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Technical Basis for LAW Vitrification Stream Physical and Rheological Property Bounding Conditions

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February 2004

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ACCEPTED FOR WTP PROJECT USE

Battelle—Pacific Northwest Division Richland, Washington 99352

COMPLETENESS OF TESTING

This report describes the results of work and testing specified by Test Specification 24590-WTP-TSP-RT-01-007, Rev. 0, Test Plan TP-RPP-WTP-205, Rev. 0, and Test Exception 24590-WTP-TEF-RT-02-070. The work and any associated testing followed the quality assurance requirements outlined in the Test Specification/Plan. The descriptions provided in this test report are an accurate account of both the conduct of the work and the data collected. Test plan results are reported. Also reported are any unusual or anomalous occurrences that are different from expected results. The test results and this report have been reviewed and verified.

Approved:

Gordon H. Beeman, Manager WTP R&T Support Project

12/04 Date

Summary

Objectives

This document describes part of the work performed under Battelle Test Plan TP-RPP-WTP-205 Rev 0, *LAW and HLW Actual Waste and Simulant Coordination*. The objective of this work is to develop a set of bounding physical and rheological properties for waste materials that can be reasonably processed and likely encountered in the Waste Treatment Plant (WTP) vitrification facilities. This information is then to be used by Bechtel National Incorporated to facilitate consensus among Research and Technology, Environmental and Nuclear Safety (E&NS), Design, and Process Engineering functions. Ultimately, a set of bounding physical and rheological properties will be used to design the process equipment. To determine the bounds for each operation, one must understand what general waste properties are anticipated and how changes in those properties can affect process operation. The process bounds are then established at the point where the properties of the material induce unacceptable risk to plant performance. Hence this set of bounding physical and rheological properties can be used to judge when a given pretreated waste or melter feed may cause transfer or processing problems by causing the system to have to operate outside its design capabilities.

Conduct of Testing

The following strategy was used to meet the task objectives:

- 1. Identify physical and chemical parameters that are significant to WTP vitrification-stream processing through the use of dimensional analysis.
- 2. Compile and compare previous historical information on the parameters identified in Step 1 for actual and simulated process streams in accordance with *Guidelines for Performing Chemical, Physical, and Rheological Properties Measurements* (24590-WTP-GPG-RTD-001, Rev 0) (Smith and Prindiville 2002).
- 3. Recommend ranges for the parameters identified in Step 1 that include upper and lower bounding ranges that will likely result in performance degradation issues if exceeded.

Results and Performance Against Objectives

The strategy employed in the development of the bounding conditions proposed in this document is to identify correlations between dimensionless groups for basic unit operations performed in the WTP flowsheet. Note that dimensionless groups are numbers made up of physical property parameters (i.e., density, flow velocity, yield strength, viscosity, etc) combined in such a way that the units all cancel and therefore are "dimensionless". Because specific correlations for equipment in the WTP have not been developed and are not readily available, correlations for similar equipment that have been developed for standard chemical processing applications are used. Sources for these correlations include various engineering handbooks, engineering textbooks, and peer-reviewed journal articles. In addition, equipment data and calculations for previous vitrification-plant designs have been used. These previous designs include the Hanford Waste Vitrification Plant (HWVP) and the Defense Waste Processing Facility (DWPF). The use of these data and correlations assumes that the equipment selected for use in

the WTP will possess similar performance properties to equipment generally used in the chemical processing industry, HWVP, and DWPF. Typically, based on these correlations, bounding conditions on the physical and rheological properties are proposed to satisfy equipment performance issues.

Actual waste data have been used to tailor the bounding ranges such that the proposed bounding conditions span the existing actual waste properties. However, not all actual waste data lie within the proposed bounding-condition range as many waste concentrations were typically tested that possess a wide range of physical and rheological property values. Consequently, the proposed bounding conditions are based upon a general engineering evaluation of process equipment to encompass as many measured values from actual waste material as possible.

Physical and rheological bounding conditions were developed for two LAW vitrification streams: 1) pretreated LAW and 2) LAW melter feed. Summary tables of the bounding conditions developed in this document for each vitrification process stream are shown in Figures S.1 and S.2.



Figure S.1. Summary of Bounding Conditions for Pretreated LAW



Figure S.2. Summary of Bounding Conditions for LAW Melter Feed

As discussed above, the bounding conditions proposed in this document are predicated on 1) actual waste data, 2) theoretical/empirical correlations, and 3) the need for a reduction in plant operational risk. Information from previous actual waste characterization efforts were compiled and compared against the proposed bounding conditions. Several of the actual wastes possessed rheological properties outside of these bounding conditions. This is expected, as in past characterization efforts, a wide range of solids concentrations were typically analyzed to gauge the effect on physical and rheological properties. An asymptotic relationship between Bingham Plastic parameters and undissolved solids concentration exists (Slatter 1997; Landel et al. 1965; Dabak and Yucel 1987) and at high undissolved solids concentrations, the Bingham Plastic parameters can become quite large, and a relatively small amount of dilution can result in a significant decrease. This relationship explains the large rheological ranges observed for the actual waste materials. However, at least one measurement from each actual waste fell inside the proposed bounding conditions, typically at lower solids concentrations.

The theoretical/empirical basis for the pretreated LAW bounding conditions (see Figure S.1) was based on unit operations in the pretreatment section of the WTP. This was done because the physical properties of the pretreated LAW in the vitrification portion of the WTP are dependent on the processing history of this stream. With this in mind, an upper rheological bound of 15 mPa•s was established to minimize performance losses (excessive pressure drops, low heat and mass transfer coefficients) because of fluid viscosity in the ion exchange columns and evaporators. Pumping requirements through a packed bed were also considered in the selection of this upper bound. A lower rheological bound on the pretreated LAW (see Figure S.1) of 0.9 mPa•s was established based on an engineering evaluation of

settling velocities of particles at sizes (i.e., $164 \mu m$) and densities (i.e., liquid density of 1 g/mL; solid particle density of 3.6 g/mL) consistent with the current glass-former chemicals that will be added to the pretreated vitrification streams.

Bounding conditions for the LAW melter feed stream include a maximum value for the settled solids shear strength (see Figure S.2). This value was established based on a plant-upset condition where restart is attempted on a mechanical agitator immersed in a layer of settled solids. Using design specifications from HWVP, if the settled solids shear strength is above approximately 625 Pa, agitator restart may be difficult. This shear strength value was also used in an engineering evaluation of another plant upset condition that involves initiating flow in a 10-ft section of pipe containing a plug of settled solids. At a shear strength of 625 Pa, an achievable pressure drop was required to initiate the flow of a settled solids plug.

The Hedstrom number upper-bounding value of 10⁸ was established based on an engineering evaluation of the pumping requirements of several Bingham plastic fluids with pumps specified in the HWVP design. The rheological upper bounds for these vitrification streams were established based on the set of Bingham Plastic parameters that would produce a turbulent flow regime in a 2-in. ID pipe. The premise for this calculation is that heterogeneity during pipeline transport can be significant in the laminar flow regime for settling slurries. Pipeline plugging and slug flow can result during laminar flow. Actual waste data were compared to a computed set of Bingham Plastic parameters that result in turbulent flow while limiting high pipeline velocities that can result in erosion problems. A single point from this set of Bingham Plastic parameters for each vitrification stream was selected as the upper Bingham Plastic parameter point that encompassed most actual waste data. These bounding conditions compared well with the DWPF and HWVP melter-feed design ranges. The lower rheological bounds were selected to be consistent with the settling velocity calculation discussed above.

To demonstrate that the proposed rheological bounding conditions are reasonable, the viscosity of the actual AP-101 pretreated waste at several concentrations^(a) has been plotted against the proposed rheological bounding conditions. These plotted data are shown in Figure S.1. The plot shows that at all sodium concentrations tested, the material possesses Newtonian viscosities that are within the proposed rheological bounding conditions. This material was converted to a melter feed by adding appropriate glass-former chemicals, and the rheology of the resulting slurry was measured. These data have been plotted on the proposed rheological bounding conditions. This plot is shown in Figure S.2. Again, this material falls within the proposed bounding conditions for LAW pretreated melter feed. These AP-101 actual waste data^(a) were not available for consideration during the development of these bounding conditions. Consequently, these data appear to reinforce the theoretical/empirical correlations and engineering evaluations used in this document.

⁽a) PR Bredt, AP Poloski, and RG Swoboda. 2003. *Rheological and Physical Properties of AP-101 Pretreated LAW and Melter Feed*, WTP-RPT-064, Rev. 0, Battelle—Pacific Northwest Division, Richland, WA.

Additionally, Duratek pilot plant LAW melter feed simulant data^a designed to simulate several actual LAW waste sub-envelopes (A1, A2, A3, B1, B2, C1, C2) are shown in Figure S.2. These data consist of rheological measurements obtained after varying the quantity of liquid waste simulant in the LAW melter feed while keeping the quantity of dry GFCs added to the liquid simulant constant. This was done to investigate the effects of melter feed variability during operation of the WTP. For example, in Figure S.2, the A1 curve represents sub-envelope simulant A1 at the nominal LAW/GFC ratio, the A1-15% represents sub-envelope simulant A1 at 15% below the nominal LAW/GFC ratio, and A1+15% represents sub-envelope simulant A1 at 15% above the nominal LAW/GFC ratio. Typically the melter feeds with lesser LAW simulant contain a greater fraction of GFCs and consequently a higher solids loading. The higher solids loading is expected to raise the viscosity of the slurries. However, the melter feeds contain soluble species which can alter the pH and electrostatic potential of the slurry particles and this expectation is not always obeyed. These differences coupled with experimental error can be seen in several of the simulant melter feed data sets in Figure S.2. These differences are exemplified in the envelope B1 simulants where variations in simulant to GFC ratio produce counterintuitive results that should be expected due to the nature of these complex fluids.

Quality Requirements

PNWD implements the RPP-WTP quality requirements by performing work in accordance with the PNWD Waste Treatment Plant Support Project quality assurance project plan (QAPjP) approved by the RPP-WTP Quality Assurance (QA) organization. This work will be performed to the quality requirements of NQA-1-1989 Part I, Basic and Supplementary Requirements, and NQA-2a-1990, Part

Twarowski A. 2002b.*RPP-WTP Pilot Melter Sub-envelope A2 Variation Test Results Report*, TRR-PLT-070, Rev. 0, 10/4/02.

Twarowski A, 2003a, RPP-WTP Pilot Melter Sub-envelope C1 Variation Test Results Report, TRR-PLT-069 Rev. 2, 2/10/03.

Twarowski A. 2003b. *RPP-WTP Pilot Melter Sub-envelope C2 Variation Test Results Report*, TRR-PLT-072, Rev. 1, 3/12/03.

Twarowski A. 2003c. *RPP-WTP Pilot Melter Sub-envelope A1 Variation Test Results Report*, TRR-PLT-071, Rev. 0, 4/28/03.

Twarowski A. 2003d. *RPP-WTP Pilot Melter Sub-envelope B1 Variation Test Results Report*, TRR-PLT-073, Rev. 0, 8/26/03.

Twarowski A. 2003d. *RPP-WTP Pilot Melter Sub-envelope B2 Variation Test Results Report*, TRR-PLT-073, Rev. 0, 10/27/03.

^a Twarowski A, 2002a, RPP-WTP Pilot Melter Sub-envelope A3 Variation Test Results Report, TRR-PLT-060 Rev. 2, 11/21/02.

2.7. These quality requirements are implemented through PNWD's *Waste Treatment Plant Support Project (WTPSP) Quality Assurance Requirements and Description Manual.* The analytical requirements are implemented through WTPSP's Statement of Work (WTPSP-SOW-005) with the Radiochemical Processing Laboratory (RPL) Analytical Service Operations (ASO).

Some HLW data is presented in Appendices A, B, C, and F which has been generated under the additional quality assurance requirements of DOE/RW-0333P, Rev. 11, *Quality Assurance Requirements and Description (QARD)*. However, the requirements of QARD were not applied to the calculations and conclusions of this report and are not QARD affecting.

A matrix that cross-references the NQA-1 and 2a requirements with the PNWD's procedures for this work is given Test Plan, TP-RPP-WTP-205, *LAW and HLW Actual Waste and Simulant Coordination*. It includes justification for those requirements not implemented.

As specified in Test Specification, 24590-WTP-TSP-RT-01-007, Rev. 0, BNI's QAPjP, PL-24590-QA00001, is not applicable since the work was not performed in support of environmental/regulatory testing, and the data will not be used as such.

PNWD addresses internal verification and validation activities by conducting an Independent Technical Review of the final data report in accordance with PNWD's procedure QA-RPP-WTP-604. This review verifies that the reported results are traceable, that inferences and conclusions are soundly based, and the reported work satisfies the Test Plan objectives. This review procedure is part of PNWD's *WTPSP Quality Assurance Requirements and Description Manual*.

Issues

The following recommendations are made based on the findings in this document:

- Physical and rheological data do not exist for the complete set of LAW wastes to be processed through the WTP. Due to this lack of data, some LAW wastes that may be produced in the WTP at desired solids concentrations may be characterized and found that exceed the bounding conditions established in this report. Processing the waste below desired solids concentrations may be required to satisfy these bounding conditions.
- This document does not address the rheological effects of gas generation and retention. Currently, gas entrainment in the slurries processed by the DWPF is causing pump problems cavitation, loss of prime). The effect of gas (e.g. air, H₂) entrainment should be investigated by the WTP. Air entrainment will effect the rheological properties of WTP slurries and will impact the future operation of WTP slurry handling systems

Acronyms

CRV	concentrate receipt vessels
DOE	U.S. Department of Energy
DWPF	Defense Waste Processing Facility
GFC	glass-former chemicals
GFSF	Glass-Former Storage Facility
HLW	high-level waste
HWVP	Hanford Waste Vitrification Plant
LAW	low-activity waste
MFPV	melter-feed preparation vessel
MFV	melter-feed vessel
PNWD	Battelle—Pacific Northwest Division
PSD	particle-size distribution
QA	quality assurance
QAP	Quality Assurance Plan
QARD	Quality Assurance Requirements and Description
RPP	River Protection Project
SBS	Submerged Bed Scrubber
SRTC	Savannah River Technology Center
TRU	Transuranic
VSL	Vitreous States Laboratory
WSRC	Westinghouse Savannah River Company
WTP	Waste Treatment Plant
WTPSP	Waste Treatment Plant Support Project

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1.0 Introduction

The Hanford Site has 177 single-shell and double-shell tanks containing radioactive waste. The Office of River Protection's Hanford Waste Treatment Plant (WTP) is being designed and built to treat and vitrify a large portion of these wastes. The WTP consists of three primary facilities: a pretreatment facility and two facilities for low-activity and high-level waste vitrification. The pretreatment facility receives waste feed from the Hanford tank farms and separates it into two treated process streams: a high-volume, low-activity, liquid process stream stripped of most solids and radioisotopes and a much smaller volume high-level waste (HLW) slurry containing most of the solids and radioactivity. In the pretreatment facility, solids and radioisotopes are removed from the tank waste by precipitation, filtration, and ion exchange processes to produce the low-activity waste (LAW) streams. The slurry of filtered solids will be blended with two ion exchange eluate streams containing soluble radioisotopes to produce the HLW streams. The pretreated HLW mixture routes to the High-Level Waste Vitrification Facility and the pretreated LAW stream routes to the Low-Activity Waste Vitrification Facility. These two vitrification facilities convert these process streams into glass, which is poured directly into stainless steel canisters.

The major unit operations of the River Protection Project (RPP)-WTP facility are shown on the process flowsheet presented in Figure 1.1. The two vitrification process streams considered in this report are identified on the diagram as 1) pretreated LAW, and 2) LAW melter feed. The initial tank waste currently stored in the Hanford tank farm has been categorized according to chemical and radiochemical properties into four categories. These categories are referred to as Envelope A, Envelope B, Envelope C, and Envelope D wastes. The plant is divided into three major facilities, pretreatment, LAW vitrification, and HLW vitrification.

The pretreatment process may begin by concentrating the waste through an evaporation-unit operation. One purpose of this step is to minimize the quantity of waste processed through the plant. Figure 1.2 and Figure 1.3^(a) summarize the number and kinds of waste and recycle (or secondary) process streams that will occur in just the pretreatment facility. The potential effects of these secondary process streams on the four vitrification streams considered in this report will be discussed in a future revision of this document. For Envelope C wastes, the next step in the process is a Sr/TRU^(b) precipitation operation. A solid/liquid separation in a crossflow filter produces a high solids stream that is collected in a feed tank for the HLW vitrification process. The low-solids liquid stream then passes through a series of ion exchange columns is further evaporated and sent to the LAW vitrification plant. In this document, the low-solids and cesium stream is referred to as "Pretreated LAW." This stream can typically be characterized as a low solids Newtonian liquid.

⁽a) DJ Sherwood. 2002. Pretreatment Integration Program Execution Strategy for Research and Technology Development. Draft Report, CCN 066843, Bechtel, Inc., Richland, WA.

⁽b) TRU = transuranics.



Figure 1.1. RPP-WTP Basic Process Flowsheet



Figure 1.2. Schematic Pretreatment Facility Process Flow



Figure 1.3. Primary Pretreatment Facility Process Streams

The focus of this document is the streams processed through the LAW Vitrification Facility (see Figure 1.4). This facility receives pretreated waste plus secondary waste from the pretreatment facilities shown schematically in Figure 1.2 and Figure 1.3. The LAW Vitrification Facility is made up of a series of receipt and mixing tanks with associated pumps and transfer lines. The treated waste is initially transferred from the pretreatment tanks to concentrate receipt vessels (CRV) where the homogenized composition is measured before transfer to the melter-feed preparation vessel (MFPV). At this point, appropriate glass-former chemicals are added to the treated waste in the MFPV. The Glass Former Chemical Supply Hopper System illustrated schematically in Figure 1.5 feeds into all of the melter-feed process vessels. Table 1.1 gives the source, grade, and chemical composition of the glass-former materials that will be stored in the Glass Former Chemical Supply Hopper System. Batches of the glass-former chemicals (GFCs) are transferred to the MFPV (Schumacher 2003). With GFCs added, the resulting stream is called "LAW Melter Feed." This stream can typically be characterized as a high-solids non-Newtonian slurry. The subsequent homogenized melter feed is pumped into the melter feed vessel (MFV) and then fed to the melter. The remainder of the flowsheet consists of unit operations dedicated to the treatment of melter-generated offgas stream.

The objective of this document is to develop a set of bounding physical and rheological properties for waste materials that can be reasonably processed and that likely will be encountered in the Waste Treatment Plant (WTP) LAW Vitrification Facility. To determine the physical and rheological bounds for each operation, one must understand what general waste properties are anticipated and how changes in these properties impact process operation. The process bounds are then established at the point where the properties of the material introduce unacceptable risk to plant performance. Hence, one can use this set of bounding physical and rheological properties to determine if a given pretreated waste or melter feed will cause processing problems by forcing the system to operate outside its design capabilities. The technical basis for these processing bounds in established in this document.



Figure 1.4. Schematic of the LAW Vitrification Flowsheet



System HLW-GFR System HLW-HFP

Figure 1.5. Schematic of the Glass-Former Storage Facility (GFSF)

No.	Oxide Added	Mineral	Grade	Vendor
1	Al ₂ O ₃	Kyanite - Al ₂ O ₂ -SiO ₂	Raw –325 Mesh	Kyanite Mining Corp.
2	B_2O_3	Boric Acid - H ₃ BO ₃	Technical Grade-Granular	U.S. Borax
3	Na ₂ O/B ₂ O ₃	10M Borax - Na2B4O7-10H2O	Technical 10 Mole Borax	U.S. Borax
4	Na ₂ O	Na ₂ CO ₃ Anhydrous	Dense Soda Ash	Solvay Minerals
5	CaO	Wollastonite - CaSiO3	NYADM325	NYCO
6	Fe ₂ O ₃	Fe ₂ O ₃	5001	Prince Mfg. Co.
7	Li ₂ O	Li ₂ CO ₃	Technical Grade	Chemettal-Foote
8	MgO	Olivine	#180	Unimin Corp.
9	SiO ₂	SiO ₂	SCS-75	U.S. Silica
10	TiO ₂	Rutile TiO ₂ /Fe ₂ O ₃	Air Floated Rutile 94	Chemalloy Co.
- 11 -	ZnO	Zinc Oxide	Kadox 920	Zinc Corp America
12	ZrO ₂	ZrSiO ₄	Zircon flour	American Mineral Inc.
13	C12H22O11	Sugar	Granular	Amalgamated Sugar Co.

Table 1.1.	Glass-Former	Chemicals	and Minerals
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2.0 Dimensional Analysis as a Basis for Vitrification Stream Bounding Conditions

The objective of this work is to develop a set of bounding physical and rheological properties for vitrification process streams in the WTP. To determine the bounds for each operation, one must understand the general range of waste properties anticipated and how changes in those properties can affect the process operation. The process bounds are then established at the point where the properties of the material induce unacceptable risk to plant performance.

In this work, we have taken a two-phased approach. The first phase involves creating a list of physical properties that are believed to have a role in the process flowsheet. The physical-property bounding conditions can be established by simply compiling the actual waste physical-property data into a range of values that account for all the previously measured values. This approach has the advantage of requiring a minimal amount of process-engineering knowledge. However, not considering the engineering knowledge of the flowsheet may lead to a set of bounds that cannot be efficiently processed.

The second phase in developing physical-property bounding conditions involves examining performance correlations for the unit operations described in the flowsheet. With these correlations, a list of significant physical properties can be developed. The effect on the performance of the equipment by varying the physical properties can be examined with these correlations. These correlations can be used to find limits on the physical properties where equipment performance may drop to unacceptable levels.

The intersection of actual waste measurements (first phase) and bounds based on performance criteria (second phase) will be evaluated to establish a set of overall bounding conditions. When engineering design information is needed, Hanford Waste Vitrification Plant (HWVP) and Defense Waste Processing Facility (DWPF) engineering data will be used to eliminate conflict with ongoing WTP design efforts.

To begin this process, the unit operations described in the flowsheet need to be established. The simplified process flowsheet discussed in Section 1.0 consists of several unit operations that involve the following processes:

- fluid flow
 - o piping
 - o pumps
- fluid mixing
 - o mechanical agitators
- vitrification.

In addition, there are several unit operations that precede the vitrification streams. These unit operations have a direct impact on the physical properties of the vitrification streams. For this reason, these unit operations should be considered in this document and include the following:

heat transfer

- evaporators
- mass transfer/fluid flow
 - o ion exchange columns.

Such unit operations cannot typically be designed completely by theoretical or mathematical methods. One method of attacking a problem for which no mathematical equation can be derived is with empirical correlations. For example, the pressure loss from friction of a Newtonian fluid in a long, round, straight, smooth pipe depends on the following variables:

- 1. length of the pipe
- 2. diameter of the pipe
- 3. flowrate of the liquid
- 4. density of the liquid
- 5. viscosity of the liquid.

If one of these variables is changed, the pressure drop also changes. Empirically obtaining an equation relating these factors to pressure drop requires that the effect of each separate variable be determined by systematically varying a single variable while keeping all others constant. The procedure is laborious, and it is difficult to correlate the results so obtained into a useful relationship for calculations.

To overcome these difficulties, a method has been developed that is a combination of mathematical and empirical concepts. It is based on the fact that if a theoretical equation does exist among the variables affecting a physical process, that equation must be dimensionally homogeneous (i.e. dimensionless). Therefore, it is possible to group many factors into a smaller number of dimensionless groups of variables. The groups themselves rather than the separate factors appear in the final empirical correlation.

Such dimensional analysis does not yield a numerical equation, and experimentation is usually required to find the correlation between the dimensionless groups. These correlations result in a valuable way for making experimental data suitable for engineering use.

Several dimensionless groups related to fluid flow, heat, and mass transfer are shown in Table 2.1. In designing equipment for these operations, the following correlations (and others) can be found:

- fluid flow
 - $\circ f = \Phi(N_{Re})$
- fluid mixing
 - $\circ N_{Po} = \Phi(N_{Re})$
 - $\circ \quad C_d = \Phi(N_{Re})$
- heat transfer
 - $\circ N_{Nu} = \Phi(N_{Re}, N_{Pr})$
- mass transfer
 - $\circ N_{Sh} = \Phi(N_{Re}, N_{Sc}).$

Name	Symbol	Formula	Special Nomenclature	Proportional to	Where Used
Bingham Number	N _{Bm}	$ au_y g_c L/VK$	L = characteristic dimension K = consistency index V = velocity τ_y = Yield Stress	Yield Stress Viscous Stress	Flow of Bingham Plastics
Drag Coefficient	C _d	(ρ–ρ')Lg/ρV	ρ = density of object ρ' = density of fluid L = characteristic dimension of object V = velocity	Gravitational Force Inertial Force	Free Settling Velocities
Fanning Friction Factor	f	$g_c D(\Delta p_F / \rho) / 2 V^2 L$	$\Delta p_F / \rho$ = friction head D = characteristic diameter of cross section L = length of pipe	Shear Stress at Pipe Wall Expressed as Number of Velocity Heads	Fluid Friction in Conduits
Hedstrom Number	N _{He}	$g_c\rho\tau_yL^2/K^2$	$\label{eq:constraint} \begin{array}{l} L = characteristic \\ dimension \\ K = consistency index \\ \tau_y = Yield \ Stress \\ \rho = density \end{array}$	Yield Stress Inertial Force Viscous Stress Viscous Force	Flow of Bingham Plastics
Nusselt Number	N _{Nu}	hL/λ	$h = heat transfer$ $coefficient$ $\lambda = thermal$ $conductivity$ $L = characteristic$ $dimension$	Characterisitic Length Theorectical Film Thickness	Heat Transfer in Flowing Systems
Power Number	N _{Po}	Pg _c /L ⁵ pn ³	P = power to agitator L = characteristic dimension of agitator paddle n = rate of rotation	Drag Force on Paddle Inertial Force	Power Consumption on Agitated Vessels
Prandtl Number	N _{Pr}	$C_p \mu / \lambda$	C_p = Specific Heat Capacity λ = thermal conductivity	Momentum diffusivity Thermal diffusivity	Heat Transfer in Flowing Systems
Reynolds Number	N _{Re}	LVρ/μ	L = characteristic dimension of the system	Inertial Force Viscous Force	Dynamic Similarity
Schmidt Number	N _{Sc}	$\mu/ ho D_{AB}$	D _{AB} = Binary Diffusion Coefficient	Momentum diffusivity Mass diffusivity	Mass Transfer in Flowing Systems
Sherwood Number	N _{Sh}	h _m L/D _{AB}	$h_m = mass transfer$ coefficient $D_{AB} = Binary$ Diffusion Coefficient	Dimensionless concentration gradient at the surface	Mass Transfer in Flowing Systems

Table 2.1. Examples of Dimensionless Groups Significant in Fluid Flow, Heat, and Mass Transfer

Compiling the parameters that appear in these dimensional groups will provide a list of significant physical properties for our system. Yield stress and viscosity indicate that rheological parameters are significant to these process operations. Parameters such as particle density, bulk density, particle diameter, fluid velocities, and characteristic lengths of processing equipment are also significant to the performance of the equipment. Additionally, operating temperatures, pressures, flowrates, and the

concentration of solid particles and chemical species are important in the partial differential equations relevant to fluid flow, heat, and mass-transfer operations. Such partial differential equations include the continuity, momentum, energy, and conservation of mass equations.

A guideline (Smith and Prindiville 2002) has been developed by the RPP-WTP project with the purpose of measuring the parameters significant to simulant development and verification. Based on the process depicted in Figure 1.1, four major simulant types can be identified within the two vitrification facilities. The properties identified in the guideline document for the LAW vitrification streams can be found in Table 2.2. One purpose of this document is to compile historical parametric data in Table 2.2 on simulants and actual wastes. This compilation of data will be the focus of the next section and will be used to develop physical-properties bounding conditions using many of the dimensionless groups shown in Table 2.1.

Property	LAW Pretreated Waste	LAW Melter Feed
Chemical Composition	Х	Х
рН	Х	Х
Particle-Size Distribution (PSD)		Х
Particle (size and shape)		
Heat Capacity		
Bulk Density		Х
Supernatant Liquid Density	Х	Х
Vol % Settled Solids		Х
Settling Rate		Х
Centrifuged Solids Density		Х
Vol % Centrifuged Solids		Х
Wt % Centrifuged Solids		Х
Wt % Oven-Dried Solids		
Wt % Total Dried Solids	Х	Х
Wt % Undissolved Solids		Х
Shear Stress Versus Shear Rate ambient and 40°C	X	X
Shear Strength		Х
Wt % Total Oxide	Х	Х

 Table 2.2. Physical Properties Considered in 24590-WTP-GPG-RTD-001, Rev 0. "X" indicates the properties to be measured.

3.0 Summary Review of RPP-WTP Project Reports on Simulants and Actual Wastes

In this section, characterization data produced by Battelle—Pacific Northwest Division (PNWD), Savannah River Technology Center (SRTC), and the Vitreous States Laboratory (VSL) are reviewed in the form of an annotated bibliography. Table 3.1 summarizes the work considered in this document. The table indicates the project reports where the information can be found. An annotated bibliography of these studies follows. Results from these studies have been compiled in the attached Appendices.

Tank (Envelope)	Simulant Waste	Actual Waste		
AW 101 (A)	N/A	PNWD (WTP-RPT-002, Rev. 1) (Bredt and		
Aw-101 (A)	IN/A	Swoboda 2000)		
AN 102 (A)	N/A	SRTC (WSRC-TR-2000-00352 [Rosencrance		
AN-105 (A)	IV/A	et al. 2000]; WSRC-TR-2000-00322 ^a		
AN-104 (A)	VSL (Hi sulfur; VSL-01R3520-1) ^b	N/A		
	SRTC (WSRC-TR-2000-00298 [Hansen and			
AN-105 (A)	Calloway 2000]; WSRC-TR-2000-00338	N/A		
	[Eibling and Nash 2001])			
AW-101/	VSL (Le culture VSL 01P2520 $1)^{b}$	N/A		
AN-105 (A)	VSL (Lo sullui, VSL-01K5520-1)			
AD 101 (A)	PNWD (WTP-RPT-057, Rev 0 [Russell et al.	PNWD (WTP-RPT-064, Rev 0 [Bredt et al.		
AF-101 (A)	2003])	2003])		
	SPTC (WSPC TP 2000 00208 [Hanson and	SRTC (WSRC-TR-2000-00352 [Rosencrance		
AZ-102 (B)	Calloway 20001)	et al. 2000], WSRC-TR-2001-00395		
	Calloway 2000])	[Crawford et al. 2002])		
	VSL (VSL-01R3520-1) ^b ;			
AZ-101/	SRTC (WSRC-TR-2000-00298 [Hansen and	N/A		
AZ-102 (B)	Calloway 2000]; WSRC-TR-2000-00338	N/A		
	[Eibling and Nash 2001])			
AN 102 (C)	VSL (Hi and Lo sulfur: VSL 01P3520 1) ^b	SRTC (WSRC-TR-2000-00371) (Crawford et		
AN-102 (C)	VSE (III and E0 suitur, VSE-01K3520-1)	al. 2001)		
AN-107 (C)	SRTC (WSRC-TR-2000-00298 [Hansen and	PNWD (WTP PPT 002 Pay 1) (Bradt and		
	Calloway 2000], WSRC-TR-2000-00338	Swebode 2000)		
	[Eibling and Nash 2001])	Sw000da 2000)		
N/A – not available				
a-Crawford CL, DM	Ferrara, RF Schumacher, and NE Bibler. 2001. C	Crucible-Scale Active Vitrification Testing		
Envelope A, Tank A	N-103 (U), WSRC-TR-2000-00322, Westinghouse	e Savannah River Company, Aiken, SC.		

 Table 3.1. Review of Physical and Rheological Measurements on Hanford LAW Pretreated Waste and Corresponding Melter Feeds Supporting Documents

a-Crawford CL, DM Ferrara, RF Schumacher, and NE Bibler. 2001. Crucible-Scale Active Vitrification Testing Envelope A, Tank AN-103 (U), WSRC-TR-2000-00322, Westinghouse Savannah River Company, Aiken, SC. b-Muller IS, H Gan, and IL Pegg. 2001. Physical and Rheological Properties of Waste Simulants and Melter Feeds for RPP WTP LAW Vitrification. VSL 01R3520 1, Vitreous States Laboratory, The Catholic University of America, Washington D.C.

3.1 Annotated Bibliography for Envelope A, B, and C Process streams

PNWD (Bredt and Swoboda 2000) conducted rheological- and physical-properties tests on actual AN-107 (Envelope C) and AW-101 (Envelope A) pretreated waste samples before adding glass formers. Analyses were repeated following the addition of glass formers and are summarized below:

- The AN-107 and AW-101 pretreated wastes were tested at target sodium values of nominally 6, 8, and 10 M.
 - With the exception of the 10 M Na AN-107 sample, the rheograms of both AN-107 and AW-101 samples before adding glass formers show Newtonian behavior.
 - With the exception of some solids in the 10 M AN-107 sample that affected behavior at shear rates ($\dot{\gamma}$) below ~100 s⁻¹, the rheology of the AN-107 and AW-101 feeds was indistinguishable.
 - The viscosities of the 6, 8, and 10 M Na feeds at $\dot{\gamma} = 500 \text{ s}^{-1}$ were 8, 12, and 21 mPa•s, respectively, at 25°C, and 4, 7, and 12 mPa•s, respectively, at 50°C.
 - o The 10 M Na AN-107 sample displayed Bingham behavior with a thixotropic component.
- The rheology of the AW-101 melter feed was measured.
 - Rheograms of the AW-101 samples after glass-former addition show nearly Newtonian behavior with only a 20 to 40% drop in viscosity between $\dot{\gamma} = 33s^{-1}$ and $500s^{-1}$.
 - No thixotropy or yield stresses were observed. The viscosities at $\dot{\gamma} = 500 \text{ s}^{-1}$ of the 6, 8, and 10 M Na feeds were 36, 88, and 230 mPa•s, respectively, at 25°C, and 16, 46, and 130 mPa•s, respectively, at 50°C.
- Rheology of the AN-107 melter feed was measured.
 - After adding glass formers, the 5 M Na AN-107 melter-feed sample showed nearly Newtonian behavior with no thixotropy or yield stresses.
 - The 6 and 8 M Na feeds displayed yield pseudoplastic behavior with a thixotropic component.
 - The viscosities at $\dot{\gamma}$ =450 to 500 s⁻¹ of the 5, 6, and 8 M feeds were 44, 360, and 1100 mPa•s, respectively, at 25°C. At 50°C and approximately $\dot{\gamma}$ =275 s⁻¹, the viscosities were 15, 175, and 1000 mPa•s. The yield stresses of the 6 and 8 M feeds were 15 and 180 Pa at 25°C, dropping slightly to 12 and 160 Pa at 50°C.
- A 1-week mixing and aging study was conducted on the 8 M Na AW-101 and AN-107 melter feed after adding glass formers.
 - The viscosity of the AW-101 slurry increased from 52 mPa•s at $\dot{\gamma} = 350 \text{ s}^{-1}$ after 1 hour to 67 mPa•s after 1 day. The viscosity then remained essentially constant as indicated at the 64 mPa•s measurement after 1 week. These measurements were all conducted at 25°C. Sample behavior was nearly Newtonian. No thixotropy or yield stresses were observed.

- The AN-107 sample viscosity increased at $\dot{\gamma} = 350 \text{ s}^{-1}$ from 280 mPa•s after 1 hour to 540 mPa•s after 1 day of mixing. The viscosity after 1 week was 440 mPa•s, indicating a possible minor drop during the week, although the viscosity at lower shear rates (33 s⁻¹) only dropped by ~8% during the week. Rheograms displayed yield pseudoplastic behavior as well as a thixotropic component.
- The 8 M Na AW-101 and AN-107 melter-feed samples were allowed to settle for 1 week. After 1 week, the settled solids were analyzed for shear stress versus shear rate at 25°C. Note that a shear-strength test using a shear vane was not conducted as part of this testing.
 - In the AW-101 sample, two settled-solids layers formed. These layers were analyzed separately and both displayed near Bingham behavior. The yield stress for both layers was approximately 4.6 Pa. Both samples also displayed a thixotropic component with a decreased viscosity and no yield point on the decreasing rate portion of the rheograms.
 - Only one settled-solids layer formed in the AN-107 sample. The 8 M Na AN-107 melter feed contained very little standing liquid. Therefore, the rheology of the settled solids was similar to that for the slurry. After 1 week of settling, the AN-107 settled solids displayed yield pseudoplastic behavior as well as a thixotropic component. The viscosity of the settled solids was similar to that of the mixed slurry, and the yield stress of the settled solids was similar to that of the mixed slurry.

SRTC (Rosencrance et al. 2000) reports the rheology of the as-received waste and diluted waste for AN-103 (Envelope A), AZ-102 (Envelope B) as-received waste and concentrated pretreated waste, and AN-102 (Envelope C) as-received, diluted, and concentrated pretreated waste. They compared the viscosities measured for the actual samples from Hanford Tanks AN-103, AZ-102, and AN-102 to the viscosities predicted for Envelopes A, B, and C wastes. The predicted viscosities were based on SRTC simulant measurements of Hanford AN-105 (Envelope A), AZ-101 (Envelope B), and AN-107 (Envelope C) simulants. Using these simulant data, correlations of simulant viscosity as a function of sodium molarity, temperature, and waste envelope were established. These correlations were then used to predict the viscosities of AN-103, AZ-102, and AN-102 under the actual measurement conditions. In general, predicted viscosities of AN-103, AZ-102, and AN-102 did not agree with measured values with only 4 out of 14 predictions within 20% of the measured values. They conclude that this is because the predicted viscosities were based on viscosity correlations for simulants of other tanks (i.e., AN-105, AZ-101, and AN-107) that possess differing chemical compositions from the actual measured waste (i.e., AN-103, AZ-102, and AN-102). Table 3.2 (Rosencrance et al. 2000) presents measured values for AN-103, AZ-102, and AN-102 wastes.

		Wt% Total		Viscosity	
Sample ID	(Na) (M)	Solids	T(°C)	(mPa•s)	
	Envelope	e A (AN-103)			
As-received	11.7	24.7	25	23.1	
As-received	11.7		50	6.2	
Diluted	5.3	0.1	25	3.2	
Diluted	5.3		50	2.5	
	Envelope	e B (AZ-102)			
As-received	2.8	0.48-1.2	25	3.7	
As-received	2.8		50	2.4	
Evap. Conc.	4.1		25	2.1	
Evap. Conc.	4.1		50	0.7	
Envelope C (AN-102)					
As-received	10.2	< 0.1	25	6.7	
As-received	10.2		50	0.8	
Diluted	6.4		25	2.7	
Diluted	6.4		50	2.0	
Pretreated	4.9		25	4.2	
Pretreated	4.9		50	2.8	

Table 3.2. Physical Properties of Actual LAW Samples Representing
Envelopes A, B, and C Reported by SRTC

SRTC (Hansen and Calloway 2000) presented the results obtained from characterization of simulated LAW Envelope A (AN-105), B (AZ-101), and, C (AN-107) melter feeds. This task involved measuring the physical and chemical properties (rheology, particle size, wt% dissolved and undissolved solids, and chemical composition) of simulated LAW melter feeds made from the different envelopes mentioned above. The rheological data were fit to several rheological models (Power Law, Bingham Plastic, and Herschel Bulkley) and the Bingham Plastic model was chosen. Hansen and Calloway (2000) explain this selection as follows:

The rheological data were fitted to several rheological models (Power Law, Bingham Plastic, and Herschel Bulkley). The three-parameter model (Herschel Bulkley) does provide a better curve fit (Higher R2 coefficient) than the two-parameter models (Power Law and Bingham Plastic), but the differences were very small. The design engineering parameters for the Bingham Plastic model, taken from Table 1 are 377 cp and 489 dynes/cm². The Power Law and Herschel Bulkley models were not selected because the design engineering parameters in those models are unnecessarily complicated, unlike the Bingham Plastic Model where there are no bounds placed on the engineering parameters. Design engineering parameters for the Power Law and Herschel Bulkley models lead to a design that is ultra conservative in determining piping pressure drop when compared to the most viscous slurry in this study. Additionally, the LAW slurries typically have yield stresses, which are not described by the Power Law model. The yield stress is important in pump selection, initial fill/startup of pipe transfer lines, natural draining of piping systems, startup of an agitator, cavern mixing, etc. Because most of the slurries in this study were shear thinning, the Bingham Plastic yield stress over predicts the actual yield stress. The Herschel Bulkley model also predicts a yield stress that was either higher or lower than the true yield stress. The Bingham Plastic model was selected because it provides 1) a conservative estimate of the yield stress, 2) the hydraulic analysis using this model is comparable to either the Power Law or Herschel-Buckley models in the laminar flow regime, and 3) hydraulic analysis for this model exists for all flow regimes.

Therefore, the Bingham Plastic model was chosen to provide the equation for apparent viscosity of simulated melter feed slurries. Table 3.3 (Hansen and Calloway 2000) gives the Bingham parameters derived from the flow curves measured on the systems indicated. The goal of this work was to provide data for the design of the RPP-WPT melter-feed system. They also recommend that a tube/pipe rheometer be obtained and used to verify the actual flow behavior of the slurries in piping systems.

Melter			
Feed			Na Range
Slurry	Consistency (μ ; mPa·s)	Yield Stress (7, Pa)	(<i>M</i> ; mol/L)
AN-105	$\mu = 3.0125M^2 - 28.225M + 75.8$	$\tau = 0.01475M^2 + 0.108M - 1.025$	6.0–10.0
AZ-101	$\mu = 46.55M^2 - 385.15M + 826.3$	$\tau = 1.7405M^2 - 13.485M + 26.145$	4.0–6.0
AN-107	$\ln[\mu] = 1.159 + 0.00083e^{M}$	$\tau = \frac{e^{0.7696 + 0.000814e^{M}}}{10}$	6.0-8.5

Table 3.3. SRTC Rheological Property Data Fit Parameters using a Bingham Plastic Model for Simulated AN-105, AN-101, and AN-107 Melter Feed Slurries at 25°C

SRTC (Eibling and Nash 2001) documents simulants developed to support various WTP programs at SRTC. Simulant recipes for waste Envelope A, B, and C simulants are included. The Envelope A simulant is based on Tanks AW-101, AN-104, AN-103, and AN-105. The project-approved Envelope B simulant was based on the best-basis inventory for Tank AZ-101. An additional Envelope B simulant is based on Tank AZ-102. The project-approved Envelope C simulant is based on Tanks AN-105 and AN-107. Entrained solids simulants were created for Envelopes A and C, based on Tanks AN-105 and AN-107, respectively. This report also discusses additional simulants, including sludge simulants,

entrained-solids simulants, and simulants to support pretreatment mixing studies. An Envelope D simulant was developed based upon Tank AZ-101 sludge. The AZ-101 (Envelope D) sludge simulant is based on averaging the compositions of two separate tank-sludge core samples.

3.2 Database Summary

A relatively large quantity of rheological- and physical-property data has been generated on the RPP-WTP waste Envelopes (A, B, and C) through the use of simulated wastes. Only limited data have been acquired on actual wastes, both because of the limited number of tanks sampled and the limited quantities of sample available for physical-property characterization. Thus far, only small quantities of two pretreated actual tank wastes have been prepared as melter feeds (LAW melter feeds AN-107 and AW-101). Pretreated waste samples from AP-101 (Envelope C) and AZ-101 (Envelope B) have recently been prepared as melter feeds. Data from the reports shown in Table 3.1 have been compiled into a database. This database was designed to present the data in a form compliant with the guideline reporting formation developed by Smith and Prindiville (2002). This database can be found in Appendix A. Additional information from these reports can be found in the remaining Appendices. An electronic version (Microsoft Excel) of these appendices can be acquired by contacting the author of this document and has been provided to BNI. A high -level summary of the data compiled in Appendices A-F is shown in Table 3.4.

Property	LAW Pretreated Waste	LAW Melter Feed		
Chemical Composition	varies (see Appendix A)	varies (see Appendix A)		
рН	~14	7–14 ^a		
Particle-Size Distribution (PSD)	n/a	<164 µm		
Heat Capacity	n/a	n/a		
Bulk Density	1.1–1.5	1.7–1.9		
Supernatant Liquid Density	1.1–1.5	1.2–1.6		
Vol % Settled Solids	0%	50%-100%		
Settling Rate	n/a	n/a		
Centrifuged Solids Density	n/a	n/a		
Vol % Centrifuged Solids	n/a	n/a		
Wt % Centrifuged Solids	n/a	n/a		
Wt % Oven Dried Solids	n/a	n/a		
Wt % Total Dried Solids	20%-60%	60%-75%		
Wt % Undissolved Solids	n/a	n/a		
Shear Stress Versus Shear Rate ambient and 40°C	Newtonian	Bingham Plastic		
Shear Strength	n/a	n/a		
Wt % total oxide	15%-30%	25%-35%		
a - addition of acidic GFCs will drop the pH of the LAW pretreated waste this drop in pH can precipitate amphoteric species such as aluminum hydroxide. Aluminum hydroxide precipitation can result in relatively high rheological parameters and processing				

difficulties.

Table 3.4. Summary of Appendix A Database
4.0 Discussion

The purpose of this section is to establish simulant bounding conditions for the data discussed in the previous section and compiled in the database shown as Appendix A. Individual unit operations will be examined in an effort to identify parameters significant to plant performance. Bounds will be established on these parameters in an effort to assure successful processing of the simulant material during pilot testing. Actual waste data will be used to tailor the bounding ranges such that the proposed bounding conditions span the existing actual waste materials. In this regard, the proposed bounding conditions will be based upon a general engineering evaluation of process equipment and measured values from actual waste material. When needed, equipment design specifications from the HWVP and DWPF were used. These bounding conditions could be used as a first iteration of the WTP operating envelope or design basis that should be developed by WTP process engineers specifically for the equipment in the WTP. These bounds will be evaluated against the data presented in Appendix A.

4.1 Development of Simulant Bounding Conditions

In this section, simulant bounding conditions will be established. The strategy employed is to identify correlations between dimensionless groups for specific unit operations performed in the WTP flowsheet. Because specific correlations for equipment in the WTP have not been developed and are not readily available, correlations for similar equipment that have been developed for standard chemical processing applications will be used. Sources for these correlations include Perry's Chemical Engineers Handbook (Perry and Green 1984), various engineering textbooks, and peer-reviewed journal articles. In addition, equipment data and calculations for previous vitrification plant designs may be used when available. These previous designs include the HWVP and DWPF. The use of these data and correlations assumes that the equipment selected for use in the WTP will possess similar performance properties to equipment generally used in the chemical processing industry, HWVP, and DWPF. Typically, based on these correlations, engineering judgment determines the overarching percentage variation that can be allowed in a given dimensionless group, e.g., drag coefficient, based on its effect on the unit-operation performance. From this point, a sensitivity analysis on the dimensionless group can be used to determine the variations allowed for physical and rheological properties of the simulant, e.g., viscosity or density. A summary of basic rheological concepts can be found in Appendix E.

4.1.1 Mixing Operations (Low-Shear-Rate Viscosity)

Based on the HWVP and DWPF designs, mixing operations considered in this section consist of mechanical agitators in mixing vessels. The WTP design also employs mechanical agitators in the LAW processes. For mechanical-agitator systems, Perry and Green (1984) use dimensional analysis to define an impeller Reynolds number as follows:

$$N_{\rm Re} = \frac{D_a^2 N \rho}{\mu} \tag{4.1}$$

where

N = rotational speed (rev/s)

 D_a = impeller diameter (m) ρ = fluid density (kg/m³)

 μ = apparent viscosity (Pa•s)

Using this definition, Perry and Green (1984) describe flow in the tank as turbulent when $N_{Re} > 10,000$. When $10 < N_{Re} < 10,000$, the flow is turbulent near the impeller and laminar in remote areas of the vessel. When $N_{Re} < 10$, the flow is laminar only.

For pseudoplastic and Bingham plastic fluids, Perry and Green (1984) recommend that the following shear rate be used:

$$\dot{\gamma} = 10N \tag{4.2}$$

where $\dot{\gamma}$ is the average shear rate (1/s).

Using a rheogram, the apparent viscosity can be found at this shear rate and used in the impeller Reynolds number equation. Perry and Green (1984) present several correlations between the impeller Reynolds number and the Power number. The Power number is defined below.

$$N_{P_{0}} = \frac{P}{\rho N^{3} D_{a}^{5}}$$
(4.3)

where *P* is motor power (N•m/s).

Correlations for several tank geometries are presented by Perry and Green (1984). To achieve a homogeneously suspended tank, a turbulent flow regime must be established. As described above, this can occur when $N_{\text{Re}} \ge 10,000$. As the Power number increases, the power requirement for the mixing motor also increases. Therefore, the correlation that results in efficient mixing was used as a basis for this calculation. At $N_{\text{Re}} = 10,000$, a conservative correlation with a given impeller-to-tank diameter ratio, impeller pitch, and number of tank baffles produces $N_{Po} = 0.3$.^(a) According to DWPF design specifications (Jones and Peterson 1996), a 100-hp motor with an impeller diameter of 36 in. would be used for homogenization purposes. A value for the bulk density of the fluid is also assumed to be at 1.2 g/mL. Using these parameters, the calculation presented in Figure 4.1 can be performed.

⁽a) See Perry and Green (1984), Curve 5, Figure 19-13, pg 19-10.

Motor Power: Impeller Diameter: Fluid Density: $\rho := 1.2 \, \frac{\text{kg}}{\text{L}}$ D _a := 36 in P := 100 hp Turbulent Impeller Reynolds Number: Power Number: N _{Re} := 10000 N Po := 0.3 $\mathbf{N} := \left(\frac{\mathbf{P}}{\mathbf{\rho} \cdot \mathbf{D}_{a}^{5} \cdot \mathbf{N}_{Po}}\right)^{\frac{1}{3}}$ Rotation Rate of Impeller at 100 hp (rpm) N = 412.108 • $\frac{1}{\min}$ Apparent Viscosity Calculation: $\mu := \frac{D_a^2 \cdot N \cdot \rho}{N_{Re}}$ $\mu = 0.689 \text{ } \bullet \text{Pa} \cdot \text{s}$ Shear Rate Calculation: $\gamma := 10 \cdot N$ $\gamma = 68.685 \bullet \mathrm{s}^{-1}$

Figure 4.1. Calculation of Maximum Viscosity for Mixing Operations

The calculation performed in Figure 4.1 indicates that a maximum apparent viscosity of approximately 700 mPa•s at a shear rate of approximately 70 s⁻¹ bounds the mixing-operation performance. Based on HWVP and DWPF design specifications and a conservatively low Power number assumption, fluids with an apparent viscosity greater than this value will most likely not result in a homogeneous mixture during mixing operations.

4.1.2 Mixing Operations (Maximum Settled Solids Shear Strength)

The slurries that will be processed through the WTP will typically possess a shear strength. The following calculation assumes a startup scenario involving the impeller being immersed in an undisturbed yield-strength slurry. This situation could potentially occur during plant-upset conditions when various systems need to be taken off-line for a period of time, and suspended slurries settle in mixing tanks. The impeller dimensions defined above and a conservative estimate of a starting torque for the mixing motor of 400 Nm (295 ft·lb) are assumed in this calculation. The equation used for shear-vane calculations (Smith and Prindiville 2002; Steffe 1996) can be applied to calculate the shear strength of the fluid at the starting torque. The calculation with this equation is performed in Figure 4.2. Based on this calculation, the maximum shear strength value before the mixing motor stalls appears to be 625 Pa. Figure 4.3 shows this calculation for various impeller diameters.

4.1.3 Mixing Operations (Homogeneous Vessel)

Another requirement for mixing operations in the WTP is to achieve a homogenous slurry. A particle falling under the action of gravity will accelerate until a drag force offsets the gravitational force. At this point, the particle will fall at a constant velocity known as the free-settling velocity. For a spherical particle, the free-settling velocity can be calculated from the equation shown below:

$$u_t = \sqrt{\frac{4gD_p(\rho_p - \rho)}{3\rho C_d}} \tag{4.7}$$

where

 u_t = free settling velocity (m/s)

- g = acceleration due to gravity (9.81 m/s²)
- D_p = diameter of particle (m)
- ρ_p = particle density (kg/m³)
- ρ = fluid density (kg/m³)
- C_d = drag coefficient (dimensionless).

Impeller Width: $W_{i} := \frac{D_{a}}{5}$ $W_{i} = 7.2 \text{ in}$ Assumed 100 hp Mixing Motor Starting Torque: $T_{m} := 400 \text{ newton } \cdot \text{m}$ $T_{m} = 295 \text{ oft} \cdot \text{lbf}$ $\tau_{y} := \frac{T_{m}}{\frac{\pi D_{a}^{3}}{2}} \cdot \left(\frac{W_{i}}{D_{a}} + \frac{1}{3}\right)$ $\tau_{y} = 624.5 \text{ Pa}$

Figure 4.2. Maximum Shear Strength Calculation



Figure 4.3. Maximum Shear Strength as a Function of Impeller Diameter when Impeller Width is One Fifth Impeller Diameter and Mixing Motor Starting Torque is 400 N•m.

Perry and Green (1984) state that it may be difficult to cause particles with settling velocities above 0.03 m/s (0.1 ft/s) to be suspended uniformly in the topmost 2 percent of a tank volume. A relationship between the drag coefficient and the particle Reynolds number exists.

$$C_d = \Phi(N_{Re}) \tag{4.8}$$

In this case, the particle Reynolds number is defined as follows:

$$N_{\rm Re} = \frac{D_p u\rho}{\mu} \tag{4.9}$$

where

 D_p = particle diameter (m)

u = particle speed (m/s) ρ = fluid density (kg/m³) μ = fluid viscosity (Pa•s).

When $0.1 < N_{\text{Re}} < 1000$, the following relationship has been empirically established:

$$C_{d} = \left(\frac{24}{N_{\rm Re}}\right) \left(1 + 0.14 \cdot N_{\rm Re}^{0.70}\right) \tag{4.10}$$

In this calculation, the particle size of the tank waste is assumed to be smaller than the glass-former chemicals (see Appendix F). From Table 4.1, olivine appears to be the insoluble melter glass-former chemical with the largest particle size. Schumacher (2003) characterized this GFC as having an upper particle size range of 164 μ m. For the purpose of this analysis, 164 μ m is the maximum assumed particle size in the WTP facility. Since particle size dominates particle density in the settling-rate calculation, the properties of the largest diameter material (olivine) should be used for the settling-rate calculations. In this case, the particle density utilized would be approximately 3.60 g/mL.

Based on the relationship shown above, a calculation can be performed to find the minimum fluid viscosity required for a 0.03 m/s settling velocity for a spherical particle with a diameter of 164 µm and a particle density of 3.6 g/mL. The resulting fluid viscosity can be found in the calculation shown in Figure 4.4. Note that an equivalent calculation can be performed without iterative solving techniques through the use of a dimensionless group called the Archimedes number (Shook et al. 2002). The calculated minimum viscosity required for homogeneity is 0.9 mPa•s. Because the apparent viscosity of WTP slurries is greater than that of WTP supernate at the low shear rates observed in the mixing vessel, the WTP supernate represents the lower bound on this calculation.

			Estimated Free Settling		Solubility in Water
		Particle Size	Particle Density	Velocity in Water	
No.	Name	(Mesh; M)	(g/mL)	(m/s)	
1	Kyanite	56.9	3.60	0.0046	insoluble
2	Boric Acid	487.0	1.51	0.030	partially soluble
3	10M Borax	549.1	1.73	0.046	partially soluble
4	Na ₂ CO ₃	380.6	2.53	0.052	partially soluble
5	Wollastonite	42.6	2.90	0.0019	insoluble
6	Fe ₂ O ₃	58.76	5.00	0.0076	insoluble
7	Li ₂ CO ₃	308.2	2.11	0.030	partially soluble
8	Olivine	164.1	3.60	0.027	insoluble
9	SiO_2	58.5	2.65	0.0030	insoluble
10	Rutile -94	52.8	5.00	0.0061	insoluble
11	ZnO	42.6	5.60	0.0046	insoluble
12	ZrSiO ₄	52.7	4.81	0.0058	insoluble
13	Sugar	609.5	1.55	0.043	partially soluble

 Table 4.1. Settling Information on Glass-Former Chemicals

To illustrate the effect of particle density and size, several of these calculations were performed to create Figure 4.5 and Figure 4.6. These figures demonstrate that a small change in interstitial liquid density (1.0 g/mL to 1.3 g/mL) does not significantly change the required minimum fluid viscosity, and any value over 1.0 g/mL is satisfactory. Based on a calculation to homogenize 164 µm particles with a particle density of 3.6 g/mL in an agitated vessel, the minimum viscosity of interstitial liquid in the WTP slurries should be considered 0.9 mPa•s. For reference, water at 25°C possesses a viscosity of 0.9 mPa•s. At 40°C, water has a viscosity of 0.7 mPa•s.

Particle shape is not considered here because it is difficult to model, and it is not always intuitively obvious which shape will fall fastest in a fluid. For example, platy or acicular particles may settle faster than spherical particles of the same mass and density because they can present a smaller cross-section in the settling direction. In other hydrological conditions, they may settle more slowly.

 $\begin{array}{ll} \mbox{Maximum Free Settling Velocity:} & u_t := 0.03 \frac{m}{sec} \\ \mbox{Acceleration Due to Gravity:} & g = 9.807 m s^{-2} \\ \mbox{Maximum Anticipated Particle Size:} & D_p := .164 \mbox{Imm} \\ \mbox{Maximum Anticipated Particle Density:} & \rho_p := 3.6 \frac{kg}{L} \\ \mbox{Minimum Anticipated Supernate Density:} & \rho := 1.0 \frac{kg}{L} \\ \mbox{Drag Coefficient:} \end{array}$

$$C_{d} \coloneqq \frac{4 \cdot g \cdot D_{p} \cdot (\rho_{p} - \rho)}{3 \cdot \rho \cdot u_{t}^{2}} \qquad C_{d} = 6.199$$

Initial Reynolds Number Guess: $N_{Re} := 5$

Correlation for 0.1 < Reynolds Number <1,000

Given
$$C_d = \left(\frac{24}{N_{Re}}\right) \cdot \left(1 + 0.14 N_{Re}^{0.7}\right)$$

 $N_{Re} := Find(N_{Re})$

 $N_{Re} = 5.706$

Supernate Viscosity Required to Maintain Max. Settling Velocity:

$$\mu_{\min} := \frac{\left(D_p \cdot u_t \cdot \rho\right)}{N_{Re}}$$

 $\mu_{\text{min}} = 8.628 \times 10^{-3}$ poise

Figure 4.4. Minimum Supernate Viscosity Calculation



Figure 4.5. Supernate Viscosity Required to Maintain a Free-Settling Velocity of 0.03 m/s as a Function of Particle Diameter and Density in a Suspending Fluid with Density of 1.0 g/mL



Figure 4.6. Supernate Viscosity Required to Maintain Free-Settling Velocity of 0.03 m/s as a Function of Particle Diameter and Density in a Suspending Fluid with Density of 1.3 g/mL

4.1.4 Heat/Mass Transfer Operations

The purpose of this section is to establish physical and rheological bounding conditions for the pretreated LAW stream. No obvious unit operations in the LAW vitrification facility can be used to create clear bounding conditions. For this reason, some of the pretreatment facility unit operations that were used to create this stream are used to establish these bounding conditions. These unit operations include evaporator and ion exchange processes.

Jones and Peterson (1996) performed overall heat-transfer-coefficient calculations for the evaporator vessels in the HWVP design. The HWVP evaporator design consisted of agitated vessels with heating coils. The WTP design consists of forced circulation evaporators under a vacuum to reduce evaporator duty. Perry and Green (1984)^(a) provide the following correlation for forced circulation evaporators:

$$U = \frac{2020 \cdot D^{0.57} (V_s)^{\frac{3.6}{L}}}{\mu^{0.25} \Delta T^{0.1}}$$
(4.13)

where

- U = overall heat transfer coefficient (Btu/hr•ft²•°F)
- D = mean tube diameter (ft)
- V_s = inlet velocity (ft/s)
- L = Tube Length (ft)
- μ = fluid viscosity (lb/hr•ft²)
- ΔT = temperature change at heater inlet (°F).

This correlation indicates that the overall heat-transfer coefficient is inversely proportional to $\mu^{1/4}$. Jones and Peterson (1996) found a similar relationship for agitated vessels with heating coils where the overall heat-transfer coefficient is inversely proportional to $\mu^{1/3}$. A similar relationship is likely to exist for the WTP evaporator design. As a consequence, a maximum processing viscosity should be considered for evaporator operations. This value should be determined experimentally in pilot-scale experiments designed to measure the required evaporator duty to meet throughput demands as a function of fluid viscosity and other parameters. The relation shown above was used to create the plot shown in Figure 4.7. Based on this figure, the overall heat-transfer coefficient will be reduced significantly when the viscosity is slightly increased over water. Since most WTP supernate viscosities are in the 1 to 5 mPa•s range, a significant reduction of the overall heat-transfer coefficient results in a fluid viscosity of 15 mPa•s. Fortunately, elevated temperatures in the evaporator are expected to drop the viscosity of the supernate liquid significantly. Due to these factors, viscosity limits for evaporator operations should be set at an upper bound of approximately 15 mPa•s.

^{(&}lt;sup>a</sup>) See Perry and Green 1984, Eq 10–141, pg 10–34.

For mass-transfer operations, such as the ion exchange columns, diffusion from the fluid phase to the resin bead should be considered. Perry and Green (1984)^(a) provide a relationship for evaluating the mass-transfer coefficient for a packed-bed operation as follows:

$$k_f \propto \mu^{-0.16} \tag{4.14}$$

where k_f is the mass-transfer coefficient (mm/s), and μ is the fluid viscosity (mPa•s).

Using this relation, viscosity effects on mass transfer in the ion exchange columns are shown in Figure 4.7. Again, a major drop in mass-transfer performance (~25%) has already occurred when increasing fluid viscosity from 1 mPa•s to 5 mPa•s. An additional 10% drop in performance is calculated at 15 mPa•s. Similar to evaporator requirements, viscosity limits for mass-transfer operations should be placed at approximately 15 mPa•s.



----Mass Transfer Coefficient for Packed Beds --- Evaporator Overall Heat Transfer Coefficient

Figure 4.7. Forced Circulation Evaporator Overall Heat-Transfer Coefficient and Mass-Transfer Coefficient in a Packed Bed as a Function of Fluid Viscosity (Uw = Overall Heat Transfer Coefficient for Water)

^{(&}lt;sup>a</sup>) See Perry and Green 1984, Eq 16–70, pg 16–22.

The flow of fluid through the packed beds of ion exchange columns is related to fluid viscosity and should also be considered. The pressure drop through the packed beds with uniform particle size in the ion exchange columns can be predicted using the Kozeny-Carman equation (see Equation 4.15). This represents a best-case scenario as the pressure drop across packed beds typically increases for particles with non-uniform diameter. Empirical equations for such systems are typically obtained experimentally for a particular bed material.

$$f_p = \frac{150 \cdot (1 - \varepsilon)}{N_{\rm Re} \phi_s} \tag{4.15}$$

where

$$f_{p} = \frac{\Delta P \phi_{s} D_{p} \varepsilon^{3}}{\rho V^{2} L(1-\varepsilon)} = \text{packed bed friction factor (dimensionless)}$$

$$N_{\text{Re}} = \frac{\rho V D_{p}}{\mu} = \text{particle Reynolds number (dimensionless)}$$

$$\varepsilon = \text{bed porosity (dimensionless)}$$

$$\phi_{s} = \text{sphericity (dimensionless)}$$

$$\Delta P = \text{pressure drop across bed (Pa)}$$

$$L = \text{length of bed (m)}$$

$$D_{p} = \text{particle diameter (m)}$$

$$\rho = \text{fluid density (kg/m^{3})}$$

$$\mu = \text{fluid viscosity (mPa \cdot s)}$$

$$V = \text{superficial fluid velocity (m/s).}$$

This equation is valid for laminar flow where viscous forces dominate ($N_{\rm Re}$ <20). The particle Reynolds number is calculated under WTP conditions in Figure 4.8. Based on this calculation, the Kozeny-Carman equation should be valid. From this equation, it becomes apparent that the pressure drop across the bed is directly proportional to the fluid viscosity. The proportionality between pressure drop and viscosity also holds for polydisperse packed beds. This relationship can be seen in Figure 4.9. As a result, a fluid with a viscosity of 10 mPa•s will produce a pressure drop an order of magnitude greater than a 1 mPa•s fluid. Based on best-engineering judgment, a maximum Newtonian fluid viscosity of 15 mPa•s is recommended. An objective of pilot-scale testing should be to establish this upper bound based on pumping performance through the packed columns with actual resin material. $\text{Bed Dimensions:} \quad D_{bed} := 4ft \qquad A_{bed} := \pi \cdot \frac{D_{bed}^{-2}}{4}$

Design Flow Rate: $F_{feed} := 15 \frac{gal}{min}$

Assumed Porosity: $\epsilon := 0.3$

Superficial Velocity Calculation:
$$V := \frac{F_{feed}}{\epsilon \cdot A_{bed}}$$
 $V = 31.914 \frac{ft}{hr}$

 $\label{eq:maximum expected Particle Size: $D_p:=0.5mm$} D_p:=0.5mm$

Minimum Fluid Viscosity: $\mu := 0.009$ poise

 $\label{eq:maximum Expected Fluid Density:} \qquad \rho := 2 \frac{gm}{mL}$

Particle Reynolds Number Calculation: $N_{Re} := \rho \cdot V \cdot \frac{D_p}{\mu}$ $N_{Re} = 3.002$





Figure 4.9. Pressure Drop in a Packed Bed as a Function of Fluid Viscosity

4.1.5 Material Transfer Operations (Pipeline Flow)

Jones and Peterson (1996) state that solids settling in process lines does not usually occur if the slurry flow is turbulent. Turbulent flow generally exists at high line velocities above 3 to 5 ft/s in 2-in. piping. However, high fluid velocities will cause excessive erosion, and a maximum line velocity of 10 ft/s has been specified for the DWPF (Jones and Peterson 1996). Therefore, the purpose of this section is to find the set of rheological parameters that will create turbulent flow conditions with a maximum superficial velocity of 10 ft/s.

For Bingham plastic fluids, the first step in this calculation is to calculate the Hedstrom number as shown below (Hanks and Dadia 1971; Desouky and Al-Awad 1998; Chang et al. 1999):

$$N_{He} = \frac{D^2 \rho \tau_y}{K^2} \tag{4.17}$$

where

 N_{He} = Hedstrom Number (dimensionless)

D = pipe diameter (m)

 ρ = fluid density (kg/m³)

 τ_y = Yield Stress (Pa)

K =consistency index (Pa•s).

The next step is to perform the following calculation to find the ratio between the yield stress and wall shear stress, ζ_{0c} (Hanks and Dadia 1971; Desouky and Al-Awad 1998; Chang et al. 1999):

$$\frac{\zeta_{0c}}{\left(1-\zeta_{0c}\right)^3} = \frac{N_{He}}{16,800} \tag{4.18}$$

The critical Reynolds Number, $N_{\text{Re}c}$, can then be calculated. This represents the transition from laminar to turbulent flow. The equation for this calculation is shown below (Hanks and Dadia 1971; Desouky and Al-Awad 1998; Chang et al. 1999):

$$N_{\text{Re}c} = N_{He} \frac{\left[1 - \frac{4}{3}\zeta_{0c} + \frac{1}{3}\zeta_{0c}^{4}\right]}{8 \cdot \zeta_{0c}}$$
(4.19)

The velocity of the fluid in the pipe can then be calculated from the definition of the Reynolds Number as shown below:

$$N_{\rm Re} = \frac{Dv\rho}{K} \tag{4.20}$$

where v is the average velocity of fluid in the pipe (m/s).

These calculations are used to create the plot shown in Figure 4.10. This plot shows fluid properties (bulk density, consistency index, yield stress) required for turbulent flow at a bulk fluid velocity of 10 ft/s. For a fluid with a particular bulk density, turbulent flow will result if the fluid possesses Bingham Plastic indices below the corresponding curve. When the yield stress is small (<0.01 Pa), the fluid behaves much like a Newtonian fluid. If one uses a small yield stress, e.g., 0.001 Pa, this turbulent flow criterion can be used to approximate the conditions for Newtonian fluids such as tank supernate. In this case, the consistency index could be considered a Newtonian viscosity.



Figure 4.10. Bingham Plastic Parameters Required for Turbulent Flow Regime at 10 ft/s in a 2-in. Pipe

Calculating the pressure drop required to maintain a given flowrate with a Bingham plastic fluid is usually performed through the use of a dimensionless parameter called the Fanning friction factor, f (Hanks and Dadia 1971; Desouky and Al-Awad 1998; Chang et al. 1999).

$$f = \frac{DP}{2L\rho v^2} \tag{4.21}$$

where

f = Fanning friction factor (dimensionless)

- D = pipe diameter (m)
- P = Pressure drop (Pa)
- L = Length of pipe (m)
- ρ = fluid density (kg/m³)
- v = fluid bulk velocity (m/s).

The following correlations for laminar ($N_{\text{Re}} < N_{\text{Re}c}$) and turbulent ($N_{\text{Re}} > N_{\text{Re}c}$) flow regimes exist between the Fanning friction factor, Hedstrom number, and Reynolds number (see Figure 4.11; Hanks 1978; Chang et al. 1999):

$$f = \begin{cases} \frac{16}{N_{\text{Re}}} \left[1 + \frac{N_{He}}{6N_{\text{Re}}} - \frac{N_{He}^4}{3f^3 N_{\text{Re}}^7} \right] & N_{\text{Re}} < N_{\text{Re}} \\ 10^c N_{\text{Re}}^{-0.193} & N_{\text{Re}} < N_{\text{Re}} \\ c = -1.378 \left[1 + 0.146 \exp\left(-2.9 \times 10^{-5} N_{He}\right) \right] \end{cases}$$

$$(4.22)$$



Figure 4.11. Fanning Friction Factor as a Function of Reynolds Number and Hedstrom Number

Correlations similar to these have also been developed for power-law fluids. Hansen^(a) developed a spreadsheet that uses correlations similar to those presented above to calculate pressure drop in pipes for Bingham plastic, power-law, and Newtonian fluids. Using this spreadsheet, the required pressure drop to pump fluids at various flowrates with rheological parameters identified by the points A-H in Figure 4.10 is plotted in Figure 4.12. A pipe diameter of 2 in. and pipe length of 100 ft are assumed in this calculation. These curves are often referred to as system curves. Data from a DWPF pump supplied by Jones and Peterson (1996) for water are also presented to illustrate the likelihood of pumping such material in the WTP. This is often referred to as a pumping curve. Because several of the operating points (points where the pumping and system curves intersect) are in the turbulent flow regime, this plot

⁽a) E Hansen (WSRC)—letter report to H Smith and G Smith (PNNL), Kerry Prindiville (WTP-RPP), and D Crowley (SRTC). 2002. Subject: "Pipe Pressure Drop Calculation for Bingham Plastic, Power Law and Newtonian Fluids." SRT-RPP-2001-00226, Rev. 1, Westinghouse Savannah River Company, Aiken, SC.

illustrates that the DWPF pump would be capable of pumping in the turbulent-flow regime for all fluids except for fluids defined by points A and B. This point represents a high-density, high-yield-strength fluid with a Hedstrom number on the order of 10^7 . The remaining fluids have Hedstrom numbers less than 10^6 , indicating that fluids with Hedstrom numbers in the 10^7 and greater range will be difficult to pump. Examining Figure 4.11, the friction factor for a Hedstrom number of 10^8 at the laminar/turbulent threshold is approximately 0.03. Depending on the fluid density, at a line velocity of 10 ft/sec in a 2-in.diameter pipe, the resulting pressure drop for a 100-ft section of pipe for these high Hedstrom number fluids is between 50 to 110 psi. These values exceed the pump performance shown in Figure 4.12, indicating that the transfer of materials with Hedstrom numbers greater than 10^8 may be difficult. For this reason, fluids with Hedstrom numbers above 10^8 are not recommended for cold commissioning.



Figure 4.12. System Curves for Fluids with Rheological Properties Defined by Points A-H in Figure 4.10 (100-ft Length of 2-in. Diameter Pipe)

4.1.6 Material Transfer Operations (Startup Pipeline Flow)

Chang et al. (1999) explains that fluids with a shear strength will not flow unless the following condition is met:

$$\tau_w = \frac{DP}{4L} > \tau_y \tag{4.26}$$

where

 τ_w = the shear stress of the fluid at the pipe wall (Pa)

- D = the pipe diameter (m)
- P = the pressure drop (Pa)
- L = the pipe length (m)
- τ_{y} = the shear strength of the fluid (Pa).

Given a 10-ft section of 2-in.-diameter pipe plugged with settled solids, the required pressure to transport the material as a function of shear strength is shown in Figure 4.13. The previously established shear strength value of 625 Pa would result in a pressure of approximately 22 psi to begin flow, which appears achievable. This situation would most likely occur during plant upset when systems go offline and solids settle and remain undisturbed until a plant restart is attempted.



Figure 4.13. Pressure Drop Required to Initiate Flow of a 10 ft Plug of Yield Strength Material in a 2-in. Pipe

4.2 Bounding Conditions Recommendation

If one takes the most restrictive values for the simulant operating bounds discussed above, then Table 4.2 can be constructed. This set of simulant operating bounds represents rheological parameters that should be compatible with many industrial chemical processing-unit operations used in the WTP.

It has been demonstrated in Section 4.1.1 that materials with apparent viscosities above 700 mPa•s at low shear conditions (\sim 70 s⁻¹) can lead to difficulties in obtaining homogenous mixing in agitated vessels. Therefore, we wish to restrict the use of simulant material to those with low shear viscosities below 700 mPa•s.

The settled-solids shear strength is a parameter that may be important during plant-upset conditions. When a plant upset occurs, the slurries in vessels and pipes may become motionless, allowing the solids to settle. When the plant is restarted, flow must be reinitiated for the settled solids in pipes and tanks. One such scenario occurs if an impeller in a tank is submerged in settled solids and then restarted. A motor with a stall torque of 400 Nm would have difficulty initiating rotation in a fluid with 625 Pa shear strength. One-hundred-horsepower motors typically have stall torques in this range.

It was demonstrated that 164 μ m olivine particles will be difficult to keep homogenized in an agitated vessel with a suspending fluid possessing a viscosity of less than 0.9 mPa•s. Since the insoluble glass-former chemicals have olivine particle sizes in this range, it is anticipated that a 0.9 mPa•s suspending medium would be a sufficient minimum viscosity for testing purposes. Suspending-fluid density was shown not to be a major concern for this particular combination of fluid viscosity and particle size.

Category	Value	Comment			
Maximum Apparent Viscosity at Low Shear Rates (~70 s ⁻¹)	700 mPa•s	Affects power requirements for mixing operations			
Maximum Settled Solids Shear Strength	625 Pa	Increases likelihood of successful startup after plant upset; Useful for high solids concentration streams (LAW melter feed)			
Minimum Newtonian Viscosity	0.9 mPa•s	Slows particulate settling during unit operations; Useful for low solids concentration streams (pretreated LAW or diluted LAW melter feed)			
Maximum Newtonian Viscosity	15 mPa•s	Increases likelihood of pumping fluid through a packed bed; limits performance losses in evaporator and ion exchange columns; Useful for low solids concentration streams (pretreated LAW)			
Maximum Bingham Plastic Parameters	See Figure 4.10	Increases likelihood that flow will be turbulent in pipeline; Useful for high solids concentration streams (LAW melter feed)			
Minimum Bingham Plastic Parameters	Consistency Index: 0.9 mPa•s Yield Stress: 0 Pa	Consistent with minimum Newtonian viscosity category; Useful for low solids concentration streams (diluted LAW melte feed)			
Maximum Hedstrom Number in 2-in. Pipe $N_{He} = \frac{D^2 \rho \tau_y}{K^2}$	108	Increases likelihood that the material can be pumped with conventional pumps; Useful for high solids concentration streams (LAW melter feed)			

 Table 4.2. Compilation of Rheological Property Bounding Conditions

On the basis that particulate settling in pipes is difficult in the turbulent flow regime, a set of Bingham plastic parameters was constructed that indicates the laminar/turbulent flow threshold in a 2-in. pipe at a fluid velocity of 10 ft/sec. Above this velocity, equipment erosion becomes a concern. These Bingham plastic parameters represent upper bounds on the simulant material and are presented in Figure 4.10. The lower Bingham plastic bounds were selected to be consistent with the Newtonian viscosity lower bounds discussed above.

The Hedstrom number appears to have a large impact on the pumping performance of Bingham plastic materials. Using pump performance data from DWPF, it was shown that fluids with Hedstrom numbers above approximately 10^8 would be difficult to pump in the turbulent flow regime. Consequently, this value was set as an upper bound for the slurry material.

The pumping head required to pump material through a packed bed of spherical particles of the same diameter varies linearly with fluid viscosity. For this reason, a value of 15 mPa•s was selected as the upper range for simulant development. This fluid would require 15 times the pumping head required for

water to pass through a packed bed. Using a fluid with a viscosity limit heat and mass transfer of 15 mPa•s should also limit performance losses in the evaporator and ion exchange columns respectively.

Table 4.2 can be simplified by comparing the bounding conditions to measurements on the actual waste (when available). The resulting sets of bounding conditions developed for each process stream are based on the intersection of the actual waste data and the engineering performance data. We will begin with the LAW pretreated process stream.

The LAW pretreated process stream is a low undissolved solids stream that is expected to behave in a nearly Newtonian manner. If a significant quantity of undissolved solids is present in the LAW pretreated process stream, the bounding conditions for the LAW melter feed stream should be used. The bounding conditions for this stream should be based on the Newtonian rheological model. These bounding conditions require the viscosity of the fluid and should be between 0.9 mPa•s and 15 mPa•s. Table 4.3 can be constructed by estimating data on the actual LAW pretreated process streams from the data compiled in Appendices A through C. In addition, the physical-properties correlations presented in Appendix B were used to estimate data and provide a more complete comparison when no data were available. Table 4.3 indicates that each tank satisfies the proposed bounding conditions when the sodium concentration is below 10 M (below approximately 50 wt% total solids; see Figure 4.14). Therefore, the proposed bounding conditions for the pretreated LAW appear to be feasible, and a rheological operating window for this stream is shown in Figure 4.15.

Description (Proposed Bounding Conditions)	Density (g/mL)	Wt % Total Solids	Viscosity at 25°C (0.9,15) (mPa·s)	Within Proposed Bounding Range? (Yes/No)
Actual LAW Envelope A 6M AW-101 PNWD	1.31	33.4	8.0	Yes
Actual LAW Envelope A 8M AW-101 PNWD	1.37	42.1	12.0	Yes
Actual LAW Envelope A 10M AW-101 PNWD	1.44	50.3	22.0	No
Actual LAW Envelope A 5.3M AN-103 SRTC	1.25	29.6	3.2	Yes
Actual LAW Envelope A 11.7M AN-103 SRTC	1.53	53.9	23.1	No
Actual LAW Envelope A 6 M AP-101 PNWD	1.33	35.8	5.2	Yes
Actual LAW Envelope A 8 M AP-101 PNWD	1.40	43.0	8.0	Yes
Actual LAW Envelope A 10 M AP-101 PNWD	1.46	49.0	11.8	Yes
Actual LAW Envelope B AZ-102 2.8M SRTC	1.10	12.5	3.7	Yes
Actual LAW Envelope B AZ-102 4.1M SRTC	1.16	25	2.1	Yes
Actual LAW Envelope B 1.75 M AZ-102 PNWD	1.10	12.1	1.4	Yes
Actual LAW Envelope B 2.75 M AZ-102 PNWD	1.15	17.9	1.8	Yes
Actual LAW Envelope B 3.75 M AZ-102 PNWD	1.20	23.1	2.4	Yes
Actual LAW Envelope C AN-102 4.9M SRTC	1.23	31.5	4.2	Yes
Actual LAW Envelope C AN-102 6.4M SRTC	1.26	40	2.7	Yes
Actual LAW Envelope C AN-102 10.2M SRTC	1.46	53.9	6.7	Yes
Actual LAW Envelope C AN-107 6M PNWD	1.28	36.3	8.0	Yes
Actual LAW Envelope C AN-107 8M PNWD	1.37	45.3	14.0	Yes
Actual LAW Envelope C AN-107 10M PNWD	1.44	53.9	18.7	No

Table 4.3. Comparison of Estimated Actual Pretreated LAWData to Proposed Bounding Conditions at 25°C



Figure 4.14. Comparison of Actual Data to Proposed Bounding Conditions as a Function of Weight Percent Total Solids for Pretreated LAW at 25°C



Figure 4.15. Proposed Bounding Conditions for Pretreated LAW

Based on the rheological data compiled in Appendix C, the remaining process streams are slurries that are expected to behave as Bingham Plastic fluids. Using the data compiled in Appendix A, estimates of the actual waste data for the LAW melter feed stream is shown in Table 4.5. These data were used to calculate the critical transition velocity for these fluids in a 2-in.-diameter pipe (see Section 4.1.5).

					Hedstrom	Critical	Critical	
	Wt %	CI.	Consistency	TH 11 G/	Number	Reynolds	Velocity in 2"	
Description	Total	Slurry		Yield Stress	In 2-In. Pipe	Number	Pipe (0.10)	Meets Proposed Bounding
(Proposed Bounding Conditions)	Solids	(g/mL)	(0.9,90) (mPa·s)	(0,13) (Pa)	(0.10^8)	Pipe	(ft/sec)	(Yes/No)
LAW MF Envelope A PNWD AP-101 (VSL-LAWA126)	58.0	1.65	13.2	0	0	2,100	1.1	Yes
LAW MF Envelope A PNWD AP-101 (VSL-LAWA126)	65.3	1.74	39.9	0	0	2,100	3.1	Yes
LAW MF Envelope A PNWD AP-101 (VSL-LAWA126) 1 hour of mixing	65.3	1.74	24.7	0	0	2,100	2.9	Yes
LAW MF Envelope A PNWD AP-101 (VSL-LAWA126) 1 day of mixing	65.3	1.74	30.6	0	0	2,100	2.4	Yes
LAW MF Envelope A PNWD AP-101 (VSL-LAWA126) 1 week of mixing	65.3	1.74	31.0	0	0	2,100	2.4	Yes
LAW MF Envelope A PNWD AW-101 (VSL-LAWA88)	61.5	1.67	35	0.4	1.4E+03	2,400	3.2	Yes
LAW MF Envelope A PNWD AW-101 (VSL-LAWA88)	68.0	1.8	86	0.8	5.0E+02	2,200	6.8	Yes
LAW MF Envelope A PNWD AW-101 (VSL-LAWA88)	73.5	1.77	228	1.1	9.7E+01	2,100	17.5	No
LAW MF Envelope B PNWD AZ-102 (VSL-LAWB83)	51.4	1.534	18.7	0.1	1.1E+03	2,300	1.8	Yes
LAW MF Envelope B PNWD AZ-102 (VSL-LAWB83)	62.7	1.736	72.1	5.3	4.6E+03	2,800	7.5	Yes
LAW MF Envelope B PNWD AZ-102 (VSL-LAWB83)	69.1	1.890	105.9	8.6	3.7E+03	2,700	9.7	Yes (Marginal)
LAW MF Envelope C PNWD AN-107 (VSL-LAWC15)	61.6	1.61	44	0.1	2.1E+02	2,100	3.8	Yes
LAW MF Envelope C PNWD AN-107 1 hr of mixing (VSL-LAWC15)	69.9	1.71	220	21.0	1.9E+03	2,400	20.2	No
LAW MF Envelope C PNWD AN- 107 1 day of mixing (VSL-LAWC15)	69.9	1.71	478	21.9	4.2E+02	2,200	39.4	No

Table 4.4. Rheological Comparison of Estimated Actual LAW Melter Feed Data to Proposed Operating Envelope at 25°C

					Hedstrom	Critical	Critical	
Description (Proposed Bounding Conditions)	Wt % Total Solids	Slurry Density (g/mL)	Consistency Index (0.9,90) (mPa·s)	Yield Stress (0,15) (Pa)	Number in 2-in. Pipe (0,10 ⁸)	Reynolds Number in 2-in. Pipe	Velocity in 2'' Pipe (0,10) (ft/sec)	Meets Proposed Bounding Conditions? (Yes/No)
LAW MF Envelope C PNWD AN-107 1 wk of mixing (VSL-LAWC15)	69.9	1.71	376	22.2	6.9E+02	2,200	31.7	No
LAW MF Envelope C PNWD AN-107 (VSL-LAWC15)	76.6	1.79	839	130.7	8.6E+02	2,300	68.6	No

Table 4.4. Rheological Comparison of Estimated Actual LAW Melter Feed Data to Proposed Operating Envelope at 25°C



Figure 4.16. Proposed Rheological Operating Envelope for LAW Melter Feed

Several of these critical velocity values are above the 10 ft/s pipe erosion threshold. To define a set of bounding conditions for the vitrification streams, a slurry density of 1.8 g/mL was used as a high characteristic slurry density for the actual LAW melter feed streams. The Bingham plastic parameters that encompass the most actual waste points at this slurry density while maintaining a critical velocity of approximately 10 ft/s were calculated as upper bounding conditions. Figure 4.16 presents the resulting rheological bounding conditions graphically along with the actual waste data, the mechanical mixing criterion developed in Section 4.1.1, and DWPF/HWVP design bases.^(a) It is important to note that the current set of WTP rheological/physical properties far exceed the set of properties that were available at the time the DWPF design basis was issued. Rheological properties for radioactive wastes had not been measured for DWPF slurries when the rheological design basis was issued.

In each case, the low-shear mixing criterion exceeds the proposed bounding conditions. This mixing criterion is defined as the set of Bingham plastic parameters that result in an apparent viscosity of 700 mPa·s at a shear rate of \sim 70 s⁻¹. This removes the mixing criterion from further examination. In

 ⁽a) DWPF Design Basis: DPSTD-80-38-2; Part 10, Item 230, Date 9-82 Rev. 2.
 HWVP Design Basis: WHC-SD-HWV-DP-01; Section, Item 300 October 1990.
 HWVP consistency index presented in this document calculated from apparent viscosity design ranges at high and low yield stress design ranges.

addition, the proposed bounding conditions always encompass the DWPF design basis and are comparable to the HWVP design basis.

Note that several of the actual waste data points lie outside the proposed bounding conditions. This is not unexpected since Bingham plastic parameters are known to increase asymptotically as undissolved solids content increases. This asymptotic behavior can result in large rheological changes due to a small change in solids concentration (Slatter 1997; Landel et al. 1965; Dabak and Yucel 1987). The consistency

index, K (mPa·s), has been previously been modeled as $K = \mu_f \left(1 - \frac{C}{C_{\text{max}}}\right)^{-m}$ where μ_f is the viscosity

of the interstitial liquid; C is the concentration of undissolved solids; C_{max} and m are fitting parameters.

The yield stress, τ_y (Pa), has been modeled as $\tau_y = a \frac{C^3}{C_{\text{max}} - C}$ where *a* is a fitting parameter. Using

forms similar to these equations, the actual waste data for each vitrification stream were fit to the following three parameter models, where *a*, *b*, *c*, *d*, *e*, and *f* are fitting parameters, and *X* is the weight percent total solids present in the slurry (see Equations 4.28 and 4.29). The resulting model parameters for the actual waste data are shown in Table 4.5.

$$K = a \left(1 - \frac{X}{b} \right)^{-c} \tag{4.28}$$

$$\tau_y = d \frac{X^f}{e - X} \tag{4.29}$$

Description	Consister	ncy Index N	Iodel Paran	neters	Yield Index Model Parameters				
	а	b	с	\mathbf{R}^2	d	е	f	\mathbf{R}^2	
AN-107	0.16	100	5.9	1.00	6.5E-56	100	31	0.96	
LAW									
Melter Feed									
AP-101	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
LAW									
Melter Feed									
AW-101	0.56	92	3.8	1.00	4.7E-06	100	3.7	0.94	
LAW									
Melter Feed									
AZ-102	1.2	100	3.9	0.96	2.2E-24	100	14.3	0.93	
LAW									
Melter Feed									
n/a: Could not be calculated because there are only two data points available for a model fit of a three-parameter							ameter		
model.									

Table 4.5. Parameters used to Correlate Bingham PlasticIndices to Total Solids Loading at 25°C

The actual waste and model fit data are displayed graphically as a function of weight-percent total solids in Figure 4.17 and Figure 4.18. These data illustrate the asymptotic effect of solids loading on the rheological properties of the slurry. In many instances, a small change in solids loading can result in a large change in rheological properties. For this reason, some of the slurries previously evaluated with higher solids loadings possess relatively large rheological properties that are likely to result in processing difficulties in the WTP. These slurries are shown outside the operational windows in Figure 4.17 and Figure 4.18. Fortunately, each tank evaluated possesses data within the proposed operational window, and a threshold solids loading for each tank needs to be established before WTP processing. As shown in Table 4.4, mixing and aging the slurries for prolonged amounts of time can result in significant rheological changes. Results from mixing and aging tests should also be a factor in determining the WTP process threshold solids loading for a particular tank. The proposed operational windows for each vitrification stream are shown in rheogram form (i.e., shear stress versus shear rate) in Figure 4.19.







Figure 4.18. Bingham Yield Index as a Function of Weight Percent Total Solids for LAW Melter Feed at 25°C



Figure 4.19. Proposed Bounding Conditions for LAW Melter Feed

4.3 Feasibility of Proposed Bounding Conditions

The bounding conditions proposed in this document are derived using the following set of information: 1) actual waste data, 2) theoretical/empirical correlations, and 3) engineering evaluations. The purpose of this section is to apply recently measured simulant and actual waste data to reinforce the theoretical/empirical correlations and engineering judgment used throughout this document.

The viscosity of the actual AP-101 pretreated waste at several concentrations has been plotted against the proposed rheological bounding conditions. This plot is shown in Figure 4.20. The plot shows that at all sodium concentrations, the material possesses Newtonian viscosities that are within the proposed rheological bounding conditions. Glass-former chemicals were added, and this material was converted to a melter feed. The rheology of the resulting melter feed was measured. These data have been plotted on the proposed rheological bounding conditions. This plot is shown in Figure 4.21. Again, this material falls within the proposed bounding conditions for LAW pretreated melter feed. These AP-101 actual waste data were not available for consideration during the development of the bounding conditions. Therefore, these data appear to reinforce the theoretical/empirical correlations and engineering evaluations that were used in this document.



Figure 4.20. Actual AP-101 Pretreated LAW Bounding Conditions Evaluation

Additionally, Duratek pilot plant LAW melter feed simulant data (Twarowski 2002a, 2002b, 2003a, 2003b, 2003c, 2003d, 2003e) designed to simulate several actual LAW waste sub-envelopes (A1, A2, A3, B1, B2, C1, C2) are shown in Figure 4.21. These data consist of rheological measurements obtained after

varying the quantity of liquid waste simulant in the LAW melter feed while keeping the quantity of dry GFCs added to the liquid simulant constant. This was done to investigate the effects of melter feed variability during operation of the WTP. For example, in Figure 4.21, the A1 curve represents subenvelope simulant A1 at the nominal LAW/GFC ratio, the A1-15% represents sub-envelope simulant A1 at 15% below the nominal LAW/GFC ratio, and A1+15% represents sub-envelope simulant A1 at 15% above the nominal LAW/GFC ratio. Typically the melter feeds with lesser LAW simulant contain a greater fraction of GFCs and consequently a higher solids loading. The higher solids loading is expected to raise the viscosity of the slurries. However, the melter feeds contain soluble species which can alter the pH and electrostatic potential of the slurry particles and this expectation is not always obeyed. These differences coupled with experimental error can be seen in several of the simulant melter feed data sets in Figure 4.21. These differences are exemplified in the envelope B1 simulants where variations in simulant to GFC ratio produce counterintuitive results that should be expected due to the nature of these complex fluids.



Figure 4.21. LAW Melter Feed Rheological Bounding Conditions Evaluation

4.4 Selection of a Shear Rate Range to Fit Realistic Boundary Conditions

To define a shear rate range that should be used when assessing when a material fits within the bounding range, two process operations are considered: pipeline flow and mechanical mixing. These process operations have been previously evaluated as explained below.

4.4.1 Pipe Flow Evaluation

The pipe velocity and diameter are based on the evaluation done in Section 4.1.5. From that section, Jones and Peterson (1996) state that solids' settling in process lines does not usually occur if the slurry flow is turbulent. Turbulent flow generally exists at high line velocities above 3 to 5 ft/s in 2-in. piping. However, high fluid velocities will cause excessive erosion, and a maximum line velocity of 10 ft/s has been specified for the DWPF (Jones and Peterson 1996).

The rheology parameters are established in Section 4.2. Table 4.2 in that section succinctly summarizes those parameters and indicates their importance to pipe flow where appropriate, such as Maximum Bingham Plastic Parameters, Maximum Hedstrom Number in 2-in. pipe. The shear stress at the pipe wall is calculated for conditions that produce a maximum shear (equation is taken from Shook et al. 2002) (Figure 4.22).

Pipeline velocity	Pipe Diameter
$\mathbf{v} := 10 \frac{\mathbf{ft}}{\mathbf{sec}}$	D :=2 in
Bingham Plastic Param	eters
τ ₀ :=30 Pa	K :=0.40 poise
Shear stress at pipe wa	II
$\tau_{\mathbf{w}} \coloneqq \frac{8 \cdot \mathbf{K} \cdot \mathbf{v}}{D} + \frac{4 \cdot \tau_0}{3}$	
Maximum shear rate at	pipe wall
$\gamma_{\text{pipe}} := \frac{\tau_{\text{w}} - \tau_0}{K}$	
$\gamma_{\rm pipe} = 730 \cdot s^{-1}$	

Figure 4.22. Basis for Calculating the Maximum Shear Rate at a Pipe Wall

This result indicates that rheological properties should be measured to at least $700 \cdot \sec^{-1}$ to match an estimate of the potential range of service conditions.

4.4.2 Mechanical Mixing Evaluations

Mechanical mixing evaluations were carried out in Section 4.1.1, Mixing Operations (Low-Shear-Rate Viscosity), and 4.1.2, Mixing Operations (Maximum Settled Solids Shear Strength), using the impeller diameter and rotational rate from Section 4.1.1 and assuming that the impeller diameter is 90% of the tank diameter. Reducing the gap between the tank wall and the impeller results in an even higher shear rate, and 90% is a reasonably conservative estimate for typical process operations. The maximum

shear rate equation for this geometry is found in Steffe (1996) and gives a value for the shear rate at the tank wall of $377 \cdot s^{-1}$ for an impeller rotational rate of 400 rpm (Figure 4.23).

It is concluded that rheological properties should be measured over a shear rate range of 0 to $700 \cdot s^{-1}$ to include an estimate of the full range of conditions that a slurry might see.

Impeller diameter d := 36 in Gap between impeller and tank wall or baffle $\Delta d := \frac{d}{0.90} - d$ $\Delta d = 4 \sin$ Impeller Rotational Rate $\Omega := 400 \cdot (2 \cdot \pi) \min^{-1}$ Maximum Estimated Shear Rate $\gamma_{tank} := \frac{\Omega \cdot d}{\Delta d}$ $\gamma_{tank} = 377 \cdot s^{-1}$

Figure 4.23. Basis for Calculating a Maximum Shear Rate in a Mixing Tank

4.5 Application of Boundary Conditions

A stated objective of this report is to develop a set of bounding physical and rheological properties for waste materials that can be reasonably processed and likely encountered in the Waste Treatment Plant (WTP) vitrification facilities. To determine the bounds for each operation, one must understand what general waste properties are anticipated and how changes in those properties can affect process operation. The process bounds are then established at the point where the properties of the material induce unacceptable risk to plant performance. Hence one can use this set of bounding physical and rheological properties to judge when a given pretreated waste or melter feed may cause transfer or processing problems by causing the system to have to operate outside its design capabilities. In this brief section, examples of LAW Pretreated Waste or Melter feed rheology are discussed with respect to the recommended rheological bounding conditions.

The boundary conditions for LAW pretreated waste and melter feed are summarized in Table 4.6. These conditions are plotted in Figure 4.19 and Figure 4.20. The PT LAW Simulant is assumed to display Newtonian behavior as the actual low activity pretreated wastes are observed to do, so in Figure 4.24, the apparent viscosity of a LAW Pretreated Waste simulant will lay between 0.9 and 15 mPa·s if it is to represent a waste that can be appropriately mixed and transported by a pretreatment facility. The Newtonian behavior of the actual low activity pretreated wastes and their simulants is expected on the basis that they are solutions with negligible suspended solid matter. The lower boundary is based on the need to maintain the fastest settling glass former particles in suspension while the glass formers are being added to the waste to make a melter feed. The upper boundary reflects the fact that waste solutions with less than about 50 wt% dissolved solids (about 10 molar sodium) have apparent viscosities less than 15 mPa·s. This upper bound also limits excessive pressure drops through packed columns and heat and mass transfer inefficiencies.

Similarly, Figure 4.25 shows the upper and lower operational boundaries for LAW Melter Feed. In this case, the lower boundary is also Newtonian and feeds falling near this boundary show little or no shear strength. The lower boundary also has the same requirement that the lower boundary for the pretreated waste, i.e., maintenance of the suspension of the added glass former chemicals and minerals. The upper boundary has been established as the maximum rheological parameters that will allow for turbulent mixing in the pipes while limiting pipe erosion at high velocities. The examples of LAW Melter Feed apparent viscosity trends are taken from reports by Matlack, Gong, and Pegg on DuraMelter 100 test results^a. These fall at or below the upper operational boundary for the LAW Melter Feed processing system. These trends also match the trend displayed by the upper operational boundary which is based on the Bingham Plastic Rheological model indicating that they are also well defined by this model.

It is expected that the amount of water in the pretreated waste and the melter feed would be minimized to increase melting efficiency. Hence the examples for both the LAW Pretreated Waste stimulant and the simulated LAW Melter Feed crowd the upper boundary.

Shear Rate (1/s)	10	100	700
PT LAW low - Apparent Viscosity (mPa-s)	0.9	0.9	0.9
PT LAW high - Apparent Viscosity (mPa-s)	15	15	15
MF LAW low - Apparent Viscosity (mPa-s)	0.9	0.9	0.9
MF LAW high - Apparent Viscosity (mPa-s)	1590	240	111

Table 4.6. Operating Conditions for LAW Pretreated Waste and Melter Feed

4.6 Rheology Modifier Assessment

Recently an effort has been undertaken to investigate the use of surfactants, dusting agents, and rheological modifiers for the purpose of minimizing foaming and dusting while adding dry glass-former chemicals in addition to lowering the yield stress of the resulting melter feed. The surfactants function by raising or lowering the interfacial tension at the boundary between two phases (Kay, Calloway et al. 2003). Dusting agents function by agglomerating the dry glass-former chemicals into larger particles while rheological modifiers alter the particle-particle interaction of particles in a slurry. All of these materials are dependent on the composition of liquid and solid phases, surface-charge effects, pH, and particle size. These agents have the potential to produce a wide range of rheological effects by adding

^a Matlack KS, WK Kot, T Bardakci, W Gong, NA D'Angelo, NA Schatz, and IL Pegg. 2002. Tests on the DuraMelter 1200 HLW Pilot Melter System Using AZ-101 HLW Simulants. VSL-02R0100-2 Rev. 1, Vitreous States Laboratory, The Catholic University of America, Washington D.C.

small quantities to a slurry. In industrial applications, quantities of surfactants and rheological modifiers in the parts per million (ppm) level are typically added to produce desired results.



PT LAW Simulant Operational Boundaries

Figure 4.24. Pretreated LAW Rheological Bounding Conditions with Examples of Actual and Simulated Pretreated Waste Superimposed

Fortunately, SRTC has evaluated the rheological effects of several surfactants and rheological modifiers on simulated melter feed slurries and pretreated waste sludges (Kay, Calloway et al. 2003). First, the rheological properties of the simulated melter feeds and pretreated waste sludges were evaluated as an experimental control. Surfactants and rheological modifiers were added to achieve a composition of 1000 ppm (0.1 wt%). The rheological properties of these experimental slurries were then evaluated.

The results from the simulated-melter-feed sludges emphasize the need for thorough characterization of actual waste with the surfactant before implementation in the WTP. Each of the three surfactants and
rheological modifiers investigated increased the yield stress of the slurries. The yield stress was increased by a factor of 1.2 to 3, depending on the surfactant. Such increases could result in slurries that are difficult to process through the WTP unit operations.



Figure 4.25. LAW Melter Feed Rheological Bounding Conditions with Examples of Simulated LAW Melter Feed Used in the DuraMelter 100 Melter Tests Superimposed.

The results from adding surfactant and rheological modifiers to simulated AZ-102 HLW pretreated sludge is more promising. Eight surfactants and rheological modifiers were investigated. Several of these surfactants decreased the yield stress of the slurry while maintaining or slightly dropping the consistency index. Depending on the surfactant, the yield stress changed by a factor of 0.8 to 1.4. The consistency index changed by a factor of 1.0 to 1.4. The authors attribute the drop in yield stress by dispersion of the particles in the slurry due to the surfactant as opposed to particle agglomeration without the surfactant.

In a separate SRTC report^a, several wetting agents were investigated for use in dry glass-former chemicals to minimize dusting. Of the 11 wetting agents considered, two were recommended for potential implementation to the WTP. The two wetting agents were water and Van-Gel.

Adding water is expected to decrease the rheological properties of the resulting melter feeds. The quantities of water added to the glass former chemicals are small, 2.5 wt% for LAW and 5 wt% for HLW. In this amount, adding water to the dry glass-former chemicals is not expected to be large enough to significantly lower throughput through the melters.

^a Schumacher R.W., E.K. Hansen, T.M. Jones, J.E. Josephs. 2003. Interim Report – Evaluation of wetting agents to mitigate dusting of glass forming chemicals during delivery to the melter feed preparation vessel. WSRC-TR-2003-00209 Rev. 0, Westinghouse Savannah River Company, Aiken, SC.

Van-Gel is the trade name of a bentonite product produced by RT Vanderbilt. Bentonite is a waterswelling clay that has dramatic rheological effects at low solids concentrations. At the concentrations investigated, 1.75 to 2.0 wt% of a 1.85-wt% Van-Gel solution, the effect on the resulting melter feed rheology is expected to be minimal. The rheological properties of the 1.85 wt% Van-Gel solution were small with a yield stress of 0.2 Pa and consistency of 3.0 mPa•s. However, bentonite is often used to impart a yield stress in industrial materials at higher concentrations. It should also be noted that the effect of the wetting agent on the rheology of the resulting melter feeds was not considered in this report.

Results from these experiments on simulated vitrification streams show that the use of surfactants, wetting agents, and rheological modifiers may produce beneficial results. However, the use of surfactants and rheological modifiers increased the yield stress and consistency indices of simulated melter feeds and simulated HLW pretreated sludges. Order of magnitude changes in rheological properties are not unexpected (Kay, Calloway et al. 2003). For slurries with rheological properties near the upper bounding conditions, such increases can produce a slurry that is difficult to process. The rheological effects of adding surfactants, wetting agents, and rheological modifiers should be thoroughly investigated with actual waste samples for each tank before WTP implementation.

4.7 Submerged Bed Scrubber (SBS) Recycle Analysis

A significant issue that has not thoroughly been investigated with actual waste experiments is the recycling of secondary waste streams. The primary recycled secondary waste stream for the LAW vitrification facility consists of SBS solution that is recycled to the pretreatment facility to an evaporator that follows ion exchange (Figure 4.26). The SBS scrubber consisted of a bubbler bed submerged in water. The melter feed offgas is passed through the bubbler bed and through the water. This unit operation is used to cool the melter offgas stream and collect particulates carried over from the melter.

SRTC has taken simulated submerged-bed-scrubber solution, mixed it with simulated pretreated waste stream, and evaporated the mixture to target concentrations (Josephs et al. 2003). The physical properties of the resulting solutions were then characterized.

The SBS solution/pretreated LAW mixture consisted of up to 70% recycled SBS solution. The simulated SBS solution only consisted of primarily water with approximately 1.0 wt% undissolved solids. Due to the large amount of silica used in the melter, the SBS solution also consists of a significant amount of dissolved silica. When the recycled mixture was evaporated to high concentrations, the silicia in the SBS solution resulted in significant solids precipitation. Upwards of 60-vol% centrifuge solids were present in the evaporated simulated Envelope C wastes. This is significant because this portion of the plant is designed primarily for liquid processing.

Fortunately, the rheological properties of the evaporated recycle mixture were measured. For each process envelope, the slurries remained Newtonian. The empirical fit of the measured viscosities as a function of sodium molarity at 25°C is shown in Figure 4.27. At high degrees of evaporation, the Envelope A and B wastes remain within the LAW bounding conditions. However, at high degrees of evaporation (~8 M Na), the Envelope C waste slightly exceeds the 15 mPa•s bounding condition.

In creating the lower bounding condition of 0.9 mPa•s for the clear liquid (i.e., supernate) viscosity, a particle size of 164 μ m was assumed. The particle size of the simulated SBS solution has been measured and can be compared to this assumption. Results indicate that the D₉₅ values for SBS fluids from six melter runs were as follows^a: 1) 24.50 μ m; 2) 54.40 μ m; 3) 26.39 μ m; 4) 4.040 μ m; 5) 9.571 μ m; 6) 13.86 μ m. The largest particles were detected in the second set of tests and possessed a small quantity of particles (~0.5 volume %) in 105 μ m micron range. This particle size is below with the assumed maximum value of 164 μ m and no significant change to the lower viscosity bound is warranted due to SBS particulates.

However, the particle size of the solids that precipitate during evaporation have not been measured. These solids may precipitate on the SBS particulates, resulting in larger particles. Large particles that are created during solids precipitation as a result of evaporation of the SBS solution/pretreated LAW mixture may result in fast settling, difficult-to-process slurries. In addition, the solids that precipitated in the simulated mixtures were sodium aluminosilicates. These solids have historically caused processing difficulties in DWPF. The effects of evaporated SBS recycle streams should be evaluated with actual waste experimentation to limit risk to the WTP.

^a Matlack KS, WK Kot, T Bardakci, W Gong, NA D'Angelo, NA Schatz, and IL Pegg. 2002. Tests on the DuraMelter 1200 HLW Pilot Melter System Using AZ-101 HLW Simulants. VSL-02R0100-2 Rev. 1, Vitreous States Laboratory, The Catholic University of America, Washington D.C.



Figure 4.26. Basic LAW SBS Recycle Schematic



Mixture at 25°C as Evaporation Proceeds

5.0 Summary and Recommendations

Bounding conditions were developed for two WTP vitrification streams: 1) pretreated LAW and 2) LAW melter feed. Summary tables of the bounding conditions developed in this document for each vitrification process stream are shown in Figure 5.1 and Figure 5.2. The strategy employed in developing the bounding conditions proposed in this document is to begin by identifying correlations between dimensionless groups for specific unit operations as described in the WTP flowsheet. Because specific correlations for equipment in the WTP have not been developed and are not readily available, correlations are used for similar equipment that has been developed for standard chemical processing applications. Sources for these correlations include various engineering handbooks, engineering textbooks, and peerreviewed journal articles. In addition, equipment data and calculations for previous vitrification-plant designs are used. These previous designs include HWVP and DWPF (Jones and Peterson 1996). Use of these data and correlations assumes that the equipment selected for use in the WTP will possess similar performance properties to equipment generally used in the chemical processing industry, HWVP, and DWPF. Based on these correlations, bounding conditions on the physical and rheological properties are proposed to satisfy equipment performance issues. Actual waste data are used to tailor the bounding ranges such that the proposed bounding conditions span the existing actual waste materials. In this regard, the proposed bounding conditions are based upon a general engineering evaluation of process equipment and measured values from actual waste material.

Information from previous actual waste-characterization activities was compiled and compared against the proposed bounding conditions. Several of the actual wastes possessed rheological properties outside of these bounding conditions. However, at lower solids concentrations, at least one measurement from each actual waste data set fell inside the proposed bounding conditions. This may be because of an asymptotic relationship between rheological parameters and undissolved solids concentration. At high undissolved solids concentrations, the Bingham Plastic parameters can become quite large, and a relatively small amount of dilution can result in a significant decrease.

The rheological effects of adding surfactants, wetting agents, and rheological modifiers should be thoroughly investigated with actual waste samples for each tank before WTP implementation. This is an important consideration because order of magnitude changes in rheological properties are not unexpected when these materials are added to slurries (Kay, Calloway et al. 2003). However, the use of rheology modifiers is warranted for the fast settling heterogeneous slurries that may compact during agitator outages. The high yield stresses expected upon settling and compaction of heterogeneous slurries could be avoided with a rheology modifier that suspends the material during outages.



Figure 5.1. Summary of Bounding Conditions for Pretreated LAW

Figure 5.2. Summary of Bounding Conditions for LAW Melter Feed



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Appendix A – Pretreated LAW and LAW Melter Feeds Chemical, Rheological, and Physical Properties Database^(a)

⁽a) Note that Appendices A through F contain data from previous reports on the physical, chemical, and rheological properties of actual and simulated WTP vitrification streams. The data in Appendix A are contained on a spreadsheet that is broken into five worksheets: 1) "Density and % Total Solids" contains information on the slurry density and wt% total solids of the materials, 2) " Rheological Property Data" contains information on the rheological properties of the materials, 3) "Physical Property Data" contains information on the physical properties of the materials, 4) "Melter Feed Preparation" contains information on the melter-feed composition and mixing of the melter feed materials, and 5) "Waste Composition" contains information on the chemical and radiochemical composition of the materials. The entries are grouped according to waste tank and envelope type. A description of the entry is given on each page of Appendix A. Entries that possess similar descriptions differ in the waste concentration. These differences can be seen in the wt% total solids data shown in the "Physical Property Data" worksheet or the sodium concentration shown in the "Waste Composition" worksheet. Calculations and approximations of the reported values from the source documents were performed to transform these data to a common reporting basis. For WTP design purposes, the author recommends that source documents be reviewed before using the data reported in Appendices A through F.

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW		Actual LAW Envelope	Actual LAW Envelope
Sample			AW-101—	AW-101—	AW-101—	AW-101—	AW-101—	Envelope A,	Actual LAW Envelope B	B AZ-102	B AZ-102,
Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	AN-103, SRTC	AZ-101 PNNL	SRTC	SRTC
Reference	WTP-RPT- 092	WTP-RPT-0 101 at 4.59 moles to the	03, Rev. 0. molar sodium indicated mo	See Table 3.1 a. The values larity of sodiu	, which gives below were Im.	s the compos calculated by	ition of AW- scaling 4.59	WSRC-TR- 2000-00322 ^a See Table 3 last column	Pretreated AZ-101 Envelope B Actual Waste Sample (technetium ion exchange effluent) RPT- WTP-02-199	WSRC-TR-2 See Tables 2	2001-00395, 2 and 5
Sodium concentration of LAW Waste or Pretreated Waste: Molar Sodium											
	4.85E+00	4.59E+00	4.59E+00	5.00E+00	6.00E+00	8.00E+00	1.00E+01	4.94E+00	4.31E+00	2.21E+00	4.39E+00
pH of the Waste											
Analyte (mg/L (LAW)):											
Cations	molar	molar									
Ag									< 0.50		
Al	2.34E-01	4.11E-01	1.11E+04	1.21E+04	1.45E+04	1.93E+04	2.42E+04	2.22E+04	5.28E+03	4.02E+02	7.98E+02
As									1.35E+01		
В	7.80E-03							1.37E+01	7.75E+00	1.14E+00	<4.6
Ba								1.80E-01	<0.20	1.34E+00	<1.8
Be											
Bi											
Ca								2.62E+00	<5.0	5.70E-01	6.70E+01
Cd								8.10E-01		< 0.07	<2.7
a-Crawford CL, DM I Savannah River Comp	Ferrara, RF So pany, Aiken, S	chumacher, ar SC.	nd NE Bibler.	2001. Cruci	ble-Scale Ac	tive Vitrificat	ion Testing E	Envelope A, Tank A	AN-103 (U), WSRC-TR-2000)-00322, We	stinghouse

Table A.1.a. Waste Composition—Envelopes A and B (blank entries are intentional)

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
Sample Identification:	AP-101		AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	Actual LAW Envelope A AN-103 SRTC	Actual LAW Envelope B AZ-101 PNNL	Actual LAW Envelope B AZ-102 SRTC	Actual LAW Envelope B AZ-102 SRTC
Ce	111 101		Inclui	Tictuui	Tetuur	Tietuur	Inclui	bille		SRIC	<287
Cl									<130		
Со								5.50E-01		1.40E-01	<4.6
Cr	2.50E-03	8.40E-04	4.37E+01	4.76E+01	5.71E+01	7.61E+01	9.52E+01	7.24E+01	5.70E+02	5.33E+02	1.02E+03
Cs	~0	6.15E-05	8.17E+00	8.90E+00	1.07E+01	1.42E+01	1.78E+01				
Cu								4.20E-01		< 0.07	<2.7
Dy											
Eu											
F									1.90E+03		
Fe								8.80E-01	< 0.50	< 0.07	<5.5
Hg											
K	6.61E-01	3.90E-01	1.41E+04	1.53E+04	1.84E+04	2.45E+04	3.07E+04	4.12E+03	3.80E+03	2.58E+03	4.56E+03
La								7.30E-01		<0.25	<10
Li								1.28E+00	< 0.60	< 0.04	<1.8
Mg								9.00E-02	<2.0	< 0.02	3.10E+00
Mn								2.10E-01		< 0.02	<0.9
Mo								3.87E+01	8.53E+01	4.30E+01	7.91E+01
Na	4.85E+00	4.59E+00	1.06E+05	1.15E+05	1.38E+05	1.84E+05	2.30E+05	1.14E+05	9.90E+04	5.09E+04	1.01E+05
Nd											
Ni								1.47E+00		< 0.16	<6.4
Р	9.30E-03	7.00E-03	2.17E+02	2.36E+02	2.83E+02	3.78E+02	4.72E+02	3.91E+02	1.60E+03	1.39E+02	2.30E+02
Pb								3.84E+01	6.65E+00	1.17E+00	2.56E+01
Pd											
Pr											
Pt											
Rb											
Rh											
Ru	2.405.02										
S	3.10E-02								5.50E+03		
Sb											

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW	Actual LAW	Actual LAW	Actual LAW
								Envelope A	Envelope B	Envelope B	Envelope B
Sample			AW-101-	AW-101-	AW-101—	AW-101-	AW-101-	AN-103	AZ-101	AZ-102	AZ-102
Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	SRTC	PNNL	SRTC	SRTC
Se											
Si								1.49E+02	5.25E+01	1.00E+02	5.61E+01
Sn								3.70E+01		7.50E+00	1.70E+01
Sr								1.80E-01	< 0.30	< 0.02	<0.9
Та											
Те											
Th											
Ti								6.40E-01	2.55E+00	< 0.04	<1.8
T1											
U											
V								3.70E-01	1.35E+00	3.60E-01	<2.7
W									5.10E+01		
Y											
Zn								1.17E+00	1.65E+00	4.30E-01	<2.7
Zr								1.16E+00	1.95E+00		<3.6
Carbon Analyses											
TIC											
TOC											
Anions											
F	1.18E-01										
Cl	3.90E-02	6.60E-02	2.34E+03	2.55E+03	3.06E+03	4.08E+03	5.10E+03				
Br											
NO_2	7.39E-01	9.70E-01	4.46E+04	4.86E+04	5.83E+04	7.78E+04	9.72E+04		6.19E+04		
NO ₃	1.55E+00	1.43E+00	8.87E+04	9.66E+04	1.16E+05	1.55E+05	1.93E+05		5.30E+04		
PO ₄	9.30E-03	7.00E-03	6.65E+02	7.24E+02	8.69E+02	1.16E+03	1.45E+03				
SO ₄	3.10E-02	1.90E-02	1.75E+03	1.91E+03	2.29E+03	3.05E+03	3.81E+03		1.65E+04		
C_2O_4	1.10E-02	8.60E-03	7.57E+02	8.24E+02	9.89E+02	1.32E+03	1.65E+03		1.00E+03		
CO ₃	4.38E-01	1.30E-01	7.80E+03	8.50E+03	1.02E+04	1.36E+04	1.70E+04				

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW	Actual LAW		
			A XX 101	A XX 101	A XX 101	A XX 101	A XX 101	Envelope A	Envelope B	Actual LAW	Actual LAW
GII	A D 101		AW-101-	AW-101—	AW-101-	AW-101	AW-101-	AN-103	AZ-101 DNNI	Envelope B	Envelope B
Sample Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	SKIC	PININL	AZ-102 SKIC	AZ-102 SKIC
INIT3 Eree OH		3.10E+00	5 27E+04	5 74E+04	6 80E+04	0.10E+04	1.15E+05		1.10E+04	-	
Total OH		3.10E+00	5.2712+04	5.74E+04	0.892+04	9.1911-04	1.15E+05		1.10E+04		
Oxide											
wt %											
Ag ₂ O											
Al ₂ O ₃											
As ₂ O ₃											
B_2O_3											
BaO											
BeO											
Bi ₂ O ₃											
CaO											
CdO											
Cl											
CeO ₂											
Co_2O_3											
Cr_2O_3											
Cs ₂ O											
CuO											
Dy_2O_3											
Eu ₂ O ₃											
F											
Fe ₂ O ₃											
HgO											
K ₂ O											
La_2O_3											
Li ₂ O											

Waste Composition											
Туре	Α	Α	Α	A	A	Α	Α	Α	В	В	В
Sample Identification:	AP-101		AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	Actual LAW Envelope A AN-103 SRTC	Actual LAW Envelope B AZ-101 PNNL	Actual LAW Envelope B AZ-102 SRTC	Actual LAW Envelope B AZ-102 SRTC
MgO											
MnO ₂											
MoO ₃											
Na ₂ O											
Nd ₂ O ₃											
NiO											
P_2O_5											
PbO											
PdO											
Pr_6O_{11}											
PtO ₂											
Rh ₂ O ₃											
RuO ₂											
SO ₃											
Sb ₂ O ₅											
SeO ₂											
SiO ₂											
SnO ₂											
SrO											
Ta ₂ O ₅											
TeO ₂											
ThO ₂											
TiO ₂											
UO ₂											
V ₂ O ₃											
Y ₂ O ₃											
ZnO											
ZrO ₂											
Volatiles g/100g oxides											

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	B	B
Sample Identification:	AP-101		AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	AW-101— Actual	Actual LAW Envelope A AN-103 SRTC	Actual LAW Envelope B AZ-101 PNNL	Actual LAW Envelope B AZ-102 SRTC	Actual LAW Envelope B AZ-102 SRTC
CO ₃											
NO ₂											
NO ₃											
TOC											
Radioisotopes mCi/mL											
³ H	3.19E-03								3.24E-02		
¹⁴ C	4.71E-04								1.92E-03		
⁵¹ Cr	<7.0E-5								< 0.0004		
⁵⁴ Mn											
⁵⁹ Fe	<2.0E-5								< 0.00002		
⁵⁹ Ni											
⁶⁰ Co	2.05E-03								1.68E-05		
⁶³ Ni	2.07E-03										
⁷⁹ Se	9.00E-06								1.40E-04		
⁸⁸ Y	<1.0E-5								< 0.00001		
⁹⁰ Sr	5.38E-02								1.60E-01		
⁹⁰ Sr/ ⁹⁰ Y									9.87E-05		
^{95M} Tc											
⁹⁵ Nb	<8.0E-6										
⁹⁹ Tc	3.42E-04								9.33E-04		
¹⁰³ Ru	<8.0E-6								< 0.00005		
¹⁰⁶ Ru	6.00E-04								< 0.00007		
¹¹³ Sn	<1.0E-5								< 0.0003		
¹²⁵ Sb	1.26E-03								9.98E-03		
¹²⁶ Sn											
Sb\ ¹²⁶ Sn	2.20E-04								2.23E-03		

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW	Actual LAW		
								Envelope A	Envelope B	Actual LAW	Actual LAW
			AW-101	AW-101	AW-101—	AW-101—	AW-101—	AN-103	AZ-101	Envelope B	Envelope B
Sample Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	SRTC	PNNL	AZ-102 SRTC	AZ-102 SRTC
120-											
122											
¹³³ C											
¹³⁴ Cs	<9.0E-6								< 0.00002		
¹³⁵ Cs											
¹³⁷ Cs	8.00E-05								3.56E-02		
¹⁴⁴ Ce	<6.0E-5								< 0.0003		
¹⁵¹ Sm	7.79E-04								6.04E-05		
¹⁵² Eu	<2.0E-5								< 0.00002		
¹⁵⁴ Eu	5.22E-05								<000002		
¹⁵⁵ Eu	2.57E-05								< 0.0002		
²³¹ Pa											
²³² Th	<2.0E-5								< 0.00008		
²³⁵ U											
²³⁴ U											
²³⁵ U											
²³⁶ U											
²³⁸ U											
²³⁷ Np											
²³⁶ Pu	<4.0E-8								< 0.0000006		
²³⁸ Pu	2.40E-06								1.07E-06		
²³⁹ Pu	1.74E-05								9.25E-06		
²⁴⁰ Pu											
^{239/240} Pu											
²⁴¹ Pu	1.14E-04								< 0.0000002		
²⁴² Pu									5.24E-05		
241 Pu/ 241 Am											
²⁴¹ Am	1.01E-04								6.75E-07		
²⁴¹ Am, ²⁴³ Am											
²⁴² Am											

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW	Actual LAW		
								Envelope A	Envelope B	Actual LAW	Actual LAW
			AW-101—	AW-101—	AW-101—	AW-101—	AW-101—	AN-103	AZ-101	Envelope B	Envelope B
Sample Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	SRTC	PNNL	AZ-102 SRTC	AZ-102 SRTC
²⁴⁵ Am									< 0.000002		
²⁴² Cm	7.80E-08								< 0.00000005		
²⁴³ Cm											
²⁴⁴ Cm											
^{243/244} Cm	8.30E-07								< 0.0000001		
Sum of alpha (TRU) = S											
(²³⁸ Pu, ²³⁹ Pu, ²⁴⁰ Pu,											
²⁴¹ Am)											
Total alpha	7.51E-05										
Total beta											
Total gamma											
Total U (mg/mL)	1.09										
Organic analytes:											
Oxalate											
Citrate											
Formate											
Gluconate											
Glycolate											
EDTA											
(ethylenediaminetetraace											
tic acid)											
HEDTA (N-(2-											
hydroxyethyl)ethylenedia											
minetriacetic acid)											
D2EHPA (bis-(2-											
ethylhexyl)phosphate											
NTA (nitrilotriacetic											
acid)											
IDA (iminodiacetic acid)											

Waste Composition											
Туре	Α	Α	Α	Α	Α	Α	Α	Α	В	В	В
								Actual LAW	Actual LAW		
								Envelope A	Envelope B	Actual LAW	Actual LAW
			AW-101-	AW-101-	AW-101-	AW-101-	AW-101-	AN-103	AZ-101	Envelope B	Envelope B
Sample Identification:	AP-101		Actual	Actual	Actual	Actual	Actual	SRTC	PNNL	AZ-102 SRTC	AZ-102 SRTC
Succinic Acid											
ED3A											
(ethylenediaminetriaceti											
c acid)											
Analytes Obtained on an											
Opportunistic Basis:											

Table A.I.a. (Contu; Diank entries are intentional)

$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Waste Composition							
Sample Identification:PNNL - AN-107- ICP-ActualPNNL - AN-107- <th>Туре</th> <th>С</th> <th>С</th> <th>С</th> <th>С</th> <th>С</th> <th>С</th> <th>С</th>	Туре	С	С	С	С	С	С	С
Reference WTP-RPT-003 (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium ICL = Actual (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium ICL = Actual (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium WSRC-TR-2020- 00371, Table 2 "Average Column" WSRC-TR-2020- 00371, Table 2 "Average Column" WSRC-TR-2020- 00371, Table 2 "Average Column" WSRC-TR-2020- 00093, See Table 4.12, Sodium Sodium	Sample Identification:	PNNL - AN-107- ICP Actual	Actual LAW Envelope C AN-102	Actual LAW Envelope C AN-102				
Reference (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium (PNNL-13372) See Table 3.1 for 4.12 Molar Sodium (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium (PNNL-13372) See Table 3.1 for 4.12 Molar Sodium (PNNL-13372) See Table 3.2 for 4.12 Molar Sodium (PNNL-1372) See Table 3.2 for 4.12 Molar Sodium (PNNL-1372	Reference	WTP-RPT -003	ICI —Actual	ICI —Actual	ICI —Actual	ICI —Actual	WSRC-TR-2000-	WSRC-TR-2002-
Table 3.2 for 4.12 Molar Sodium Molar Sodium 4.12, Sodium 4.12, Sodium Sodium concentration of LAW Waste or Pretreated Waste: Molar Sodium A. an ethods. A. an ethods. Molar Sodium 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 PH of the Waste Malar Sodium 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 PH of the Waste Analyte (mg/L (LAW)): A. A. A. A. A. A. Ag A. A. A. A. A. A. A. A. All 7.68E+02 9.60E+02 1.12E+03 1.49E+03 1.86E+03 5.36E+03 8.39E+03 As	Kelerence	(PNNL-13372) See					00371 Table 2	00093 See Table
Molar Sodium Molar Sodium Molarity 7.24 is the average of ICP and AA methods. Sodium AA methods. AA methods. Sodium AA methods. AA methods. Canona 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 PH of the Waste Analyte (mg/L (LAW)): Analyte (mg/L (LAW)): Aage Aagee Aagee		Table 3.2 for 4.12					"Average Column"	4.12. Sodium
Sodium concentration of LAW Waste or Pretreated Waste: Molar Sodium A methods. 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 pH of the Waste		Molar Sodium						Molarity 7.24 is the
Sodium concentration of LAW Waste or Pretreated Waste: Molar Sodium AA methods. 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 PH of the Waste Analyte (mg/L (LAW)): Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Analyte (mg/L (LAW)): Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Analyte (mg/L (LAW)): Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Ag Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Ag Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Ag Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Ag Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste Ag Image: Constant of the Waste Image: Constant of the Waste Image: Constant of the Waste All 7.68E+02 9.60E+02 1.12E+03 1.49E+00 2.43E+00 1.34E+01 2.22E+								average of ICP and
Sodium concentration of LAW Waste or Pretreated Waste: Molar Sodium 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 PH of the Waste Analyte (mg/L (LAW)): 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 Cations								AA methods.
concentration of LAW Waste or Pretreated Waste; Molar Sodium second	Sodium							
LAW Waste or Pretreated Waste: Molar Sodium	concentration of							
Pretreated Waste: Molar Sodium 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 pH of the Waste Analyte (mg/L (LAW)): Image: Construction of the construction	LAW Waste or							
Molar Sodium 4.12E+00 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 pH of the Waste	Pretreated Waste:							
H of the Waste 5.15E+00 6.00E+00 8.00E+00 1.00E+01 4.90E+00 7.24E+00 Analyte (mg/L (LAW)): Image: Construct of the Waste Image: Construlite Im	Molar Sodium							
pH of the Waste Image: Construct on the second		4.12E+00	5.15E+00	6.00E+00	8.00E+00	1.00E+01	4.90E+00	7.24E+00
Analyte (mg/L (LAW)):	pH of the Waste							
CAW): Cations	Analyte (mg/L							
Cations Image: Constraint of the second	(LAW)):							
Ag								
Al 7.08E+02 9.00E+02 1.12E+03 1.49E+03 1.30E+03 3.30E+03 8.39E+03 As	Ag	7.69E+02	0.60E+02	1.12E+02	1.40E+02	1 96E+02	5 26E+02	9 20E + 02
AS Image: Constraint of the second secon		7.06E+02	9.00E+02	1.12E+05	1.49E+03	1.00E+05	J.30E+03	0.39E+03
B 1.002+00 1.202+00 1.002+	AS B	1.00F+00	1 25E+00	1.46E+00	1 94F+00	2.43E+00	1 34F+01	2 22E+01
Ba 1.33E102 1.33E102 2.12E102 2.03E102 0.23 Be Image: Second	B Ba	1.00E+00 1.09E+02	1.25E+00	1.40E+00	2.12E+02	2.45E+00	<0.25	2.22E+01
Bi Image: Constraint of the system of th	Be	1.071102	1.501102	1.571102	2.121+02	2.051102	<0.25	
Ca 8.86E+02 1.11E+03 1.29E+03 1.72E+03 2.15E+03 1.11E+02 1.76E+02 Cd 2.20E+01 2.75E+01 3.20E+01 4.27E+01 5.34E+01 1.99E+01 3.29E+01 Ce	Bi							
Cd 2.20E+01 2.75E+01 3.20E+01 4.27E+01 5.34E+01 1.99E+01 3.29E+01 Ce	Ca	8.86E+02	1.11E+03	1.29E+03	1.72E+03	2.15E+03	1.11E+02	1.76E+02
Ce	Cd	2.20E+01	2.75E+01	3.20E+01	4.27E+01	5.34E+01	1.99E+01	3.29E+01
	Ce							
	Cl							

 Table A.1.b. Waste Composition—Envelope C (blank entries are intentional)

Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRIC
Co	2.00E+00	2.50E+00	2.91E+00	3.88E+00	4.85E+00	1.56E+00	2.80E+00
Cr	6.00E+00	7.50E+00	8./4E+00	1.1/E+01	1.46E+01	7.03E+01	1.1/E+02
Cs	1.105.01	1.005.01	1.605.01	0.145-01		2 505 00	5 (05 00
Cu	1.10E+01	1.38E+01	1.60E+01	2.14E+01	2.6/E+01	3.58E+00	5.60E+00
Dy							
Eu							
F	2.005.00	2.755.00	4.075.00	5 02E 00	7.005.00	1.025.00	2.525.00
Fe	3.00E+00	3./5E+00	4.3/E+00	5.83E+00	7.28E+00	1.93E+00	3.53E+00
Hg	7.510.00	0.005.00	1.005.02	1.465.02	1.005.00		1.045.00
K	7.51E+02	9.39E+02	1.09E+03	1.46E+03	1.82E+03	.1.25	1.24E+03
La						<1.35	6.20E+00
Li						<0.27	1.045.01
Mg						<0.09	1.04E-01
Mn	1.200.01	1.625.01	1.005.01	2.525.01	2.175.01	7.98E-01	1.28E+00
Mo	1.30E+01	1.63E+01	1.89E+01	2.52E+01	3.16E+01	2.15E+01	3.4/E+01
Na	9.47E+04	1.18E+05	1.38E+05	1.84E+05	2.30E+05	1.12E+05	166484*
Nd	17(5.02	2.205.02	2.565.02	2.425.02	4.075.00	1.045.00	2.005.02
N1	1.76E+02	2.20E+02	2.56E+02	3.42E+02	4.2/E+02	1.24E+02	2.00E+02
P	4.30E+01	5.38E+01	6.26E+01	8.35E+01	1.04E+02	6.8/E+02	1.06E+03
Pb	2.20E+01	2.75E+01	3.20E+01	4.27E+01	5.34E+01	4.44E+01	7.96E+01
Pa							1.45E+00
Pr							
Pt D1							
K0 D1							4 295 00
Kn D							4.28E+00
KU							
<u>2</u>							
50							
2. 26						2.205.01	7.115.01
S1						3.39E+01	7.11E+01
Sn						1.10E+01	2.44E+01

 Table A.1.b (Contd; blank entries are intentional)

Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRTC
Sr	7.00E+00	8.75E+00	1.02E+01	1.36E+01	1.70E+01	1.26E+02	2.03E+02
Та							
Те							
Th							
Ti						< 0.358	
Tl							
U							
V						<0.61	5.82E-01
W							
Y							5.70E-01
Zn	4.00E+00	5.00E+00	5.83E+00	7.77E+00	9.71E+00	1.29E+00	1.91E+00
Zr						< 0.399	1.22E+00
Carbon Analyses							
TIC	2.07E+03	2.59E+03	3.01E+03	4.02E+03	5.02E+03		
TOC	1.31E+04	1.64E+04	1.91E+04	2.54E+04	3.18E+04		
Anions							
F	3.00E+03	3.75E+03	4.37E+03	5.83E+03	7.28E+03	7.66E+02	
Cl						1.57E+03	
Br							
NO_2	2.96E+04	3.69E+04	4.30E+04	5.74E+04	7.17E+04	3.62E+04	
NO ₃	1.73E+05	2.16E+05	2.52E+05	3.36E+05	4.20E+05	8.59E+04	
PO ₄						2.20E+03	
SO ₄	9.70E+02	1.21E+03	1.41E+03	1.88E+03	2.35E+03	5.47E+03	
C_2O_4						1.07E+03	
CO ₃							
CN							
NH ₃	7.00E+00	8.75E+00	1.02E+01	1.36E+01	1.70E+01		
Free OH	3.19E+05						
Total OH							

Table A.1.b	(Contd;	blank	entries	are	intentional	I)
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Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRTC
Oxide							
wt %							
Ag ₂ O							
Al ₂ O ₃							
As ₂ O ₃							
B_2O_3							
BaO							
BeO							
Bi ₂ O ₃							
CaO							
CdO							
Cl							
CeO ₂							
Co_2O_3							
Cr_2O_3							
Cs ₂ O							
CuO							
Dy_2O_3							
Eu ₂ O ₃							
F							
Fe ₂ O ₃							
HgO							
K ₂ O							
La_2O_3							
Li ₂ O							
MgO							
MnO ₂							
MoO ₃							
Na ₂ O							
Nd ₂ O ₃							
NiO							

Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRTC
P_2O_5							
PbO							
PdO							
Pr_6O_{11}							
PtO ₂							
Rh ₂ O ₃							
RuO ₂							
SO ₃							
Sb ₂ O ₅							
SeO ₂							
SiO ₂							
SnO ₂							
SrO							
Ta ₂ O ₅							
TeO ₂							
ThO ₂							
TiO ₂							
UO ₂							
V_2O_3							
Y_2O_3							
ZnO							
ZrO ₂							
Volatiles g/100g							
oxides							
CO ₃							
NO ₂							
NO ₃							
TOC							
Radioisotopes							
mCi/mL							
³ H							

Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRTC
¹⁴ C							
⁵¹ Cr							
⁵⁴ Mn							
⁵⁹ Fe							
⁵⁹ Ni							
⁶⁰ Co							
⁶³ Ni							
⁷⁹ Se							
⁸⁸ Y							
⁹⁰ Sr							
⁹⁰ Sr/ ⁹⁰ Y							
^{95M} Tc							
⁹⁵ Nb							
⁹⁹ Tc							
¹⁰³ Ru							
¹⁰⁶ Ru							
¹¹³ Sn							
¹²⁵ Sb							
¹²⁶ Sn							
Sb\ ¹²⁶ Sn							
¹²⁷ I							
¹²⁹ I							
¹³³ C							
¹³⁴ Cs							
¹³⁵ Cs							
¹³⁷ Cs							
¹⁴⁴ Ce							
¹⁵¹ Sm							
¹⁵² Eu							
¹⁵⁴ Eu							
¹⁵⁵ Eu							
²³¹ Pa							

Waste Composition							
Туре	С	С	С	С	С	С	С
						Actual LAW	Actual LAW
Sample	PNNL - AN-107-	Envelope C AN-102	Envelope C AN-102				
Identification:	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	ICP—Actual	SRTC	SRTC
²³² Th							
²³³ U							
²³⁴ U							
²³⁵ U							
²³⁶ U							
²³⁸ U							
²³⁷ Np							
²³⁶ Pu							
²³⁸ Pu							
²³⁹ Pu							
²⁴⁰ Pu							
^{239/240} Pu							
²⁴¹ Pu							
²⁴² Pu							
²⁴¹ Pu/ ²⁴¹ Am							
²⁴¹ Am							
²⁴¹ Am, ²⁴³ Am							
²⁴² Am							
²⁴³ Am							
²⁴² Cm							
²⁴³ Cm							
²⁴⁴ Cm							
^{243/244} Cm							
Sum of alpha (TRU)							
= S (²³⁸ Pu, ²³⁹ Pu,							
²⁴⁰ Pu, ²⁴¹ Am)							
Total alpha							
Total beta							
Total gamma							
Total U (mg/mL)							

Waste Composition	G	G	C	G	G	G	G
Туре	U	C	C	C	C	C	C
Samula	DNINI ANI 107	Actual LAW	Actual LAW				
Sample Identification:	ICD Actual	ICP Actual	ICP Actual	ICP Actual	ICP Actual	Envelope C AN-102	SPTC
Organic analytes:	ICI —Attual	ICI —Actual	ICI —Actual	ICI —Actual	ICI —Actual	SKIC	SKIC
Organie anarytes. Ovalate							
Citrata							
Eormate							
Gluconeto							
Glucolate							
EDIA (ethylenediaminetetr							
(euryieneurannineteu							
HEDTA (N (2							
hvdroxyethyl)ethylen							
ediaminetriacetic							
acid)							
D2FHPA (bis-(2-							
ethylhexyl)phosphate							
NTA (nitrilotriacetic							
acid)							
IDA (iminodiacetic							
acid)							
Succinic Acid							
ED3A							
(ethylenediaminetria							
cetic acid)							
,							*av. AA & ICP-AES
Analytes Obtained							
on an Opportunistic							
Basis:							
*							

Waste Type	Α	Α	Α	Α	В	С	С	С	С	С
Melter Feed Identification	AP-101	AW101	AW101	AW101 Actual	PNNL Actual AZ-	PNNL	PNNL	PNNL	PNNL	PNNL
	(VSL LAW-	Actual -	Actual -	- PNNL (VSL	101(B) - VSL -	(VSL	(VSL	(VSL	(VSL	(VSL
	A126)	PNNL (VSL	PNNL	LAWA88)	LAWB83	LAWC15)	LAWC15)	LAWC15)	LAWC15)	LAWC15)
		LAWA88)	(VSL			for AN107	for AN107	for AN107	for AN107	for AN107
			LAWA88)			Actual	Actual	Actual	Actual	Actual
Reference		BNFL-TP-2995	53-059 Rev 2,	See Attachment	VSL Notebook (if	BNFL-TP-2	9953-059 Re ⁻	v 2, See Attac	chment 4, M	ultiply the
		2, Multiply the	batching amo	ounts for 4.59	used): VSL-1052-02	batching am	ounts for 1.29	moles of so	dium by 4.1/1	1.29 =
		moles of sodiur	n by 6/4.59 =	1.307 to obtain	Batch Sheet calls for	3.1783 to ob	tain the amou	ints to be bat	ched in one li	ter of 4.1
		the amounts to	be batched in	one liter of 6	639 mL of pretreated	molar sodiur	n waste			
		molar sodium v	vaste		waste. Values given					
					below for GF amounts					
					have been normalized					
					to one liter.					
Pretreatment History (include:										
washing, leaching, chemical										
precipitation, mechanical										
agitation of any kind [time and										
intensity]):										
Sodium Concentration of LAW	6.00E+00	6.00E+00	8.00E+00	1.00E+01	4.31E+00	4.10E+00	5.00E+00	6.00E+00	8.00E+00	1.00E+01
Pretreated Waste, Na Molarity:										
Waste Oxide Loading of Glass	2.47E+01	2.62E+01	2.62E+01	2.62E+01	6.68E+00	2.14E+01	2.14E+01	2.14E+01	2.14E+01	2.14E+01
Product—Wt% Oxide										

 Table A.2. Melter Feed Preparation (blank entries are intentional)

	Waste Type		Α	Α	Α	Α	В	С	С	С	С	С
Melter	Feed Identificati	ion	AP-101	AW101	AW101	AW101	PNNL	PNNL (VSL				
			(VSL LAW-	Actual -	Actual -	Actual -	Actual AZ-	LAWC15)	LAWC15)	LAWC15)	LAWC15)	LAWC15)
			A126)	PNNL (VSL	PNNL (VSL	PNNL (VSL	101(B) - VSL	for AN107				
				LAWA88)	LAWA88)	LAWA88)	- LAWB83	Actual	Actual	Actual	Actual	Actual
Actual Mass A	dded (g) per Lite	er of Waste										
Source Chemical	Manufacturer	Oxide										
Kyanite	Kyanite Mining	Al_2O_3	5.67E+01	5.46E+01	7.27E+01	9.09E+01	2.44E+02	7.14E+01	8.70E+01	1.04E+02	1.39E+02	1.74E+02
	Corp											
Alumina A-2	Alcoa Alumina	Al ₂ O ₃										
Boric Acid	U.S. Borax	B_2O_3	1.39E+02	1.67E+02	2.23E+02	2.78E+02	4.43E+02	1.02E+02	1.25E+02	1.50E+02	2.00E+02	2.50E+02
Technical												
10M Borax	U.S. Borax	Na ₂ O/B ₂ O ₃										
Soda Ash	Solvay Minerals	Na ₂ CO ₃										
NaOH												
Wollastonite	NYCO	CaO	3.36E+01	4.24E+01	5.65E+01	7.07E+01	3.70E+02	2.44E+01	2.98E+01	3.58E+01	4.77E+01	5.96E+01
Fe ₂ O ₃ 5001	Prince Mfg. Co.	Fe ₂ O ₃	4.35E+01	4.88E+01	6.51E+01	8.14E+01	1.19E+02	4.16E+01	5.07E+01	6.09E+01	8.12E+01	1.01E+02
LiOH*H ₂ O												
LiBO ₂												
Li ₂ CO ₃	Chemettal-Foote	Li ₂ O					2.65E+02					
Olivine	Unimin Corp	MgO	2.46E+01	2.89E+01	3.85E+01	4.81E+01	1.50E+02	2.69E+01	3.28E+01	3.94E+01	5.25E+01	6.56E+01
	-											
SCS-75	U.S. Silica	SiO ₂	2.92E+02	3.44E+02	4.58E+02	5.73E+02	8.10E+02	2.21E+02	2.69E+02	3.23E+02	4.31E+02	5.39E+02
Rutile (Air floated)	Chemalloy Co.	TiO ₂	1.67E+01	1.87E+01	2.50E+01	3.12E+01	3.70E+01	1.34E+01	1.63E+01	1.95E+01	2.60E+01	3.26E+01
Kadox	Zinc Corp	ZnO	2.38E+01	2.77E+01	3.70E+01	4.62E+01	1.20E+02	1.91E+01	2.33E+01	2.79E+01	3.72E+01	4.65E+01
	Amer.											
Zircon	Amer. Miner.	ZrO ₂	3.60E+01	4.18E+01	5.57E+01	6.96E+01	1.19E+02	2.97E+01	3.62E+01	4.34E+01	5.79E+01	7.23E+01
	Inc.											
Sucrose	Amalgamated	Sugar		6.67E+01	8.89E+01	1.11E+02	4.63E+01	7.31E+01	8.91E+01	1.07E+02	1.43E+02	1.78E+02
	Sugar Co.											
				8.40E+02	1.12E+03	1.40E+03						

 Table A.2 (Contd; blank entries are intentional)

 Table A.2 (Contd; blank entries are intentional)

Waste Type	Α	A	A	А	В	С	С	С	С	С
Melter Feed Identification	AP-101	AW101	AW101	AW101	PNNL	PNNL	PNNL	PNNL	PNNL	PNNL
	(VSL	Actual -	Actual -	Actual -	Actual AZ-	(VSL	(VSL	(VSL	(VSL	(VSL
	LAW-	PNNL	PNNL	PNNL	101(B) -	LAWC15)	LAWC15)	LAWC15)	LAWC15)	LAWC15)
	A126)	(VSL	(VSL	(VSL	VSL -	for AN107				
		LAWA88)	LAWA88)	LAWA88)	LAWB83	Actual	Actual	Actual	Actual	Actual
Mixing Operation Data Processing Scale (lab/bench, pilot, or full):										
Activity/Property Order of Chemical Additions:										

			Wt %	
		Density –	total	
Waste		Bulk slurry	dried	
Туре	Sample Description	(g/mL)	solids	Comment
Α	AW-101 - Actual	1.23		
Α	AW-101 - Actual	1.31	33.4	WTP-RPT-002, Rev. 0, See Table 3.1 and page 6 of the test plan in Appendix B.
Α	AW-101 - Actual	1.37	42.1]
Α	AW-101 - Actual	1.44	50.3]
Α	AN-103 - Actual	1.22	28.4	WSRC-TR-2000-00322 ^a , See Table 3 last column.
Α	AN-103 - Actual - 5.3 molar	1.25	29.6	Densities estimated from observed correlation between sodium concentration for LAWs
	sodium			and density. See Figure B.1 this report. The weight percent dried solids was estimated
Α	AN-103 - Actual - 11.7 molar	1.53	53.9	from the observed correlation between density and weight percent dried solids. See
	sodium			Figure B.4 this report.
Α	AW101 Actual - PNNL (VSL	1.59	61.5	WTP-RPT-002, Rev. 0, See Table 3.1, The weight percent total solids numbers are
	LAWA88)			calculated by adding up the total solids in one liter of waste (see waste composition
Α	AW101 Actual - PNNL (VSL	1.8	68	section) and adding the total amount of glass formers (see Melter feed preparation
	LAWA88)			section) for one liter of LAW waste with the given sodium molarity. The total can be put
Α	AW101 Actual - PNNL (VSL	1.77	73.5	back on a per-liter basis by assuming that the melter feed density is an accurate measure
	LAWA88)			of the weight of one liter melter feed. The total weight of one liter of waste plus the
				weight of the glass formers is divided by the weight of one liter of melter feed. This
				number is divided into the sum of the total solids in one liter of LAW plus the total glass
				formers it give the total solids in one liter of the melter feed. Dividing this number by the
				weight of one liter of melter feed and multiplying by 100 gives the weight percent total
				solids in the melter feed.
В	Actual LAW Envelope B AZ-102	1.097	12.52	WSRC-TR-2001-00395, See Tables 2 and 5.
	2.21M SRTC			
В	Actual LAW Envelope B AZ-102	1.161	25]
	4.39M SRTC			
С	PNNL - AN-107- ICP - Actual			
a- Craw	ford CL, DM Ferrara, RF Schumache	r, and NE Bibler	r. 2001. C	Crucible-Scale Active Vitrification Testing Envelope A, Tank AN-103 (U), WSRC-TR-
2000-00	322, Westinghouse Savannah River (Company, Aiken	, SC.	

Table A.3. Density and Percent Total Solids (blank entries are intentional)

			Wt %	
		Density –	total	
Waste		Bulk slurry	dried	
Туре	Sample Description	(g/mL)	solids	Comment
С	PNNL - AN-107- ICP - Actual	1.207	25.3	WTP-RPT-002, Rev. 0 See Table 3.1 for 5, 6, 8, and 10 molar sodium. See Table 3.2 in
С	PNNL - AN-107- ICP - Actual	1.22		WTP-RPT-003, Rev. 0 for 4.12 molar sodium. Wt % solids for 4.12 molar sodium LAW
С	PNNL - AN-107- ICP - Actual	1.28	36.3	was calculated by dividing the mass of the solids in the LAW (319.2g see waste
С	PNNL - AN-107- ICP - Actual	1.37	45.3	composition section) by the density (1.207).
С	PNNL - AN-107- ICP - Actual	1.44	53.9	
	Actual LAW Envelope C AN-102 SRTC	1.46	48.6	Densities estimated from observed correlation between sodium concentration for LAWs and density. See Figure B.1 this report. The weight percent dried solids was estimated from the observed correlation between density and weight percent dried solids. See Figure B.4 this report.
С	Actual LAW Envelope C AN-102 SRTC	1.23	31.5	WSRC-TR-2000-00371, See Table 2, Average Column.
С	Actual LAW Envelope C AN-102 SRTC	1.29	40	WSRC-TR-2002-00093, See Table 4.9. Table 4.12 gives density and weight percent solids for the LAW at a higher concentration. See Table 4.42 and following for more viscosity data. See Table 6.5 for additional density and weight percent solids data
С	PNNL (VSL LAWC15) for AN107 Actual			WTP-RPT-002, Rev. 1, See Table 3.1, The weight percent total solids numbers are calculated by adding up the total solids in one liter of waste (see waste composition
С	PNNL (VSL LAWC15) for AN107 Actual			section) and adding the total amount of glass formers (see Melter feed preparation section) for one liter of LAW waste with the given sodium molarity. The total can be put
С	PNNL (VSL LAWC15) for AN107 Actual	1.61	61.56	back on a per-liter basis by assuming that the melter feed density is an accurate measure of the weight of one liter melter feed. The total weight of one liter of waste plus the
С	PNNL (VSL LAWC15) for AN107 Actual	1.71	69.88	weight of the glass formers is divided by the weight of one liter of melter feed. This number is divided into the sum of the total solids in one liter of LAW plus the total glass
С	PNNL (VSL LAWC15) for AN107 Actual	1.79	76.63	formers it give the total solids in one liter of the melter feed. Dividing this number by the weight of one liter of melter feed and multiplying by 100 gives the weight percent total solids in the melter feed.

 Table A.3 (Contd; blank entries are intentional)

Waste Type	Α	Α	Α	Α	Α	
					6 M Na AP-101	8 M Na AP-101
Sample Description	AP-101 - Actual	AP-101 - Actual	AP-101 - Actual	AP-101 - Actual	Melter Feed	Melter Feed
Reference	WTP-RPT-092	WTP-RPT-064	WTP-RPT-064	WTP-RPT-064	WTP-RPT-064	WTP-RPT-064
Physical Property						
Sodium concentration of LAW waste or	4.85	6	8	10	6	8
pretreated waste (Molar)						
Oxides loading of HLW sludge or						
pretreated sludge (total grams oxide/Liter)						
pH (aging 1day, 1week, 1mo)					12.3	12.5
Solid phases present						
Particle size distribution - Mean Vol.						
Distribution - (µm)						
Particle size distribution - Mean No.						
Distribution - (µm)						
Density – Bulk slurry (g/mL) (aging	1.258	1.325 @ 25°C,	1.399 @ 25°C,	1.461	1.645 @ 25°C,	1.742 @ 25°C,
1 day, 1 week, 1 mo)		1.293 @ 40°C	1.360 @ 40°C		1.587 @ 40°C	1.734 @ 40°C
Density – settled solids (g/mL)					1.95 @ 25°C,	1.97 @ 25°C,
					1.78 @ 40°C	1.81 @ 40°C
Density – centrifuged solids (g/mL)					2.11 @ 25°C,	2.11 @ 25°C,
					1.99 @ 40°C	2.04 @ 40°C
Density - supernatant liquid (g/mL)		1.33	1.4	1.45	1.34 @ 25°C,	1.39 @ 25°C,
					1.30 @ 40°C	1.38 @ 40°C
Vol. % settled solids after [48 hours] 72		3.8 @ 25°C,	9.9 @ 25°C,		49.9 @ 25°C,	59.7 @ 25°C,
hours (aging 1 day, 1 week, 1 mo)		2.3 @ 40°C	8.4 @ 40°C		60.1 @ 40°C	80.9 @ 40°C
Vol. % centrifuged solids		1.9	6.8		39.9 @ 25°C,	49.3 @ 25°C,
					41.4 @ 40°C	54.3 @ 40°C
Wt % total dried solids					58.0 @ 25°C,	65.3 @ 25°C,
					58.1 @ 40°C	65.2 @ 40°C
Wt % centrifuged solids					51.2 @ 25°C,	59.6 @ 25°C,
					52.1 @ 40°C	63.7 @ 40°C
Wt % oven dried solids	30.9	35.8	43	49		
Wt % undissolved solids			1.2 @ 25°C,	6.7	32.9 @ 25°C,	37.7 @ 25°C,
			0.81 @ 40°C		31.4 @ 40°C	36.0 @ 40°C
Wt % dissolved solids	30.9	35.8	42.4	45.3	37.3 @ 25°C,	44.1 @ 25°C,
					35.3 @ 40°C	44.8 @ 40°C
Waste % Oxides	17					
a- Crawford CL, DM Ferrara, RF Schumac	cher, and NE Bibler. 2	001. Crucible-Scale Ad	ctive Vitrification Testi	ng Envelope A, Tank A	N-103 (U), WSRC-TR	2-2000-00322,
Westinghouse Savannah River Company, A	Aiken, SC.					

Table A.4. Physical Property Data (blank entries are intentional)

Waste Type	A	A	Α	Α	Α	Α	Α	
	AW-101 -	AW-101 -	AW-101 -	AW-101 -	AN-103 -			
Sample Description	Actual	Actual	Actual	Actual	Actual	AN-103 - Actual	AN-103 - Actual	
Reference	WTP-RPT-00	02, Rev. 0, See	Table 3.1 and pa	age 6 of the	WSRC-	WSRC-TR-2000-00352, Densities estim	ated from observed correlation	
	test plan in Appendix B.				TR-2000-	between sodium concentration for LAWs and density. See Figure B.1 the		
					00322 ^a ,	report. The weight percent dried solids v	vas estimated from the observed	
					See Table	correlation between density and weight p	ercent dried solids. See Figure B.4	
					3 last	this report.		
		ŋ	T	r	column.		1	
Physical Property			-					
Sodium concentration of LAW waste or	4.59	6	8	10	4.94	5.3	11.7	
pretreated waste (Molar)								
Oxides loading of HLW sludge or pretreated								
sludge (total grams oxide/Liter)							-	
pH (aging 1day, 1week, 1mo)							-	
Solid phases present								
Particle size distribution - Mean Vol.								
Distribution - (µm)								
Particle size distribution - Mean No.								
Distribution - (µm)								
Density – Bulk slurry (g/mL) (aging 1day,	1.23	1.31	1.37	1.44	1.22	1.25	1.53	
lweek, lmo)							-	
Density – settled solids (g/mL)								
Density – centrifuged solids (g/mL)							-	
Density - supernatant liquid (g/mL)								
Vol. % settled solids after [48 hours] 72 hours								
(aging Iday, Iweek, Imo)								
Vol. % centrifuged solids		22.1	12.2		20.4	2 0 <i>c</i>		
Wt % total dried solids		33.1	42.3	50.2	28.4	29.6	53.9	
Wt % centrifuged solids								
Wt % oven dried solids							-	
Wt % undissolved solids								
Wt % dissolved solids							-	
Waste % Oxides								
a- Crawford CL, DM Ferrara, RF Schumacher,	and NE Bibler.	2001. Crucible	-Scale Active V	itrification Tes	sting Envelope	e A, Tank AN-103 (U), WSRC-TR-2000-0	0322, Westinghouse Savannah	
River Company, Aiken, SC.								

Table A.4 (Contd; blank entries are intentional)	
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Waste Type		Α	Α	Α			
	AP-101 Actual - PNNL	AW101 Actual - PNNL (VSL	AW101 Actual - PNNL (VSL	AW101 Actual - PNNL (VSL			
Sample Description	(VSL LAW-A126)	LAWA88)	LAWA88)	LAWA88)			
Reference		LAWA80 LAWA80 LAWA80 WTP-RPT-002, Rev. 0, See Table 3.1, The weight percent total solids numbers are calculated by adding up the total solids in one liter of waste (see waste composition section) and adding the total amount of glass formers (see Melter feed preparation section) for one liter of LAW waste with the given sodium molarity. The total can be put back on a per-liter basis by assuming that the melter feed density is an accurate measure of the weight of one liter melter feed. The total weight of one liter of waste plus the weight of the glass formers is divided by the weight of one liter of melter feed. This number is divided into the sum of the total solids in one liter of LAW plus the total glass formers it give the total solids in one liter of the melter feed. Dividing this number by the weight of one liter of melter feed and multiplying by 100 gives the weight percent total solids in the melter feed.					
Physical Property							
Sodium concentration of LAW waste or pretreated waste (Molar)		6	8	10			
Oxides loading of HLW sludge or pretreated							
sludge (total grams oxide/Liter)							
pH (aging 1day, 1week, 1mo)							
Solid phases present							
Particle size distribution - Mean Vol.							
Distribution - (µm)							
Particle size distribution - Mean No.							
Distribution - (µm)							
Density – Bulk slurry (g/mL) (aging 1day,		1.59	1.8	1.77			
lweek, 1mo)							
Density – settled solids (g/mL)							
Density – centrifuged solids (g/mL)							
Density - supernatant liquid (g/mL)							
Vol. % settled solids after [48 hours] 72							
Nours (aging Iday, Iweek, Imo)							
Vol. % centriluged solids	50.1	69.1	74.6				
Wt % total dried solids	59.1	08.1	/4.0				
Wt % centrifuged solids							
Wt % updissolved solids							
Wt % dissolved solids							
Weste 0/ Ovides							
waste 70 Oxides							
Table A.4	(Contd;	blank	entries	are	intentional)		
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Waste Type	В	В	В
Sample Description	Actual LAW Envelope B AZ-101 PNNL	Actual LAW Envelope B AZ-102 2.21M SRTC	Actual LAW Envelope B AZ-102 4.39M SRTC
Reference	Pretreated AZ-101 Envelope B Actual Waste	WSRC-TR-2001-00395, See Tables 2 and 5.	
	Sample (technetium ion exchange effluent) RPT- WTP-02-199		
Physical Property	10.2	4.87	6.02
Sodium concentration of LAW waste or pretreated			
waste (Molar)			
Oxides loading of HLW sludge or pretreated sludge			
(total grams oxide/Liter)			
pH (aging 1day, 1week, 1mo)			
Solid phases present			
Particle size distribution - Mean Vol. Distribution -			
(µm)			
Particle size distribution - Mean No. Distribution -	1.46	1.23	1.26
(µm)			
Density – Bulk slurry (g/mL) (aging 1day, 1week,			
1mo)			
Density – settled solids (g/mL)			
Density – centrifuged solids (g/mL)			
Density - supernatant liquid (g/mL)			
Vol. % settled solids after [48 hours] 72 hours (aging			
1day, 1week, 1mo)			
Vol. % centrifuged solids	48.6	31.5	40
Wt % total dried solids			
Wt % centrifuged solids			
Wt % oven dried solids			
Wt % undissolved solids			
Wt % dissolved solids			
Waste % Oxides			

Waste Type	С	С	С	С	С	С
	PNNL - AN-107- ICP	PNNL - AN-107- ICP	PNNL - AN-107- ICP	PNNL - AN-107- ICP	PNNL - AN-107- ICP	PNNL - AN-107- ICP
Sample Description	- Actual	- Actual	- Actual	- Actual	- Actual	- Actual
Reference	WTP-RPT-002, Rev. 0 \$	See Table 3.1 for 5, 6, 8, an	d 10 molar sodium. See Ta	ble 3.2 in WTP-RPT-003, I	Rev. 0 for 4.12 molar sodiu	m. Wt % solids for 4.12
	molar sodium LAW was	calculated by dividing the	mass of the solids in the LA	W (319.2g see waste comp	osition section) by the dens	ity (1.207).
Physical Property	4.1	5	6	8	10	
Sodium concentration of LAW waste						
or pretreated waste (Molar)						
Oxides loading of HLW sludge or						
pretreated sludge (total grams						
oxide/Liter)						
pH (aging 1day, 1week, 1mo)						
Solid phases present						
Particle size distribution - Mean Vol.						
Distribution - (µm)						
Particle size distribution - Mean No.		1.61	1.71	1.79		
Distribution - (µm)						
Density – Bulk slurry (g/mL) (aging						
1day, 1week, 1mo)						
Density – settled solids (g/mL)						
Density – centrifuged solids (g/mL)						
Density - supernatant liquid (g/mL)						
Vol. % settled solids after [48 hours]						
72 hours (aging 1day, 1week, 1mo)						
Vol. % centrifuged solids			61.56	69.88		
Wt % total dried solids						
Wt % centrifuged solids						
Wt % oven dried solids						
Wt % undissolved solids						
Wt % dissolved solids						
Waste % Oxides						

Table A.4	(Contd;	blank	entries	are intentional)
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Waste Type	Α	Α	Α	Α
Sample Description	AP-101 - Actual	AP-101 - Actual	AP-101 - Actual	AP-101 - Actual
Reference	WTP-RPT-092	WTP-RPT-064	WTP-RPT-064	WTP-RPT-064
Sodium Molarity	4.9	6	8	10
Flow Curve Summary Report:				
Steady State Shear				
Flow Curve (10-S) (cP) 20°C (aging 1 hr, 1 day, 1 week)				
Flow Curve (10 ^{-S}) (cP) 25°C (aging 1 hr, 1 day, 1 week)				
40°C				
Flow Curve (33 ^{-S}) ave. ascending -descending (cP) 25°C (aging				
1 hr, 1 day, 1 week)				
40°C				
50°C				
Flow Curve (100 ^{-S}) ave. ascending -descending (cP) 25°C				
40°C				
50°C				
Flow Curve (150 ^{-S}) ave. ascending -descending (cP) 25°C				
50°C				
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 20°C				
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 25°C				
40°C				
Flow Curve (300 ^{-S}) ave. ascending -descending (cP) 25°C				
40°C				
50°C				
Flow Curve (350 ^{-S}) ave. ascending -descending (cP) 25°C				
Flow Curve (500 ^{-S}) ave. ascending -descending (cP) 25°C				
50°C				
newtonian 25°C	3.5	5.2	8	11.8
40°C	2.5	3.6	5.4	7.2
50°C				
Yield Stress (Pa) - 25°C (aging 1 hr, 1 day, 1 week)				
Yield Stress (Pa) - 40°C				
Yield Stress (Pa) - 50°C				

Table A.5. Rheological Property Data (blank entries are intentional)

Waste Type	Α	Α	Α	Α	Α	Α
Sample Description	AP-101 Melter Feed	AP-101 Melter Feed	AW-101 - Actual	AW-101 - Actual	AW-101 - Actual	AW-101 - Actual
Reference	WTP-RPT-064	WTP-RPT-064	WTP-RPT-002, Rev. 1, See Table 3.3.			
Sodium Molarity	6	8				
Flow Curve Summary Report:						
Steady State Shear						
Flow Curve (10-S) (cP) 20°C (aging 1hr, 1day, 1week)						
Flow Curve (10 ^{-S}) (cP) 25°C (aging 1hr, 1day, 1week)						
40°C						
Flow Curve (33 ^{-S}) ave. ascending -descending (cP) 25°C (aging 1hr, 1day, 1week)				8	13	22
40°C						
50°C				6	7	14
Flow Curve (100 ^{-S}) ave. ascending -descending (cP) 25°C						
40°C						
50°C						
Flow Curve (150 ^{-S}) ave. ascending -descending (cP) 25°C						
50°C						
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 20°C						
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 25°C						
40°C						
Flow Curve (300 ^{-S}) ave. ascending -descending (cP) 25°C						
40°C						
50°C						
Flow Curve (350 ^{-S}) ave. ascending -descending (cP) 25°C						
Flow Curve (500 ^{-S}) ave. ascending -descending (cP) 25°C				8	12	21
50°C				4	6	12
newtonian 25°C	13.2	39.9				
40°C	9.7	27				
50°C						
Yield Stress (Pa) - 25°C (aging 1 hr, 1 day, 1 week)						
Yield Stress (Pa) - 40°C						
Yield Stress (Pa) - 50°C						

Table A.5 (Contd; blank entries are intentional)

Table A.5	(Contd;	blank	entries a	are i	ntentional)
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Waste Type	Α	Α	Α	Α	Α
		AP-101 Actual - PNNL	AW101 Actual - PNNL	AW101 Actual - PNNL	AW101 Actual - PNNL
Sample Description	AN-103 - Actual	(VSL LAW-A126)	(VSL LAWA88)	(VSL LAWA88)	(VSL LAWA88)
Reference	WSRC-TR-2000-00322 ^a	BNFL-RPT-034, Rev. 0,			
		See Table 3.5.			
Sodium Molarity					
Flow Curve Summary Report:					
Steady State Shear					
Flow Curve (10-S) (cP) 20°C (aging 1hr, 1day, 1week)					
Flow Curve (10 ^{-S}) (cP) 25°C (aging 1hr, 1day, 1week)					
40°C					
Flow Curve (33 ^{-S}) ave. ascending -descending (cP) 25°C			46	(59, 77, 76) 110	260
(aging 1hr, 1day, 1week)					
40°C					
50°C			26	60	160
Flow Curve (100 ^{-S}) ave. ascending -descending (cP) 25°C					
40°C					
50°C					
Flow Curve (150 ^{-S}) ave. ascending -descending (cP) 25°C					
50°C					
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 20°C					
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 25°C					
40°C					
Flow Curve (300 ^{-S}) ave. ascending -descending (cP) 25°C					
40°C					
50°C					
Flow Curve (350 ^{-S}) ave. ascending -descending (cP) 25°C				52, 67, 64	
Flow Curve (500 ^{-S}) ave. ascending -descending (cP) 25°C			36	88	230
50°C			16	46	130
newtonian 25°C					
40°C					
50°C					
Yield Stress (Pa) - 25°C (aging 1 hr, 1 day, 1 week)				(0, 0, 0) ND	ND
Yield Stress (Pa) - 40°C					
Yield Stress (Pa) - 50°C				ND	ND
a- Crawford CL, DM Ferrara, RF Schumacher, and NE Bible	r. 2001. Crucible-Scale Activ	ve Vitrification Testing Envel	ope A, Tank AN-103 (U), W	SRC-TR-2000-00322, Westi	nghouse Savannah River
Company, Aiken, SC.					

Waste Type	В	В	В	С	С	С	С	С
			Actual LAW	PNNL -	PNNL -	PNNL -	PNNL -	PNNL -
		Actual LAW	Envelope B	AN-107-	AN-107-	AN-107-	AN-107-	AN-107-
	Actual LAW Envelope B	Envelope B AZ-	AZ-102 4.1M	ICP -	ICP -	ICP -	ICP -	ICP -
Sample Description	AZ-101 PNNL	102 2.8M SRTC	SRTC	Actual	Actual	Actual	Actual	Actual
Reference	Pretreated AZ-101 Envelope	WSRC-TR-2000-0	0352, See Table		WTP-RPT-0	02, Rev. 1, Se	e Table 3.3.	
	B Actual Waste Sample	XXXXIII. Summa	ry of Rheology					
	(technetium ion exchange	Testing Results, W	/SRC-TR-2001-					
	effluent) RPT-WTP-02-199	00395, not ch	aracterized					
		rheologi	cally.		1	T	I	T
Sodium Molarity		2.8	4.1	4.12	5	6	8	10
Flow Curve Summary Report:								
Steady State Shear								
Flow Curve (10-S) (cP) 20°C (aging 1hr, 1day, 1week)								
Flow Curve (10 ^{-s}) (cP) 25°C (aging 1hr, 1day, 1week)								
40°C								
Flow Curve (33 ^{-s}) ave. ascending -descending (cP) 25°C						9	14	56
(aging 1hr, 1day, 1week)								
40°C								
50°C						6	10	14
Flow Curve (100 ^{-s}) ave. ascending -descending (cP) 25°C								
40°C								
50°C								
Flow Curve (150 ^{-S}) ave. ascending -descending (cP) 25°C								
50°C								
Flow Curve (200 ^{-s}) ave. ascending -descending (cP) 20°C								
Flow Curve (200 ^{-s}) ave. ascending -descending (cP) 25°C								
40°C								
Flow Curve (300 ^{-s}) ave. ascending -descending (cP) 25°C								
40°C								
50°C								
Flow Curve (350 ^{-s}) ave. ascending -descending (cP) 25°C								
Flow Curve (500 ^{-S}) ave. ascending -descending (cP) 25°C						8	13	21
50°C						4	8	11
newtonian 25°C								
40°C								
50°C								
Yield Stress (Pa) - 25°C (aging 1 hr, 1 day, 1 week)								
Yield Stress (Pa) - 40°C								
Yield Stress (Pa) - 50°C								

Table A.5 (Contd; blank entries are intentional)

Table A.5 (Contd; blank entries are intentional)

Waste Type	С	С	С	С	С	С	С	С
	Actual LAW	Actual LAW	Actual LAW	PNNL (VSL	PNNL (VSL	PNNL (VSL	PNNL (VSL	PNNL (VSL
	Envelope C AN-102	Envelope C AN-	Envelope C AN-	LAWC15) for	LAWC15) for	LAWC15) for	LAWC15) for	LAWC15) for
Sample Description	SRTC	102 SRTC	102 SRTC	AN107 Actual	AN107 Actual	AN107 Actual	AN107 Actual	AN107 Actual
Reference	WSRC-TR-2000-00	352, See Table XXX	XIV. (not entered)		WTP-RP	T-002, Rev. 1, See T	able 3.5.	
Sodium Molarity								
Flow Curve Summary Report:	Ĩ							
Steady State Shear								
Flow Curve (10-S) (cP) 20°C (aging 1hr, 1day, 1week)								
Flow Curve (10 ^{-S}) (cP) 25°C (aging 1hr, 1day, 1week)								
40°C								
Flow Curve (33 ^{-S}) ave. ascending -descending (cP) 25°C					46	855, 1140, 1050	4800	
(aging 1hr, 1day, 1week)								
40°C								
50°C					27	510	5700	
Flow Curve (100 ^{-S}) ave. ascending -descending (cP) 25°C								
40°C								
50°C								
Flow Curve (150 ^{-S}) ave. ascending -descending (cP) 25°C								
50°C								
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 20°C								
Flow Curve (200 ^{-S}) ave. ascending -descending (cP) 25°C								
40°C								
Flow Curve (300 ^{-S}) ave. ascending -descending (cP) 25°C								
40°C								
50°C								
Flow Curve (350 ^{-S}) ave. ascending -descending (cP) 25°C						280, 540, 440		
Flow Curve (500 ^{-S}) ave. ascending -descending (cP) 25°C					44	360	1100	
50°C					15	175	1000	
newtonian 25°C								
40°C								
50°C								
Yield Stress (Pa) - 25°C (aging 1 hr, 1 day, 1 week)					ND	15, 10, 15	180	
Yield Stress (Pa) - 40°C								
Yield Stress (Pa) - 50°C					ND	12	160	

	AP-101 4.9 M Na	AP-101 4.9 M Na	AP-101 6 M Na	AP-101 6 M Na	AP-101 8 M Na
	Pretreated Waste				
	Rheology Data at				
Sample ID	25°C	40°C	25°C	40°C	25°C
Model/Model Parameter					
Shear Strength (by Vane Method):					
Shear Strength (Pa)	n/a	n/a	n/a	n/a	n/a
Newtonian:					
h – Newtonian viscosity (cP)	3.4	2.5	5.1	3.5	8.1
R^2 – correlation coefficient	0.9932	0.9978	0.8442	0.9569	0.9359
Ostwald (or Power Law):					
m – the consistency coefficient (cP)	6.1	3.2	27.7	11	25
n – the power law exponent	0.9129	0.9621	0.7432	0.8266	0.8291
R^2 – correlation coefficient	0.997	0.9986	0.8894	0.975	0.953
Bingham Plastic:					
the Bingham yield stress (Pa)	0.09669	0.03	0.622	0.2235	0.654
h _p – the plastic viscosity (cP)	3.3	2.5	4.2	3.2	7.2
R^2 – linear correlation coefficient	0.9958	0.9982	0.9034	0.9712	0.96
Herschel-Bulkley:					
the yield stress (cP)	0	0	0.643	0.008968	0.7452
k - the Herschel-Bulkely consistency coefficient (cP)	6.1	3.2	3.8	10.66	5.4
b - the Hershel-Bulkely power law exponent	0.9129	0.9621	1.015	0.8312	1.04
R^2 – correlation coefficient	0.997	0.9986	0.9034	0.975	0.9602

Table A.6. Rheological Model Parameters (blank entries are intentional)

	AP-101 8 M Na	AP-101 10 M Na	AP-101 10 M Na	AP-101 6 M Na	AP-101 6 M Na
	Pretreated Waste	Pretreated Waste	Pretreated Waste	Melter Feed	Melter Feed
	Rheology Data at				
Sample ID	40°C	25°C	40°C	25°C	40°C
Model/Model Parameter					
Shear Strength (by Vane Method):					
Shear Strength (Pa)	n/a	n/a	n/a	n/a	790
Newtonian:					
h – Newtonian viscosity (cP)	5.3	12.2	7.5	12.4	9
R^2 – correlation coefficient	0.9837	0.6959	0.016	0.9986	0.9918
Ostwald (or Power Law):					
m – the consistency coefficient (cP)	10.4	78.6	568	16.9	3.7
n – the power law exponent	0.8976	0.7161	0.3361	0.953	1.134
R^2 – correlation coefficient	0.9892	0.7436	0.1122	0.9996	0.998
Bingham Plastic:					
the Bingham yield stress (Pa)	0.1821	1.177	2.394	0.235	0
h _p – the plastic viscosity (cP)	5	10.44	3.9	12.1	9
R^2 – linear correlation coefficient	0.9876	0.7235	0.119	0.9996	0.9918
Herschel-Bulkley:					
the yield stress (cP)	0	0	2.583	0.1603	0.34
k - the Herschel-Bulkely consistency coefficient (cP)	10.4	78.6	1.2	13.7	1.7
b - the Hershel-Bulkely power law exponent	0.8976	0.7161	1.171	0.9816	1.241
R^2 – correlation coefficient	0.9892	0.7436	0.1191	0.9998	0.9994

Table A.6	(Contd;	blank	entries	are	intention	al)
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			AP-101 8 M Na Melter	AP-101 8 M Na Melter	AP-101 8 M Na Melter
	AP-101 8 M Na	AP-101 8 M Na	Feed Rheology Data at	Feed Rheology Data at	Feed Rheology Data at
	Melter Feed	Melter Feed	25°C one hour after	40°C one hour after	25°C one day after
	Rheology Data at	Rheology Data at	Glass Former	Glass Former	Glass Former Chemical
Sample ID	25°C	40°C	Chemical Addition	Chemical Addition	Addition
Model/Model Parameter					
Shear Strength (by Vane Method):					
Shear Strength (Pa)	n/a	79	n/a	n/a	n/a
Newtonian:					
h – Newtonian viscosity (cP)	39.4	25.9	23.7	19	30
R^2 – correlation coefficient	0.9954	0.993	0.9982	0.9984	0.999
Ostwald (or Power Law):					
m – the consistency coefficient (cP)	21	54	18	16.6	31.7
n – the power law exponent	1.096	0.8883	1.042	1.021	0.9916
\mathbf{R}^2 – correlation coefficient	0.999	0.9998	0.999	0.9986	0.999
Bingham Plastic:					
the Bingham yield stress (Pa)	0	1.003	0	0.02001	0.255
h _p – the plastic viscosity (cP)	39.4	24.4	23.7	19	29.6
\mathbf{R}^2 – linear correlation coefficient	0.9954	0.998	0.9982	0.9984	0.9992
Herschel-Bulkley:					
the yield stress (cP)	0.9813	0	0.4566	0.5572	0.6848
k - the Herschel-Bulkely consistency	13.1	54	12.8	9.81	21.4
coefficient (cP)					
b - the Hershel-Bulkely power law	1.161	0.8883	1.09	1.094	1.046
exponent					
\mathbf{R}^2 – correlation coefficient	0.9994	0.9998	0.9992	0.9994	0.9994

 Table A.6 (Contd; blank entries are intentional)

				AP-101 8 M Na Melter	AP-101 8 M Na Melter
	AP-101 8 M Na Melter	AP-101 8 M Na Melter	AP-101 8 M Na Melter	Feed Settled Solids	Feed Settled Solids
	Feed Rheology Data at	Feed Rheology Data at	Feed Rheology Data at	Rheology Data at 25°C	Rheology Data at 40°C
	40°C one day after	25°C one week after	40°C one week after	one week after Glass	one week after Glass
	Glass Former	Glass Former	Glass Former	Former Chemical	Former Chemical
Sample ID	Chemical Addition	Chemical Addition	Chemical Addition	Addition	Addition
Model/Model Parameter					
Shear Strength (by Vane Method):					
Shear Strength (Pa)	n/a	n/a	n/a	2624	609
Newtonian:					
h – Newtonian viscosity (cP)	20.8	29.2	28.3	246.6	179
R^2 – correlation coefficient	0.9934	0.996	0.992	0.9305	0.9894
Ostwald (or Power Law):					
m – the consistency coefficient (cP)	42.6	15.7	16	1367	329.2
n – the power law exponent	0.8907	1.095	1.087	0.7391	0.9074
R^2 – correlation coefficient	0.9998	0.9994	0.995	0.9801	0.994
Bingham Plastic:					
the Bingham yield stress (Pa)	0.7562	0	0	26.4	7.569
h _p – the plastic viscosity (cP)	19.7	29.2	28.3	207.3	167.7
R^2 – linear correlation coefficient	0.9978	0.996	0.992	0.9771	0.9954
Herschel-Bulkley:					
the yield stress (cP)	0	0.6235	0.7993	11.31	8.104
k - the Herschel-Bulkely consistency	42.6	10.5	9.4	742.1	156.7
coefficient (cP)					
b - the Hershel-Bulkely power law	0.8907	1.15	1.16	0.8216	1.01
exponent					
R^2 – correlation coefficient	0.9998	0.9998	0.9956	0.9813	0.9954

 Table A.6 (Contd; blank entries are intentional)

Appendix B

Physical-Property Correlations

Bulk Density as a Function of Sodium Molarity

As shown in Figure B.1, there is a good correlation observed between the LAW solution density and the sodium concentration for both actual and simulated wastes.



Figure B.1. Actual and Simulated LAW Solution Densities as a Function of Sodium Molarity. These values were measured by PNNL, SRTC, and VSL and indicate a good inter-laboratory correlation for these measurements.

Settling-Rate Characteristics of LAW and HLW Melter Feeds and HLW Pretreated Waste Sludge

The settling of suspended solids in pretreated waste sludge and in melter feed slurries is significant because it relates directly to the ease of maintaining a homogenous slurry during processing. Homogeneity is a compliance criterion because the quality control of the glass product is directly affected by the degree of homogeneity during processing. The historical settling-rate information discussed in this section relates to the height of the supernate/settled solids interface as a function of time. This interface represents the slow-settling portion of the slurry and is directly related to particle-size distribution, particle-density distribution, particle shape, slurry aging, temperature, size of the measurement container, degree of flocculation, etc. A comparison of these data across multiple laboratories with different measurement techniques will vary these parameters and be difficult.

LAW Melter Feeds

In Figure B.2, the volume percent of the initial volume occupied by the suspended solids is plotted as a function of the mass of suspended solids for each LAW melter-feed slurry. The values plotted in the figure are averages of values from slurries aged from a few days to an entire month. The settling period in each case is more than 2 days. The total suspended solids loading was chosen as a plotting parameter because the suspended solids should consist of nearly all glass-former additives. These slurries include a range of compositions for LAW Envelopes A, B, and C, and the data points are grouped based on the grain size of the glass-former minerals added to prepare the melter feed or if the glass-former elements were added as oxides. Each group of data points was fitted using a linear fit. It appears that little settling occurs at suspended-solids loadings above ~800 g/L (a hindered settling state). These data suggest that the melter feeds prepared with fine and medium-coarse grain glass formers settle faster and to a greater extent than those prepared from the simulants containing clay additives.



LAW Melter Feed Settled Volume After 48 Hours

Fine Grained Minerals (Mesh 325 to 200) = "Fine" or "F" Medium to Coarse Grained Minerals (Mesh 120 and below) = "Medium" or "M" Oxides (Generally Mesh 325 to 200) = "Oxides" or "O" Clay as the Alumina Source = "Clay" or "C"

Figure B.2. LAW Melter Feed Settling Characteristics

HLW Pretreated Waste Sludge and Melter Feeds

In Figure B.3, the volume percent of the initial volume occupied by the suspended solids of HLW sludge and melter feeds is plotted as a function of bulk density. The dissolved solids concentration of these streams is low. Hence, it is expected that the density will be proportional to the suspended solids loading and will relate to the settling data in a similar way as the previous section. The HLW pretreated sludge and melter feeds show decreasing amounts of settling as the amount of suspended solids, i.e., bulk density, increases. It is observed that adding glass-former minerals appears to increase the settling behavior. This is most likely due to the addition of large/dense particles from glass formers. As a result, the melter feeds show similar settling behavior to the HLW pretreated sludges, only shifted to a higher density.



Figure B.3. HLW Sludge and HLW Melter Feed Settling Characteristic

Correlation of Bulk Density to Weight Percent Solids and Oxide Loading

Figures B.4 through B.5 indicate that the bulk density of pretreated wastes and melter feeds correlate well with concentration parameters such as weight percent total solids or the total gram oxides per liter. Figure B.3 shows the relationship between bulk density and both weight percent total solids and the related total gram oxides per liter recalculated as weight-percent oxides. The percentage difference between these values is the amount of material that volatizes at high temperatures.



Wt% Solids and Wt% Oxides vs Bulk Density

Figure B.4. Weight Percent Total Solids and Weight Percent Oxides as a Function of Bulk Density for Pretreated LAW, HLW Sludge, and LAW and HLW Melter Feed

Figures B.5 and B.6 indicate that the bulk density correlates system by system with the percent total solids and the related total gram oxides per liter recalculated as weight percent oxides, all in a similar way.



Weight % Solids vs Bulk Density for Both High and Low Activity Wastes and Melter Feeds and their Simulants

Figure B.5. Observed Weight Percent Total Solids as a Function of Bulk Density for LAW, HLW Sludge, and LAW and HLW Melter Feed

Weight % Oxides vs Bulk Density for Both High and Low Activity Wastes and Melter Feeds and their Simulants



Figure B.6. Observed Weight Percent Oxides as a Function of Bulk Density for LAW, HLW Sludge, and LAW and HLW Melter Feed

Appendix C

Rheological Comparison of LAW Pretreated Wastes and Associated Melter Feeds Figure C.1 compares the flow-curve behavior of the actual Hanford LAW from Tank AW-101 and AN-103 with a simulated Tank AN-105 LAW. As is observed at equal sodium concentrations, the actual waste (AW-101) displays a Newtonian viscosity about twice that of the simulated LAW (AN 105). The reasons for this difference are not clear from the compositions or physical-property data in Appendix A. On the other hand, AN-103 appears to be rheologically similar to the AN-105 simulant. Differences in overall chemical species present could explain the observed difference. For instance, the data relating to organic chemicals present is scarce and could account for rheological differences.



Shear Stress Versus Shear Rate for Envelope A LAW Concentrated Pretreated Waste

Figure C.1. Shear Stress Versus Shear Rate Plots for both Simulated and Actual Pretreated Envelope A LAW Wastes

Figures C.2 and C.3 compare the rheology of Envelope A LAW melter feeds showing the effects of feed concentration, aging, temperature, grain size of glass formers added, and types of glass formers added. In general, one observes that viscosity increases with concentration and finer grain-sized materials. Viscosity generally decreases with increasing temperature, coarser grain-sized additives, age, and decreasing concentration.



Envelope A Melter Feed (SRTC) - LAWA44 GLASS for LAW AN-105 Simulant

Shear Rate (1/s)

Figure C.2. SRTC Aging Data for a LAW AN-105 Containing Melter Feed at 8 and 10 M Sodium Concentration



Flow Curves For Envelope A (AW-101/AN-107) Melter Feeds

Figure C.3. VSL Data for 25°C Aging of 6, 8, and 10 M Sodium Envelope A (AW-101/AN-105) Melter Feeds Prepared with Fine Grained Additives

Envelope B LAW and B LAW Melter Feed

The Envelope B LAW and simulated melter feed data are shown in Figures C.4 and C.5. Note the high apparent viscosities for the VSL simulants.



Figure C.4. Shear Stress Versus Shear Rate Plots for Actual Pretreated Envelope B LAW Wastes (AZ-102)



Figure C.5. VSL Data for 25°C 3, 4, and 5 M Sodium Melter Feed Prepared with Fine-Grained Additives

Envelope C LAW and C LAW Melter Feed

Figure C.6 compares the rheology of the actual and simulated AN-107 at several different concentrations based again on Na molarity and at 25°C. Actual AN-102 measured by SRTC is also included in the figure. The fact that the compositions of the actual and the simulant for AN-107 do not match exactly may account for the difference in apparent rheology. This is probably because the actual composition is based on analytical data of the actual sample measured, and the simulant composition was batched on the basis of analytical data for earlier analyses of Tank 241-AN-107 LAW. Also, the sodium concentrations match exactly only at a molarity of six, but the actual molarity of 8 should be close to the average of the simulant molarities at 7.5 and 8.5. At all comparable concentrations, the actual LAW has about twice the viscosity of the simulant. Again, there is some ambiguity because of differences in the actual and simulated LAW Envelope C composition.



Shear Stress Versus Shear Rate for Envelope C LAW Waste AN-107 and AN-102 - Actual and Simulated

Figure C.6. Shear Stress Versus Shear Rate for Two Actual Envelope C LAW Wastes AN-107 and AN-102

Figure C.7 compares the rheology of the simulated AN-107 melter feed at a sodium molarity of 7.5 and 8.5 at 25°C as a function of aging for 30 days. There is considerably more aging observed with the higher concentration feed (8.5 M sodium) than at 7.5 M sodium. Note that the viscosities of these simulated feeds were observed to peak during the aging period. The high and low values are plotted in the figure with the high values measured at 22 days for the 7.5 M sodium concentration and at 15 days for the 8.5 M sodium concentration.



Envelope C Melter Feed Flow Curves - SRTC

Figure C.7. SRTC Envelope C Simulated Melter Feed (AN-107) at Sodium Molarities of 7.5 and 8.5 as a Function of Slurry Aging

Figure C.8 presents Envelope C melter-feed data, this time based on AN-102 pretreated LAW. Notice the significant range of rheological properties for the Envelope C melter feeds (AN-102), 500-mL batches prepared with fine-grained additives by different technicians. These data almost span the entire range of data plotted in the figure. This is an indication of the sensitivity of the rheological properties to the make– up history of the slurry and is a strong argument for the use of a well-defined procedure used to make up slurries when the properties are to be compared. It indicates that any flowsheet used to make-up a slurry and condition it as it progresses to the next processing step can have a significant influence on its rheological nature.



VSL Envelope C LAW Melter Feed Flow Curves

Figure C.8. VSL Data for 25°C Envelope C Melter Feeds (AN-102)

Envelope D HLW and D HLW Melter Feed

Figure C.9 compares the actual and simulants of the AZ-102 HLW sludge at an insoluble solids loading of about 15 wt%. Note that the total solids in a pretreated HLW sludge are almost totally insoluble because the waste sludge is produced from the raw waste by a washing process that removes almost all of the soluble chemical compounds, so it can be said with reasonable confidence that a sludge with 15 wt% suspended solids is about 85 wt% water. The principle observation to be made is that the waste simulant made by the hydroxide precipitation method (SRTC) has rheological properties closer to the actual HLW AZ-102 than that made by just mixing the appropriate hydroxide chemicals (VSL).

AZ-102 Pretreated Sludge Flow Curves - Actual and Simulated



Figure C.9. Rheology of Simulated and Actual AZ-102 HLW Sludge

Figure C.10 compares the rheology of the actual and simulated AZ-102 melter feeds. The relationships are similar to those shown in Figure C.9 with the feed made with the "hydroxide precipitation and wash method" sludge simulant having a higher viscosity than the melter feed made with actual HLW sludge. Note that this relationship between the actual and simulated waste materials was reported by Morrey Tingey, and Elliott (1996). The melter feed made with the "hydroxide precipitation and wash method" simulant is slightly more concentrated than the feed made with actual HLW sludge (67 wt% water vs 69 wt% water). Again the "mixing the appropriate hydroxide chemicals method" for producing a simulant resulted in a simulated melter-feed system with a significantly lower viscosity for the same water concentration.



AZ-102 Pretreated Sludge and HLW Melter Feed Flow Curves

Figure C.10. The Addition of Glass Formers to the AZ-102 Actual Waste is Observed to Lower the Viscosity of the Slurry by more than a Factor of Two

Figures C.11 and C.12 summarize the effects of temperature and water concentration on the viscous behavior of C-104 actual sludge and melter feed. Note the considerable increase in viscosity when glass-former additives are added to C-104 pretreated sludge.



C-104 Actual Pretreated Waste Flow Curves

Figure C.11. C-104 HLW Pretreated Sludge Rheology



Figure C.12. Flow curves for C-104 HLW Pretreated Sludge and Melter Feed

Figure C.13 provides an overall summary plot of the observed viscosities of the HLW sludges and melter feeds for AZ-102 and C-104.



Figure C.13. Rheograms of HLW Envelope D Actual and Simulated Sludge and Melter Feed

References

Morrey EV, JM Tingey, and ML Elliott. 1996. *Comparison of Simulants to Actual Neutralized Current Acid Waste: Process and Product Testing of Three NCAW Core Samples from Tanks 101-AZ and 102-AZ*, PNNL-11025, Pacific Northwest National Laboratory, Richland, WA.

Appendix D

Quality Level Summary

This Section identifies the Quality Assurance levels applied to reviews and reports prepared for the Waste Treatment Plant (WTP) based on completion of Research and Technology activities that were performed under British Nuclear Fuels Limited (BNFL), CH2M Hill Hanford Group (CHG) and Bechtel National, Inc. (BNI) since 2000.

The various Quality Assurance Program Plans had different requirements under the different contractors. These differences should be programmatic in nature and should not impact data quality. However, an evaluation to determine the nature of these differences is outside the scope of this document.
Reference	Quality Information Stated			
	QA requirements as directed by test specification TS-W375LV-TE00001 states, "The contractor shall have a			
	quality system based on recognized standards, QA requirements, and guidelines in the context of commercial and			
WTP-RPT-002, Rev. 1 (Bredt	DOE and EPA practices such as ASME NQA-1, 10CFR830.120, and ASQC-Q9001.			
and Swoboda 2000)				
Rheological Studies on	QA requirements as directed by contract DE-AC06-96RL13308 states, "The Contractor shall implement a Quality			
Pretreated Feed and Melter	Assurance program for the immobilized low-activity waste form development, qualification, characterization, and			
Feed from AW-101 and	certification. The QA program shall be based upon a nationally recognized standard consistent with the			
AN-107	Contractor's responsibility for producing a product that meets the requirements of the ILAW specification. The QA			
	Plan shall address the quality assurance/quality control requirements addressed in SW-846 and WAC-173-303-			
	806."			
	No test specification identified.			
WSRC-TR-2000-00298				
(Hansen and Calloway 2000)	QA requirements as directed by contract DE-AC06-96RL13308 states, "The Contractor shall implement a Quality			
Characterization of Simulant	Assurance program for the immobilized low-activity waste form development, qualification, characterization, and			
LAW Envelope A, B, and C	certification. The QA program shall be based upon a nationally recognized standard consistent with the			
with Glass Formers	Contractor's responsibility for producing a product that meets the requirements of the ILAW specification. The QA			
	Plan shall address the quality assurance/quality control requirements addressed in SW-846 and WAC-173-303-806.			
Crawford CL, DM Ferrara, RF				
Schumacher, and NE Bibler.				
2001. Crucible-Scale Active				
Vitrification Testing Envelope	0.4 requirements were applied in accordance with Contract DE-AC27-96BI 11308			
A, Tank AN-103 (U), WSRC-	QA requirements were appred in accordance with Contract DE-AC27-90KE11508.			
TR-2000-00322,				
Westinghouse Savannah River				
Company, Aiken, SC.				

Table D.1. Review of Physical and Rheological Measurements on Hanford LAW PretreatedWaste and Corresponding Melter Feeds Supporting Documents Quality-Assurance Level

Reference	Quality Information Stated
WSRC-TR-2000-00338 (Eibling and Nash 2001) Hanford Waste Simulants Created to Support the Research and Development of the River Protection Project	The formulation and testing of Hanford waste simulants to support development of the RPP-WTP was conducted in accordance with the quality assurance requirements of 10CFR830.120 as implemented in the Savannah River Site quality assurance plan (BNF-003-98-0008).
WSRC-TR-2000-00352 (Rosencrance et al. 2000) Physical Characterization for Hanford Tank Waste Samples AN-102, AN-103, and AZ-102	No test specification identified. QA requirements as directed by contract DE-AC06-96RL13308 states, "The Contractor shall implement a Quality Assurance program for the immobilized low-activity waste form development, qualification, characterization, and certification. The QA program shall be based upon a nationally recognized standard consistent with the Contractor's responsibility for producing a product that meets the requirements of the ILAW specification. The QA Plan shall address the quality assurance/quality control requirements addressed in SW-846 and WAC-173- 303-806.
WSRC-TR-2000-00371 (Crawford et al. 2001) Crucible-scale Active Vitrification Testing Envelope C, Tank 241-AN-102	QA requirements were applied in accordance with Contract DE-AC27-96RL11308.
WSRC-TR-2000-00395 Interim Report for Crucible- scale Active Vitrification Testing Envelope B (AZ-102)	QA requirements were applied in accordance with Contract DE-AC27-96RL11308.

 Table D.1 (Contd)

References

Bredt PR, and RG Swoboda. 2000. *Rheological Studies on Pretreated Feed and Melter Feed From AW-101 and AN-107*, PNWD-3034 (WTP-RPT-002, Rev. 1), Revision 0, Battelle—Pacific Northwest Division, Richland, WA.

Crawford CL, DM Ferrara, RF Schumacher, and NE Bibler. 2001. Crucible-Scale Active Vitrification Testing Envelope C, Tank AN-102 (U), WSRC-TR-2000-00371, Westinghouse Savannah River Company, Aiken, SC.

Eibling RE, and C Nash. 2001. *Hanford Waste Simulants Created to Support the Research and Development on the River Protection Project – Waste Treatment Plant,* WSRC-TR-2000-00338, Westinghouse Savannah River Company, Aiken, SC.

Hansen EK, and TB Calloway. 2000. *Characterization of Simulant LAW Envelope A, B, and C with Glass Formers,* WSRC-TR-2000-00298, Rev. 0, Westinghouse Savannah River Company, Aiken, SC.

Rosencrance SW, WD King, and C Nash. 2000. *Physical Characterization for Hanford Tank Waste Samples AN-102, AN-103, and AZ-102.* WSRC-TR-2000-00352, Westinghouse Savannah River Company, Aiken, SC.

Appendix E

Rheology Primer^(a)

⁽a) Much of the information in this Appendix was derived from JF Steffe. 1996. *Rheological Methods in Food Process Engineering*, 2nd Edition. Freeman Press. An online version of this book can be downloaded from <u>http://www.egr.msu.edu/~steffe/freebook/offer.html</u>

Rheology is the study of the flow of matter. When a force (i.e., stress) is placed on an object, the object deforms or strains. Many relationships have been found relating stress to strain for various fluids. The flow behavior of a fluid can generally be explained by considering a fluid placed between two plates of thickness x (see Figure E.1). The lower plate is held stationary while a force, F, is applied to the upper plate of area, A, that results in the plating moving at velocity, v. If the plate moves a length, ΔL , the strain, γ , on the fluid can be defined by Equation E.1.

$$\gamma = \frac{\Delta L}{x}$$
(E.1)
Force, F Area, A Shear stress, $\tau = \frac{F}{A}$ (Pa)
shear rate, $D = -\frac{v}{x}$ (s⁻¹)
viscosity, $\eta = \frac{\tau}{D}$ (Pa.s)

Figure E.1. Diagram of Fluid Flow between Stationary and Moving Plates

The rate of change of strain (also called shear rate), $\dot{\gamma}$, can be defined by Equation E.2. Since the shear rate is defined as the ratio of a velocity to a length, the units of the variable are the inverse of time, typically s⁻¹.

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d}{dt} \left(\frac{\Delta L}{x}\right) = \frac{v}{x}$$
(E.2)

Typical shear rates of food-processing applications can be seen in Table E.1. Depending on the application, shear rates in the range of 10^{-6} to 10^7 s⁻¹ are possible.

Situation	Shear Rate Range (1/s)	Typical Applications
Sedimentation of Particles in a Suspending Liquid	$10^{-6} - 10^{-3}$	Medicines, paints, spices in salad dressing
Leveling due to surface tension	$10^{-2} - 10^{-1}$	Frosting, Paints, printing inks
Draining under gravity	$10^{-1} - 10^{1}$	Vats, small food containers
Extrusion	$10^{0} - 10^{3}$	Snack and pet foods, toothpaste, cereals, pasta, polymers
Calendering	$10^1 - 10^2$	Dough sheeting
Pouring from a Bottle	$10^1 - 10^2$	Foods, cosmetics, toiletries
Chewing and Swallowing	$10^1 - 10^2$	Foods
Dip Coating	$10^1 - 10^2$	Paints, confectionery
Mixing and Stirring	$10^1 - 10^3$	Food processing
Pipe Flow	$10^0 - 10^3$	Food processing, blood flow
Rubbing	$10^2 - 10^4$	Topical application of creams and lotions
Brushing	$10^3 - 10^4$	Brush painting, lipstick, nail polish
Spraying	$10^3 - 10^5$	Spray drying, spray painting, fuel atomization
High speed coating	$10^4 - 10^6$	Paper
Lubrication	$10^3 - 10^7$	Bearings, gasoline engines

Table E.1. Typical Shear Rates in Food Processing Applications

The shear stress applied to the fluid can be found by Equation E.3. Since the shear stress is defined as the ratio of a force to an area, the units of the variable are pressures, typically Pa (N/m^2) .

$$\tau = \frac{F}{A} \tag{E.3}$$

The apparent viscosity of the fluid is defined as the ratio of the shear stress to shear rate (see Equation E.4). Since the viscosity is defined as the ratio of shear stress to shear rate, the units of the variable are Pa•s. Typically, viscosity is reported in units of centipoise (cP) where 1 cP = 1 mPa•s.

$$\eta(\dot{\gamma}) = \frac{\tau(\dot{\gamma})}{\dot{\gamma}} \tag{E.4}$$

For Newtonian fluids, the apparent viscosity is independent of shear rate (see Equation E.5). Examples of the viscosity of common Newtonian materials can be seen in Table E.2.

$$\tau = \eta \dot{\gamma} \tag{E.5}$$

where τ is the shear stress, η is the Newtonian viscosity, and $\dot{\gamma}$ is the shear rate.

Material	Viscosity at 20°C (mPa•s)		
Acetone	0.32		
Water	1.0		
Ethanol	1.2		
Mercury	1.6		
Ethylene Glycol	20		
Corn Oil	71		
Glycerin	1,500		

Table E.2.	Viscosities of Several Common
	Newtonian Fluids

Fluids that do not behave as Newtonian fluids are referred to as non-Newtonian fluids. Rheograms or plots of shear stress versus shear rate are typically used to characterize non-Newtonian fluids. Examples of typical rheograms can be seen in Figure E.2.



Shear Rate

Figure E.2. Rheograms of Various Fluid Types

Shear-thinning and shear-thickening fluids can be modeled by the Ostwald equation (see Equation E.6). If n < 1, then the material is referred to as pseudoplastic (shear thinning). If n > 1, that material is referred to as dilatant (shear thickening). These fluids exhibit decreasing or increasing

apparent viscosities as the shear rate increases, depending on whether the fluid is shear thinning or shear thickening, respectively. Since shear-thickening flow behavior is rare, shear-thickening behavior is often an indication of possible secondary flow patterns or other measurement errors.

$$\tau = m\dot{\gamma}^n \tag{E.6}$$

where *m* is the power law consistency coefficient, *n* is the power law exponent, and $\dot{\gamma}$ is the shear rate.

A Bingham plastic rheogram does not necessarily pass through the origin. When a rheogram has a non-zero y-intercept, that fluid is said to posses a yield stress. A yield stress is a shear stress threshold that defines the boundary between solid-like behavior and fluid-like behavior. The fluid will not begin to flow until the yield stress threshold is exceeded. For Bingham plastic materials, once enough force has been applied to exceed the yield stress, the material approaches Newtonian behavior at high shear rates (see Equation E.7). Since Bingham plastic behavior is used throughout this document, a Bingham plastic model was fit to rheological data for many common types of materials (see Table E.3). Note that many of these materials would not typically be classified as Bingham plastic materials. The purpose of the Bingham plastic would fits is to provide the reader with a relative understanding of the magnitude of Bingham plastic values used in this document to common materials. Human perception is typically based on a shear rate of approximately 60 s^{-1} .

$$\tau = \tau_O^B + \eta_P \gamma \tag{E.7}$$

where τ_0^B is the Bingham yield stress, η_p is the plastic viscosity (consistency), and γ is the shear rate.

		Yield Stress	
Material	Consistency (mPa•s)	(Pa)	\mathbf{R}^2
Squeeze Margarine	49	11	0.80
Ketchup	190	38	0.81
Whipped Desert Topping	190	45	0.80
Tub Margarine	320	125	0.77
Mustard	400	50	0.84
Mayonnaise	610	130	0.80
Whipped Butter	660	350	0.75
Stick Butter	690	240	0.77
Stick Margarine	860	350	0.77
Whipped Cream Cheese	910	480	0.75
Peanut Butter	1,200	570	0.75
Apple Butter	1,600	300	0.82
Canned Frosting	1,900	450	0.79
Honey	15,000	5.3	1.00
Marshmallow Cream	23,000	1,200	0.92

Table E.3. Bingham Plastic Model Fit to Various Common Materials

Fluids that exhibit a non-linear rheogram with a yield stress are modeled by the three-parameter Herschel-Bulkley equation (see Equation E.8). Again, shear-thickening behavior is uncommon, and typically, the Hershel-Bulkley power-law exponent is less than unity.

$$\tau = \tau_O^H + k\gamma^b \tag{E.8}$$

where

 τ_{O}^{H} = yield stress

k = Herschel-Bulkley consistency coefficient

- b = Hershel-Bulkley power law exponent
- γ = shear rate.

Many methods have been developed to evaluate yield stress. These methods produce varying results based on the rheological technique and assumptions used in the evaluation. To explain these variations, the concept of static and dynamic yield stress is introduced. The idea behind static and dynamic yield stress can be explained by assuming that there are two structures present in yield stress exhibiting fluids. One structure is insensitive to shear rate and defines the dynamic yield stress associated with a flow curve. However, a second weak structure is also present that forms while the fluid is at rest. The second structure is sensitive to shear rate, and breaks down as the fluid is sheared. Combined, these two stresses define the static yield stress value (see Figure E.3).



Figure E.3. Rheogram Illustrating the Concept of Dynamic and Static Yield Stress

The use of the static and dynamic yield-stress values varies with application. For instance, the dynamic yield-stress value extrapolated from a rheogram should be used when performing pipeline head-loss calculations. The static yield stress should be used for process restart applications where the second structure could form while the fluid is at rest.

A common method of measuring the static shear strength of a fluid is with a device called a shear vane. A WTP procedure for measuring the static yield stress of a fluid was provided in 24590-WTP-GPG-RTD-001 Rev 0. The WTP-adopted WTP convention is to refer to the static yield stress as "shear strength." The dynamic yield stress is often referred to as "yield stress" or "yield index."

Since shear-strength values are discussed throughout this document, values of shear strength for common food items as measured by the vane method are given in Table E.4. Note that yield-stress values are given in Table E.3. This table should provide a reference point for the magnitude of shear-strength and yield-stress values discussed in this document.

Material	Shear Strength (Pa)		
Baby food, peaches	22.9	\pm	3.4
Spaghetti sauce, Brand B	24.8	±	3.4
Spaghetti sauce, Brand A	26.3	±	4.5
Tomato puree, Brand B	30.0	±	4.2
Baby food, pears	31.8	±	5.0
Tomato puree, Brand A	34.4	±	3.7
Tomato ketchup, Brand B	43.2	±	3.4
Apple sauce, Brand B	48.2	±	4.7
Tomato ketchup, Brand A	51.3	±	5.0
Baby food, carrots	64.0	±	4.0
Apple sauce, Brand A	77.3	±	0.0
Mustard, Brand A	82.5	±	5.3
Mustard, Brand B	103.8	±	5.0
Mayonnaise, Brand B	163.8	<u>+</u>	4.2
Mayonnaise, Brand A	204.4	±	5.0

Table E.4. Shear Strength of Various Common Materials

Appendix F

Particle-Size Data

Particle size is a significant factor in the processing of the WTP vitrification streams considered in this document. The pretreated LAW stream is expected to be solids free (i.e., less than 2 wt% undissolved solids as specified in the WTP contract). The LAW melter feed stream is expected to contain a significant quantity of undissolved solids. Consequently, this stream is the focus of this section.

The maximum particle size of the insoluble glass-former chemicals is expected to be in the 74 μ m to 177- μ m range (see Table 4.1). Because the pretreated LAW is expected to be solids free, the maximum particle size of the LAW melter feed stream is expected to be dominated by glass-former chemicals. The particle size of actual AP-101 LAW melter feed (Bredt et al. 2003) is shown in Figure F.2. These data indicate particles sizes in the 2 μ m to 40 μ m range. No particles in the 74- μ m to 177- μ m range were observed. A possible explanation for the lack of larger particles includes dissolution of the glass-former chemicals in the highly caustic pretreated LAW. Another possible explanation is the precipitation of undissolved solids from the pretreated LAW due to boric acid addition, which could bias the particle-size distribution to smaller sizes. The particle-size distribution of the AP-101 glass-former chemical mix (LAWA-126) in deionized water is also shown in Figure F.2. This particle-size distribution shows particles in the 74 μ m to 120 μ m range and illustrates that particles of this size are possible in the LAW and HLW melter-feed streams.

References

PR Bredt, BW Arey, EC Buck, ED Jenson, BK McNamara, AP Poloski, and RG Swoboda. 2003. *Rheological and Physical Properties of AP-101 Pretreated LAW and Melter Feed*, WTP-RPT-064, Rev.0, Battelle—Pacific Northwest Division, Richland, WA.



Figure F.1. Particle-Size Distribution of Actual HLW Pretreated Sludge Streams



Figure F.2. Particle-Size Distribution of Actual AP-101 Melter Feed and Glass Former Chemical Mix

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