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Evaluation of A-105 Waste Properties and Potential Simulants for Confined Sluicing Testing

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Executive Summary

The alternative retrieval process of confined sluicing is currently being evaluated for retrieving waste from tank A-105 at the Hanford Site, which is a single-shell tank that previously leaked due to a tear in the tank liner. This report summarizes the key waste properties for defining performance-based simulants for evaluating confined sluicing and evaluates existing information on A-105 waste to define preliminary estimates for the likely ranges of these key waste properties. Previously developed simulants are assessed, in comparison to A-105 waste, to determine if they are suitable for representing A-105 behavior in planned testing of confined sluicing and/or if new simulants need to be developed.

The key operations for a confined sluicing system, and thus the challenges that need to be represented by simulants, are waste erosion by water jets (mobilization), capture of the liquid and waste slurry (typically by a localized vacuum including the potential for plugging inlet screen), and conveyance both vertically and horizontally to a point of collection. The key waste properties are the erosion rate from liquid jets (shear and/or tensile strength have been used historically as an alternate waste property that represents the difficulty to erode and represents a bound for applied stress) and the size and density of the eroded particles and aggregates (that might plug inlet screens or challenge transport). In addition, for conveyance testing, both cohesive and non-cohesive simulants are needed to represent the different behaviors of materials that form accumulations as a mode of plugging.

There is only limited information on A-105 waste, and the current assessment agrees with a recent evaluation that waste is probably best described as hardpan/dried sludge. Previous estimates have given shear strength values ranging from 50,000 to 1,700,000 Pa for hardpan. A new analysis estimates that regions of the A-105 waste may be as strong as 1,100,000 Pa, based on the A-105 waste only allowing a core sampler with a weight of 600 lb to penetrate 1.5 inches into a hard layer during a 1968 core sampling event at one location. The A-105 waste was sprayed with acid after the core sampling event, to soften this hard layer, but it is likely that some of this hard layer was not effectively softened and remains in A-105. It is also anticipated that some of the A-105 waste could be typical wet sludge (a few thousand Pa) or typical hardpan (on the order of 100,000 Pa). There are no data to estimate the erosion rate of A-105 waste with a water jet and no data to estimate the size range of eroded particles and agglomerates. Recent waste retrieval operations in C-105 with the Mobile Arm Retrieval System – Vacuum (MARS-V) found that large aggregates of waste would collect and plug the inlet screen to the vacuum capture system, but there is no information to determine if A-105 will have similar aggregates in eroded waste.

Previous simulants have been evaluated, in the context of representing A-105, for use in quantifying the key performance operations for a confined sluicing system. The previous simulants generally span the expected range of strength for hardpan/dried sludge, but there is no information on the erosion rate of the simulants and A-105 waste for this key waste property for confined sluicing. For the planned Phase I (initial) testing of erosion and capture performance of confined sluicing, one or more existing simulants are suitable. These simulants, however, do not fully represent all expected challenges, and new simulants that target these challenges will need to be developed for more thorough system performance testing if Phase I effectiveness testing proves promising.

For the planned Phase I effectiveness testing of confined sluicing with an emphasis on eroding and capturing simulated waste (and neglecting the challenge from aggregates that may plug the inlet screen), we recommend using any of the following existing simulants (shown from least to most challenging for erosion):

- Wet sludge: ~3,500 Pa, kaolin/water
- Hardpan/Dried sludge: ~150,000 Pa, kaolin/plaster of Paris/water
- Hardpan/Dried sludge for A-105 hard crust estimate of 1,100,000 Pa:
  ~15,000,000 Pa K-Mag/water is a hard saltcake simulant that should be bounding for this target.

If Phase I effectiveness testing proves promising, two new simulants should be considered for the next phase of testing to represent key waste properties for A-105 that are not adequately covered by simulants developed in previous simulant studies. The first is a heterogeneous hardpan/dried sludge simulant that gives the screen-plugging challenge of eroded waste including aggregates, which are capable of being further eroded into smaller aggregates but that may remain as chunks depending on the confined sluicing performance. The second new simulant is a hardpan/dried sludge material to represent the 1,100,000 Pa estimate of shear strength for the hard crust in A-105. This would eliminate using K-Mag, which is a hard saltcake simulant that exceeds this strength by about a factor of 10, as a bounding alternate material. Finally, although not a new type or simulant target, materials need to be defined to represent appropriate debris (e.g., rocks, pebbles, tapes).

Acronyms and Abbreviations

ART	Alternate Retrieval Technology
ASTM	American Society for Testing and Materials
BBI	Best-Basis Inventory
CSEE	confined sluicing end effector
K-Mag	potassium magnesium sulfate
MARS	Mobile Arm Retrieval System
MARS-S	Mobile Arm Retrieval System – Sluicing
MARS-V	Mobile Arm Retrieval System – Vacuum
SEM	scanning electron microscopy
SST	single-shell tank
WREE	waste retrieval end effector

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1.0 Introduction

Recent planning efforts for retrieval of radioactive waste from underground single-shell tanks (SSTs) at the Hanford Site have included evaluating confined sluicing as alternate retrieval technology for SSTs that are known to have previously leaked (Wooley 2016; Hatchell et al. 2016). Retrieval of waste from tank 241-A-105 (A-105), which has a large tear and bulge in the tank bottom (Disselkamp 2009; Laurenz 2016), is the initial focus for retrieval using confined sluicing. The Alternate Retrieval Technology (ART) A-105 Program at Washington River Protection Solutions (Wooley 2016) has been created to conduct the needed technology maturation and eventual deployment of a confined sluicing system, should this technology be selected.

Hatchell et al. (2016) describe confined sluicing, in the context of waste retrieval, as a method that uses medium-pressure water jets (~ 5000 to 10,000 psi) together with a closely coupled waste removal system (vacuum). The water jets are smaller and use ten-fold less water flow (2 to 4 gpm) than jets used for conventional sluicing, and the effective range for these jets is only a few inches. An initial evaluation of the use of confined sluicing to retrieve waste from A-105 is provided by Hatchell et al. (2016). Hatchell et al. (2016) also summarized the history of physical simulant development at Hanford for waste retrieval testing and further recommended the use of performance-based simulants where the simulants are tailored to give representative performance for the key phenomena associated with the use of confined sluicing.

The purpose of this report is to define key waste properties for evaluating the performance of confined sluicing systems and then to evaluate what is known about A-105 waste properties for these key waste properties. This evaluation is then combined with what is known about previously developed simulants to determine if existing simulant formulations are suitable for planned testing of a confined sluicing system and/or if new simulants need to be developed. The ART program has four phases (see Section 1.1 below); simulants will be needed for the first three phases, and the suitability of existing and new simulants needs to be considered for all of these phases of the planned testing.

This report is organized as follows. Section 1.1 summarizes the four phases of the ART program, Section 1.2 describes the confined sluicing process, Section 1.3 discusses the key challenges for this process, and Section 1.4 discusses the key physical properties for testing confined sluicing. Section 2.0 summarizes the waste chemistry and estimated ranges for key physical properties for A-105 waste. Section 3.0 summarizes previously developed and characterized simulants and discusses what simulants have been tested with conditions and geometries that are representative of water jets and confined sluicing systems. Finally, Section 4.0 combines this information and evaluates existing and new simulants for their suitability for testing confined sluicing as an alternate retrieval technology for A-105.

1.1 Alternate Retrieval Technology A-105 Program

The overall objective of the ART program is to identify, develop, and deploy alternate retrieval technologies at the Hanford Site tank farms (Wooley 2016). For underground waste tanks that are known or suspected leakers, the current planning baseline assumes deploying the Mobile Arm Retrieval System – Vacuum (MARS-V) (Wooley 2016, Burke et al. 2012). One goal of the ART program is to mature technologies that can minimize both the quantity of liquid used in the retrieval process and the quantity of residual liquid remaining in a tank following retrieval. The ART program has four technology maturation phases, summarized below, and simulants will be needed for the first three phases.

- Phase I: ART End Effector Development – Select the most promising end effector for confined sluicing to meet goals of reduced liquid usage and retrieval performance, select suitable simulants for

Phase I testing, fabricate the selected end effector, and conduct testing to quantify the effectiveness of the selected ART end effector.

- Phase II: ART Integrated System Development – Test an integrated system that includes supporting equipment necessary to convey collected simulated waste from the end effector out of a tank and then transfer it to a selected destination; identify and develop systems to position the end effector, including the ability to avoid expected obstructions in A-105; and demonstrate the effectiveness of the integrated ART system.
- Phase III: Full-Scale ART System Cold Testing – Demonstrate effectiveness of a complete integrated ART system at full-scale with simulants.
- Phase IV: ART System Retrieval Project Deployment – Deploy and demonstrate ART system in A-105 for retrieving remaining waste.

1.2 Confined Sluicing Process

The confined sluicing process, as generally described and defined in Hatchell et al. (2016), involves three components: (1) water jets to erode and dislodge the waste, (2) a capture system for collecting liquid and waste particles (typically a vacuum from a fluid-drive jet eductor/jet pump with a coarse screen on the inlet), and (3) a conveyance system to transport the captured waste slurry both vertically and horizontally. The confined sluicing end effector (CSEE) has the additional attribute of using multiple water jets that are oriented to direct the eroded waste particles and liquid towards the inlet of the capture system (DOE/EM 1998). Figure 1.1 shows a general schematic of an overall system. Figure 1.2 shows the confined sluicing system deployed in tank W-3 at the Oak Ridge Reservation (DOE/EM 1998).

The erosion process occurs is when the hydraulic force from the water jet dislodges individual waste particles or larger aggregates or chunks. With the CSEE, three jets are positioned around the circumference of an inlet port and tend to collide (DOE/EM 1998), which may cause further erosion of the aggregates or chunks and also directs the water and waste slurry to the inlet screen. The key waste properties for this process are discussed in Section 1.4.1.

The capture process involves the vacuum system pulling the liquid slurry with waste particles/aggregates/chunks through the inlet screen and into the suction line. A liquid jet eductor was used previously with the CSEE at Oak Ridge (DOE/EM 1998), and a similar system was used with the MARS-V for creating a vacuum to capture waste (Burke et al. 2012). For eductor applications in Hanford tanks, the screen is typically a 3/8-inch mesh (Hatchell et al. 2016). The key waste properties for this process are discussed in Section 1.4.2.

The conveyance process involves the transport of the waste slurry with liquid and entrained air that were captured at the inlet to the vacuum capture system and then pumped with pressure provided by the jet eductor to a collection tank. The key waste properties for this process are discussed in Section 1.4.2.

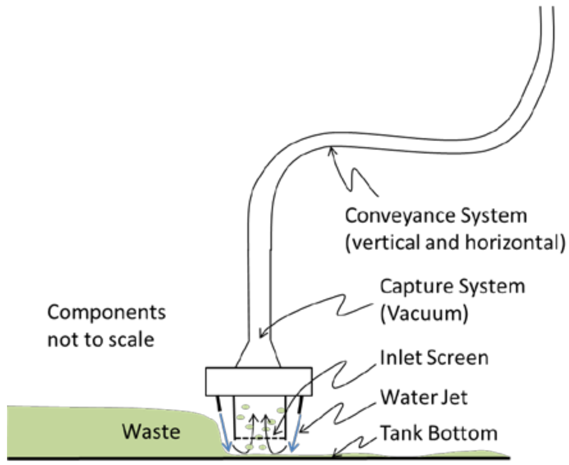

Figure 1.1. Conceptual Components of a Confined Sluicing End Effector Retrieval System

Figure 1.2. Confined Sluicing System Deployed in Tank W-3 at Oak Ridge Reservation (reproduced from Figure 4 of DOE/EM 1998)

1.3 Previous Retrievals at Hanford with Similar Systems

The Mobile Arm Retrieval System (MARS) has been developed for retrieving wastes from SSTs at Hanford. The MARS – Sluicing (MARS-S) system uses a small sluicing jet to mobilize and direct waste to a centrally located retrieval pump, and the MARS-V system uses a fluid-eductor to create a vacuum at a suction location that is near the liquid jets used to mobilize waste (Burke et al. 2012). The MARS-V system includes a conveyance system for transferring captured waste slurry to a receiver tank. One of the challenges for the MARS-V system when it was deployed for retrieval in C-105 was that hard agglomerates of dislodged waste would frequently plug the vacuum screen (Hendrickson 2015). This type of behavior should be represented in simulants used to test the performance of waste capture and conveyance with confined sluicing.

1.4 Key Physical Properties

American Society for Testing and Materials (ASTM) Method C1750-11 provides general considerations for the development, verification, validation, and documentation of high-level waste tank simulants. As described by that standard, the first step should be to determine what the simulant is to be used for, whereby the key processing properties required for development of the simulant are determined. Simulant use is defined here by the retrieval process described in Section 1.2, which in general includes sediment mobilization or erosion with the fluid jets, entrainment of mobilized aggregates into the transfer system via vacuum collection, and conveyance or transport of the entrained aggregates in the transfer system. While the waste chemistry provides the fundamental basis of the waste's physical properties, the retrieval system processes are dominated by the physical/rheological characteristics of the waste. Therefore, key physical properties of a simulant for these processes are briefly described here.

Other parameters of interest are not considered, such as material adhesion to process equipment, which would affect equipment decontamination for example, or abrasive wear, which could negatively influence the equipment. Particle shape, which can influence all aspects of the system, is also not addressed, given the paucity of actual waste information.

As the ART program makes progress on developing and evaluating all the components of an integrated system, this evaluation of key physical properties (and subsequent selection of suitable simulants) should be updated as needed.

1.4.1 Sediment Erosion

The rate of sediment mobilization or erosion can be described by the applied stress, in this case resulting from a fluid jet, required to overcome the sediment's resistance to erosion. The word erosion is used here to describe the mobilization of sediment material, not erosion of system components.

A discussion of erosion mechanisms is provided in Wells et al. (2009). Within the literature, the breakup or disassociation of particulate materials is discussed in terms of material failure, mobilization, and erosion. Material failure is the initiation of relative movement of the particulate, such as deformation, fracture, shearing, and initial particle/material separation (removal). Mobilization is the rearranging of the spatial order of the bulk material beyond that of the initial failure. Erosion is the combination of both material failure and removal of the material. Material detachment via erosion can be in the form of individual particles, flocs, or larger masses, the whole of which are described as aggregates in this report.

Wells et al. (2009) summarized erosion mechanisms as follows:

- For non-cohesive materials (typically large particles, > 75 μm, where mechanical interaction such as packing, interlocking, and size variation provides the majority of the material bed strength), the key parameters for assessing the erodibility via fluid jets are particle size, particle density, liquid density, and liquid viscosity. These parameters will allow the use of Shields' diagram (e.g., Vanoni 1975; Julien 1998) or a related tool to determine the critical shear stress, the applied shear stress for which greater values result in the onset of erosion at a certain rate, for the initiation of particle movement.
- For cohesive materials (typically particle sizes < 75 μm, and for which resistance to erosion depends on the strength of the cohesive forces binding the particles, which may far outweigh the influence of the physical characteristics of the individual particles), the fluid jet density and viscosity are again key, and for the sediment material yield stress in shear (shear strength) provides an upper bound for the applied shear stress necessary to initiate materials erosion and is associated with a maximum erosion rate. A material's critical shear stress for surface erosion provides a lower bound for the

applied shear stress required to initiate erosion at a minimum rate. Higher applied stress values are required for a range of erosion rates, and critical shear stress values can be defined for each rate. Correlations exist for predicting the critical shear stress of cohesive materials from the bulk density, plasticity index, and combination of yield stress and plasticity index. However, there do not appear to be tools for predicting sediment erosion without obtaining data for similar or related types of material, and caution should be taken in applying a model outside of the specific study area used to develop the model.

A key point from the discussion in Wells et al. (2009) for the erosion of cohesive materials is that although the shear strength of a sediment provides an upper bound for erosion and can be associated with a maximum erosion rate, different materials with the same shear strength may erode at substantially different rates under the same applied stress. As an example, Dunn (1959) used a submerged vertical jet to apply a stress to a number of different soil samples consolidated to different vane strengths (S_V) ranging from approximately 50 to over 500 lb/ft^2 (approximately 2,400 to over 24,000 Pa). The critical hydraulic shear stress, T_C, was defined by Dunn for his experiments by incrementally increasing the applied stress until there was a substantial erosion rate increase and the water in the test vessel became cloudy and remained that way. This critical point was described as definite and reproducible.

As shown in Figure 1.3, taken from Dunn (1959), increasing vane strength increased the critical hydraulic shear stress for a given soil.[1] Some of the soils had identical erosion behavior (for example, soils 3c and 5, and soils 4 and 9), but the majority did not. Similar critical hydraulic shear stress (i.e., erosion rates as defined by Dunn's experiments) was found for different consolidated soils over the tested vane strength range of a factor of 10 (e.g., see test results at $T_C \sim 0.32$ lb/ft^2). Likewise, variation in the critical hydraulic shear stress (erosion rate) of a factor of 10 was achieved for different soils at constant vane strength (e.g., see test results at $S_V \sim 0.32$ lb/ft^2). Thus, the use of a simulant's shear strength relative to the shear strength of a simulant with a different composition can be misleading with respect to the erosion rate at a given applied stress; a simulant with a higher shear strength can erode at a faster rate than a different simulant with a lower shear strength when the same stress is applied.[2]

[1] Dunn (1959) notes, "The lines [in Figure 1.3] are not valid in the range of $0<S_V<60$ lb/ft^2, and only represent the extension of lines through the region investigated. The Y intercept of the lines does not indicate the value of critical tractive stress for the case of zero vane strength." Bracketed text added.

[2] For example, from Figure 1.3, consider soil 3d at $S_V \sim 300$ lb/ft^2 and soil 7 at ~100 lb/ft^2. For an applied shear stress of ~ 0.25 lb/ft^2, the critical hydraulic shear stress for soil 7 at 100 lb/ft^2 has not been reached, and it is exceeded for soil 3d at 300 lb/ft^2; thus, the higher vane strength soil will be eroded at a faster rate.

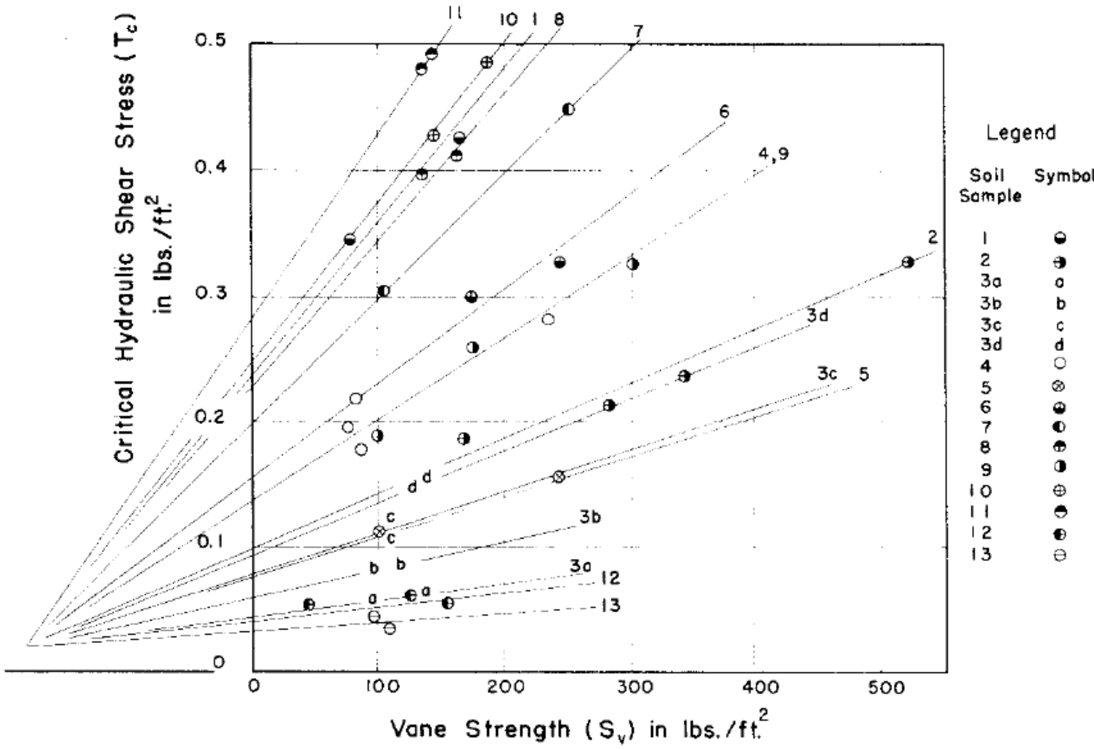

Figure 1.3. Critical Hydraulic Shear Stress as a Function of Vane Strength for Consolidated Soil Samples (from Dunn 1959)

The soil samples evaluated by Dunn (1959) were pre-sieved to remove any coarse fraction (defined as failing to pass through a No. 10 U.S. Standard sieve; 2,000-µm opening). Numerous researchers have shown that varying the concentration of "coarse" material in a cohesive matrix can significantly alter a material's critical stress for erosion; see Wells et al. (2009). Further, heterogeneity (e.g., large aggregates of millimeter scale with high individual strength [i.e., high critical shear stress for erosion]) in a relatively weaker cohesive material may present a unique challenge for fluid jet erosion, as once the large aggregates are mobilized from the sediment matrix, they may simply be moved by the fluid jet instead of eroded.

1.4.2 Vacuum Collection and Conveyance

With sufficient applied stress, applying the fluid jet to the sediment will result in material detachment in the form of aggregates (see Section 1.4.1). For retrieval to proceed, these aggregates (or rocks, pebbles, and debris) must be entrained into the transfer system via vacuum collection and conveyed in the transfer line. To identify key physical properties of a simulant for this scenario, the evaluation is simplified to consider the pneumatic pickup velocity, where "pickup" is defined as entrainment of the aggregates from a surface into a flow, and pneumatic transport velocity or saltation velocity can be defined as the minimum velocity required for conveying solids without formation of stationary beds and dunes on the bottom of the pipe (Cabrejos and Klinzing 1994). This simplification does not address inlet flows (e.g., the velocity field formed by the flow into the vacuum inlet) or the three-phase nature of the flow.

The particle transfer inlet ingestion and vertical pipe transport evaluations in Meacham et al. (2012) had the key parameters of particle size, particle density, liquid density, and liquid viscosity. The particle inlet ingestion in Meacham et al. (2012) was unique from pickup as the particles were assumed to enter the inlet flow field as opposed to being stationary on a surface. A review of theoretical and empirical models for threshold velocities is provided by Rabinovich and Kalman (2011). Incipient motion, pickup from particle layer, pickup from a particle deposit, and saltation velocity are considered for both liquid and gas flows. They defined the different threshold velocities using the same dimensionless numbers to present a generalized flow regime curve. Again, particle size, particle density, liquid density, and liquid viscosity are the dominant material parameters.

Translating these parameters to the pneumatic vacuum retrieval process, aggregate size and density are identified as the key parameters. Of course, aggregate size is also of significance if it is large enough to block the inlet screen of the collection system.

2.0 A-105 Properties

2.1 Chemistry

The simulant to be developed will be most appropriate if it matches the physical properties and solubility in water of the waste in tank A-105. This section first discusses the observations and samples that have been taken during the tank's operational history. The remaining discussion focuses on the waste composition.

2.1.1 Observations and History of Tank A-105 Waste

Several references were drawn on to provide the discussion that follows (Templeton 2016; Beard et al. 1967; Disselkamp 2009; Kaser and Veneziano 1978; Schmidt and Smith 1968). These are not always specifically identified in the text, but are always identified when directly quoted.

Tank A-105 was filled primarily with non-aged, self-concentrating PUREX waste that brought itself to boiling temperature in March 1963, attained a concentration of 7 M Na in September 1964, and reached its maximum recorded temperature of 285°F in January or February of 1965. At about this same time, water entered between the tank liner and the tank bottom and generated a steam release that forced the tank bottom into an upward bulge, under which some of the waste penetrated. No further waste was added, but water was added periodically to maintain cooling though 1968. In August 1968, sluicing began. The first sluicing campaign was obstructed by a hard upper layer. Later sluicing campaigns alternately applied inhibited 1 M sulfuric acid to soften the waste, and sluiced the softened waste. At least some of the sluicing was carried out using the supernatants then present in tanks A-101 and A-102. At the end of sluicing in August 1970, the remaining supernatant was described as being a mixture of cesium-depleted B-Plant waste and PUREX high-level waste. Cooling water was added periodically between the end of sluicing and the end of 1978.

Core samples were taken in September 1968. It is not clear whether supernatant was present at the time of sampling, but about half of the solids initially present had been removed and sluicing had become ineffective. Shortly before this, on August 29, 1968, photos of the waste surface showed large, dry-looking, sharp-edged blocks. The sampling event is described as follows (Templeton 2016):

> "The sample was cored from the sludge by impacting with a 300-pound weight. The sampler sank 1-1/2 inches from its own weight (approximately 600 pounds) and was then impacted an additional 19 inches. The sludge appeared to be relatively hard near the surface with a softer layer near the tank liner. The sampler contained only a 10-12-inch core, even though it passed through 20-21 inches of sludge. The sample did not have the consistency expected for the hard blocks observed in the photographs; it had the color and consistency of brown mud and lost its shape when the core sampler barrel was opened."

Schmidt and Smith (1968) comment that the first 1 to 2 inches were an extremely hard crust, although the rest was soft and mobile. Although these pre-sluicing 1968 observations may not pertain to the sluiced waste, they are presented for general information about the potential for crust formation. In addition, and more specifically, they provide information on any parts of the existing waste that might not have been contacted by sulfuric acid.

At some point before January 1972, after sluicing had ended and while water was still being added, two samples of the remaining waste were taken. One sample was referred to as "dry" and described as hard, dry, brown lumps. The other "wet" sample was described as a wet slurry (Schulz and Hobbick 1972). The wet and dry samples came from different locations in the tank. Like the 1968 core samples, these may not have penetrated to the deeper waste layers.

In 1979, tank A-105 was described as follows (Templeton 2016):

> "The surface appears dry with the exception of a wet spot trailing away from a circulator. The floor is approximately 40% bare metal, 30% a thin layer of sludge and the remaining 30% a heavier sludge primarily around the perimeter of the tank. The manual tape touches on a pile of old tapes and piping leading one to believe readings would be erratic. The liner of the tank is almost free of scale except for a small ridge around the lower perimeter."

Although the liner was almost free of scale in photographs taken in June 1979, a visual inspection on September 27, 2010, found crystals on all interior surfaces. These were suspected to be ammonium nitrate.

2.1.2 Chemical Composition of Tank A-105 Waste

The waste composition in tank A-105 has been described as follows: "neutralized PUREX high-level waste that has been leached with inhibited sulfuric acid and supernatant from various tanks...is unique." (Disselkamp 2009). The Best-Basis Inventory (BBI) uses the arithmetic average of concentrations measured in the post-sluicing 1972 samples to calculate the inventories of Al, Fe, Mn, Na, Si, and total U. Almost all of the concentrations of other major analytes are based on the template for the P2 waste-type,[1] because it is the closest approach to applicable data even though it does not account for sulfuric acid addition and may not account for sluicing effects.

The extent to which the waste has been dried is unknown, although some drying can be assumed based on the temperature – the bottom temperature as of March 31, 2004 was 233°F (112°C). Templeton (2016) assumes 44.2 wt% water, based not on sample data (which are lacking), but on the template for the P2 waste type, which does not account for drying. A value of 44 wt% water is unlikely unless free liquid is present, so the water content in the A-105 BBI is likely to be an overestimate.

The BBI is also based on an assumption of zero free hydroxide: "Tank 241-A-105 was sluiced with inhibited sulfuric acid; hence any free hydroxide present would have been neutralized" (Disselkamp 2009). Note though that if the crystals on the in-tank surfaces in 2010 were ammonium nitrate, their presence might indicate that at some point between 1979, when no scale was observed, and 2010, when crystals were seen on tank surfaces, the waste had been sufficiently alkaline to allow the release of ammonia vapor. In this case, the explanation might be that the acidifying effect of the sulfuric acid had been offset by the alkalinity of interstitial liquid and of the sluicing liquid taken from supernatants of other tanks, and that free hydroxide was not neutralized. This explanation is consistent with calculations made by Schmidt and Smith (1968), who estimated that there was more than enough base in the waste to neutralize the then-planned sulfuric acid spray and to guarantee that no pockets of acid would remain.

Table 2.1 presents a review of the composition data from the A-105 BBI, the 1972 samples from A-105, a composition that was recently modeled for A-105 waste (Laurenz 2016), and the AX-104 BBI. The AX-104 information is presented because AX-104 is the only other tank that contains solids composed of sluiced P2 waste, though sulfuric acid was not used in AX-104, and because the compositions for these analytes are sample-based in the AX-104 inventory rather than template-based. The small set of analytes was selected because it is the limited set measured in 1972 for A-105.

[1] "P2" denotes PUREX high-level waste generated between 1963 and 1967.

A larger set of analytes was measured in core samples from 1968, before sulfuric acid addition began (Schmidt and Smith 1968). Like the 1972 core samples, the top 10 inches of core in the 1968 samples showed Na concentration generally greater than 20 wt%, Fe about 4%, and Al lower than Fe. However, the 1968 cores from levels between 10 and 18 inches deep contained 15 to 20 wt% of Na and about 25 wt% Fe, clearly a separate composition, and possibly one not captured in the 1972 sampling. Note, however, that the 1968 samples had not been subjected to sulfuric acid sluicing. Their composition is presented for a general comparison, and to provide information about any areas of the waste that might not have been contacted during acid sluicing.

The composition from the 1972 samples has been preferred for inventory calculations, for the few analytes that were measured in 1972: Na, Al, Fe, Mn, Si, U, and some radionuclides (Templeton 2016). For lack of other information, the majority of analytes' concentrations in the A-105 BBI come from the P2 template, which does not include the effect of sluicing. Thus, the BBI composition combines data for sluiced and unsluiced conditions.

The three sets of concentrations from the 1972 samples, and the A-105 BBI concentrations derived from them, agree in having (a) a large proportion of Na to metals, (b) significantly more Al than Si, and (c) about as much Al as Fe, in molar terms. This composition suggests a significant amount of either sodium salts, more or less soluble in water, or sodium-containing minerals. The concentrations from the AX-104 BBI may suggest what the P2 waste in A-105 would have contained if sulfuric acid had not been applied—in AX-104, Na is a much lower proportion of the waste, Al dominates Na, and Fe dominates Al in molar terms.

The modeled composition (Laurenz 2016) for A-105 waste is considerably different from that indicated by the A-105 BBI and its source samples (although it resembles the AX-104 BBI in its Na, Al, Fe, and Mn concentrations). The model for A-105 waste predicts that Al, Na, and Si are present only in the form of cancrinite (a sodium aluminosilicate) and that, in molar terms, Fe (in the form of FeOOH) exceeds Al. There is a pronounced difference between the limited composition data measured in 1972 and the modeled composition. The difference may have originated in the modeling approach. In modeling, the solids composition was calculated by combining the BBI solids with an estimated amount and composition of original as-fed supernatant and raising the composition of the mixture to 120°C to 130°C (the model's upper temperature limit). The application of inhibited 1 M sulfuric acid to A-105 waste does not seem to have been included in the modeling.

Note that the composition cited in the Alternate Retrieval Program Plan (Wooley 2016) is the same one calculated by modeling. The composition is subject to question as a basis for simulant because its sodium and metals concentrations are significantly different from those measured in the 1972 samples. The modeled composition is closer to that in the deeper core samples from 1968, but still overestimates metals and underestimates sodium.

If the 1972 samples represent the solids in A-105, cancrinite can be expected to be present, as predicted by the model. The Al present in excess of that in the cancrinite can plausibly be assigned to AlOOH, whose formation is favored at the high temperatures characteristic of A-105 (Laurenz 2016). A large amount of Na remains to be accounted for, since only a small fraction of the Na would be contained in the cancrinite. Sodium salts may be present, probably in anhydrous form because the temperature is above 100°C. The most likely salt anions would be sulfate, carbonate, oxalate, phosphate, and nitrate, in whatever forms do not decompose at tank temperatures. The core samples taken in September 1968, after the initial sluicing but before spraying with inhibited sulfuric acid, contained 40 to 50 wt% carbonate and sulfate (Schmidt and Smith 1968). Nitrate was present only at a few weight percent.

The sodium might also be present in compounds that include the metals; the presence of $NaAlO_2$ might be possible under concentrated alkaline conditions. It is also worth considering the possibility that Al and Fe are present in forms that are more dehydrated than AlOOH and FeOOH, such as Al_2O_3, Fe_2O_3, or $FeMnO_4$. These compounds have been found in other Hanford tanks (Disselkamp 2010).

The compounds in the waste remaining in A-105 have not been identified from samples, and chemical reasoning leads to the ranges of possible compounds suggested above. Any choice of compounds should be judged in terms of the fact that these are the materials that were not removed, and possibly could not be removed, by sulfuric acid addition followed by sluicing.

Furthermore, in the decades since sluicing ended, a hard carbonate crust may have formed because of carbon dioxide absorbed from headspace air by the surface of the alkaline waste. There is strong evidence that such a process occurred over two decades in the undisturbed waste in tank C-105: "trona had formed at the expense of thermonatrite and served as the cementing phase in the hard crust. In addition, aluminum and uranium phases had converted from (hydr)oxides (gibbsite and clarkeite) into carbonates (dawsonite and cejkaite)."[1] The C-105 sludge waste was a different type than that sampled in A-105, but, like the waste in A-105, contained significant amounts of Na, Al, Fe, and Si.

Table 2.1. Analyte Concentrations in Measured and Modeled A-105 Waste

	Dry Sample, 1972[(a)]	Replicate of Dry Sample, 1972[(a)]	Wet Sample, 1972 (after air-drying)[(a)]	2016 BBI for A-105[(b)]	Modeled A-105[(c)]	2016 BBI for AX-104[(b)]
g/g dry solid						
Na, g/g	0.24	0.22	0.31	0.257	0.0870	0.0431
Fe, g/g	0.058	0.13	0.081	0.0897	0.305	0.271
Al, g/g	0.032	0.046	0.038	0.0387	0.0766	0.0529
Mn, g/g	0.0025	0.004	0.0026	0.00303	0.00716	0.00469
Si, g/g	0.018	0.028	0.022	0.0227	0.0797	0.000868
mole ratios						
Na/Al	8.8	5.6	9.6	7.8	1.3	0.96
Al/Si	1.8	1.7	1.8	1.8	1.0	63
Mn/Fe	0.044	0.031	0.033	0.034	0.024	0.018
Al/Fe	1.1	0.73	0.97	0.89	0.52	0.40

(a) Schulz and Hobbick (1972)
(b) Downloaded from the Tank Waste Information Network System in late November 2016.
(c) Table A-10, Laurenz (2016). The composition is given there in terms of modeled mass fractions of different minerals. For those minerals containing the analytes above, the model predictions were 36.9% Fe_2O_3, 9.89% $NiFe_2O_4$, 46.2% $Na_8Al_6Si_6O_{24}CO_3.1H_2O$, and 1.16% $Mn(OH)_2$.

2.2 Physical Properties & Ranges

This section discusses the physical waste properties of tank A-105 specific to the key physical properties for the retrieval system described in Section 1.0. In the absence of erosion rate information, A-105 sediment material shear strength is considered for mobilization. As discussed in Section 1.4.1, the

[1] Page JS, JG Reynolds, TM Ely, and GA Cooke. 2016. "Development of a Carbonate Crust on Alkaline Nuclear Waste Sludge at Hanford." WRPS-60240, article submitted to journal in 2016, Washington River Protection Solutions LLC, Richland, Washington.

erosion rates of different materials depend on shear strength differently; however, shear strength is used in the absence of erosion rate data and provides an upper bound for the applied shear stress necessary to initiate materials erosion and is associated with a maximum erosion rate. For vacuum collection and conveyance, potential adverse aggregates and debris size and density are summarized.

2.2.1 Estimates for A-105 Waste Strength from 1968 Core Sample Event

A material's shear strength provides an upper bound for the applied shear stress (i.e., from the water jet) necessary to initiate material erosion, and is associated with a maximum erosion rate (see Section 1.4). As described in Section 2.1.1, core samples were taken from A-105 in September 1968. Templeton (2016) summarizes observations made during this sampling event, and estimates of the waste strength at the time of sampling are made from these observations.

The 1968 core sample from A-105 was taken through bottom detection riser No. 7 in the northeast portion of the tank near the tank wall. Templeton (2016) reported:

> "The sample was cored from the sludge by impacting with a 300-pound weight. The sampler sank 1-1/2 inches from its own weight (approximately 600 pounds) and was then impacted an additional 19 inches. The sludge appeared to be relatively hard near the surface with a softer layer near the tank liner. The sampler contained only a 10-12-inch core, even though it passed through 20-21 inches of sludge. The sample did not have the consistency expected for the hard blocks observed in the photographs; it had the color and consistency of brown mud and lost its shape when the core sampler barrel was opened."

Two methods are used to approximate the waste strength from these observations: penetration load and sample appearance.

A method to estimate a material's shear strength based on the force required to penetrate an object into the material's surface was developed in Rassat et al. (2000). The shear strength was written as

$$\tau = \frac{F}{\eta A} \tag{2.1}$$

where F is the weight required to impinge the object into the material and A is the object's area (or projected area). The empirical constant η was determined by Rassat et al. (2000) using simulants and differing the impinging object's size and shape. Although a large range was observed for η, it was suggested that $\eta = 7$ was representative of the operations. Analytical analyses indicated $\eta > 5$ for plastic media (applicable to Hanford waste). For waste sediment shear strength with impingement of a sludge weight or densitometer in that sediment, estimates from Eq. (2.1) were shown in Appendix B of Gauglitz et al. (2009) to compare reasonably well with in-tank ball rheometer results as well as estimates for sediment shear strength at the static equilibrium of those devices.

The 1968 A-105 core sampler was 1.25 inches in diameter (Schmidt and Smith 1968). If it is assumed that the sampler has a similar configuration to the core sampler assembly of drawing H-2-690140, Rev. 1 (attached as Appendix A), the sampler (pipe) end area is 3.5 E-4 m^2.[1] The shear strength of the "relatively hard" surface estimated from Eq. (2.1) would thus be approximately 1.1 million Pa from the

[1] Core sampler assembly from drawing H-2-690140, Rev. 1, has a 1.246-inch average inside diameter and 1.50-inch outside diameter (Appendix A).

force of 600 pounds (2,669 N). With the experimentally determined variation in η from approximately 3 to 10 reported in Rassat et al. (2000), the shear strength estimate can range from 760 to 2,500 kPa.

The representative result of 1,100 kPa is a factor of 60 larger than the highest shear vane measured shear strength reported for Hanford waste sediment (see entry for AY-101 in Table I.2 of Wells et al. 2011), and 44 times larger than the maximum shear vane measured shear strength reported for Hanford waste crust (see entry for SY-101 in Figure 11.3 of Poloski et al. 2007). However, Powell et al. (1997) provide estimates of the shear strength of Hanford waste hardpan from the analysis of three different qualitative observations. The estimated values were 50,000 Pa, 53,000 to 178,000 Pa, and 1,720,000 Pa.

In addition to the uncertainty of Eq. (2.1) and the sampler configuration, there may also be uncertainty from the applied load. The configuration of the core sampling system used for A-105 is not known. As reported in Rassat et al. (2003), there are substantial uncertainties for load data for later core sampling systems. Rassat et al. (2003) noted:

> "Investigation of the load data for the core sampling apparatus was not encouraging. Comments on the data ranged from 'down forces are independent of material properties'[1] to 'don't use (load values) quantitatively…data is affected by internal friction of the sampling apparatus'[2]."

Thus, depending on the core sampling methodology and determination of the A-105 sampler weight, the 1,100 kPa result may be inaccurate. It is important to note, however, that the concerns reported in Rassat et al. (2003) were for load measurements of the mass of the sampling apparatus and hydraulics on the sampler truck. It is unknown if the reported A-105 sampler weight was determined via the same method.

The description of the core sample reported in Templeton (2016), wherein the waste core sample lost its shape when the core sampler barrel was opened, may indicate substantially different shear strength results. Rassat et al. (2003) provide an approach for shear strength from the deformation or slump of a horizontal cylinder of waste as

$$\tau = \frac{\rho g d}{2}\left[1 - \left(\frac{s}{d}\right)^{\frac{1}{2}}\right] \quad (2.2)$$

where ρ is the sediment density, g is the acceleration of gravity, d is the original cylinder diameter, and s is the slump length. Deformation of a 1.25-inch cylinder of waste at a representative sediment density of 1.6 g/mL (e.g., Yarbrough 2013) configuration of only 1% (representing a minimum "lost its shape" [Templeton 2016] and therefore upper bound shear strength with deformation) results in a shear strength of approximately 225 Pa. Obviously, this is a significantly different result than 1,100 kPa from above, and comparison of the A-105 core sample image in Templeton (2016), shown herein as Figure 2.1, to a waste surface image at the time of the core sample, Figure 2.2,[3] suggests much stronger material, at least at the top of the waste.

1 Personal communication from AM Templeton (CH2M Hill) to BE Wells (PNNL) on January 14, 2003.
2 Personal communication from J Douglas (CH2M Hill) to BE Wells (PNNL) on January 14, 2003.
3 Image from file *241-A-105_-_[1006160315]* provided by TA Wooley (WRPS) to PNNL via 12/8/16 e-mail.

Figure 2.1. Image of 1968 A-105 Core Sample (from Templeton 2016, edited to increase brightness)

Figure 2.2. A-105 Waste Surface Image, 1968

The waste surface in Figure 2.2 supports the description of the sludge at the time of sampling from Schmidt and Smith (1968):

> "…remaining sludge is in the form of large crust-covered cakes…top layer of 1 to 2 inches which was extremely hard."

The vertical edges of the "crust" shown in Figure 2.2 can also be used to indicate the material's minimum shear strength. An expression for the maximum angle of repose, θ, for a granular sediment has been derived[1] as

$$\tan\theta = \frac{8\tau\Delta\rho gH}{(\Delta\rho gH)^2 - 16\tau^2} \tag{2.3}$$

where H is the vertical distance and Δρ is the density difference between the sediment and surrounding fluid. With a nearly vertical slope, which would give an upper bound (e.g., 89.9°), a height extent of approximately 1 foot, and the representative sediment density of 1.6 g/mL, the shear strength is at least about 1,200 Pa, again much less than the 1,100 kPa estimate.

The A-105 waste sample at the time of the 1968 core sample likely had layers of different strength, and the "extremely hard" surface, intended to be dissolved by the inhibited 1 M sulfuric acid addition (see Section 2.1.1), may have had a shear strength of up to 1,100 kPa, as estimated from the applied core sampler load. Estimates from the sampled waste and waste surface appearance are substantially less and are unlikely to be adverse for water jet retrieval methodologies.

The potential for the "extremely hard" surface material of the 1968 core to currently be present can be inferred from the process history and in-tank images. Schmidt and Smith (1968) described the apparatus used to distribute the sulfuric acid over the sludge as a 10-foot radial arm deployed through a central riser. The arm could be rotated 1 foot above the sludge surface and had four spray heads to spray the underlying area. The process description specified that prior to deployment of the acid distributor, an in-tank photograph would be taken to determine the location of sludge within the vicinity of the deployment riser, and the operating procedure would be written such that only the surface of the tank bottom would be sprayed. Since A-105 has an 11.443-m radius (Yarbrough 2013), less than 10% of the surface area of the waste would be covered by the acid distributor. Templeton (2016) describes the tank's interior from photographs taken in 1979 as follows:

> "The surface appears dry with the exception of a wet spot trailing away from a circulator. The floor is approximately 40% bare metal, 30% a thin layer of sludge and the remaining 30% a heavier sludge primarily around the perimeter of the tank."

Thus, there is potential that some of the "extremely hard" surface material of the 1968 core sample is still present in the tank.

2.2.2 Aggregates and Debris

Aggregate size and density are identified in Section 1.4 as the key parameters for the pneumatic vacuum retrieval process. Aggregate size can also directly affect the retrieval process if the aggregates are large enough to block the inlet screen of the collection system. Miscellaneous debris in the tank from its process history can also affect the inlet.

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[1] Meyer PA, CW Stewart, SD Rassat, RT Allemann, G Terrones, and DP Mendoza. May 1999. *Potential Gas Release by Bubble Slurry Flow Through a Hole in the Crust Layer in SY-101*. Letter Report TWS99.27, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Limited sampling and in-tank visual observations suggest that some large waste agglomerates remained in SSTs following retrievals, and it is confirmed that large agglomerates exist. Meacham et al. (2012) summarized tank retrieval heel properties for S-112, C-108, and C-110 as follows:

- **S-112** – Several large particles ranging from 1 to 5 mm in diameter and one large body with a diameter of approximately 10 mm were observed. X-ray diffraction analysis of tank S-112 heel solids revealed that a majority of the samples were composed of gibbsite, $Al(OH)_3$. Trace amounts of sodium carbonate monohydrate, $Na_2CO_3 \cdot H_2O$ (thermonatrite), were also identified. Polarized light microscopy and scanning electron microscopy (SEM) energy-dispersive X-ray spectroscopy analyses also confirmed that the solids were dominated by coarse gibbsite crystals. The average particle density of tank S-112 heel solid composite was estimated as 2.53 g/mL.
- **C-108** – Heel solids were initially separated into greater than 1/4-inch and less than 1/4-inch fractions using coarse sieves (Figure 2.3). The greater than 1/4-inch fraction made up 18.6 wt% of the composite sample, with the less than 1/4-inch fraction making up the remainder. Gibbsite was the dominant mineral phase identified. The calculated dry density of the remaining solids was reported as 1.933 g/mL.
- **C-110** – A mixture of coarse-to-fine-grained sand-sized materials was observed (Figure 2.4). X-ray diffraction analysis detected natrophosphate as the only solid mineral phase. Polarized light microscopy and SEM analyses indicated the minor presence of gibbsite, sodium aluminosilicate, sodium diuranate, and nastrophite.

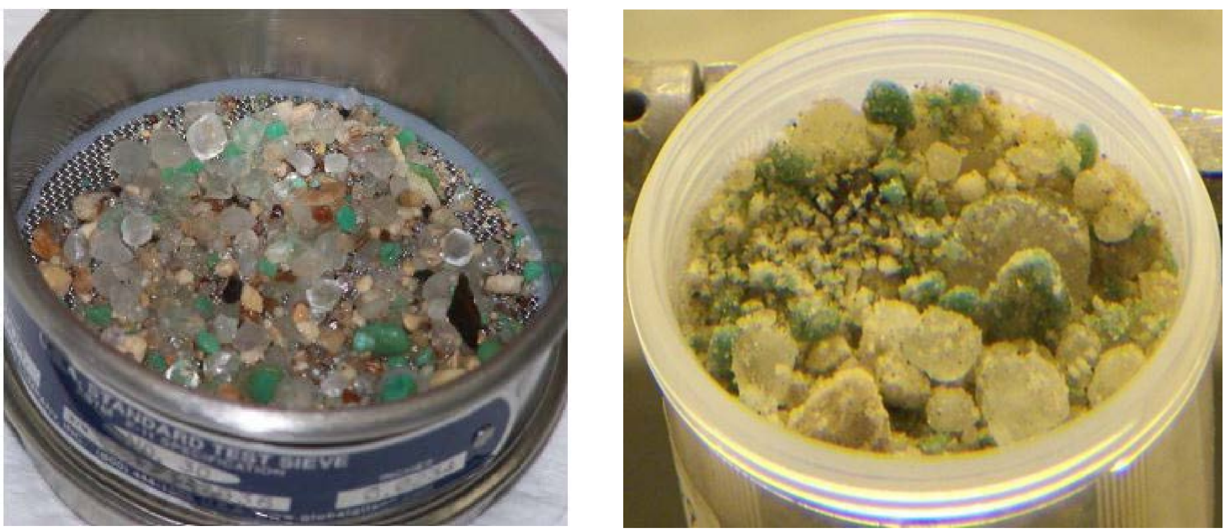

Figure 2.3. Tank C-108 Heel Solids (Meacham et al. 2012)

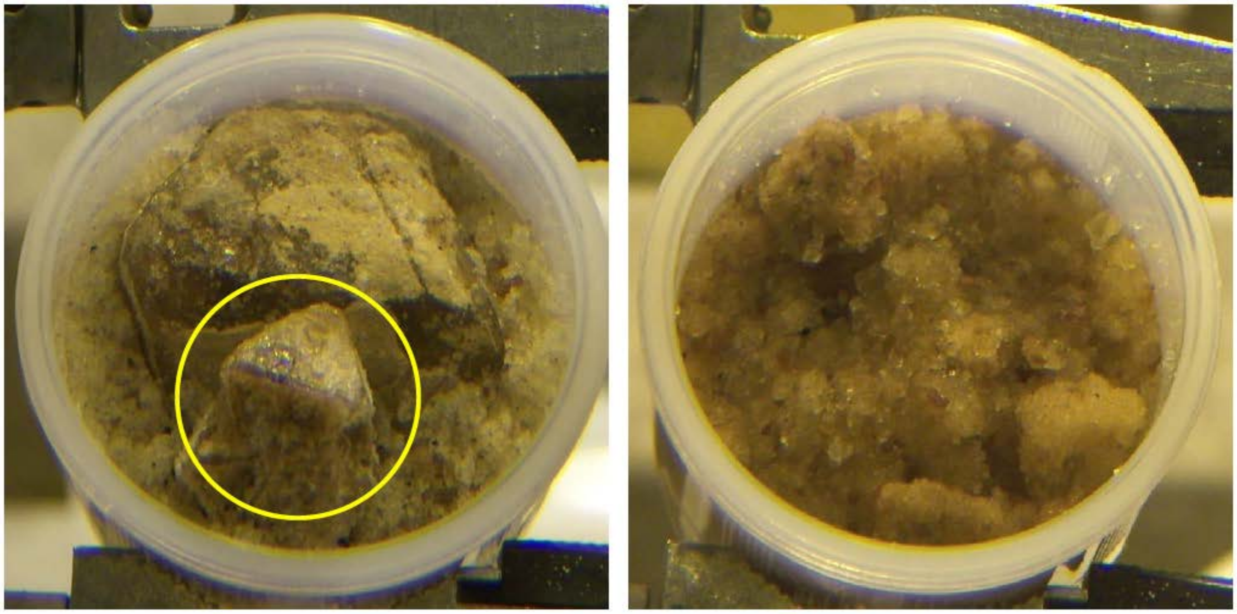

Figure 2.4. Tank C-110 Heel Solids (Meacham et al. 2012)

Golcar et al. (1997) recommended that different simulants ranging in size from 0.1 to 3 cm with densities within the range of 2.6 to 3 g/mL be tested for the steady operating capabilities of a conveyance system. It was suggested that correlation of the conveyance system performance to particle diameter might provide a method to optimize the cuttings size produced by the mobilization system.

Debris such as rocks, tapes, and wrenches has been observed in Hanford waste tanks. For testing the prototype waste retrieval end effector (WREE), tapes, rocks, and other debris were added to the "wet sludge" and "hardpan" simulants prepared following Powell (1996) (Hatchell et al. 2016).

3.0 Historical Studies

3.1 Simulant Types and Characterization

Hatchell et al. (2016) summarized simulant types and specific materials that have previously been developed and suggested that sludge and hardpan (dried sludge) simulants would be most applicable for evaluating confined sluicing methods for A-105. Two additional simulant types noted by Hatchell et al. (2016) based on the original work by Powell et al. (1997) are hard and soft saltcake. Several recipes for the different types of simulants have been developed for previous retrieval testing studies. Table 3.1 summarizes a selection of these simulants, grouped by simulant type, that are potential candidates for use in confined sluicing testing. This table does not give specific recipes, but shows the materials that were used, the general range of strengths that was measured, and the primary references for simulant development studies with recipes and characterization measurements. Note that all of the previously developed simulants used materials that are not chemically representative of Hanford tank waste (sludge and saltcake), and the materials and recipes were selected to match specific physical parameters, such as strength. This type of simulant is often described as a physical simulant in contrast to chemical simulants the match chemical components in the waste.

A shear strength estimate of 1,100,000 Pa was determined for the hard crust layer in A-105, as discussed in Section 2.5, and this material can be described as hardpan/dried sludge. The previously developed simulants for hardpan/dried sludge have only been prepared and characterized for strengths up to about 150,000 Pa. Accordingly, an entry of 1,100,000 Pa is included in this table under hardpan/dried sludge as a suggested new simulant target. An entry is also included for heterogeneous hardpan as a new simulant type that needs to be developed to represent how eroded waste may include large aggregates of hard material that might plug the inlet screen of a capture system. Table 3.1 also includes suggested materials for these new simulants. Finally, simulants that match chemical compounds in the actual waste, or chemical simulants, are a typical class of type and an entry is included for this simulant type. Although a chemical simulant for A-105 waste has not previously been developed, there are a few recent studies focused on developing hard heel and crust chemical simulants for waste in C-103 and C-105.

Table 3.1. Summary of Simulants Developed Previously and Needed Simulants

Simulant Type	Simulant Material	Typical Strength Range (Pa)	Reference
Wet Sludge	Clay (kaolin and/or bentonite)	500 – 10,000[(a)]	Powell et al. (1995) Powell (1996) Powell et al. (1997) Burns et al. (2010) Gauglitz et al. (2012)
	Kaolin/Plaster	1,000 to 4,000[(a)]	Powell et al. (1997) Onishi et al. (2011)
Hardpan/Dried Sludge	Kaolin/Plaster	30,000 to 150,000[(a)]	Powell (1996) Onishi et al. (2011)
	A-105 Hard crust target (kaolin/plaster is a candidate material)	1,100,000[(a)]	New (never prepared)
Soft Saltcake	Rock Salt/Plaster	10,000 to 48,000[(b)]	Powell (1996) Powell et al. (1997)
Hard Saltcake	K-Mag ($K_2SO_4 \cdot 2MgSO_4$)	10,000,000 to 30,000,000[(b)]	Powell (1996) Powell et al. (1997) Golcar et al. (1997)
Conveyance	Steady Operation • Range of crushed rock, gravel, and sand (0.2 to 2 cm) • Coarse-grained K-Mag Plugging, Choking, Slugging • Range of kaolin, bentonite, and kaolin/bentonite mixtures • Min-U-Sil 30 silica flour Line Erosion • Coarse-grained K-Mag slurry produced by jet erosion	NA	Golcar et al. (1997)
Heterogeneous Hardpan (New)	Heterogeneous (strong breakable aggregates in second material) Candidate materials: • Kaolin/plaster chunks in clay • K-Mag chunks in kaolin/plaster • Debris & K-Mag in kaolin/plaster	TBD	New (never prepared)
Chemical (New)	Chemical Simulant of A-105	TBD	New (never prepared)[(c)]

(a) Shear strength
(b) Compressive strength
(c) In two recent memorandums, a chemical simulant of a gibbsite heel was developed and characterized: HJ Huber to WB Barton, "Report on Gibbsite Heel Formation Simulation and 241-C-103 Heel Analysis," WRPS-0900975, July 8, 2009; and HJ Huber to WB Barton and DA Adkisson, "Gibbsite Heel Production Report," WRPS-0901882, October 9, 2009. See also Page JS, JG Reynolds, TM Ely, and GA Cooke. 2016. "Development of a Carbonate Crust on Alkaline Nuclear Waste Sludge at Hanford," WRPS-60240, article submitted to journal in 2016, Washington River Protection Solutions LLC, Richland Washington.

3.2 Simulant Performance with Jet/Vacuum

Table 3.2 summarizes the historical water jet testing that is representative of a confined sluicing operation. The summary is grouped into the three types of simulants that were used to mimic various Hanford tank waste conditions expected during waste retrieval operations: (1) wet sludge, (2) hardpan/ dried sludge, and (3) hard saltcake. Table 3.2 includes information on the simulant recipe and strength together with details on the water jets used, the test operation and results for jet penetration, and the reference that documented the testing. Most of this testing was conducted and reported in the 1990s, and the testing focused on quantifying solid retrieval rates and solid loading. For evaluating jet erosion performance, measurements such as the depth of jet penetration would be useful. Unfortunately, this type of data was typically not reported.

During retrieval operations with the water jets over a range of pressures from 150 to 50,000 psi, various phenomena were observed from different simulant types that included cut healing on the softer wet sludges to fracturing of material into chunks on the hard materials. Lower pressures tended not to penetrate the harder simulants, but higher pressures, which effectively penetrated all simulant types, could create other issues, including aerosol generation. Water jet testing indicates that the water jet details and operation should be tailored to the specific type of simulant being retrieved.

Transporting the waste dislodged by the water jets historically has been done using jet inductor systems because these vacuum/pumps have no moving parts and therefore are considered more reliable. In general, these types of systems have been highly reliable; however, the most typical problem has been plugging of the jet inductor's inlet by larger chunks of in-tank materials (e.g., larger waste pieces, in-tank debris, and similar) or a viscous sludge plug that exceeds the transport force provided by the jet eductor, or a combination of both. The typical culprit of transport plugging has been the coarse inlet screen, which is included to prevent large particles from getting wedged in the jet inductor transport piping. Past solutions to screen plugging have utilized a back-flushing capability that uses pressurized liquid on the upstream side of screen to clear the screen, and this has been mostly successful and could be optimized through enhanced design features.

The ideal water jet operation for retrieval of all tank waste types would be to dislodge and break waste/in-tank debris into small particles and create a liquefied slurry contained locally that is easily transported by a localized vacuum such as a jet eductor pump. In reality, water jet dislodging operations instead have shown that hard waste may fracture into large chunks or in-tank debris may not be broken down into transportable particle sizes, or the waste mix dislodged for transport may not be adequately liquefied to a viscosity/density within the operational constraints of the transport system. In-tank debris like large rocks, steel tapes, and similar can be especially challenging for any retrieval system including confined sluicing. Water jets at high pressure can generate adequate forces to cut or break almost anything, including steel tape; however, at these pressures, the tank wall containment barrier must be adequately protected.

For water jets to work most effectively at cutting into various materials, that material must be confined or restrained. The problem that can occur with large chunks of hard waste or in-tank debris is that unrestrained material is just pushed around and not broken into smaller particle sizes adequate for jet eductor transporting. These large materials, along with a waste mixtures having too high of a viscosity and/or density for the transport system, have caused transport plugging issues on inlet screens, including screens used on confined sluicers with integrated jet eductor transport systems. Historically for the confined sluicing systems, the screen plugging issue has not been addressed with enhanced design because it was not a barrier to completing tank retrieval at the Oak Ridge National Laboratory gunite and associated tanks. Plugging of waste retrieval transport lines is likely an issue that needs to be addressed for any in-tank retrieval system and is not unique to the confined sluicer and associated jet eductor transport system.

For the confined sluicer systems used in tank waste retrieval operations, the goal is to dislodge and break the waste efficiently and at an acceptable rate into small particles and/or liquefied slurry that is easily transportable by the jet eductor system. The most ideal environment for a leaking tank like A-105 is one where the liquid from the water jet and subsequent waste fracturing/liquefying is very localized and then locally removed without spreading beyond the confined sluicing environment. Localized confinement of waste and liquid historically has not been a primary driver for confined sluicing systems, but has instead been designed and utilized to dislodge and transport a large range of waste types with a single system. However, of all water-based retrieval systems, confined sluicing has the most potential to achieve localized dislodging and conveyance of waste material and associated liquids out of the waste tanks with minimal liquid addition and liquid migration. Various design features could be added to confined sluicing systems to address these additional retrieval requirements for leaking tanks like A-105.

Table 3.2. Historical Water Jet Testing Typical of Confined Sluicing Operation

Simulant			Water Jet Details		Water Jet Operation and Results				
Type	Ratio to H_2O (wt%/wt%)	Strength (kPa [psi])	Feature	Nozzle Diameter (inches)	Surface Standoff Distance (inches)	Traverse Speed (in./sec)	Pressure (1,000 psi)	Cut Depth into Simulant (inches)	References
Kaolin "Wet Sludge"	66/34	3.5 [0.5][(a)]	WREE[(c)] w/pump	0.054	Unknown	5	0.15 - 1.02	Unknown	Hatchell et al. (2016) (see Appendix A)
	66/34	4.8 [0.7][(a)]	1 & 2 jets	0.015 - 0.025	0.625[(d)]	8.3 & 83	40 - 50	Unknown	Bamberger et al. (1994)
Kaolin/Plaster "Hardpan/ Dried Sludge"	22.5/40/37.5	200 [29][(a)]	WREE[(c)] w/pump	0.038	0.25 - Unknown	3.75	2.0 – 3.2	1.7 - 2.6	Hatchell et al. (2016) (see Appendix A)
	0/46/54	> 210 [30.5][(a)]	1 & 2 jets 5 jets in row 7 jets in showerhead	Unknown	6 6[(d)] 6[(d)]	Rotate ~ 6° / sec	2.3 2.5 0.4	Unknown	Criddle (2011)
K-Mag "Hard Saltcake"	90/10	20,700 [3,000][(b)]	1 & 2 jets	0.015 - 0.025	0.625[(d)]	8.3 & 83	40 - 50	Unknown	Bamberger et al. (1994)
	Unknown	Unknown	1 jet w/pump	Unknown	Unknown	3.14 - 9.42	5 - 11	Unknown	Summers et al. (1994)
	84/16, 82/18, 80/20	24,100 [3,500][(a)]	1 jet	0.018 - 0.032	2 - 5	10	10 - 14, 30, 50	Unknown	Powell et al. (1997)

(a) Shear strength
(b) Compressive strength
(c) Waste retrieval end effector (i.e., confined sluicing)
(d) Value is assumed from sources within reference.

4.0 Evaluation and Recommendations

This section combines the information on existing and needed simulants and the previous use of these simulants in water jet testing, and then provides an evaluation of the suitability of these simulants for representing the behavior of A-105 waste with a confined sluicing system. Table 4.1 summarizes this evaluation. The table has three main sections: on the left is a summary of the simulant materials and ranges of strengths that have been measured for recipes tested, the middle section summarizes how much information is known about the simulant (previously made, previously characterized, previously used successfully in confined sluicing geometry), and the right section is an evaluation of the specific simulants for representing A-105 waste behavior in alternate retrieval (confined sluicing) testing. Cell colors indicate whether information is known or if a particular simulant is suitable for representing A-105 in testing: green is favorable or good, yellow is intermediate, and red is lacking in information or poor. The table notes add clarification on the limitations for each simulant for the different process operations.

Overall, there are several different simulants that have been developed and characterized. The clay, clay/plaster, and K-Mag simulants have also been tested in representative configurations for confined sluicing with water jets. While these simulants can be used in testing of an alternate retrieval method, such as confined sluicing, they have a limitation in that they may not erode and make large and hard aggregates that might plug the inlet screen for the capture process. This limitation for these simulants is shown in the "Capture" column as "L-3."

Two new simulants are needed to represent key waste properties for A-105 that are not adequately covered by simulants developed in previous simulant studies. Both of these are shown in Table 4.1. The first is a heterogeneous hardpan/dried sludge simulant that is intended to recreate the screen-plugging challenge of eroded waste including aggregates, which are capable of being further eroded into smaller aggregates but that may remain as chunks depending on the confined sluicing performance. The second new simulant is a hardpan/dried sludge material to represent the 1,100,000 Pa estimate of shear strength for the hard crust in A-105. The table notes that K-Mag, which is a hard saltcake simulant that exceeds this strength by about a factor of 10, could be suitable as a bounding alternate material. A shear strength target for this new simulant is specified, but as discussed previously (see Section 1.4.1), the shear strength is being used as an alternate physical property because information on the erosion behavior is generally not known. As part of selecting a simulant to represent the A-105 hard crust estimate, the erosion characteristic of the simulant should be quantified and then evaluated to determine if the new simulant is appropriately challenging for representing A-105. Although not a new type or simulant target, materials need to be defined to represent appropriate debris (e.g., rocks, pebbles, tapes). While a new chemical simulant for A-105 could be developed, and is included as a final row in Table 4.1, it is typically difficult to develop chemical simulants to represent specific physical property targets, though recent work has successfully develop a hard heel chemical simulant for C-103 (see table note "(c)" in Table 3.1). Accordingly, this simulant is highlighted in red for suitability for confined sluicing testing.

For the planned Phase I testing of confined sluicing to demonstrate the potential effectiveness for A-105 retrieval, which is scheduled to begin in the near future, it is recommended that testing be performed with previously developed simulants. As a minimum, a Kaolin/plaster of Paris simulant representing a mid-range dried sludge condition and a K-Mag simulant representing an extreme hard pan condition should be used in the Phase I testing. A clay (such as kaolin) simulant could also be considered if it is deemed necessary to test performance of a wet sludge condition. This testing will determine the suitability of the confined sluicing system to retrieve a mid-range and extreme hardpan dried sludge and can demonstrate other system requirements such as the efficiency of sluicing operations and water management effectiveness. Specific targets for these simulants are given below.

- Wet sludge: ~3,500 Pa, kaolin/water - The strength value of 3,500 Pa was selected because it was used in the most recent testing of confined sluicing with the WREE (see Appendix A of Hatchell et al. 2016).
- Hardpan/Dried sludge: ~150,000 Pa, kaolin/plaster of Paris/water - The strength value of 150,000 Pa was selected because this was the strength used for this simulant used in the previous WREE testing. (See Appendix A of Hatchell et al. 2016; during curing, the peak strength is about 200,000 Pa as reported by Hatchell et al. while the final strength is about 150,000 Pa as reported in Powell et al. [1997] for this simulant recipe.)
- Hardpan/Dried sludge for A-105 hard crust estimate of 1,100,000 Pa: ~15,000,000 Pa K-Mag/water is a hard saltcake simulant that should be bounding for this target, and this value of strength is representative of the K-Mag recipes used in high-pressure jet erosion studies reported by Powell et al. (1997).

If initial effectiveness testing proves promising, it is recommended that development of additional simulants be initiated in time to support the follow-on integrated system testing. As a minimum, a heterogeneous hardpan simulant should be developed to understand erosion fracturing and subsequent size reduction that could lead to excessive screen plugging. A less extreme hardpan simulant that more closely matches the anticipated A-105 hard pan erosion behavior (and strength) could also be considered.

Table 4.1. Summary of Simulants, Previous Characterization and Testing, and an Evaluation of Suitability for Representing A-105 Waste Behavior in Alternate Retrieval (Confined Sluicing) Testing

			Previously Characterized				Suitable for Representing A-105 Waste Behavior in Alternate Retrieval (Confined Sluicing) Testing							
							Erosion					Conveyance		
Simulant	Strength Range (Pa)	Previously Made	Strength	Erosion[c]	Size Range of Eroded Material	Previously Used Successfully in Confined Sluicing Geometry	Wet Sludge[d]	Hardpan Dried Sludge[d]	Soft Saltcake[d]	Hard Saltcake[d]	Capture	Steady Operation	Plugging, Choking, and Slugging	Line Erosion (abrasion)
Clay (kaolin and/or bentonite)	500-10,000[a]	Yes	Yes	Yes	No	Yes	Yes (L-2)	-	-	-	Yes (L-3)	Yes (L-4)	Yes (L-4)	-
Kaolin/Plaster	10,000 - 150,000[a]	Yes	Yes	No (L-1)	No	Yes	-	Yes	-	-	Yes (L-3)	Yes (L-4)	Yes (L-4)	-
A-105 Homogeneous Hard Crust Target (kaolin/plaster a candidate)	1,100,000[a]	No	No	No	No	No	-	Yes A-105 Target	-	-	Yes (L-3)	Yes (L-4)	Yes (L-4)	-
Rock Salt/Plaster	10,000 - 48,000[b]	Yes	Yes	No	No	No	-		No (L-5)	-	Yes (L-3, L-5)	-	-	-
K-Mag ($K_2SO_4 \cdot 2MgSO_4$)	10,000,000 - 30,000,000[b]	Yes	Yes	No (L-1)	No	Yes	-	Yes Bounding for Hardpan	-	No (L-5)	Yes (L-3)	-	-	Proposed (L-6)
Conveyance (various components)	NA	-	-	-	Yes (L-8)	No	-	-	-	-	-	Yes	Yes	Proposed (L-6)
Heterogeneous Hardpan (breakable aggregates in sludge) Candidate materials: • Kaolin/plaster chunks in clay • K-Mag chunks in kaolin/plaster • Debris & K-Mag in kaolin/plaster	TBD	No	No	No	No	No	-	Yes	-	-	Yes	Yes	Yes	Possible (L-6)
Chemical Simulant of A-105 Composition	TBD	No	No	No	No	No	-	Possible (L-7)	-	-	Possible (L-7)	Possible (L-7)	Possible (L-7)	Possible (L-7)

(a) Shear strength
(b) Compressive strength
(c) Critical shear stress for erosion or erosion rate

Limitations
L-1: no direct measurement, but some data available
L-8: most material has known size, but the size range of some eroded material recommended for testing is not known

(d) these names represent simulant types as described by Powell et al. (1997)

Limitations
L-2: does not challenge erosion (simulant strength too low and hence erosion too easy compared with estimated A-105 behavior)
L-3: does not challenge screen plugging with vacuum capture (will likely not create simulant chunks capable of plugging the screen)
L-4: may not challenge conveyance
L-5: likely not representative of A-105 waste
L-6: may not challenge line erosion (abrasion)
L-7: likely difficult to make simulant that appropriately challenges the key physical operations

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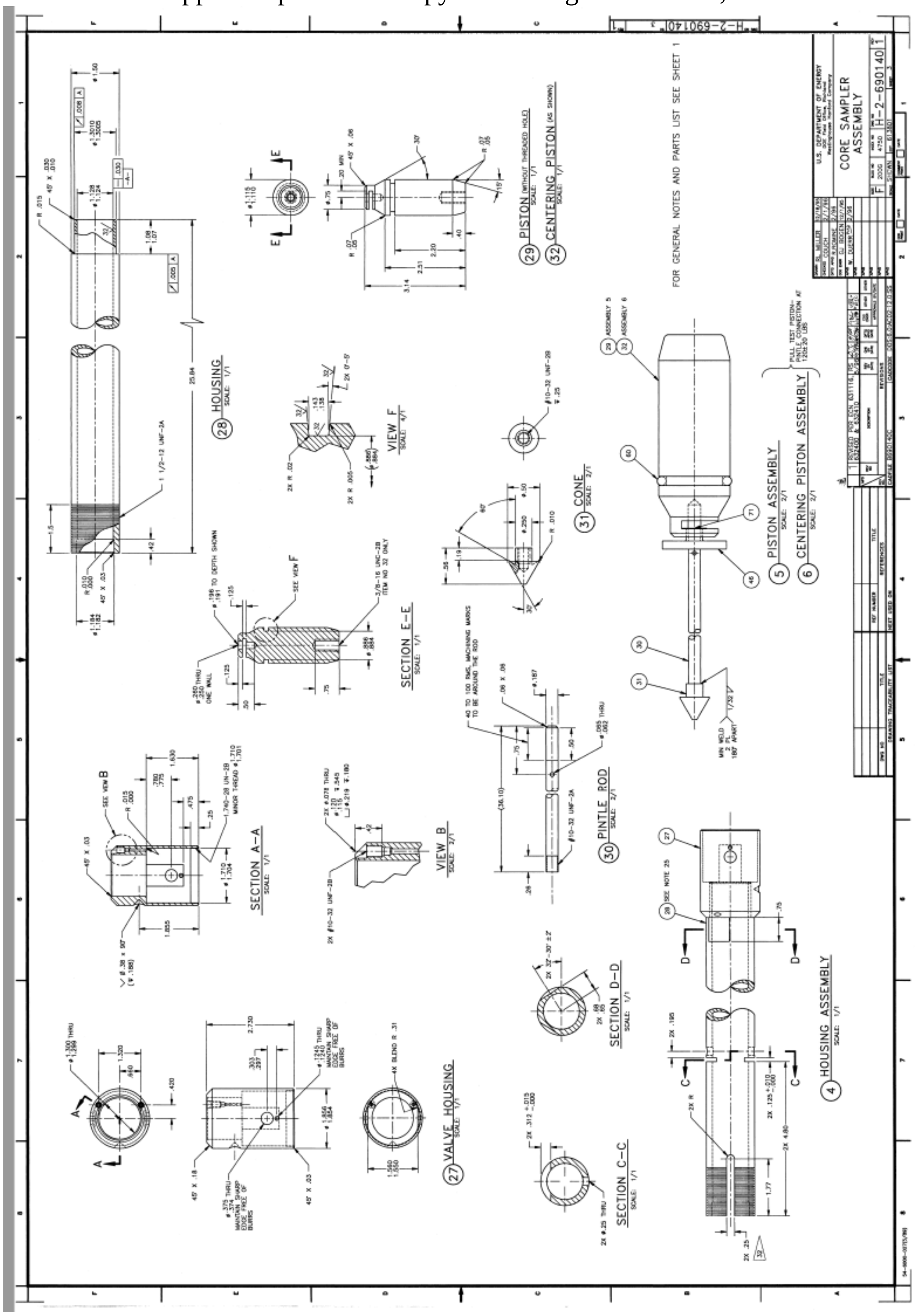
Appendix A

Core Sampler Assembly

Appendix A

Core Sampler Assembly

This appendix provides a copy of drawing H-2-690140, Rev. 1.



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