2}{2g} \qquad 9$$

Exit: $$h_{exit} = K_{exit}\frac{V^2}{2g} = 1\frac{V^2}{2g} \qquad 10$$

Piping: $$h_{piping} = f_T\frac{L}{4R}\frac{V^2}{2g} \qquad 11$$

Elbow: $$h_{elbow} = K_{elbow}\frac{V^2}{2g} = f_T\left(\frac{L}{4R}\right)_{eff}\frac{V^2}{2g} \qquad 12$$

where:

$f_T = turbulent\ friction\ factor\ (unitless)$,
$L = length\ of\ piping\ (ft)$, and
$\left(\frac{L}{4R}\right)_{eff} = constant\ for\ specific\ pipe\ bend\ in\ turbulent\ flow$; note $\left(\frac{L}{4R}\right)_{eff}$ is equivalent to K on page A-29 of Crane.[17]

The total frictional loss is the sum of the above losses and the results are shown in Equation 13.

$$\begin{aligned} h_L &= 0.5\frac{V^2}{2g} + \frac{V^2}{2g} + \sum_{i=1}^{n} f_T\left(\frac{L}{4R}\right)_{eff,i}\frac{V^2}{2g} + f_T\frac{L}{R}\frac{V^2}{8g} \\ &= 1.5\frac{V^2}{2g} + \sum_{i=1}^{n} f_T\left(\frac{L}{4R}\right)_{eff,i}\frac{V^2}{2g} + f_T\frac{L}{4R}\frac{V^2}{2g} \end{aligned} \qquad 13$$

In the case of gravity flow, $P_1 \cong P_2$ since the pressure where the waste enters the header in Building 221-H and exiting into the H Pump Pit #5 or #6 are essentially the same. It is also assumed that the pipe is partially full, and the inlet and outlet velocities are the same. The differences in inlet/outlet velocities would have little impact in the overall hydraulics of the system, due to the length of piping and other minor frictional losses. Additionally, the effect of air entrainment on the hydraulics of the system or filling of the pipe was ignored. The effect of air entrainment can drastically impact the hydraulics, reducing the flowrate.[19-21] With these assumptions, substituting Equation 13 into Equation 6, and combining terms yields Equation 14.

$$z_1 - z_2 = h_L = \frac{V^2}{2g}\left[1.5 + f_T\left(\sum_{i=1}^{n}\left(\frac{L}{4R}\right)_{eff,i} + \frac{L}{4R}\right)\right] \qquad 14$$

The loss coefficients used above are for turbulent flow conditions and can be determined using Reynolds number (N_{RE}), Equation 15, and the flow is considered turbulent when N_{RE} is greater than 4,000. Calculation of Reynolds number was included in the flow calculations.

$$N_{RE} = \frac{4V\rho R}{\mu} \qquad 15$$

where:

$\rho = density\ of\ the\ fluid\ (\frac{lbm}{ft^3})$, and
$\mu = fluid\ viscosity\left(\frac{lbm}{ft \cdot s}\right)$.

There are several methods for calculating the turbulent friction factor, f_T. Two methods are utilized in this analysis, one assuming the fluid is Newtonian and one modeling the fluid as a Bingham plastic.

2.3.1 *Methods to Determine Newtonian Pipe Frictional Losses*

In modeling as a Newtonian fluid, f_T was calculated with the Darcy-Weisbach friction factor for fully developed turbulent flow in conduit using the Colebrook-White Equation, specifically Equation for filled conduit and Equation 17 for partially filled conduit.[18]   These equations were solved by iteration.

$$\frac{1}{\sqrt{f_T}} = -2log\left(\frac{k}{14.8R} + \frac{2.51}{N_{RE}\sqrt{f_T}}\right), full\ conduit \qquad 16$$

$$\frac{1}{\sqrt{f_T}} = -2log\left(\frac{k}{12R} + \frac{2.51}{N_{RE}\sqrt{f_T}}\right)\ partially\ filled\ conduit \qquad 17$$

where:

$k = pipe\ roughness\ (ft)$.

For a Reynolds number between the 2100 and 4000, the flow is considered transitional, where the friction factor cannot be explicitly determined it is derived as shown in the Moody diagram (Figure 2-1) for Newtonian fluids.[22]

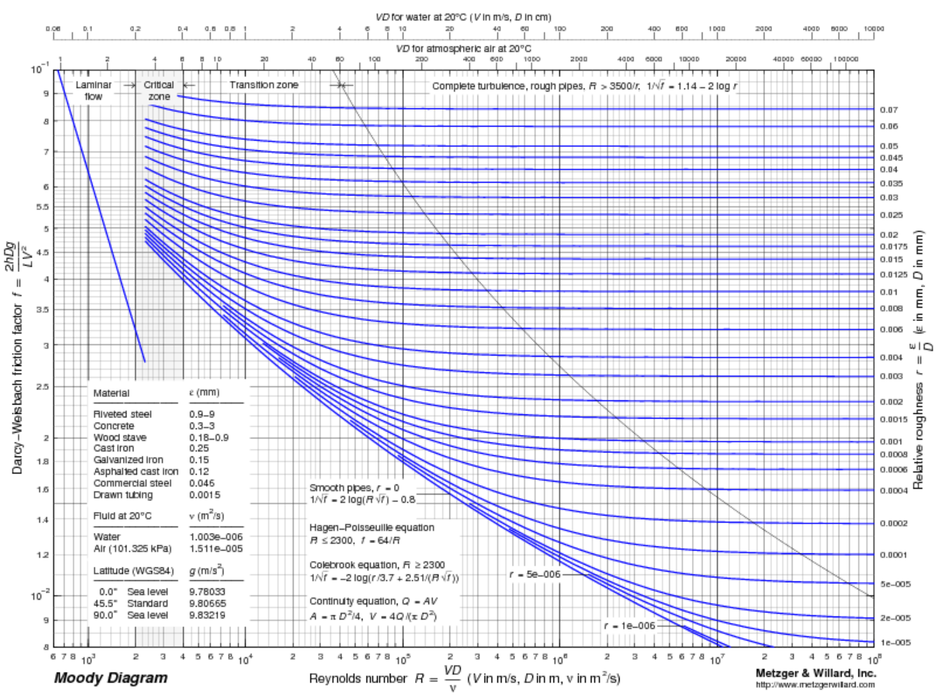


Figure 2-1. Moody Diagram

2.3.2 *Methods to Determine Non-Newtonian pipe frictional losses*

The non-Newtonian slurries were analyzed as a Bingham Plastic fluid. Two dimensionless parameters are required to further assess the pressure drop associated with this model and they are the Reynolds Bingham Number (Equation 18) and the Hedstrom number (Equation 19).

$$Re_B = \frac{4RV\rho}{\eta_\infty} \quad 18$$

$$He = \frac{16R^2\rho\tau_o}{\eta_\infty^2} \quad 19$$

For non-Newtonian flow, the friction factor can be determined using the following relationship developed for a Bingham Plastic fluid.[23] Note that pipe roughness is not included in the turbulent term; hence, this calculated value could be lower than expected, but no correction was performed. The laminar and turbulent friction factors are determined using Equations 20 and 21:

$$f_{BP-L} = \frac{16}{Re_B}\left[1 + \frac{He}{6Re_B} - \frac{1}{3}\left(\frac{He^4}{f_{BP}^3 \cdot Re_B^7}\right)\right] \ (Laminar) \quad 20$$

$$f_{BP-T} = 10^a Re_B^b \ (Turbulent) \quad 21$$

where:

$f_{BP-L} = Bingham\ Plastic\ laminar\ friction\ factor$,
$f_{BP-T} = Bingham\ Plastic\ Turbulent\ friction\ factor$,
$a = -1.47\left[1 + 0.146e^{-2.9x10^{-5} \cdot He}\right]$, and
$b = -0.193$.

The laminar and turbulent friction factor can be combined into a single friction factor, Equation 22. Note the factor of 4. This is required to convert the Fanning friction factor to the Darcy friction factor which was used to determine the pressure drop.

$$f_{BP} = 4 \cdot (f_{BP-T}^m + f_{BP-L}^m)^{\left(\frac{1}{m}\right)} \quad 22$$

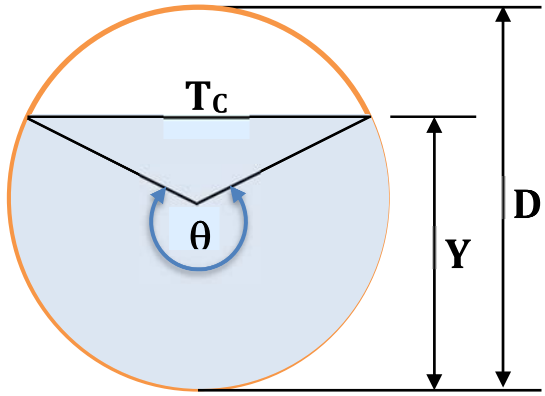
where:

$m = 1.7 + \frac{40{,}000}{Re_B}$.

Correcting the minor losses if the flow becomes laminar was not performed. By not performing such a calculation, the calculated velocity will be larger since the loss coefficient is larger in laminar flow as compared to turbulent flow. Laminar minor loses can be determined using either the 2-K or 3-K method[24] or from Idelchik (pg. 291).[25] Crane provides a procedure to correct for laminar flow when the Reynolds number is less than 1000, see page 2-11.[17]

2.3.3 *Impact of Partial Pipe Fill*

In addition to calculating maximum flow through the drain system, flowability was evaluated at a fixed flow rate. With a fixed flow less than the maximum flow, partially filled pipe flow is expected. The two streams were modeled as Newtonian fluids. While the Tank 16.3 and 16.4 materials exhibit Bingham Plastic behavior, there is no technical data to support using the friction factor for partially filled pipe for non-Newtonian flow. There is an underlying basis to use the Newtonian friction factor (Equation 17) for partially filled pipe flow. Calculation of the friction factor is identical to that described above; however, the hydraulic radius must be calculated. The method for calculating the hydraulic radius is illustrated in Figure 2-2., and calculated with Equation 23.



where:

D = diameter of pipe (ft),
Y = Fill Height (ft),
$F = Fill\ Factor = \frac{Y}{D}\ (dimensionless)$,
$\theta = 2 \cdot acos(1 - 2 \cdot F)$ (radians),
$T_C = cord\ length\ at\ fill\ height = Dsin\left(\frac{\theta}{2}\right)$ (ft),
$A = cross\ sectional\ area\ of\ flow = \frac{D^2 \cdot (\theta - sin\theta)}{8}$ (ft^2), and
$P_w = wetted\ perimeter = \frac{D \cdot \theta}{2}$ (ft).

Figure 2-2. Partial Pipe Fill to Determine the Hydraulic Radius for a Given Fill Height

$$R = \frac{\frac{D^2 \cdot (\theta - sin\theta)}{8}}{\frac{D \cdot \theta}{2}} = \frac{D \cdot (\theta - sin\theta)}{4 \cdot \theta} \qquad 23$$

The hydraulic radius is used in the energy equation, Reynolds number calculation, and friction coefficient determination (Equations 14, 15, and 17, respectively). The energy equation in this case is solved using the goal seek option in EXCEL. The Newtonian frictional factor (Equation 17) is determined using eight iterations.

2.4 Inputs for Flow Calculations

Length, $z_1 - z_2$, elbows, etc., were determined from review of the drain system drawings.[26-34] Table 2-3 shows these values for the entire drain system. Data for the less-sloped and smaller $z_1 - z_2$ initial section of the system are given in Table 2-4. Per e-mail from W. M. Bennett,* WF1100 (WH#1) was used for the current SRE and future Accelerated Basin Deinventory (ABD) transfers to the HPP. However, WF1101 (WH#3) and/or WF1102 (WH#4) could be repurposed for ABD use if needed. WF1103 (WH#2) is currently not connected to the pump tank, and there are currently no plans on using it in the future. Therefore, flow through WF1100, WF1101, and WF1102 were evaluated.

The $\left(\frac{L}{4R}\right)_{eff}$ values in the table were taken from Crane, page A-29.[17] Note that in this edition of Crane, the values are referred to as "K".

* E-mail can be found in ELN experiment L3293-00022-37.

Table 2-3. Complete Elevation, Piping Run, Elbows, Entrance and Exit Data for Waste Transfer Line between Building 221-H to HPP#5 and HPP#6

Variable		Units	Pipe Number (221-H High & Low Level Waste Header Number/ Outside Pipe or Line Number) and discharge HPP		
			(HL-1 / WF1100) HPP#6	(LL-4 / WF1101) HPP#5	(LL-3 / WF1102) HPP#5
Elevation Difference	$z_1 - z_2$	feet	19.03	17.22	115.81
Piping	L	feet	756.9	760.6	775
Entrance	$K_{entrance}$	unitless	1	1	1
Elbows	r/d	$\left(\frac{L}{4R}\right)_{eff}$ (unitless)	Number of elbows		
	1	20	1	1	1
	1.5	14	5	5	4
	6	17	0	1	1
	15	40*	2	2	2
	21	50*	3	3	3
90° Mitre	--	60	2	2	2
Exit	K_{exit}	unitless	1	1	1

* Values for r/d=15 and 21 are not given. The value for r/d=15 was determined by interpolation between the values of r/d of 14 and 16. The r/d=20 value was used for the r/d of 21.

Table 2-4. Initial Elevation Drop and 0.005 Sloped Piping Run, Elbows, Entrance for Waste Transfer Exiting Building 221-H

Variable		Units	Pipe Number (221-H Waste Header/ Outside Line Number) and discharge HPP		
			(HL-1 / WF1100) HPP#6	(LL-4 / WF1101) HPP#5	(LL-3 / WF1102) HPP#5
Elevation Difference	$z_1 - z_2$	feet	4.91	3.11	1.71
Piping	L	feet	105.26	103.46	105.04
Entrance	$K_{entrance}$	unitless	1	1	1
Elbows	r/d	$\left(\frac{L}{4R}\right)_{eff}$ (unitless)	Number of elbows		
	15	40*	2	2	2
	21	50*	1	1	1

* Values for r/d=15 and 21 are not given. The value for r/d=15 was determined by interpolation between the values of r/d of 14 and 16. The r/d=20 value was used for the r/d of 21.

The waste generated in Tank 8.4 in Building 221-H is transferred through a 3-inch diameter line to the 0.5% sloped, 10-inch diameter header using a Type C steam jet[35], which supplies flow of 75 gallon per minute (gpm).[36]

Calculations for both the complete hydraulic system and that of the initial sloped section were completed. The initial section has a smaller slope and less head than the overall system and could potentially be a "bottleneck"; thus it was evaluated separately.

In modeling as a Newtonian fluid, the pipe roughness is a significant input. The pipe roughness used in the calculations for a clean pipe (k = 0.00015 ft[24]) was used. An evaluation with other pipe roughness factors, including that evaluated in Daniel, et al.,[1], were used to evaluate for the WF1100 flow path.

2.5 Determining Deposition Velocity and Sediment Transport

The deposition velocity (i.e., velocity at which particles will settle out of the flow stream) was determined assuming the particles are considered hard bodies (e.g., they are not considered flocculated material that contains interstitial fluids) and the particles are not cohesive. The assumption that these freshly made solids are hard bodies makes this calculation conservative, since the interstitial fluids would reduce the "average" density of the particle as determined using the light scattering results.

The deposition velocity for open channel flow is shown in Equation 24.[22] The form of this equation is consistent with that used for completely filled piping used to transport non-cohesive solids, though the power coefficients may be slightly different and other physical properties considered.[37] The d_{90} particle size was used for this analysis instead of d_{85}.

$$V_D = 1.833 \left[\frac{8gR}{\rho}(\rho_S - \rho)\right]^{\frac{1}{2}} \left(\frac{d_{85}}{R}\right)^{0.158} \left(\frac{ft}{sec}\right) \qquad 24$$

where:

$V_D = deposition\ velocity$,
$\rho_S = density\ of\ solid$, and
$d_{85} = particle\ size\ at\ the\ 85th\ percentile\ by\ volume$.

2.6 Calculation of Drain Volume

The volume of the WF1100 drain line is calculated to assess time for the waste to backup in cases when calculated flow of the waste is less than the 75 gpm steam jet. The volume is calculated by multiplying the cross-sectional area of the 3 in Schedule 40 line by the length from Table 2-3:

$$\frac{\pi(3.06)^2 in^2}{4} \times \frac{ft^2}{144\ in^2} \times 757\ ft \times \frac{7.48\ gal}{ft^3} = 291\ gal$$

In addition to the volume of the drain line, waste can backup into the 10-inch diameter header. Level in the header is monitored and flow is procedurally paused when the level reaches 90% of the pipe height (pipe diameter).[38] The 10-inch diameter header has a slope of 0.5%.[33] This data, along with the diameter of 10 inch schedule 40 pipe was input to an online calculator with inputs and results shown in Figure 2-3 [†] Note that at a depth of 90%, with a slope of 0.5%, liquid would backup to approximately 150 ft $\left(10\ inches \times 90\% \times \frac{1\ ft}{0.005\ ft} \times \frac{1\ ft}{12\ inches}\right)$.

[†] https://www.engineeringtoolbox.com/content-cylindrical-tank-d_1301.html, accessed 10/6/2020.

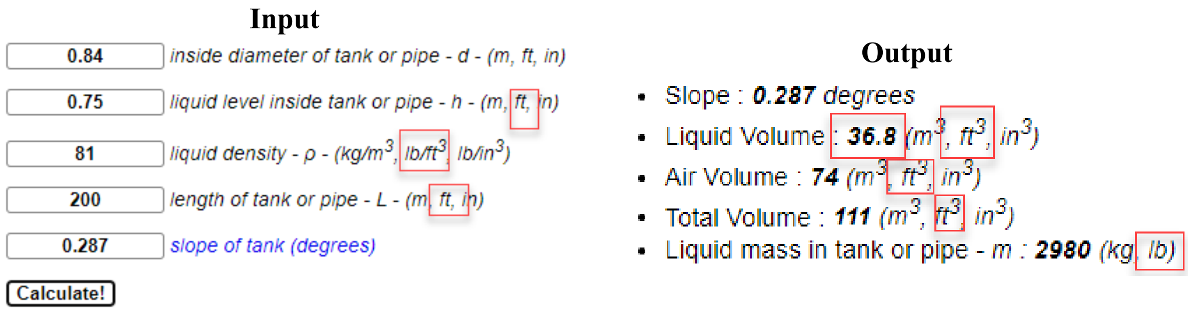


Figure 2-3. Input and Output of Online Calculator for Determination of Header volume at 90% Depth

Multiplying 36.8 ft^3 by 7.48 gal/ft^3 yields 275 gal.

Adding the volume in the header to the volume in the drain line yields:

$$291\ gal + 275\ gal = 576\ gal$$

The time to fill the drain line (time to backup and reach the instrumentation to stop flow) is calculated with Equation 25.

$$time\ to\ back\ up\ into\ header = \frac{Volume\ to\ reach\ instrumetation}{Flow_{in} - Flow_{out}} \qquad 25$$

2.7 Quality Assurance

Requirements for performing reviews of technical reports and the extent of review are established in manual E7 2.60.[39] This document, including all calculations, was reviewed by Design Verification by Document Review. SRNL documents the extent and type of review using the SRNL Technical Report Design Checklist contained in WSRC-IM-2002-00011, Rev. 2.[40] Data are recorded in the electronic laboratory notebook system as experiment L3293-00022-37.[41]

This task has a Functional Classification of General Service, and Functional Requirements and Functional Design Criteria are not applicable.[2]

3.0 Results and Discussion

3.1 Description of Mn, NaOH, and Water Additions

As stated in the experimental section, H-Canyon material, manganous nitrate, sodium hydroxide, and water were added to clear centrifuge tubes and mixed by shaking followed by mixing using a vortex mixture. Large particles were observed when pouring the contents from the centrifuge tube into the HDPE bottle; they did not easily transfer to the HDPE bottle. Solids tended to stick to the shoulder of the centrifuge tube. The contents in the HDPE bottle were allowed to settle; rinsing with the supernate and tapping of the centrifuge tube were used to further assist in removing the large particles into the HDPE bottles.

Prior to transfer of the material from the centrifuge tubes to the HDPE bottles, settling was observed. After approximately 90 minutes, sludge level was at approximately 60 mL in the tubes. The samples were allowed to settle overnight and for both Tank 16.3 and Tank 16.4; approximately half the volume was supernate with a settled sludge layer.

A picture of Tank 16.4 in the centrifuge tube prior to transfer to the HDPE bottle is shown in Figure 3-1., where the larger particles can be observed.

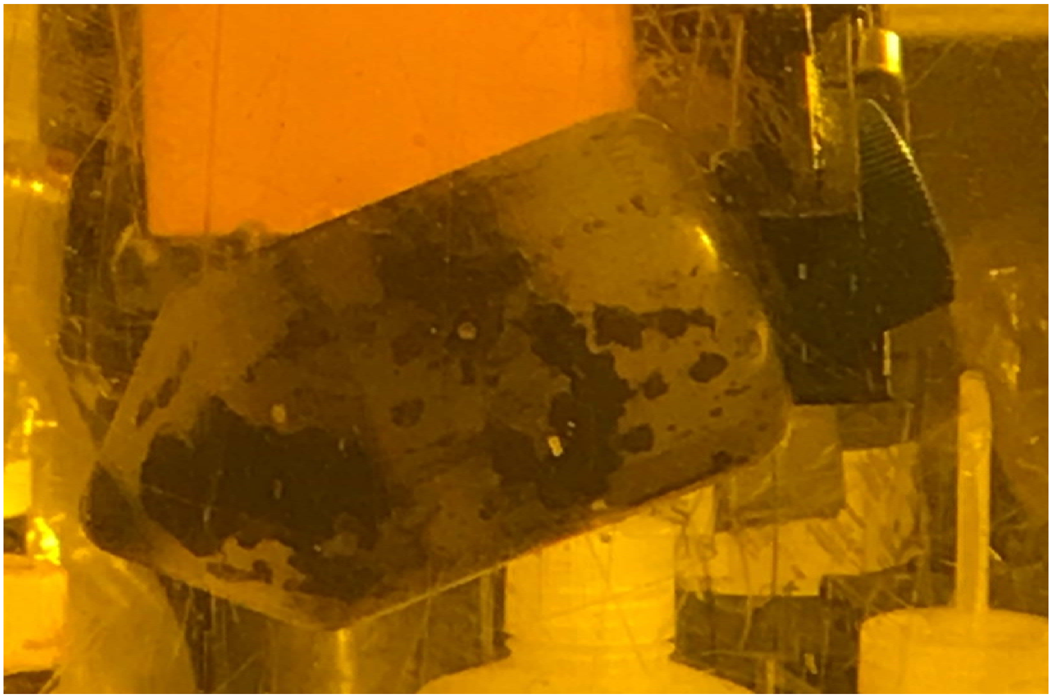


Figure 3-1. Solids of Neutralized Tank 16.4 in Centrifuge Bottle After First Transfer to HDPE Bottle

3.2 Physical Properties

Densities, weight percent solids and rheological properties for the neutralized SRE products in Tanks 16.3 and 16.4 samples are presented in Table 3-1. The densities were slightly lower than the target of 1.33 g/mL. Tank 16.4 had approximately 1.6 times more undissolved solids than Tank 16.3. This result is expected; Tank 16.4 had significantly more total uranium than Tank 16.3, resulting in more insoluble solids. A calculation of expected undissolved solids was also completed. As can be seen in the table, the measured undissolved solids in both samples was lower than expected. This deviation could be due to large particles settling out while pulling aliquots for density and wt% solids measurements.

The rheological results for Tank 16.4 had a higher resulting Bingham Plastic viscosity and yield stress and apparent viscosity compared to Tank 16.3 and is attributed to the higher UDS in Tank 16.4.

For the flow calculations, the apparent viscosity was used when modeling the waste streams as a Newtonian fluid and the plastic viscosity and Bingham yield stress were used when modeling as a non-Newtonian Bingham Plastic fluid.

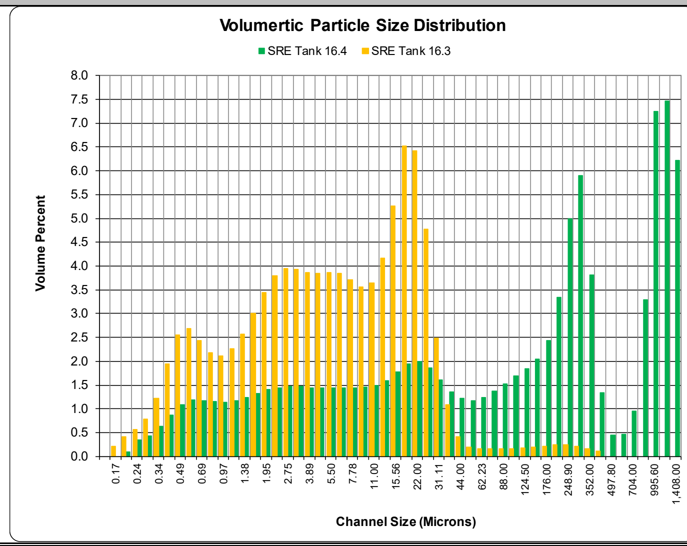
Table 3-1. Weight% Solids, Density, and Rheological Properties Results

Property	Neutralized Tank 16.3		Neutralized Tank 16.4	
	Expected	Measured	Expected	Measured
Slurry Density (g/mL)	1.33	1.30	1.33	1.28
Supernatant Density (g/mL)	--	1.26	--	1.24
wt.% Total Solids Slurry Basis)	--	34.4	--	32.8
wt.% Soluble Solids in Supernatant	--	32.3	--	29.2
wt.% Undissolved Solids in Slurry	6 *	3.1	7.1 *	5.1
Plastic Viscosity (cP)	--	6.6	--	9.7
Bingham Plastic Yield Stress (Pa)	--	0.6	--	1.5
Apparent Viscosity (cP) at $600 s^{-1}$	--	7.7	--	12.4

* Expected wt.% undissolved solids at 64:1 Mn:U-235 equivalents are 5% for Tank 16.3 and 5.8% for Tank 16.4.

Particle size distributions were obtained for the SRE neutralized Tank 16.3 and Tank 16.4 samples. Results are shown in Table 3-2. As can be seen in the results, the Tank 16.4 material had significantly larger particle size than Tank 16.3 material. Larger particles were visually observed in the centrifuge tube for both neutralized samples during the transfer to the HDPE sample bottles. The larger particles captured in Tank 16.4 could be due its yield stress maintaining (or slowing down the settling) the larger particles suspended and/or due to the sampling location for the SRNL-prepared Tank 16.4 being closer to the bottom as compared to Tank 16.3. These particle size distributions do not reflect what is expected in Tank 8.4. Tank 8.4 will be mixed with impellers, mixing will be turbulent, chemical additions will be made slowly, etc. Also, because of dose rate concerns, only small samples of each material were taken; the results may not be representative of the SRNL-made material. This data was used for deposition velocity calculations. The larger particles can impact the following properties: density of the slurry, weight percent of insoluble solids in the slurry, and the rheology. The main issue with the larger particle sizes is solids settling and ability to pull representative aliquots, particularly for density and wt.% solids measurements. If the larger particles were made smaller, these properties would increase in value.

Table 3-2. Particle Size Distribution, Percentiles and Mean Values

Parameter		Microns		Volumetric Particle Size Distribution
		Neutralized Tank 16.3	Neutralized Tank 16.4	
Volume Percentiles Distribution	10	0.564	1.261	
	20	1.209	4.23	
	25	2.097	13.43	
	40	3.26	35.13	
	50	5.11	118.3	
	60	8.07	222.1	
	70	12.79	301.9	
	75	17.40	840.1	
	90	22.83	1061	
	95	28.40	1191	
Mean Volume		12.22	332.6	

3.3 Flow Calculations

3.3.1 *Full Pipe – Maximum Flow*

Full pipe calculations provide the maximum flow the hydraulic system can provide, via gravity. The pipe run and fittings for each flow path were entered into the energy equation, Equation 14, (i.e., $z_1 - z_2$ and $\left(\sum_{i=1}^{n}\left(\frac{L}{4R}\right)_{eff,i} + \frac{L}{4R}\right)$) for full pipe flow. Additionally, entrance and exit losses were included. The equations are shown in Table 3-3. The friction factor, f_T, for the Newtonian evaluation is calculated using Equations 15 and , with inputs of the density, rheological properties (apparent viscosity), wall roughness, hydraulic radius, and average velocity. The friction factor for the non-Newtonian, Bingham Plastic evaluation is calculated using Equations 19, 20, 21, and 22, with inputs of the density, rheological properties (Bingham Plastic viscosity and yield stress), hydraulic radius, and average velocity. The solutions to these equations involve iterations using a Microsoft Excel spreadsheet. Microsoft Excel's Solver function was used to find solutions.[41] The resulting velocity was then used to calculate a flow rate using the cross sectional area of the pipe. Results for the full drain system and the initial drain section are shown in Table 3-4 and Table 3-5, respectively.

As stated in Section 2.4, the pipe roughness for clean pipe was used in the Newtonian flow evaluation. Results using other friction factors are shown in Table 3-6 for waste line WF1100 to show the effect of pipe roughness on the calculational results. As can be seen, pipe roughness has a significant impact on flow.

Table 3-3. Energy Equations for Velocity Determination for Waste Transfer Lines Between Building 221-H and HPP

Line Number		$\sum_{i=1}^{n} \left(\frac{L}{4R}\right)_{eff,i}$	$\frac{L}{4R}$	Energy Equation
WF1100	Overall	440	2960	$17.1 = \frac{V^2}{2g}(1.5 + 3400 f_T)$
	Initial Section	130	412	$4.91 = \frac{V^2}{2g}(1.5 + 542 f_T)$
WF1101	Overall	457	2975	$15.3 = \frac{V^2}{2g}(1.5 + 3432 f_T)$
	Initial Section	130	405	$3.12 = \frac{V^2}{2g}(1.5 + 535 f_T)$
WF1102	Overall	443	3031	$13.9 = \frac{V^2}{2g}(1.5 + 3474 f_T)$
	Initial Section	130	411	$1.71 = \frac{V^2}{2g}(1.5 + 541 f_T)$

Table 3-4. Average Velocity, Reynolds Number, and Maximum Flow Rate (Full Pipe) for Waste Transfer Lines Between Building 221-H and HPP

	Model*	WF1100			WF1101			WF1102		
		V (ft/s)	N_{Re}	Q (gpm)	V (ft/s)	N_{RE}	Q (gpm)	V (ft/s)	N_{Re}	Q (gpm)
Tank 16.3	N	3.48	13937	80.1	3.27	13106	75.3	3.09	12403	71.3
	BP	4.22	19762	97.3	3.98	18603	91.6	3.77	17624	86.8
Tank 16.4	N	3.25	7972	74.9	3.05	7490	70.4	2.89	7083	66.6
	BP	4.00	12538	92.2	3.77	11824	86.9	3.58	11232	82.6

* The pipe roughness used in the calculations for a clean pipe (k = 0.00015 ft) was used in the Newtonian (N) model. Pipe roughness is not an input when modeling as a Bingham Plastic (BP).

Table 3-5. Average Velocity, Reynolds Number, and Flow rate (Full Pipe) for Initial Section of the Waste Transfer Lines Leaving Building 221-H

	Model*	WF1100			WF1101			WF1102		
		V (ft/s)	N_{Re}	Q (gpm)	V (ft/s)	N_{RE}	Q (gpm)	V (ft/s)	N_{Re}	Q (gpm)
Tank 16.3	N*	4.36	17479	100.4	3.41	13669	78.5	2.42	9699	55.7
	BP	5.18	24236	119.4	4.06	18993	93.5	2.90	13586	66.9
Tank 16.4	N*	4.11	10083	94.8	3.20	7843	73.7	2.26	5547	52.1
	BP	4.96	15546	114.3	3.86	12102	89.0	2.41	7565	55.6

* The pipe roughness used in the calculations for a clean pipe (k = 0.00015 ft) was used in the Newtonian (N) model. Pipe roughness is not an input when modeling as a Bingham Plastic (BP).

Table 3-6. Maximum Newtonian Flow at Varying Pipe Roughness Through Waste Line WF1100

Pipe roughness[24] (ft)		Tank 16.3		Tank 16.4	
		V (ft/s)	Q (gpm)	V (ft/s)	Q (gpm)
New	0.00015	3.5	80.1	3.3	74.9
Light Rust	0.00125	3.1	72.2	3.0	69.2
General Rust	0.00667	2.5	57.6	2.5	56.7

3.3.2 *Evaluation of Partial Pipe Fill*

Given a flow rate of 75 gpm (Tank 8.4 transfer jet rate), the energy equation, Equation 14, was again solved as a Newtonian fluid with pipe roughness of 0.00015 ft (new). At this flow rate, the pipe would be partially full, with a hydraulic radius R. Given a flow rate, velocity and hydraulic radius are related (see Equations 7, 8, 23, and Figure 2-2.). Again, Microsoft Excel's Solver function was used to solve the energy equations. Results are presented in Table 3-7 for the overall drain system and Table 3-8 for the initial section. Because the overall system cannot handle 75 gpm for WF1101 and WF1102, only results for WF1100 are shown. Cases where the drain line cannot handle 75 gpm (see Table 3-4 and Table 3-5) are not shown.

Table 3-7 Fill Ratio, Velocity and Reynolds Number for the Waste Transfer Lines Between Building 221-H and HPP at 75 gpm

	WF1100		
	Fill Factor	V (ft/s)	N_{Re}
Tank 16.3	0.78	3.90	18984

Table 3-8 Fill Ratio, Velocity and Reynolds Number for the Initial Section of the Waste Transfer Lines Leaving Building 221-H at 75 gpm

	WF1100		
	Fill Factor	V (ft/s)	N_{Re}
Tank 16.3	0.66	4.67	21684
Tank 16.4	0.68	4.46	12860

3.3.3 *Deposition Velocity*

The deposition velocity for the neutralized Tanks 16.3 and 16.4 samples was calculated using Equation 24. An input to the deposition velocity calculation is hydraulic radius, which is related to the fill ratio. Fill ratios of 0.66, 0.68, and 0.78 were calculated (see Table 3-7 and Table 3-8). These values were rounded to 0.7 and 0.8 and used to calculated hydraulic radius and deposition velocity for the two tanks. Deposition velocity is reported in Table 3-9. Also, since the solids density was not measured, the solids density of 3.50 g/mL used in the previous analysis, was used.[1] Note that the density of $Mn(OH)_2$, which makes up approximately 70% of the UDS, is 3.26 g/mL[42]; using 3.50 g/mL is therefore reasonable. Comparing the deposition velocities to the fluid velocities, the deposition velocities do not exceed fluid velocity for Tank 16.4. For Tank 16.3, the calculated fluid velocity exceeds the deposition velocity.

Because, for Tank 16.4, the calculated fluid velocity is less than the deposition velocity; the larger particles would be expected to settle during transport. However, as discussed elsewhere, neutralization of the material in H Canyon, with turbulent agitation and slow addition of sodium hydroxide, would result in smaller particles, and deposition would be less likely.

Table 3-9 Deposition Velocity at a flow rate of 75 gpm

Sample	Deposition Velocity (ft/s)	
	Fill Ratio=0.7	Fill Ratio=0.8
Tank 16.3	3.5	3.6
Tank 16.4	6.6	6.6

3.4 Evaluation of Potential for Material to Backup into the 10-inch Diameter Header

Depending on pipe roughness, maximum pipe flow may not exceed the steam jet flow of 75 gpm. This will result in some accumulation of fluid in the 3-inch diameter line and up to the 10-inch diameter header during transfer. Per e-mail from W. M. Bennett, transfers will be completed in batches of approximately 2,100 gal.[‡] The volume of drain line WF1100 and the combined volume of drain line WF1100 and 10-inch diameter header before a transfer may be temporarily paused by turning off the steam jet were calculated in Section 2.6 to be 275 gal and 576 gal, respectively. The time to fill these volumes was then calculated for the flow rates for Tank 16.4 using the flowrates in Table 3-6 for light rust (69.2 gpm) and general rust (56.7) using Equation 25. The time for a transfer of 2100 gal at 75 gpm ($2100gal \div 75gal/min$) was also calculated. Tank 16.4 bounds Tank 16.3. Results are shown in Table 3-10.

Table 3-10. Time Before Tank 16.4 Material backs up into the 10 Inch Header

Flow Out (gpm)	Time Until Drain Line Fills (min)	Time Until Transfer Would be Paused (min)
69.2 (light rust)	47	99
56.7 (general rust)	15	31
Time to transfer 2,100 gal at 75 gpm		
28 min		

As can be seen from the table, waste may backup into the 10-inch dimeter header, especially if the transfer line has a roughness comparable to general rust. A backup to the level necessitating a temporary pause in the transfer is not expected with these calculated flow rates.

3.5 Projection of Tank 16.3 and 16.4 Weight% UDS and Dilution Recommendation

The highest wt.% UDS material measured by SRNL (Tank 16.4, Table 3-1) was 5 wt.% and was considered flowable and is recommended as an wt.% UDS endpoint for Tanks 16.3 and 16.4.

Using the projected Mn, U, Th metal concentrations, volume, and specific gravity from the Waste Characterization report[6] (values in the Concentrations in Neutralized Solution post-Dilution column), the projected wt.% UDS were calculated. Minor metal components were not considered in this calculation

[‡] E-mail from W. M. Bennett on August 26, 2020. A copy can be found in ELN experiment L3292-00022-37.

given these metals are insignificant contributors. It is assumed that Mn precipitates to $Mn(OH)_2$, U precipitates as $Na_2U_2O_7$, and Th precipitates to $Th(OH)_4$. The mass of fluid required to dilute the projected UDS to 5 wt.% UDS was calculated. Inputs and calculation results are shown in Table 3-11. If water is used as the diluent, approximately 21,000 L is needed for each tank to lower the wt.% UDS to 5%. This does not include the dilution from the steam jet which, if included, would reduce the needed mass/volume addition of the diluent to obtain 5wt% UDS.

Table 3-11. Calculation of wt.% UDS in Neutralized, Diluted Tanks 16.3 and 16.4

	Tank 16.3	Tank 16.4
Concentrations in the neutralized diluted tanks (g/L)		
Mn	42.70	49.10
U	1.26	2.02
Th *	7.47	8.25
Total neutralized, diluted - volumes and masses		
Volume (L)	76,707	40,047
Density (g/mL)	1.33	1.33
Mass (g)	1.02E+08	5.33E+07
Calculated mass of UDS and expected wt.% UDS		
$Mn(OH)_2$ (g)	5.30E+06	3.18E+06
$Na_2U_2O_7$ (g)	1.29E+05	1.08E+05
$Th(OH)_4$ (g)	7.41E+05	4.27E+05
Total (g)	6.17E+06	3.72E+06
Expected wt.% UDS	6.1	7.0
Calculated 5 wt.% UDS concentration		
Total mass to obtain 5wt% UDS (g)	1.23E+08	7.44E+07
Additional mass needed (g)	2.14E+07	2.11E+07
Vol If additional mass is water (L)	21,447	21,116
Calculated density of diluted material (g/mL) †	1.22	1.25

* Thorium was reported as Th-232 dpm/mL. This was converted to g/L using the Th-232 specific activity.
† This calculation assumes water as the diluent.

4.0 Conclusions

Based on the physical property results of the neutralized SRE products from Tanks 16.3 and 16.4 and a feed rate to the drain system of 75 gpm, the material may backup into the 10-inch diameter header. Maximum flows range from 66.6 to 80.1 gpm when modeled as a Newtonian fluid and 82.6 to 97.3 when modeled as non-Newtonian Bingham Plastic when considering waste lines WF1000, WF1001, and WF1002. WF1003 is not considered due to flow path not being complete. With uncertainties in the rheological measurements from the way the samples were made, uncertainties in the pipe roughness, and potential buildup of solids in the lines, these calculations may not be conservative.

Another concern is the transport of the precipitated solids. The precipitated waste streams made by SRNL would result in setting of the larger solids, in both the 3-inch and 10-inch diameter lines. Simulant testing performed by SRNL showed the impact of shearing and caustic addition rate, where increased shearing and slower addition rate yielded a smaller precipitated particle size distribution.[13] It is expected that the highly turbulent mixing conditions and slow caustic addition in Tank 8.4 will yield a much smaller particle size distribution. These smaller particles would result in slower settling solids and more viscous fluid. A more viscous fluid would yield lower flow rates. However, the H-Canyon procedure requires Operations to monitor backup in the 10-inch diameter header during transfer; transfers can be paused in the event of backup.

This analysis did not account for steam jet dilution in transferring the material from Tank 8.4 to the 10-inch diameter waste header. Also, the manganese accounts for more than 88% of the undissolved solids. If less manganese is added, wt.% undissolved solids would be lower, resulting in lower viscosity and yield stress relative to using an 80:1 Mn to U-235 equivalent ratio.

The highest w.t% UDS sample SRNL prepared was for Tank 16.4. The measured UDS was 5.1 wt.%. SRNL recommends targeting 5wt.% UDS prior to discharge of the neutralized 16.3 and 16.4 material.

5.0 Recommendations

SRNL recommends processing the Tank 16.3 and 16.4 material to target a 5 wt.% UDS slurry (including the dilution from the Tank 8.4 transfer steam jet). SRNL calculated that an additional 21,000 L of water for Tank 16.3 and 16.4 would be needed to obtain this target. This volume does not include any added water from the steam jet. Though the fluids would be slightly non-Newtonian, the yield stress would assist in the transport of the solids in the both the 10-inch diameter header and the 3-inch diameter line. While material may backup into the header, pausing flow by temporarily turning off the steam jet and allowing the line to partially drain before restarting the steam jet per current procedure[38] would overcome this issue.

6.0 References

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Distribution List:

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Joseph.fields@srs.gov
jeffrey.gillam@srs.gov
barbara.hamm@srs.gov
robert.hoeppel@srs.gov
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bill.holtzscheiter@srs.gov
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Jeremiah.Ledbetter@srs.gov
jeff.ray@srs.gov
Azadeh.Samadi-Dezfouli@srs.gov
Jocelin.Stevens@srs.gov
hasmukh.shah@srs.gov
aaron.staub@srs.gov
celia.aponte@srs.gov
timothy.baughman@srs.gov
earl.brass@srs.gov
Azikiwe.hooker@srs.gov
lauryn.jamison@srs.gov
Ryan.McNew@srs.gov
phillip.norris@srs.gov
Christine.Ridgeway@srs.gov
arthur.wiggins@srs.gov
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Spencer.Isom@srs.gov
MARIA.RIOS-ARMSTRONG@SRS.GOV
daniel.tenpenny@srs.gov
marvin.barnett@srs.gov
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eloy.saldivar@srs.gov
james.therrell@srs.gov
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bill.giddings@srs.gov
david.henley@srs.gov
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