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Sandia National Laboratories

Waste Isolation Pilot Plant (WIPP)

Waste Erodibility with Vertical and Horizontal Erosion Flumes

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Acronyms and Abbreviations

ASSET flume	Adjustable Shear Stress Erosion and Transport flume
CCA	Compliance Certification Application
CCDF	Complementary Cumulative Distribution Functions
CPR	Cellulosics, Plastics, and Rubbers
CRA	Compliance Recertification Application
DAS	Data Acquisition System
DBR	Direct Brine Releases
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ES&H	Environmental Safety and Health
HMI	Human Machine Interface
I/O	Input or Output modules used in the Data Acquisition System
M&TE	Measurement and Test Equipment
NP	Nuclear Waste Management Procedure
PA	Performance Assessment
PABC	Performance Assessment Baseline Calculation
PAVT	Performance Assessment Verification Test
QA	Quality Assurance
RTD	Resistive Temperature Device
RTU	Remote Terminal Unit
SEAWOLF flume	Sediment Erosion Actuated by Wave Oscillation and Linear Flow flume
SEDflume	Sediment Erosion at Depth flume
SNL	Sandia National Laboratories
SP	Activity/Project Specific Procedure
SSTL	Soil and Sediment Transport Laboratory
SWRC	Sandia National Laboratories WIPP Records Center
TAUFAIL	effective shear strength for erosion (typically referred to as the “waste shear strength”)
TRU	Transuranic
UCSB	University of California, Santa Barbara
UF	University of Florida
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VEF	Vertical Erosion Flume
VFD	Variable Frequency Drive
WES	Waterway Experimental Station
WIPP	Waste Isolation Pilot Plant

Revision History

The following text is the original issue of this Test Plan; no prior revisions exist. Changes to this document, other than those defined as editorial changes per Sandia National Laboratories Waste Isolation Pilot Plant Nuclear Waste Management Procedure NP 6-2 (Document Control), will be reviewed and approved by individuals having the same level of responsibility as those who performed the original review and approval. All revisions will have at least the same distribution as the original document.

1.0 Purpose and Scope

The primary objective of this testing program is to determine the critical shear stress for the initiation of erosion of surrogate waste samples subjected to a hydrodynamic shear stress. This study is needed to assess the critical shear stresses that might be experienced as a result of a human intrusion scenario. This scenario consists of an exploratory drill hole vertically penetrating the sealed Waste Isolation Pilot Plant (WIPP) repository after it is filled with transuranic (TRU) radioactive waste. Critical shear stress is a measure of the erodibility of the waste and parameters necessary for its calculation can be directly determined with the use of a vertical and/or horizontal erosion flume. The critical shear stress – BOREHOLE : TAUFAIL – is one of the most sensitive WIPP performance assessment (PA) parameters used in the calculation of potential radionuclide releases. Since the Compliance Certification Application (CCA) the lower limit of this parameter has been estimated from data for the surface layer of soft, fine-grained, cohesive mud. The use of the surface layers of soft mud to estimate the lower limit of critical shear stress is considered questionable as that material is not a realistic analog for future states of anticipated WIPP waste. The research described in this test plan strives to realistically describe and measure behavior critical to containment of WIPP waste from a potential, future drill penetration. Specifically, this work will measure the response of previously accepted surrogate waste materials subjected to a fluid shear stress, providing realistic experimental data necessary for calculating waste critical shear stress, and thus assisting parameter development for the Cutting and Cavings model calculations used for WIPP re-certification.

1.1 Background of Direct Release Mechanisms and the Drill Penetration Scenario

Throughout the regulatory period, releases from the WIPP as estimated by PA have fallen into two principle categories, namely:

1. direct releases, and
2. long-term releases.

Direct releases occur during a drilling intrusion event and are subdivided into three components, namely:

- cuttings and cavings,
- spallings, and
- direct brine releases (DBR).

Cuttings refer to the waste material encountered and removed by a drill bit as it passes through the waste. Cavings include materials eroded from the walls of the waste and brought to the surface by the drilling fluid. Cuttings and cavings are generally grouped together in PA. Spallings account for additional material that may be brought to the surface through venting of repository gases into the lower-pressure borehole. DBRs are flows of pressurized brine from the repository to the surface during the few days before a borehole is assumed to be plugged.

Long-term releases include radionuclide transport in groundwater through the various geologic units to the land withdrawal boundary. The most transmissive unit is the Culebra Dolomite Member of the Rustler Formation. Radionuclides may be transported to the Culebra primarily by

brine flow up boreholes. Helton et al. (1998) have demonstrated that other transport pathways, e.g., shaft seals or marker beds, are not considered a significant means of radionuclide transport.

The cavings component of a direct release is caused by the shearing action of the drilling fluid (mud). Drilling mud flows helically up the borehole and applies a hydrodynamic shear stresses on the borehole wall as shown in Figure 1. It is hypothesized that material erodes from the borehole wall when the shear stresses in the drilling mud exceed the shear strength of the wall material (Berglund, 1992). As a result, the borehole diameter increases locally at the level of the repository. Cavings allow the volume of waste removed from the repository to exceed the volume of the original borehole. As the diameter of the borehole increases, the fluid shear stresses at the outer boundary decrease. The cavings process will cease when the failure strength of the wall material equals or exceeds the fluid shear stress at the outer boundary of the flow region.

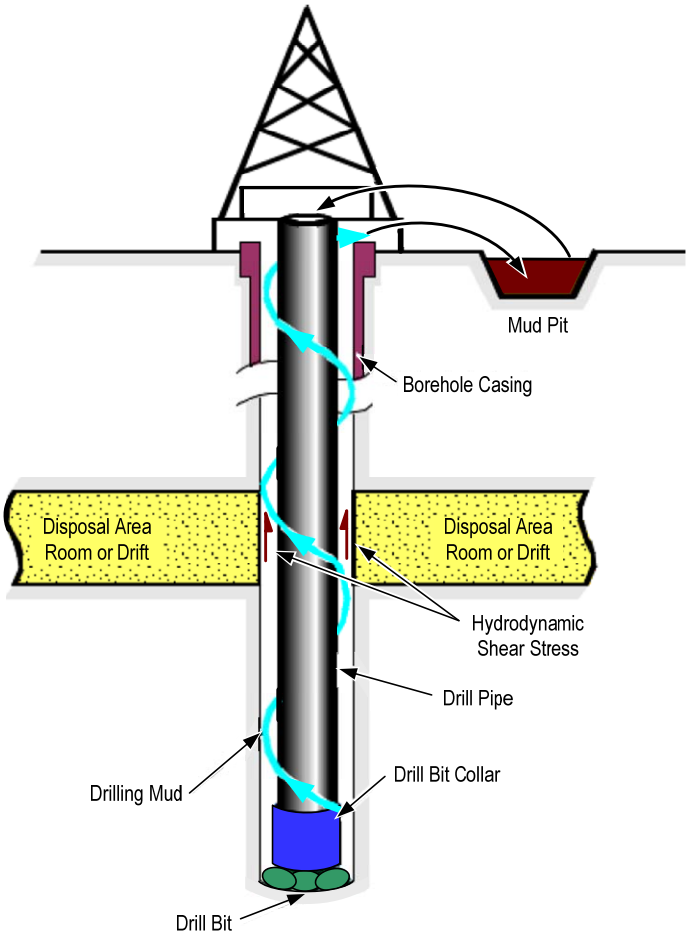

Figure 1. Standard rotary drilling operation inadvertently penetrating the repository (not to scale).

1.2 History of the Parameter BOREHOLE:TAUFAIL

Berglund (1992) performed the first analyses and created the original models for cuttings, cavings, and spallings for WIPP PA. He assumed that the effective shear strength would be similar to montmorillonite clay, approximately 1 to 5 Pa (Sargunam et al., 1973). TAUFAIL was later examined by Butcher (1994) who argued that the degraded waste would be similar to a clay-sand mixture with an estimated strength between 0.1 and 1 Pa and a median of 0.5 Pa. Based upon a subsequent reevaluation of the literature, Butcher et al. (1995) used a range of 0.1 to 10 Pa and a median of 1 Pa in a constructed distribution. Berglund (1996) reported the range of shear strength values for the surface layer of San Francisco Bay mud (Partheniades and Paaswell, 1970) and montmorillonite clay (Sargunam et al., 1973). The analyses supporting the CCA (DOE, 1996) used a uniform distribution with a range of 0.05 to 10 Pa and a median of 5.0 Pa based on Berglund's (1996) assessment. There is a consensus that ocean-bay mud, especially the weak surface layer, is not representative of the future state of repository waste, and that the lower limit of TAUFAIL values were very conservatively chosen to be the lowest value cited in the literature which happens to be that of the surface layer of San Francisco Bay mud.

It is important to note that at the time of Berglund's work all standard methods for determining critical shear strength of sediments considered only the surface layer of the sediment bed, i.e., approximately the top 1 cm., although breakthrough technologies were being developed to overcome this obstacle. The surface layer of fine grained sediment beds, e.g., those containing clay or other particles less than ~ 200 μm, are considerably weaker than layers just a few centimeters directly below due to consolidation processes (Jepsen et al., 1997a). Essentially, the additional weight of the overlying sediments causes a pressure build-up in the deeper interstitial waters which eventually migrate to the surface bringing sediment particles closer together. This increases the sediment density and cohesive bonds thereby strengthening the bed with increasing depth (Jepsen et al., 1997a).

For the Performance Assessment Verification Test (PAVT), the sensitivity of the cavings model to changes in the waste shear strength was studied by the Environmental Protection Agency (EPA) (Trovato, 1997a). The cavings model is extremely sensitive to the parameter TAUFAIL, especially the lower limit, because a weaker material produces greater cavings releases. Consequently, the EPA required the Department of Energy (DOE) to estimate the waste shear strength based on particle size distributions rather than experimental analog data, as was done for the CCA analyses (Trovato, 1997b). Based on expert elicitation (CTAC, 1997), the lower limit of the mean particle size of WIPP waste was estimated to be 1 mm, while the upper limit was 10 cm, assuming no cementation, and it could approach room size if cementation occurred (Wang, 1997).

For the PAVT analyses, the Department of Energy's (DOE) approach was to use the Shields parameter, following the method in Simon and Senturk (1992), as suggested by the EPA (Trovato, 1997b) and as outlined in a facsimile to DOE by Peake (1997). The Shields parameter is a measure of the threshold conditions between erosion and sedimentation of a single particle (Julien, 1998). This condition is usually referred to as incipient motion. Threshold conditions occur when the hydrodynamic forces acting on a particle balance the resisting gravitational

forces, i.e., the particle's weight. The Shields diagram remains the most widely used criterion for incipient motion of a non-cohesive sediment (Cao et al., 2006).

As discussed above the mean particle size was estimated to be between 0.1 and 10 cm (Wang, 1997). Wang and Larson (1997) assumed this particle size range and a minimum mean particle density of 2.5 g/cm^3, which yielded a range for TAUFAIL between 0.64 and 77 Pa (Wang, 1997; Wang and Larson, 1997). However, in the PAVT analyses, the DOE used the minimum value from the CCA (0.05 Pa) and the maximum value from the Shields parameter method (77 Pa) for conservativism as directed by the EPA (Kruger, 1997). A loguniform distribution was used to provide equal weighting over shear stress values (0.05-77 Pa) that ranged over three orders of magnitude (EPA, 1998).

Another approach used to obtain a realistic value of the lower limit of TAUFAIL was to directly measure the erosion resistance of degraded surrogate waste material. Jepsen et al. (1998a) used the Sediment Erosion at Depth flume (SEDflume) first introduced in McNeil et al. (1996) to test highly degraded surrogate waste recipes developed by Hansen et al. (1997, 2003) for the spallings model review panel. In the sediment transport community SEDflume marked a major advance in the field of sediment dynamics. By allowing for the measurement of shear strength of sediment beds at and well below the sediment surface through application of a wide range of fluid shear stresses, it made examination of shear strength of the entire sediment body possible. Today SEDflume is considered the industry standard for measuring sediment erosion and is being widely used by the US EPA, the US Army Corps of Engineers (USACE), and consulting companies (Lick, 2009).

Initial SEDflume studies measured erosion rates of a 10 × 15 cm compacted surrogate waste samples, and these data were used to determine critical shear stress (Jepsen et al., 1998a). These studies were conducted by the University of California, Santa Barbara (UCSB) under Sandia contract AX-9022 in FY98. The results obtained with the SEDflume demonstrated the feasibility of testing samples of various compositions prepared to simulate anticipated WIPP repository wastes. The surrogate waste materials used for these initial tests are described in Hansen et al. (1997) as 50% and 100% degraded waste, where the percent degradation indicates the anticipated amount of iron that is corroded and the amount of cellulosics, plastics, and rubbers (CPR) that is degraded by weight.

Hansen et al. (1997, 2003) developed the surrogate waste recipes based on the anticipated future state of the waste considering inventory, evolution of the underground environment, and experimental results. The waste comprised a mixture of raw materials including iron, glass, cellulosics, rubber, plastic, solidification cements, soil, and WIPP salt. Hansen et al. (1997) also considered degradation of each waste constituent. The authors asserted that the degraded waste material properties represented the lowest plausible realm of the future waste state because no strengthening processes were included, such as compaction, cementation, mineral precipitation, more durable packaging and compressed waste, and less corrosion. The 50% degraded surrogate waste material was used by Hansen et al. (1997, 2003) to establish the parameters for the spallings model, which was accepted by the Spallings Conceptual Model Peer Review Panel (Yew et al., 2003) and incorporated into the CRA-2004 PABC. It was believed that the samples

used by Jepsen et al. (1998a) represent an unobtainable degraded state and are thus far weaker than any possible future state of the waste (Hansen et al., 1997, 2003; Hansen, 2005).

The experimental measurements of erosion rate made by Jepsen et al. (1998a) were used to calculate the critical shear stress for erosion. Jepsen et al. (1998a) defined the critical shear stress as the shear stress at which a very small, but accurately measurable, rate of erosion occurs. They chose an erosion rate of 10^{-4} cm/s, which closely matched the incipient motion work of other prominent scientists (Roberts et al., 1998). Since it is difficult to measure a critical shear stress at exactly 10^{-4} cm/sec, erosion rates were generally measured above and below 10^{-4} cm/s at shear stresses that differed by a factor of two or less. The critical shear stress was then linearly interpolated to an erosion rate of 10^{-4} cm/s. According to Jepsen et al. (1998a), this produced results within a 20% accuracy for the critical shear stress.

Herrick et al. (2007b) independently analyzed the Jepsen et al. (1998a) data and differentiated between two erosive zones in the material. The first, known as “surface erosion,” involves particle-by-particle entrainment of the surficial sediments. The surface layer is an active layer, consisting of unconsolidated material freshly laid down and continually churned by fluid currents and biological activity. It is often associated with fluidized mud particles in the uppermost sections of deposited sediment beds. The second zone is known as “bed erosion” or “mass erosion,” results from shear loading of the bed. In this zone, the plane of failure is deeper into the bed and erosion takes place by the removal of relatively large pieces of soil. As consolidation proceeds, the material in layers below the surface is crushed. The material becomes more tightly packed and comparatively stronger. The bed becomes stratified and the material shear strength and density typically increase monotonically with depth.

Herrick et al. (2007b) argued that the applicable shear strength of the waste should be a measure of the bed or mass erosion of the surrogate waste material and not that of the surface material. They reasoned that in the repository there are no freshly laid down sediments and thus, no active surface layer. In addition, the salt will creep into the repository compacting the waste and a subsequent drilling event will have to cut vertically into the consolidated waste as shown in Figure 2.

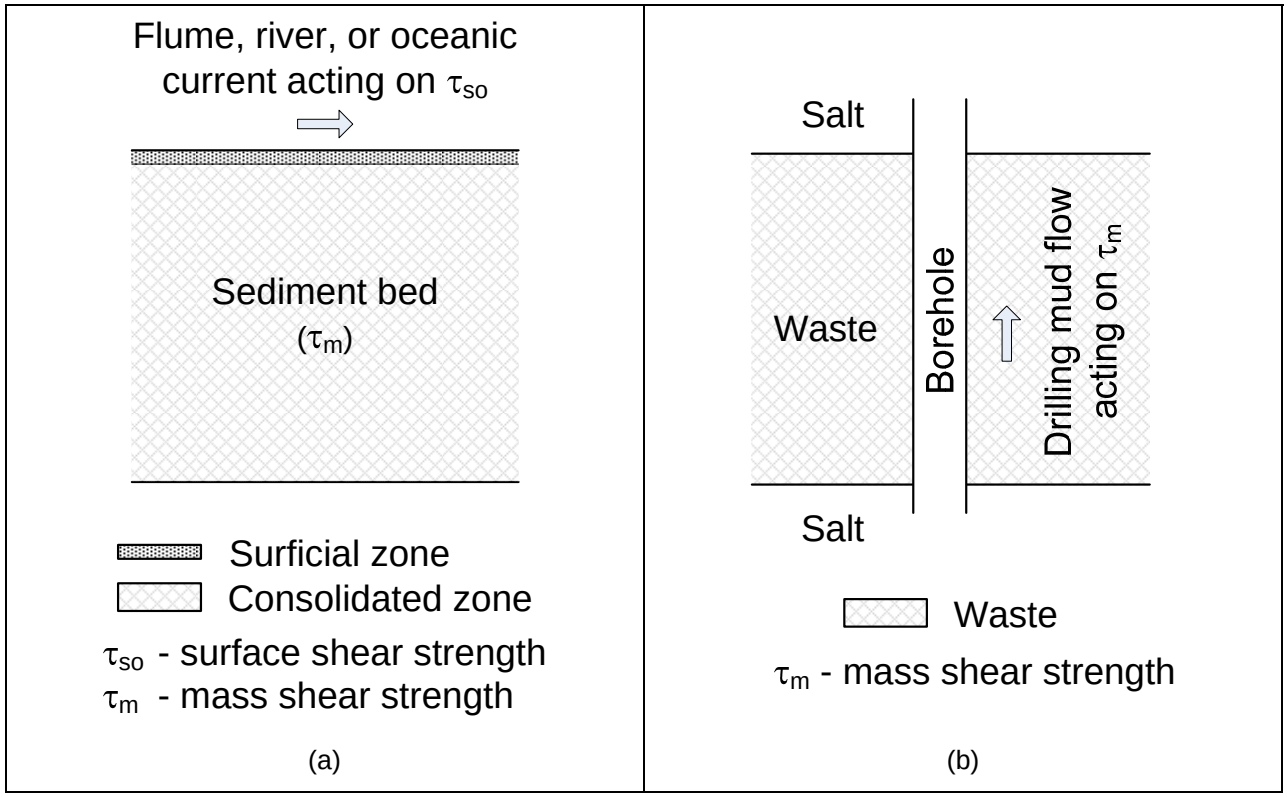

Figure 2. Schematic of various shear strength values and the direction of the currents acting on them: (a) flume experiment, which simulates a river or oceanic current, and (b) WIPP repository.

Herrick et al. (2007b) used a method proposed by Parchure and Mehta (1985), and advanced in Teeter (1987), to assess the bed strength using a piecewise linear fit of the erosion rate versus the shear stress. Herrick et al. (2007b) selected the mass shear strength of the material τ_m, which is an extension of the upper line to where the erosion rate is zero as shown in Figure 3. This shear strength is also known as the operational shear strength (Teeter, 1987).

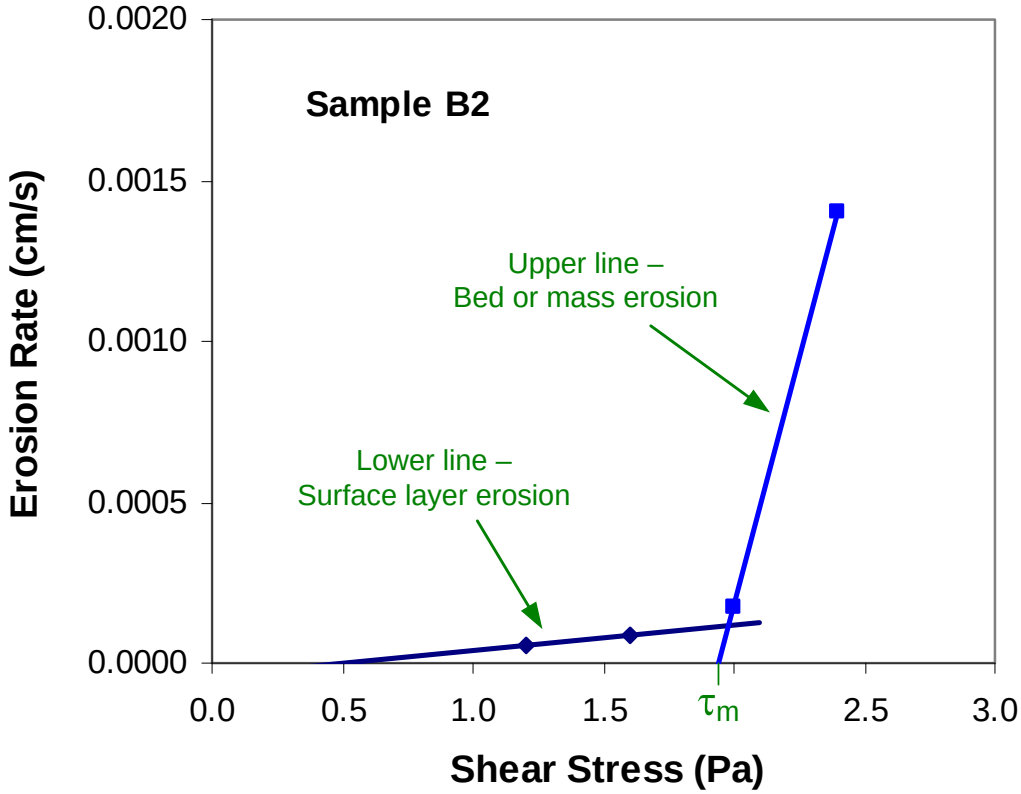

Figure 3. Example of piecewise linear fit to Sample B2 data from Jepsen et al's. (1998a) erosion tests on a surrogate waste. τ_m is a measure of the mass shear strength of the material.

Both Hansen (2005) and Herrick et al. (2007b) recommended using the experimental data for the 50% degraded surrogate waste material for the lower limit of TAUFAIL. A comparison of the values for the lower limit of the waste shear strength obtained by Jepsen et al. (1998a) and Herrick et al. (2007b) are provided in Table 1.

Table 1. Comparison of experimental results of Jepsen et al. (1998a) versus Herrick et al. (2007b).

Sample	Mass Shear Strength, τ_m (Pa)	
	Jepsen et al. (1998a)	Herrick et al. (2007b)
B2	1.67	1.94
B3	2.20	2.11
B4	1.06	1.25
B5 [a]	0.72	0.80
B6 [b]	1.40	1.40
Average	1.41	1.50

Notes:
[a] one data point
[b] two data points at the same erosion rate

Since Berglund (1996) a more detailed literature review was conducted that includes more recent independent studies of the erosion behavior of San Francisco Bay mud. Additional data was obtained for the erosion behavior of San Francisco Bay mud since it is the currently accepted model for the erosion behavior of WIPP waste. Both the US Army Corps of Engineers (USACE) and US Geological Survey (USGS) have performed extensive studies on these muds (Teeter, 1987; Sea Engineering, 2009a and 2009b). For their 1987 studies, the USACE used two laboratories to perform the work, one at the Waterways Experimental Station (WES) and the other at the University of Florida (UF). Sea Engineering (2009a, 2009b) used the latest technology in flume testing provided by SEDflume to obtain new data. The test results are shown in Table 2.

Table 2. Comparison of San Francisco Bay mud shear strength values obtained from different laboratories.

Laboratory	Number of Tests Performed	San Francisco Bay mud mass shear strength, τ_m (Pa) [a]
USACE WES (Teeter, 1987)	18	1.16
University of Florida (Teeter, 1987)	7 [b]	0.42
Sea Engineering (2009a, b)	7	1.12 [c]
Weighted average		0.99

Notes:
[a] Assumes that the bulk density of the mud is the same as the initial bulk density of the emplaced waste determined from the CRA-2004 PABC inventory
[b] Test results include five new tests plus the two reported in Partheniades and Paaswell (1970)
[c] Reported value is the average of the mean shear strengths at each location

As show in the above table, the results are substantially higher than the accepted value of 0.05 Pa from Partheniades and Paaswell (1970), which is currently used as the lower limit of TAUFAIL.

The lower limit of the waste shear strength has been examined by a number of different methods since the CCA, yielding fairly consistent results, ranging from 0.64 Pa (Wang and Larson, 1997) to 1.63 Pa (Herrick et al., 2007a). Using only the mass shear strength estimates, the range narrows even more (0.99 to 1.63 Pa). However, all of these results are more than an order of magnitude greater than the currently accepted value of 0.05 Pa.

1.3 Impact on Performance Assessment Predictions

WIPP PA uses the parameter BOREHOLE : TAUFAIL to represent the “effective shear strength for erosion,” (typically referred to as the “waste shear strength”) in the CUTTINGS_S code (see WIPP PA 2004a, 2004b, 2005a, 2005b for a thorough description of the CUTTINGS_S code). TAUFAIL is treated as an uncertain parameter in WIPP PA, and its value is sampled from a log-uniform distribution, ranging from 0.05 to 77 Pa.

The PA code CCDFGF calculates the complementary cumulative distribution functions (CCDFs) of normalized releases of radionuclides to the environment. Each individual CCDF summarizes the likelihood of releases across all possible futures for one vector of parameter values. The

uncertainty in parameter values results in a distribution of CCDFs, and PA results are presented as a distribution of CCDFs of releases.

The mean CCDFs for all release pathways for the first replicate (R1, which consists of 100 sets of 10,000 simulations) of the 2004 Compliance Recertification Application (CRA-2004) PA Baseline Calculation (PABC) are shown in Figure 4. Cuttings and cavings releases are the dominant release mechanism at probabilities greater than about 0.003, and DBRs exceed all other release mechanisms at lower probabilities. Above a probability of about 0.02, the cuttings and cavings mean CCDF exceeds other mean CCDFs by at least an order of magnitude (Vugrin and Dunagan, 2005). On average, cavings comprise about 70% of the CRA-2004 PABC cuttings and cavings area, contributing up to 90% for some vectors (Vugrin, 2005). As shown in Figure 4, the releases produced by subsurface transport in the Culebra (and/or the Salado) make essentially no contribution to the mean total CCDF.

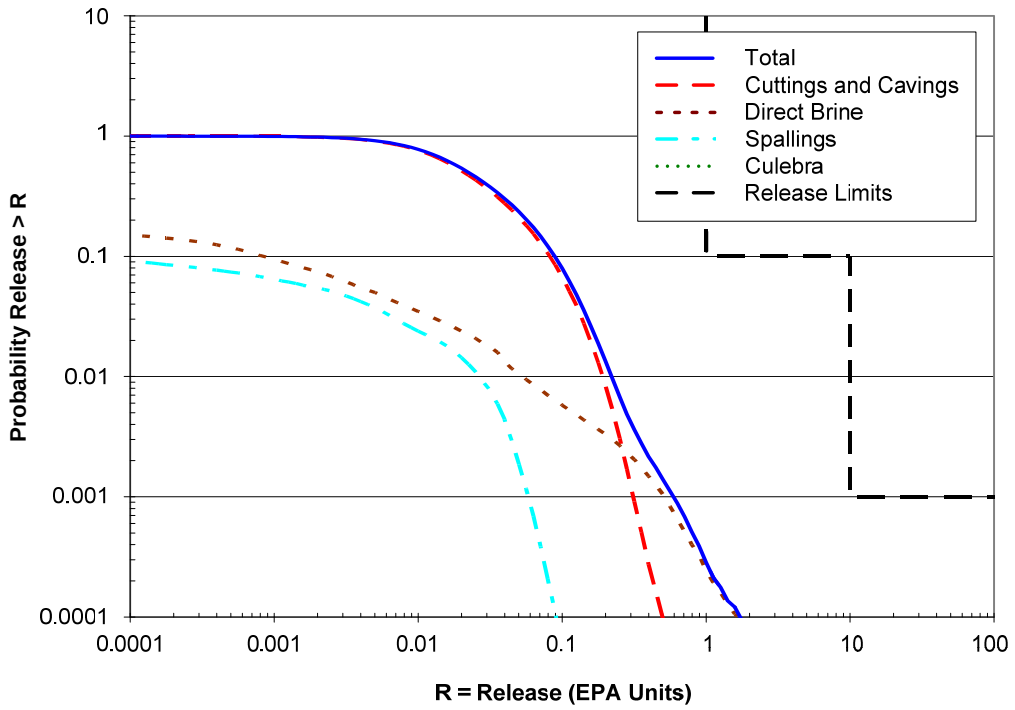

Figure 4. Mean CCDFs for all release pathways for replicate R1 of the CRA 2004 PABC (Vugrin and Dunagan, 2005).

Kirchner (2005) used the code STEPWISE to demonstrate that the release of radionuclides to the accessible environment is extremely sensitive to the waste shear strength. In the CRA-2004 PABC, the uncertainty in the total normalized releases is largely due to uncertainty in the waste shear strength. This is shown in Table 3 where the waste shear strength parameter (called WTAUFAIL in STEPWISE) accounts for about 88% of the regression error in the model for total releases, making WTAUFAIL the most important variable in the CRA-2004 PABC. This is consistent with other PA results. The volumes of cuttings and cavings are primarily controlled by shear strength and the negative correlation was expected.

Table 3. STEPWISE ranked regression analysis for mean total releases: replicate R1 of CRA-4004 PABC (Kirchner, 2005).

Step[a]	Expected Normalized Release		
	Variable[b]	R^{2c}	SRRC[d]
1	WTAUFAIL	0.88296	-0.94369
2	WSOLVAR3	0.90538	0.14323
3	DOMEGA	0.91685	0.10497
4	WFBETCEL	0.92613	-0.09382
5	BPINTPRS	0.93357	0.08050
6	BPPROB	0.93852	0.07062
7	SHURGAS	0.94285	-0.06464
8	SHLPRM2	0.94638	0.05951

[a] Steps in stepwise regression analysis
[b] Variables listed in order of selection in regression analysis
[c] Cumulative R^2 value with entry of each variable into regression model
[d] Standardized Rank Regression Coefficient in final regression model

Increasing the value of the waste shear strength could have a significant impact on the calculated cuttings and cavings releases, and hence, the total releases. PA calculations AP-132-0, AP-132-1, and AP-132-AM (Ismail, 2009) incorporated parameter changes to the waste shear strength deemed more representative of WIPP long-term performance. The calculations were compared to those for the CRA-2009 analyses in which the same range and distribution of values were used as for the PAVT, CRA-2004, and CRA-2004 PABC. The values used in AP-132 are based on the recommendations of Herrick et al. (2007a, 2007b), where the minimum value of TAUFAIL was increased, narrowing the range to nearly two orders of magnitude. The decrease in range also allows for the use of a uniform distribution. The range of TAUFAIL values along with the distributions used for CRA-2009 and AP-132 are given in Table 4.

Table 4. Ranges and distributions of TAUFAIL used in various cuttings and cavings analyses (Ismail, 2009).

Analysis	Range	Distribution
CRA-2009 [a]	0.05 – 77.0 Pa	Loguniform
AP-132-0	1.33 – 77.0 Pa	Uniform
AP-132-1, AP-132-AM	1.50 – 77.0 Pa	Uniform

Note: [a] The range and distribution of TAUFAIL used in CRA-2009 is the same as that for the PAVT, CRA-2004, and CRA-2004 PABC.

Ismail (2009) compared the cuttings and cavings results from the different analyses and found that increasing the minimum TAUFAIL value and changing to a uniform distribution had a large effect on the cavings area and the number of vectors that had no cavings (Table 5). He showed that the mean cavings area for CRA-2009 was approximately 16 times larger that the mean cavings areas for the three AP-132 analyses and that the maximum observed cavings area in CRA-2009 was six times larger than in those for AP-132. In addition, Ismail (2009) found that

for CRA-2009 only 30 of the 300 vectors did not have cavings, whereas for the AP-132 calculations the number of vectors without cavings has increased to 141 out of 300. Figure 5 shows a strong inverse relationship between cuttings and cavings areas and TAUFAIL for all analyses (note that the low end of the vertical axis represents the drill bit area, 0.0760 m^2, which corresponds to zero cavings). Again, it is clear from the nearly linear trend that increasing the minimum TAUFAIL value directly, and significantly, reduces cavings releases. For example, the maximum cuttings and caving areas decreased by about 75%, from about 0.8 to 0.2 m^2.

Table 5. Cavings area statistics for the CRA-2009 and AP-132 analyses (Ismail, 2009).

Analysis	Replicate	Cavings Area (m^2)		Vectors with no Cavings
		Maximum	Mean	
CRA-2009	R1	0.748	0.177	9
	R2	0.785	0.175	10
	R3	0.753	0.178	11
AP132-0	R1	0.122	0.011	50
	R2	0.118	0.011	43
	R3	0.100	0.011	50
AP132-1, AP132-AM	R1	0.114	0.011	50
	R2	0.111	0.011	44
	R3	0.094	0.011	50

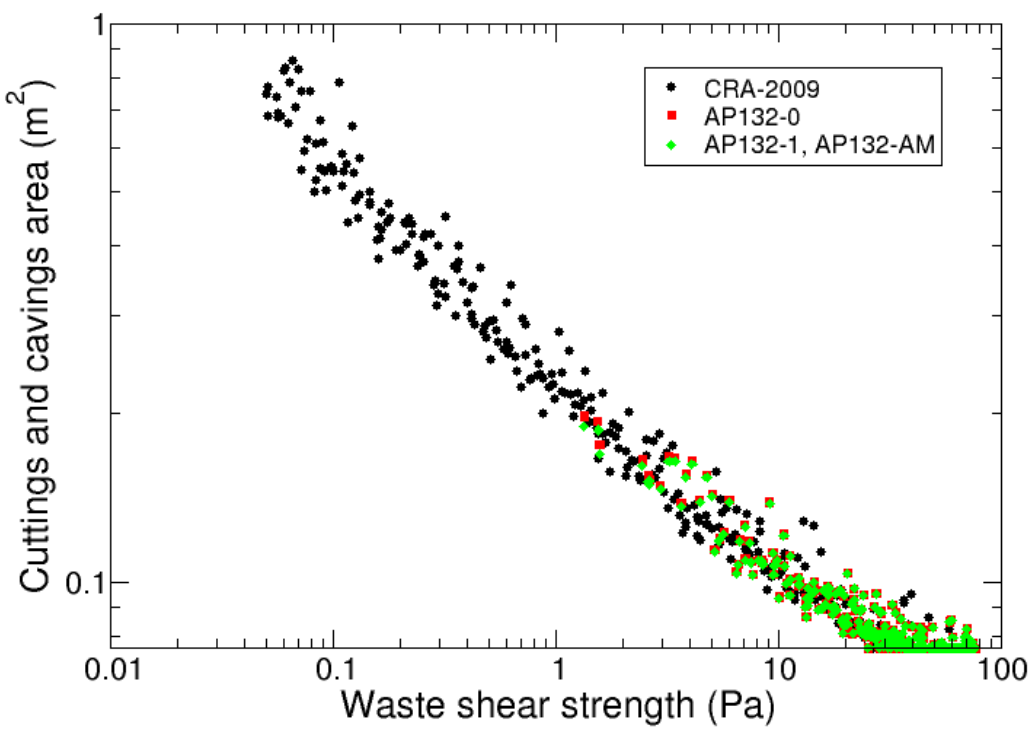

Figure 5. Cuttings and cavings area as a function of waste shear strength (Ismail, 2009).

1.4 Proposed Tests Designed to Address Criticisms of Historical Methods Used for Obtaining Estimates for the Lower Limit of TAUFAIL

Despite all of the aforementioned approaches to define a more realistic value of TAUFAIL, none of the results of these approaches have been adopted. The approach that received the most support was the use of SEDflume to directly measure the erosion resistance of degraded surrogate waste material. In fact the primary criticism of this approach noted by a peer review panel was that waste strength values were derived from horizontal flume testing (Coons et al. 2007). Tests conducted in a horizontal configuration may overestimate the shear strength, to some extent, due to the effects of gravity. However, scoping calculations performed to address the panel's concerns have suggested that the effect would be small. Regardless, laboratory testing using a vertical flume would resolve this issue, and the modified SEDflume experiments proposed herein will address the significance of sample orientation on sample shear strength.

For the experiments proposed in this test plan, a modified SEDflume oriented vertically, will be used to determine the critical shear stress for erosion of surrogate waste samples (which represent the degraded WIPP waste) subjected to a hydrodynamic shear stress. The vertically oriented modified SEDflume will be known as the Vertical Erosion Flume (VEF). The VEF design is intended to simulate a situation where a drilling operation penetrates a waste-filled room of the WIPP repository. Fluid shear stress imposed by the flowing drill fluid may erode material from the intrusion borehole wall and transport it to the surface. Due to the difficulties of directly measuring critical shear stress (discussed in detail later in this document), experiments will be performed at shear stresses greater than critical to measure erosion rates and these data will be used to calculate critical shear stress using multiple methodologies. Investigators will also note the erosion mechanisms of the samples such as aggregate and mass failure erosion modes which are typical of compressed or very cohesive sediments (Partheniades, 1965; Parchure and Mehta, 1985; Roberts et al., 1998). Aggregate erosion is defined as the erosion of chunks of material stuck together, whereas mass failure erosion is when an entire layer of sample fails at once.

Experiments will be duplicated with the horizontal sediment flume to test the effect of orientation on the erosion of the surrogate waste material.

1.5 History of the Development SEDflume-Based Erosion Measurement Devices

The vertical erosion flume is based on a horizontal sediment flume first built and routinely used in the Department of Mechanical and Environmental Engineering, UCSB (Taylor and Lick, 1996; Jepsen et al., 1997a; Roberts et al., 1998). The UCSB flume was named the Sediment Erosion at Depth flume, or SEDflume for short. The original purpose of SEDflume was to directly measure the erosion rate and critical shear stress of relatively undisturbed or laboratory developed sediments over a wide range of unidirectional flow induced shear stresses (quiescent to storm event) and variation with depth below the sediment-water interface. The SEDflume's capabilities were a tremendous step forward in the science of sediment dynamics. As mentioned earlier, today SEDflume is considered the industry standard for measuring sediment erosion and

is being widely used by the US EPA, the US Army Corps of Engineers, and consulting companies (Lick, 2009).

In 1999, Sandia National Laboratories (SNL) created the Soil and Sediment Transport Laboratory (SSTL) in Carlsbad, NM to help WIPP and non-WIPP customers resolve geotechnical related erosion and transport issues. In 2002, SNL received a patent for modifications to SEDflume that enabled the subsequent measurement of the transport mode (bedload or suspended load) of the eroded sediment. The new device was named the Adjustable Shear Stress Erosion and Transport (ASSET) flume (Roberts and Jepsen, 2001; Roberts et al., 2003). The ASSET flume holds US Patent No. US 6,494,084 B1. In 2004, Sandia National Laboratories received another patent for different modifications to SEDflume that allowed for characterizing and quantifying sediment erosion under combined current-wave action to simulate the near bottom shear stresses in wave dominated environments. The new device was named the Sediment Erosion Actuated by Wave Oscillation and Linear Flow (SEAWOLF) flume (Jepsen et al.; 2002, Jepsen et al., 2004). The SEAWOLF flume holds US Patent No. US 6,679,105 B1.

2.0 Experimental Process Description

2.1 Description of Vertical and Horizontal Erosion Flumes

The description of the flume and information in this section is based in large part on articles by Jepsen et al. (1997b), McNeil et al. (1996), Taylor and Lick (1996), and Jepsen et al. (1997a). It should be noted that the horizontal sediment erosion capability/portion of this flume is primarily the same as the flume used in the initial surrogate waste erosion studies performed at UCSB (Jepsen et al., 1998a). Also, the operation of the horizontal and vertical material erosion capabilities is essentially the same. Therefore, a description of only the vertical material erosion capability will be given, however, when appropriate, differences between the two capabilities will be pointed out and discussed further.

A schematic of the vertical erosion flume is shown in Figure 6. It is a straight flume, containing a test section with an open side through which a rectangular or circular cross-section coring tube containing surrogate waste samples can be inserted. The main components of the flume are the sample container; the erosion channel including erosion test section; an inlet section for uniform, fully developed, turbulent flow; a flow exit section; a fluid storage tank; a pump to force fluid through the system; and a screw jack motor/controller combination to extrude the sample level with the test channel wall. The test section, inlet section, and exit section are made of clear polycarbonate (Lexan™) so that the sample-fluid interactions can be observed visually. The fluid in the vertical flume is contained in a large storage tank. To prevent fouling of the pump, baffles are emplaced in the reservoir to allow the larger and heavier eroded surrogate waste debris to settle out of suspension prior to recirculation. To prevent lighter material from recirculation, a screen is placed on the inlet of the recirculation pump. The fluid is pumped through the system from the 450 l storage tank, through a 5 cm diameter pipe, and then into the rectangular erosion channel. The fluid used in these tests will either be a brine similar to typical drilling mud used in the Salado formation or tap water. Of importance is that the density and viscosity of the fluid are

determined through water quality measurements (temperature and conductivity) such that the flow can be regulated to subject the samples to a known hydrodynamic shear stress. The method for determining the applied shear stress as a function of fluid properties discussed in a later section.

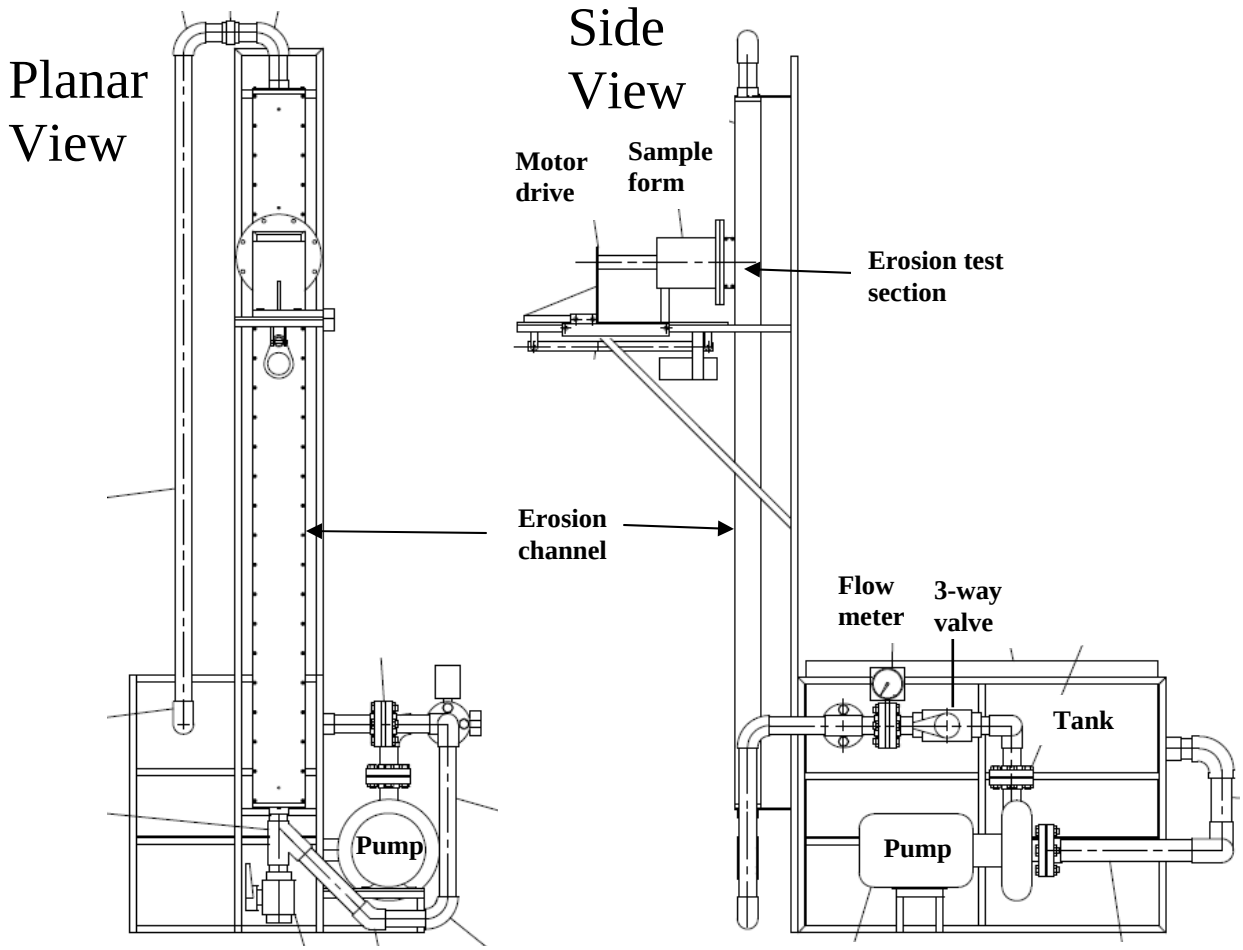

Figure 6. Schematic of vertical erosion flume (not to scale).

The vertical erosion flume is modular in design such that the erosion channel and pump can be swapped out to generate a variety of flow conditions. The vertical erosion flume's enclosed (internal flow) erosion channels vary from 5.0-6.0 cm thick, 10.5-15.5 cm wide and 180-220 cm long (Figure 6). In this way, the thickness of the channel, the distance between the channel's far edge and the surrogate waste sample surface, can match the typical distance between the borehole wall and the drill stem (5.4 cm). The erosion channel houses the erosion test section and is adaptable to fit either 10-15 cm diameter or 10-15 cm square sample forms. The erosion test section is preceded by at least 180 cm of enclosed rectangular channel, a 20 cm circular-to-rectangular flow converter, and several meters of inlet pipe to create fully developed turbulent flow over the surrogate waste sample. Note that the erosion test section is slightly narrower (10-15 cm) than the erosion channel (10.5-15.5 cm) to reduce the effect of the walls.

A three-way valve regulates the flow so that part of the flow goes into the erosion channel while the remainder returns to the tank. The flow rate of the circulating fluid is monitored by an Endress-Hauser in-line magnetic flow meter. There is a small valve in the erosion channel immediately downstream from the test section, which can be opened at higher flow rates to prevent artificially developed pressure gradients from affecting the erosion behavior of the surrogate waste material. The horizontal configuration of these erosion tests is identical to what is described above except that the specimen is below the erosion channel and is raised up into the flow of the current.

At the start of each test, the sample container and the surrogate waste sample it contains are attached to the test section on the side of the channel. An operator moves the sample laterally using a piston inside the waste holder. The piston is connected to a screw jack and motor/controller combination which can extrude at least a 20 cm of sample. Extensions may be placed on the drive to allow the extrusion of up to a meter or more of surrogate waste sample. By this means, the sample can be moved and leveled with the side of the test section. The extrusion speed of the surrogate waste sample can be controlled at a variable rate in measurable increments as small as 0.25 mm.

The fluid is forced upward through the enclosed channel and across the surface of the sample. The shear produced by this flow may cause the sample to erode. If at a particular flow rate and shear stress no erosion is observed, the flow is incrementally increased until erosion is observed or the limit of the pump is reached. If the surrogate waste sample in the tube erodes, additional material is extruded laterally by the operator so that the sample-fluid interface remains flush with the side of the test and inlet sections. The erosion rate is recorded as the lateral movement of the sample in the coring tube over time. The time of erosion and the sample extrusion distance, for each run, are recorded in the scientific notebook. The erosion rate is the sample extrusion distance divided by the time of extrusion. These data and calculations are recorded in the scientific notebook. The erosion rate data are generally reported in units of cm/s. The surrogate waste sample erosion activity will be documented using a digital video camera when possible.

The vertical flume has two main controls. One control is the flow rate of the circulating fluid, which is determined by the use of the single flow rate pump and three-way valve system. The rate of flow in the channel can exceed 375 l/m and is monitored by an inline flow meter. The second control is the amount of sample extruded as the flowing fluid erodes its surface. In the current configuration of the vertical flume, both control processes are manual and performed by the operator. It is anticipated that prior to beginning these experiments, SNL will utilize a data acquisition system (DAS) to assist with the control and collection of data for these test activities to enable more accurate and reliable measurements.

It should be noted that the vertical flume experiments described in this test plan have not been performed before, either by SNL or elsewhere. Therefore, specific procedures may be required for some tasks. All procedures will be recorded in the scientific notebook including those modified as work progresses and decisions are made as to the best methods for optimizing and refining the experimental process.

2.2 Sample Preparation

It is proposed that the same surrogate waste materials used in the original testing performed by Jepsen et al. (1998a) will be tested as part of this test plan. The surrogate waste material developed for those tests and the procedure followed to form the specimens will be re-created as nearly as possible. Initial development of the surrogate waste materials for those tests is described in Hansen et al. (1997) and the method used to fabricate the samples in Mellegard (1998). Two surrogate waste types were used, 50% and 100% degraded surrogate waste, saturated in brine similar to the WIPP brine. The surrogate waste samples for those tests were subjected to 5 MPa compaction pressures for 15 minutes during fabrication. Not only will these materials be used in the vertical flume, but also in a duplication of some of the Jepsen et al. (1998a) horizontal flume tests as a baseline and to supplement the existing dataset.

The surrogate waste materials will be placed into a steel form and subjected to the desired compaction pressure for a short period of time. One compacting pressure will be a repeat of those used previously for the Jepsen et al. (1998a) tests, i.e. 5 MPa for 15 minutes (Mellegard, 1998). The numerical modeling performed by Herrick et al. (2007a) suggests that a compacting pressure of 2.3 MPa is more appropriate. Compacting pressures used in sample preparation will be noted in the laboratory notebook. The steel form containing the sample will be fastened to the channel test section for the erosion measurements. If other surrogate waste material recipes are developed, they will be noted in the scientific notebook.

The use of replicate samples will help provide a measure of the precision and repeatability of the test method. In addition, replicate samples will help assess the variability of the erosion rate measurements and critical shear stress determinations for different waste surrogate samples.

2.3 Determination of Applied Hydrodynamic Shear Stress

Turbulent flow through pipes has been studied extensively, and empirical functions have been developed which relate the mean flow rate to the wall shear stress. In general, flow in circular cross-section pipes has been investigated. However, the relations developed for flow through circular pipes can be extended to non-circular cross-sections by means of a shape factor. An implicit formula relating the wall shear stress to the mean flow in a pipe of arbitrary cross-section can be obtained from Prandtl's Universal Law of Friction (Schlichting, 1979). For a pipe with a smooth surface, this formula is

$$\frac{1}{\sqrt{\lambda}} = 2.0\log\left[\frac{UD\sqrt{\lambda}}{\nu}\right] - 0.8 \qquad (1)$$

where U is the mean flow speed, ν is the kinematic viscosity, λ is the friction factor, and D is the hydraulic diameter defined as the ratio of four times the cross-sectional area to the wetted perimeter. For a pipe with a rectangular cross-section, or duct, the hydraulic diameter is

$$D = 2hw/(h + w) \qquad (2)$$

where w is the duct width and h is the duct height. The friction factor is defined by

$$\lambda = \frac{8\tau}{\rho U^2} \qquad (3)$$

where ρ is the density of water and τ is the wall shear stress. Inserting Eqs. (2) and (3) into Eq. (1) then gives the wall shear stress τ as an implicit function of the mean flow speed U.

For all shear stresses in the range of 0.05 to 10 Pa created with the use of tap water, the Reynolds numbers, UD/ν, are on the order of 10^4 to 10^5. These values are sufficient for turbulent flow to exist for the shear stresses of interest in this study. For brine, which has a higher density (~1.2 g/cm^3) and viscosity (0.04167 cm^2/s), the Reynolds numbers are on the order of 10^3 to 10^4 for the same shear range. The Reynolds numbers for brine at lower shear stresses indicates transitional flow although the plumbing connections, bends, and transitions will act to trip turbulence.

For flow in a circular pipe, turbulent flow theory suggests that the transition to fully developed turbulent flow occurs within 25 to 40 diameters from the entrance to the pipe. Since the hydraulic diameters of the ducts ranges from 6.8-8.7 cm, this suggests an entry length as short as approximately 170-220 cm and as long as 270-350 cm. The length of the erosion channel leading to the test section is between 180-220 cm and is preceded by a 20 cm flow converter and several meters of inlet pipe. These arguments, along with direct observations, indicate that the flow will be fully turbulent in the test section.

2.4 Measurements of Waste Sample Erosion Rates

The procedure for measuring the erosion rates of the samples with the vertical erosion flume as a function of shear stress and depth are in development as this specific type of experiment has not been performed before. The following is a sample procedure based upon experience with the ASSET flume used at SNL.

The samples are formed as described above, attached to the testing apparatus, and then moved laterally into the test section until the sample surface is even with the side of the test section. A measurement is made of the sample length to the end of the sample in the tube. The flume is then run at a specific flow rate corresponding to a particular shear stress. The flume is capable of creating shear stresses exceeding 10 Pa on the surface of the sample. As the fluid speed is increased, the shear stress across the face of the sample increases until erosion of the material begins. Erosion rates are obtained by measuring the remaining sample length at different time intervals, taking the difference between each successive measurement, and dividing by the time interval.

In order to measure erosion rates at several different shear stresses using only one sample, a procedure similar to the following is expected to be used. Starting at a low shear stress, the flume is run sequentially at higher shear stresses with each succeeding shear stress raised at a step determined by the principal investigator. The manner in which the shear stresses are raised will

be noted in the laboratory notebook. Each shear stress will be run until at least 0.25 mm, but no more than 1 cm, of the sample's length is eroded. In manual operation mode, the time interval will be recorded for each run with a stopwatch and the sample extrusion distance will be recorded with a ruler. If the DAS is used to support the experimental tests, the DAS will record the time and extrusion distance automatically with an internal clock and a motion sensor. The flow will then be increased to the next shear stress, and so on until the highest shear stress is reached. A detailed description of the proposed DAS is provided later in this document.

A detailed description of these procedures will be written at a later time and recorded in the scientific notebook, after the work has progressed sufficiently and the test method has be refined.

2.5 Determination of Critical Shear Stress for Erosion

Due to a gradual increase in erosion as the shear stress increases, it is difficult to precisely define a critical velocity or shear stress at which erosion first takes place. This complexity is compounded as the nature of the erosion near incipient motion often occurs in isolated spots over a larger surface. Therefore to determine the critical shear stress for the initiation of erosion, it is necessary to subject the sample to a range of shear stresses such that at the lowest applied shear stresses no erosion will occur. Progressively higher levels are applied, leading to the beginning of erosion and multiple erosion rates thereafter. Critical shear stress is calculated from these measurements of erosion rates in a number of ways. In this test plan we will describe two accepted SEDflume-based methodologies and a third methodology universally applicable across devices, although a complete discussion of definitions and methods used to determine critical shear stresses will be addressed in a subsequent analysis plan. The three methods are:

1. SEDflume based linear interpolation
2. SEDflume based power law relationship
3. Piecewise linear fit

Each method has its advantages and the shear stresses calculated generally agree and are described in detail here.

2.5.1 SEDflume-based Methods for Determining Critical Shear Stress

The critical shear stress of a sediment bed, τ_{cr}, is defined quantitatively as the shear stress at which a very small, but accurately measurable, rate of erosion occurs. For SEDflume studies, this rate of erosion has been practically defined as 10^{-4} cm/s. This represents 1 mm of erosion in approximately 15 minutes.

Since it is difficult to measure τ_{cr} exactly at 10^{-4} cm/s, erosion rates are practically measured above and below 10^{-4} cm/s. The τ_{cr} is then determined by linear and power law regression (McNeil et al., 1996; Roberts et al., 1998). This is done at different depths within the sample to account for surface effects.

2.5.1.1 Linear Interpolation

The linear interpolation is simply a log-linear regression between the shear stresses where erosion rates were measured above and below 10^{-4} cm/s.

2.5.1.2 Power Law Relationship

A power law relationship that describes the erosion behavior of well mixed sediments is (Jepsen et al., 1997):

$$E = A\,\tau^n \rho^m \qquad (4)$$

Where E is the erosion rate (cm/s), τ is the shear stress exerted by the moving fluid on the sediment surface (Pa) and ρ is the material bulk density (g/cm^3) and A, n, and m are constants that depend on the material characteristics. The equation used in this analysis is an abbreviated variation of Eq. 4:

$$E = A\,\tau^n \qquad (5)$$

where the material bulk density parameter is a function of the constant A. Due to the compacting of the surrogate waste samples to represent the encapsulation of waste over time, density variations will be minimal and any effect will be absorbed by the constant A. For each depth interval, the measured erosion rate (E) and applied shear stress (τ) are used to determine the A and n constants that provide a best fit power law curve to the data for that interval. With good fits (i.e. $R^2 > 0.7$), these parameters can be used to predict erosion rates and critical shear stress (τ_{cr}) for the interval of interest. Rearranging Equation 5 to solve for shear stress, substituting the critical value of erosion rate of 10^{-4} cm/s (Roberts et al., 1998), and using the empirically determined coefficients A and n yields a direct means to calculate the critical shear stress for a given depth interval (Equation 6).

$$\tau_{cr} = (0.0001/A)^{1/n} \qquad (6)$$

Three erosion measurements at different shear stresses are required to determine the constants A and n in the power law relationship.

2.5.2 Piecewise Linear Fit

The piecewise linear method was originally proposed by Parchure and Mehta (1985). They showed that a plot of the erosion rate versus shear stress of their flume testing results could typically be divided into two distinct linear regions. An example of such a plot was shown previously in Figure 3 for the results of Jepsen et al. (1998a). The lower line corresponds to the behavior of the surface layer and the upper line to the mass or bed material. Teeter (1987) suggested that the most conservative estimate of the mass shear strength of the material is given by an extension of the upper line to where the erosion rate is zero (Figure 3). In this test plan, this

mass shear strength has been labeled τ_m. Herrick et al. (2007b) used this value as an estimate of the minimum shear strength of the surrogate waste material.

Ideally, five or six different levels of shear stress including the beginning of erosion are desired for this method of analysis.

2.6 Data Acquisition and Control

The incorporation of a data acquisition system (DAS) on the VEF could greatly enhance the accuracy and reliability of this test program. The DAS will consist of three subsystem components that control and collect the data from sediment flumes. The three components are: hardware, instrumentation, and the operator interface computer and software.

The DAS hardware will be designed and built utilizing a modular approach which will incorporate components directly available from SIXNET incorporated. The SIXNET hardware includes the SixTRAK remote terminal unit (RTU), discrete input/output (I/O) modules, and analog I/O modules. The SixTRAK RTU processor is equipped with: 512 KB static RAM, 16 MB dynamic RAM, and 16 MB flash RAM; uses the LINUX operating system; and features both Ethernet and serial communication ports. The I/O modules can measure various types of analog signals to a 16-bit resolution and can be expanded from 8 to 512 channels with additional modules. All modules have an operating temperature range of -30° to 70°C. The DAS components will be mounted within a rack mounted enclosure, which also incorporates the power supplies, circuit breakers, fuses, and relays to protect and control the system.

The hardware will include a 3-way valve to proportionally divide the direction of the fluid flow and a variable frequency drive (VFD) to control the pump motor speed. This control includes the starting/stopping of the pump motor and control of the motor speed which is directly proportional to the fluid flow rate. A closed loop control process can be established by monitoring the flow rate (as the control variable) and automatically adjusting the 3-way valve position and the motor speed (as the process variable) to maintain a constant flow through the system. The target flow rate will be selected by the operator, and the system will maintain flows better than ± 5% of the target flow rate.

2.6.1 Instrumentation

Flow through the flume system is measured by an in-line flow meter located near the upstream end of the flume supply line. The flow meter will be capable of measuring the flow to an accuracy of ± 1% of the full scale range of the instrument (Table 6). The flow into the primary flume line will be controlled using a 3-way directional valve and pump motor speed controller (a VFD to power the pump). The pump and associated controls will be capable of developing water flow rates of 35-950 l/m in the existing flume channels. The pump performance will vary if other than water is used as the erosion fluid. The flow meter will be the control variable for the 3-way valve position and the pump motor speed.

Water quality (temperature and specific conductance), used for the determination of fluid density and viscosity, will be measured near the downstream end of the flume line, which is also equipped with a valve port to collect water samples for laboratory analyses if required. The temperature will be measured with a resistive temperature device (RTD) or similar device capable of ± 1.0°C accuracy. The conductance of the fluid used in the flume will be measured using a GLI 3725E2T probe or similar device with an accuracy of ± 5.0% of selected range of measurement (Table 6).

The sample feed rate and control systems for advancing the sample into the flow stream will be based on a linear rail table that advances the sample by using an encoder to count the revolutions of the motor which will correlate with the distance that the table advances. This travel distance will be independently verified using a linear variable transducer mounted on the rail table. Using this method the travel of the sample can be tracked within ± 0.1 mm.

The laboratory temperature and ambient pressure will also be monitored throughout the testing to verify that these environmental parameters have not been adversely affected during testing or the test equipment was used within accepted conditions.

Table 6. Proposed quality-affecting M&TE

Type	Function	Accuracy
Flow Meter	Measures flow rates between 35 and 950 l/m (water)	1% of full scale
GLI 3725E2T Specific Conductance Probe & Pro-E3 Transmitter	Measures specific conductance of produced water; data logged by DAS	5% of full scale
Omega 3-Wire RTD 806 Series Temperature Probe	Measures fluid and laboratory temperatures	1.0°C
Druck PDCR-130-W-C Pressure Sensor	Used to measure atmospheric pressure of the laboratory	1% of full scale

All M&TE that is used to collect qualified data will be maintained and/or calibrated consistent with the requirements of NP 12-1 (Control of Measuring and Test Equipment).

2.6.2 Software

Using the Human Machine Interface (HMI) software the operator will be able to select and configure system set points that will be utilized to operate the test. This includes setting flow rates for the test, sample advancement, and data storage rates, etc. Finally the operator interface will visually display real-time feedback on the test parameters being monitored. These parameters will be presented both graphically and as tabular data. The system can be developed to automatically calculate values based on the measured parameters, eliminating the need to process the data off-line after the test completion.

The operator interface computer is also the primary data collection point for the historical data generated during an experiment. Figure 7 depicts the general arrangement of the software

relative to their functions in supporting the primary computers ability to monitor, control and collect data from the DAS.

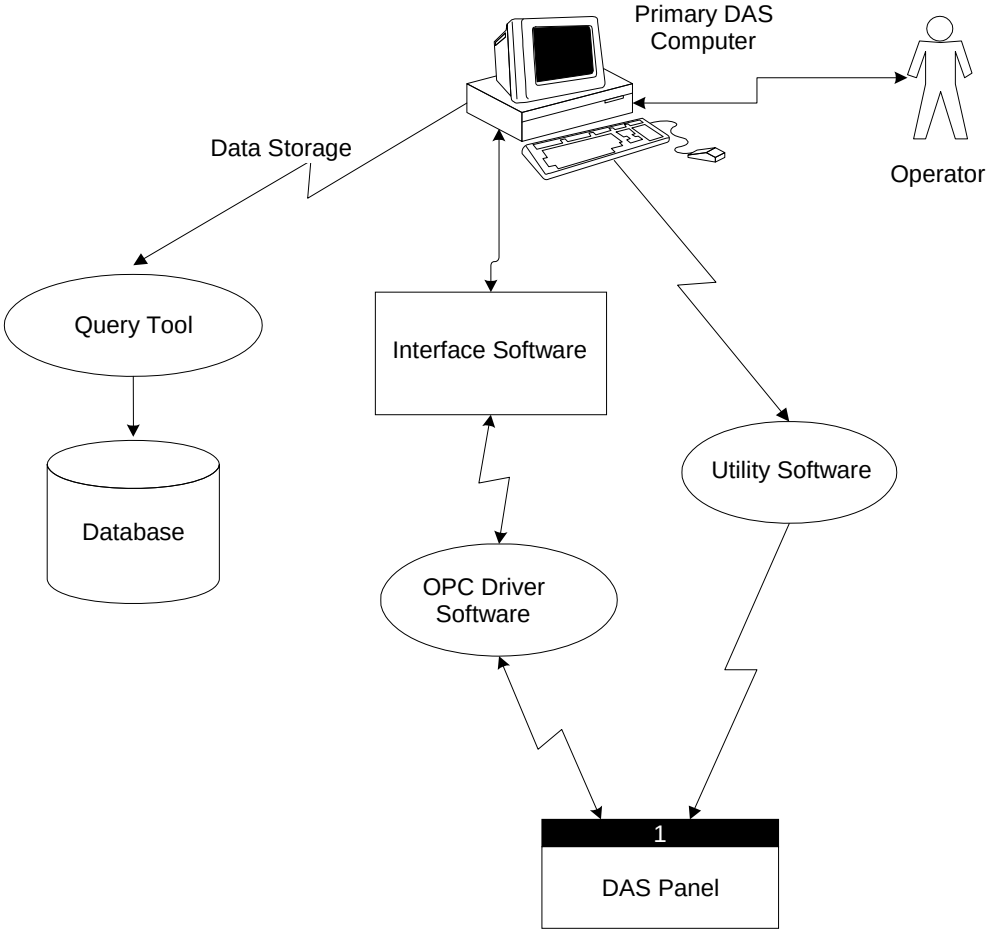

Figure 7. Block diagram of software interface

2.6.3 Quality Assurance for the Software and Instrumentation

Qualification of all DAS software must meet the requirements of NP 19-1 (Software Requirements) unless the DAS software is an integral part of an off-the-shelf system and not subsequently modified. Under this exception, DAS software is qualified using the requirements of NP 20-1 (Test Plans). NP 20-1 specifically states that the qualification requirements for off-the-shelf commercial software used without modification are limited to documentation of the software name, version, and hardware for which it is used.

All of the DAS software identified previously is off-the-shelf and will not be modified (cannot be modified because the source code for the software has not been provided); therefore only those parts of NP 20-1 related to identifying the software name, version, and hardware are applicable. Since the DAS software does perform simple data manipulation consisting of converting measured signals into engineering units, the requirements of NP 9-1 will apply. The conversion of the raw inputs to engineering units is performed using simple analytical operations that can be verified by hand calculations. If calibration of the DAS is required, it will be done according to SP 12-4 (Sixnet DAS Calibration). Table 7 lists the documents that control the development and testing of the DAS software and instrumentation.

Table 7. Controlling documents

Document I.D.	Document Title	Applicable Features
NP 9-1	Analyses	Provides requirement for documenting routine hand calculations needed to verify simple data manipulations, formulae, and unit conversions performed by the DAS software
NP 20-1	Test Plans	Describes requirements for qualifying off-the-shelf DAS software that is not subsequently modified
SP 12-4	Sixnet DAS Calibration	Prescribes the process for the calibration and maintenance of the Sixnet product line of industrial controllers and analog input modules installed as part of a data acquisition system.

3.0 Planning Overall Strategy and Process

All activities conducted by Sandia National Laboratories or its contractors in support of this test plan (TP 09-01) shall be done in accordance with the current SNL WIPP Quality Assurance (QA) program procedures (NPs and SPs) and Environmental Safety and Health (ES&H) procedures.

- The primary objective of this testing program is to determine the critical shear stress of various surrogate waste materials with depth. Methods of measuring the critical shear stresses of differing surrogate waste materials relies upon the accurate measurement of the flow rate within the channel and the amount of material extruded to the level of the side of the channel.

- The critical shear stresses of different waste surrogate materials can vary by over an order of magnitude depending on the type of material tested as documented in the report to Sandia, "Development and Testing of Waste Surrogate Materials for Critical Shear Stress" by Jepsen et al., (1998a). The critical shear stress of each different waste surrogate material is unique and must be experimentally determined because presently the physical processes of erosion of the waste surrogate material are not well understood. Since the surrogate wastes to be tested in these experiments have never been tested before in a vertical flume, there is no data to compare measurements. Comparisons of the critical shear stress of the surrogate waste will be made from replicate samples and by duplication of the horizontal flume tests performed by Jepsen et al. (1998a).

- The critical shear stress data will be used by the WIPP Repository Performance program in support and development of the Cuttings and Cavings model parameters used to calculate direct releases to the surface during a drilling intrusion scenario. No compatibility problems with the conceptual or mathematical models are foreseen at this time. If problems become apparent during the testing phase, they will be discussed, resolved and documented in the project's scientific notebook.

- The procedures expected to be used in these experiments are described in Section 2.0 Experimental Process Description. These procedures are similar to those that have been previously developed for the horizontal sediment flume, which can be found in the literature (Jepsen et al., 1997a; Jepsen et al., 1997b; Jepsen et al., 1998a; Jepsen et al., 1998b; Jepsen et al., 1999; Roberts et al., 1998; Lick, 2009). Since the vertical erosion flume has not been used before, the specific procedures and/or changes to those procedures for completion of the test plan will be written at a later time, when work progresses and decisions can be made as to the best methods for proceeding. Documentation will be recorded in the project's scientific notebook as well as the data acquisition system (if operational) and supported by digital video recording when appropriate.

- As the sample in the tubes erodes, it is moved towards the flow in the channel by the operator so that the sample-water interface remains flush with the side of the test and inlet sections. When and how much material to extrude is determined by the operator and these data are recorded in the project's scientific notebook. The results obtained using a similar, horizontal erosion flume have been shown to be reproducible within a ± 25% error and were independent of the operator (Jepsen et al., 1997a; Jepsen et al., 1997b; Jepsen et al., 1998a; Jepsen et al., 1998b; Jepsen et al., 1999; Roberts et al., 1998).

The following QA records are expected to be generated through implementation of this test plan:

- Copies of all instrument calibration records
- Activity/Project Specific Procedures (SP)
- A hard-copy of the data
- Any calculations performed as part of these activities. These items will be included in the project's scientific notebook (both manual and electronic).
- Digital video records (removable storage)

These records shall be submitted to the SNL WIPP Records Center in accordance with NP 17-1 (Records).

3.1 Sample Control

- Samples shall be identified and controlled in accordance with NP 13-1 (Control of Samples and Standards) and SP 13-1 (Chain of Custody). These NPs specify procedures for labeling and identification, Chain of Custody, sample storage and environmental controls, and sample disposal.

- There are no specific environmental control requirements for sample storage, although, samples will not be stored in temperature extremes causing brittleness, melting, or other conditions affecting integrity. Also, samples will be stored in areas that are not open to the weather or where excessive humidity or moisture might affect the samples or sample labeling. Because of the destructive nature of the tests, the disposition section of the chain of custody records for tested samples shall be annotated as ‘consumed during testing.’ Any surrogate waste in excess of what is required for sample preparation will be placed in the facility trash (i.e. sanitary waste) for disposal.

3.2 Data Quality Control

- Data and calculations performed as part of these activities will be recorded in the project’s scientific notebook. The data will be verified by the technical reviewer who will note concurrence by co-signing the scientific notebook. If a discrepancy is found, that discrepancy and its resolution will be documented in the scientific notebook. All activities (stated here and in the rest of the document) involving the scientific notebook, its review, and any corrections to be made will be done in accordance with NP 20-2 (Scientific Notebooks) and NP 6-1 (Document Review Process).

- All measurement and testing equipment for use in the execution of this test plan shall be calibrated and maintained to the specifications stated within NP 12-1 (Control of Measuring and Test Equipment). Calibration schedules for laboratory testing equipment have already been established based on use and recommendations of the equipment manufacturers. Equipment and calibrations will be documented in the project’s scientific notebook.

- Duplicate samples of waste surrogate material will be tested to assess the veracity and reproducibility of the critical shear stress measurements. In addition, the test samples and flume will be locked in a laboratory with access given only to appropriate project personnel.

Any deviations from test procedures or sample preparation will be documented in the scientific notebook and reviewed by the technical reviewer in accordance with NP 6-1 (Document Review Process).

3.3 Data Identification and Use

- Experimental data derived from the activities described in this test plan will be used in the development of a lower limit for waste shear strength under WIPP conditions.

- Various data printouts from the DAS will be attached directly to the project's scientific notebooks or submitted to the SNL WIPP Records Center (SWRC). For instruments that do not have direct data printout, the instrument readings will be recorded directly into the scientific notebook. The data will be verified by the technical reviewer who will note concurrence by co-signing the scientific notebook. If a discrepancy is found, that discrepancy and its resolution will be documented in the scientific notebook.

- Data transfer and reduction shall be performed in such a way as to ensure that data transfer is accurate, that no information is lost in the transfer, and that the input is completely recoverable. Also, analysis and reduction shall be controlled, in accordance with NP 9-1 (Analyses), to permit independent reproducibility by another qualified individual.

- From the scientific notebook(s) or from the instrument's direct electronic data output file, numerical data will be transferred into a Microsoft Excel spreadsheet and/or into a suitable graphing program. The data will be verified by a second person to ensure that no data transcription errors have occurred. The data will be directly analyzed, in accordance with NP 9-1 (Analyses), and plotted from the spreadsheet. Technical data, including scientific notebooks, will be submitted to the SWRC.

4.0 Training

- All personnel involved in the experiments described in this document will be trained and qualified for their assigned work. This requirement is implemented through NP 2-1 (Training and Qualification) for those working under the SNL WIPP QA Program. All qualification and QA training records are submitted to and maintained by the SWRC. The training records for the following ES&H courses are maintained in the Training Education and Development System (TEDS) and/or with the SWRC:

  ESH 100: ES&H Awareness
  PRS 102: Basic Pressure Safety
  LAB 100: Laboratory Standard Information and Training
  LAB 103: Site-Specific Laboratory Safety Training

- Those personnel working under the SNL WIPP QA Program will be required to submit the following forms to the SWRC prior to beginning work, if the form is not currently on file:

  Form NP 2-1-1 Qualification and Training Form

- Training on assigned SNL WIPP QA Program Procedures (NPs and SPs), this test plan, ES&H procedures, and any other required training shall be completed and documented prior to beginning work.

5.0 Health and Safety

- All of the health and safety requirements relevant to the work described in this TP and the procedures that will be used to satisfy these requirements are described in the SNL Environmental Safety and Health (ES&H) manual and ES&H standard operating procedures for the locations the work occurs.

- The hazards identified are:

    - Pressure Safety – Fluids being pumped. An approved pressure safety package must be completed prior to the start of work.

    - Electrical Safety – Electrical equipment being operated in a wet location. All electrical service must comply with current electrical code for wet locations prior to the start of work.

6.0 Permitting/Licensing

- No permitting or licensing activities are required for this work.

7.0 References

Berglund, J.W. (1992). Mechanisms governing the direct removal of wastes from the Waste Isolation Pilot Plant repository caused by exploratory drilling. SAND92-7295. Sandia National Laboratories, Albuquerque, NM.

Berglund, J.W. (1996). Parameters required for the CUTTINGS_S code for use in WIPP Performance Assessment. ERMS 236766. Sandia National Laboratories, Carlsbad, NM.

Butcher, B.M. (1994). A model for cuttings release waste properties. Memorandum to distribution. January 6, 1994. ERMS 309846. Sandia National Laboratories, Carlsbad, NM.

Butcher, B.M., Webb, S.W., Berglund, J.W., and Johnson, P.R. (1995). Systems Prioritization Method – Iteration 2. Baseline position paper: Disposal room and cuttings models, vol. 1. ERMS 228729. Sandia National Laboratories, Carlsbad, NM.

Cao, Z., Pender, G., and Meng, J. (2006). Explicit formulation of the Shields diagram for incipient motion of sediment. Journal of Hydraulic Engineering, 132 (10), 1097-1099.

Coons, W.E., Gibbons, J.F., and Burgess, A.S. (2007). Interim Report for the Revised DRZ and Cuttings & Cavings Sub-models Peer Review. A peer review conducted for the Carlsbad Field Office Technical Assistance Contractor in support of the U.S. Department of Energy. December, 2007

CTAC (Carlsbad Area Office Technical Assistance Contractor). (1997). Expert elicitation on WIPP waste particle diameter size distribution(s) during the 10,000-year regulatory post-closure period: Final report. U.S. Department of Energy – Carlsbad Area Office, Carlsbad, NM. ERMS 541365. Sandia National Laboratories, Carlsbad, NM.

DOE (U.S. Department of Energy). (1996). Title 40 CFR Part 191 Compliance Certification Application for the Waste Isolation Pilot Plant. DOE/CAO-1996-2184. October 1996.

EPA (U.S. Environmental Protection Agency). (1998). Technical Support Document for Section 194.23: Parameter Justification Report. Docket A-93-02, V-B-14.

Hansen, F.D. (2005). A revisit of waste shear strength. ERMS 541354. Sandia National Laboratories, Carlsbad, NM.

Hansen, F.D., Knowles, M.K., Thompson, T.W., Gross, M., McLennan, J.D., and Schatz, J.F. (1997). Description and evaluation of a mechanistically based conceptual model for spall. SAND97-1369. Sandia National Laboratories, Albuquerque, NM.

Hansen, F.D., Pfeifle, T.W., and Lord, D.L.. (2003). Parameter justification report for DRSPALL. SAND2003-2930. Sandia National Laboratories, Albuquerque, NM.

Helton, J.C., Bean, J.E., Berglund, J.W., Davies, F.J., Economy, K., Garner, J.W., Johnson, J.D., MacKinnon, R.J., Miller, J., O.Brien, D.G., Ramsey, J.L., Schreiber, J.D., Shinta, A., Smith, L.N., Stoelzel, D.M., Stockman, C., and Vaughn, P. (1998). Uncertainty and sensitivity analysis results obtained in the 1996 Performance Assessment for the Waste Isolation Pilot Plant. SAND98-0365. Sandia National Laboratories, Albuquerque, NM.

Herrick, C.G., Riggins, M., and Park, B.Y. (2007a). Recommendation for the lower limit of the waste shear strength (Parameter BOREHOLE : TAUFAIL), Rev. 0. ERMS 546033. Sandia National Laboratories, Carlsbad, NM.

Herrick, C.G., Riggins, M., Park, B.Y., and Vugrin, E.D. (2007b). Recommendation for the lower limit of the waste shear strength (Parameter BOREHOLE : TAUFAIL), Rev. 1. ERMS 546343. Sandia National Laboratories, Carlsbad, NM.

Ismail, A.E. (2009). Analysis package for cuttings, cavings, and spallings: AP-132 Performance Assessment. ERMS 551184. Sandia National Laboratories. Carlsbad, NM.

Jepsen, R., Roberts, J., and Lick, W. (1997a). Effects of bulk density on sediment erosion rates. Water, Air, and Soil Pollution, 99, 21-31.

Jepsen, R., Roberts, J., and Lick, W. (1997b). Long Beach Harbor sediment study. Report to the U.S. Army Corps of Engineers, Los Angeles District.

Jepsen, R., Roberts, J., and Lick, W. (1998a). Development and testing of waste surrogate materials for critical shear stress. Sandia Contract AX-9022. Dept. of Mechanical and Environmental Engineering, University of California-Santa Barbara. ERMS 533809. Sandia National Laboratories, Carlsbad, NM.

Jepsen, R., Roberts, J., and Lick, W. (1998b). New York Harbor sediment study. Report to the U.S. Army Corps of Engineers, New York District.

Jepsen, R., Roberts, J., and Lick, W. (1999). Grand River sediment study. Report to the Environmental Protection Agency, Great Lakes District.

Jepsen, R., Roberts, J., Gailani, J., and Smith, J. (2002). The SEAWOLF Flume: Sediment Erosion Actuated by Wave Oscillations and Linear Flow. SAND2002-0100. Sandia National Laboratories, Albuquerque, NM.

Jepsen, R., Roberts, J., and Gailani, J. (2004). Erosion measurements in linear, oscillatory, and combined oscillatory and linear flow regimes. Journal of Coastal Research, 20(4), 1096-1104.

Julien, P.Y. (1998). Erosion and Sedimentation. Cambridge University Press, Cambridge, U.K.

Kirchner, T. B. (2005). Sensitivity of Performance Assessment Baseline Calculation releases to parameters. ERMS 540767. Sandia National Laboratories, Carlsbad, NM.

Kruger, M. (1997). Performance assessment parameter values identified in EPA letters, dated April 17 and 25, 1997, to DOE. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C. Docket A-93-02, II-I-33.

Lick, W. (2009). Sediment and Contaminant Transport in Surface Waters. CRC Press, Boca Raton, FL.

McNeil, J., Taylor, C., and Lick, W. (1996). Measurements of erosion of undisturbed bottom sediments with depth. Journal of Hydraulic Engineering, ASCE, 122(6), 316-324.

Mellegard, K. (1998). Fabrication of surrogate waste bricks for erosion studies: Laboratory Notebook (Volume 1 of 1). RSI Job 325 Task 20.1. Sandia National Laboratories Contract No. AG-4911. RESPEC, Rapid City, SD. ERMS 251625.

Parchure, T.M. and Mehta, A.J. (1985.). Erosion of soft sediment deposits. Journal of Hydraulic Engineering, 111(10), 1308-1326.

Partheniades, E. (1965). Erosion and deposition of cohesive soils. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 91(HY1), 105-139.

Partheniades, E. and Paaswell, R.E. (1970). Erodibility of channels with cohesive boundary. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 96 (HY3), 755-771.

Peake, T. (1997). Shear resistance to erosion (TAUFAIL). EPA facsimile to G. Basabilvazo. April 28, 1997. Copy available as ERMS 545768. Sandia National Laboratories, Carlsbad, NM.

Roberts, J., Jepsen, R., and Lick, W. (1998). Effects of particle size and bulk density on erosion of quartz particles. Journal of Hydraulic Engineering, ASCE, 124 (12), 1261-1267.

Roberts, J. and Jepsen, R. (2001). Separation of bedload and suspended load with modified high shear stress flume. SAND2001-2162. Sandia National Laboratories, Albuquerque, NM.

Roberts, J., Jepsen, R., and James, S. (2003). Measurements of sediment erosion and transport with the ASSET flume. Journal of Hydraulic Engineering, ASCE, 129 (11), 862-871.

Sargunam, A., Riley, P., Arulanandan, K., and Krone, R.B. (1973). Physico-chemical factors in erosion of cohesive soils. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, 99 (HY3), 555-558.

Simon, D.B. and Senturk, F. (1992). Sediment transport technology: water and sediment dynamics. Sedimentation Engineering Manual No. 54. American Society of Civil Engineers, Water Resources Publication.

Sea Engineering, Inc. (2009a, in press). Aquatic Transfer Facility sediment transport analysis. Prepared for the U.S. Army Corps of Engineers, San Francisco District.

Sea Engineering, Inc. (2009b, in press). Data report for Sedflume core analysis South San Francisco Bay mudflats. Prepared for the Bruce Jaffe, U.S. Geological Survey.

Schlichting, H., (1979). Boundary-Layer Theory. Seventh ed, McGraw-Hill.

Taylor, C., and Lick, W. (1996). Erosion properties of Great Lakes sediments. Report, Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, California.

Teeter, A.M. (1987). Alcatraz Disposal Site investigation. Report 3. San Francisco Bay – Alcatraz Disposal Site Erodibility. Miscellaneous Paper HL-86-1. AD Number A181837. Department of the Army. Waterways Experimental Station, Corps of Engineers, Vicksburg, MS.

Trovato, E.R. (1997a). Letter to G. Dials (DOE), April 17. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C. Docket A-93-02, II-I-25.

Trovato, E.R. (1997b). Letter to G. Dials (DOE), April 25. Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, D.C. Docket A-93-02, II-I-27.

Vugrin, E. D. (2005). Analysis package for CUTTINGS_S: CRA-2004 Performance Assessment Baseline Calculation. ERMS 540468. Sandia National Laboratories, Carlsbad, NM.

Vugrin, E. D. and Dunagan, S. C. (2005). Analysis package for CCDFGF, CRA 2004 Performance Assessment Baseline Calculation. ERMS 540771. Sandia National Laboratories, Carlsbad, NM.

Wang, Y. (1997). Estimate WIPP waste particle sizes based on expert elicitation results: Revision 1. Memorandum to M.S.Y. Chu and M.G. Marietta, Aug 5, 1997. ERMS 246936. Sandia National Laboratories, Albuquerque, NM.

Wang, Y. and Larson, K.W. (1997). Estimate waste critical shear stress for WIPP PA caving model. Sandia Memorandum to M.S.Y. Chu and M.G. Marietta, June 27, 1997. ERMS 246696. Sandia National Laboratories, Albuquerque, NM.

WIPP PA (WIPP Performance Assessment). (2004a). Design document for CUTTINGS_S (Version 6.00). ERMS 537038. Sandia National Laboratories, Carlsbad, NM.

WIPP PA (WIPP Performance Assessment). (2004b). User's manual for CUTTINGS_S (Version 6.00). ERMS 537039. Sandia National Laboratories, Carlsbad, NM.

WIPP PA (WIPP Performance Assessment). (2005a). Addendum to the design document for CUTTINGS_S (Version 6.00). ERMS 539236. Sandia National Laboratories, Carlsbad, NM.

WIPP PA (WIPP Performance Assessment). (2005b). Addendum to the user's manual for CUTTINGS_S (Version 6.00). ERMS 539238. Sandia National Laboratories, Carlsbad, NM.

Yew, C., Hanson, J., and Teufel, L. (2003) Waste Isolation Pilot Plant spallings conceptual model peer review report. ERMS 532520. Sandia National Laboratories, Carlsbad, NM.

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