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SANDIA NATIONAL LABORATORIES
WASTE ISOLATION PILOT PLANT

AP-180
Revision 0

Analysis Plan for the Development of a Model for the Compaction Behavior of Emplaced WIPP Waste

Task 4.4.2.4.1

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1 Introduction and Objectives

The Waste Isolation Pilot Plant (WIPP) is a United States (US) Department of Energy (DOE) mined, underground repository, certified by the Environmental Protection Agency (EPA), and designed for the safe management, storage, and disposal of transuranic (TRU) radioactive waste resulting from the United States defense programs. The wastes are emplaced in panels excavated at a depth of 2,150 ft in the Permian Salado Formation. The repository is presently linked to the surface by four shafts, with others being considered, that ultimately will be sealed at decommissioning.

In the original concept, the panels would have been isolated from the operational mine using an approved closure system following emplacement of waste and the MgO engineered barrier material. However, the February 2014 radiological release event stopped waste emplacement activities at the facility for approximately three years. While clean-up of the contaminated areas was underway, underground access was limited, and routine ground control maintenance activities were not possible. Ground conditions deteriorated significantly during this time, resulting in a number of discrete events including roof fall, floor heave, and rib spalling. As a result, to protect workers, DOE decided to restrict access to the south end of the mine, thus possibly abandoning a set of open drifts that were originally planned to hold waste (i.e., Panel 9).

Performance Assessment (PA) modeling of WIPP performance requires full and accurate understanding of coupled mechanical, hydrological, and geochemical processes and how they evolve through time. This analysis plan focuses specifically on the compaction behavior of waste and the constitutive relations to model this behavior during room closure. A principal goal of this study is to make use of an improved waste constitutive model parameterized to well-designed data obtained in the experimental program outlined in test plan TP 08-01 (Broome and Costin 2010). This will address certain technical issues arising from the use of the earlier waste model. Ultimately, any changes in the room closure model or other elements of the underground evolution will require peer review and acceptance by EPA.

The specific objectives of this analysis plan are:

- Use data obtained from hydrostatic, uniaxial, and triaxial loading tests on ¼-scale standard waste packages filled with a representative range of simulated fresh waste forms to allow for the determination of a complete set of waste constitutive model parameters. One-fourth-scale testing was convenient for this task since it has been shown that the response of 55-gal prototype waste drums undergoing moderate amounts of deformation is well characterized in ¼-scale experiments using No. 12 food cans to simulate the waste packages (Baker et al. 1980, Huerta et al. 1983, Butcher et al. 1991). The ¼-scale standard waste packages appear to provide all the information needed to characterize principal components of stress and deformation.

- Utilize full-scale hydrostatic and uniaxial loading tests to develop scaling assumptions and provide a basis for evaluating the performance of the waste constitutive model in predicting the compressive behavior of standard waste package systems.

- Include the results of hydrostatic, uniaxial, and triaxial loading tests on simulated degraded waste (Broome et al., 2014, Broome et al., 2016). These results are included to assist in the modeling efforts for the long-term effects of WIPP room closure characteristics.

Since the objective of the analyses proposed herein is to improve the waste constitutive model which will be used in porosity surface calculations during PA modeling for the next recertification application of WIPP, the analyses are compliance decision analyses.

2 Model Process Description

This section describes the processes required to develop the parameters of a cap plasticity model for the standard 55-gal drum waste package with a variety of simulated fresh contents and for degraded surrogate waste materials without a container. The modeling program will be implemented in a large deformation, thermal-mechanical finite element program such as JAS3D or Adagio.

Detailed studies were performed on ¼-scale waste packages, and full-scale packages that will be used to verify the data from the scaled tests, to provide a data set for validation of a cap plasticity model. In addition to the drum compaction tests, a suite of tests was performed on simulated degraded waste. These tests will assist in the performance assessment for long term room closure characteristics.

While the standard waste drum will make up approximately 80% of the packages emplaced in WIPP, there are other waste package configurations that if emplaced in significant numbers, might result in different closure characteristics of specific rooms. These alternate waste forms could be in many different configurations and quantities, such as excess Pu. Configurations under consideration for placement will be evaluated analytically before inclusion at WIPP. A revised analysis plan will describe additional analyses required for specific alternate waste forms should their inclusion become necessary.

2.1 Discussion of Previous Work

Previous work has been performed to determine the mechanical response of waste packages for WIPP (Baker et al. 1980, Huerta et al. 1983, Butcher et al. 1991, VandeKraats 1987, and Wawersik 2001). These studies focused on simulated waste response to a variety of loading conditions, including transport, varying emplacement conditions, and varying emplacement configurations. The major conclusion of these studies is that ¼-scale experiments adequately modeled the behavior of the full scale 55-gallon drums, however the study was limited to uniaxial drum failure modes. One other significant finding was that the surrogate containers had a much greater axial load bearing capacity when confined in a seven-pack arrangement versus an isolated, confined can (Wawersik 2001).

Since the current emplacement method does not include packing of backfill around the waste containers, it is anticipated that early deformation resulting from vertical closure will occur with little confinement until the ribs close sufficiently to contact the packages, consistent with current full-scale data. The currently available data on compaction of waste canisters with some

confinement is derived mainly from tests that use backfill as a confining media (Wawersik 2001). While some measurements of maximum lateral stresses were made, the exact load path experienced by the waste and container is highly uncertain. Therefore, these data should not be used directly in determining parameters for the waste package model.

Additionally, in the previous studies only axial load – axial deformation measurements or lateral load – lateral deformation measurements were made on either the ¼-scale or the full-scale tests. No hydrostatic tests or other reliable pressure versus volume change measurements were made. Thus, it is impossible to distinguish between uniaxial compression along the major axis of the waste drum and confined compaction, where lateral stresses are present. As room closure progresses, increasing lateral confinement will be applied to the waste packages. This load path was not simulated in laboratory experiments until Broome et al. (2014).

This lack of multi-axial data, led modelers to adopt an isotropic, volumetric plasticity approach that can provide good predictability under unconfined conditions, but not under multi-axial states of stress and has resulted in some observed non-physical behavior of the material model. This lack of appropriate data that could be applied in more complex constitutive material models was motivation for a series of tests designed to provide this data and are outlined in the TP08-01 and reported in Broome et al. (2014) and Broome et al. (2016). This data provides a more complete set that can be used to determine appropriate parameters for more complex models, e.g. a cap plasticity model. While inadequate for model parameter development, the previous data obtained is valuable for providing comparisons of model prediction of the compaction tests with backfill to provide an initial validation of the cap plasticity model (for the waste and canister system) and the backfilled salt.

Another area of concern to modelers was the lack of good data representing the mechanical behavior of degraded waste. Interest in the mechanical properties of degraded waste arose from two primary issues as discussed by Hansen et al. (1997): 1) Degraded waste strength greatly influences potential spall release and 2) Mechanical properties are used in modeling methods to understand the response should the waste be subject to accidental human intrusion. The current interest in understanding the behavior of the waste stems from long term modeling capabilities that provide a well-defined performance assessment of the closure of the rooms. It is assumed that a cap plasticity model will also be adequate to model the response of degraded waste. While Hansen et al. performed tests on simulated degraded waste to determine various mechanical properties, there was no measurement taken to understand the volumetric strain response of the material in relation to other mechanical properties. In addition, only two confinement pressures were tested in the triaxial test arrangement. To enhance assessment of long term room closure characteristics, additional triaxial confining pressures were performed by Broome et al. (2014) to better define the failure surface.

2.2 Load Paths and Deformation States

Modeling assemblages of waste packages requires some basic assumptions regardless of the constitutive model used. The most fundamental assumption is that the waste package forms the basic “unit cell” of the model. Ideally a constitutive relationship can be developed that will describes the single waste package behavior that can then be extrapolated to an average behavior

of groupings of waste packages with characteristics of transverse isotropy. However, this level of detail and complexity, in a system performance model with the current computing capabilities would prove intractable. Thus, for this next increment of improved modeling, we will stick with the assumption that each unit cell is homogeneous, isotropic, porous, and pressure sensitive (plastic shear deformation and failure is sensitive to the imposed mean stress), which leads to a model class assumption of "cap plasticity" for continuum simulations. In many simulations, the current soil and foams model (SAF) has been used. The difference between the SAF model and other cap plasticity models is in the level of complexity adopted in the formulation. The SAF model was degenerated to a pure volumetric plasticity formulation that is simple, but assumes that in the absence of shear failure, all three principal plastic strains are equal. Figure 1 illustrates the essentials of this model in stress space where the ordinate is proportional to the maximum shear stress and the abscissa is the mean stress or pressure. Any load path between hydrostatic (along the abscissa, path x-y-z in Figure 1) and uniaxial compression (path a-b-c) will result in similar compaction of the material once the stress reaches the plastic yield surface or "cap". Thus, under uniaxial stress (path a-b-c), all three principal plastic strains will be equal, leading to a uniform volumetric compaction, in contradiction to experimental results. Attempts to adjust the slope of the shear limit surface (adjusting parameter a_1 to less than 3), only result in yielding at lower stress (with subsequent volumetric plastic compaction) and reducing the apparent load bearing capacity of the waste drum. To address this problem with the model, a slightly different formulation is required. Cap plasticity models appear to have the basic formulation that will allow for both shear compaction or dilation and volumetric compaction.

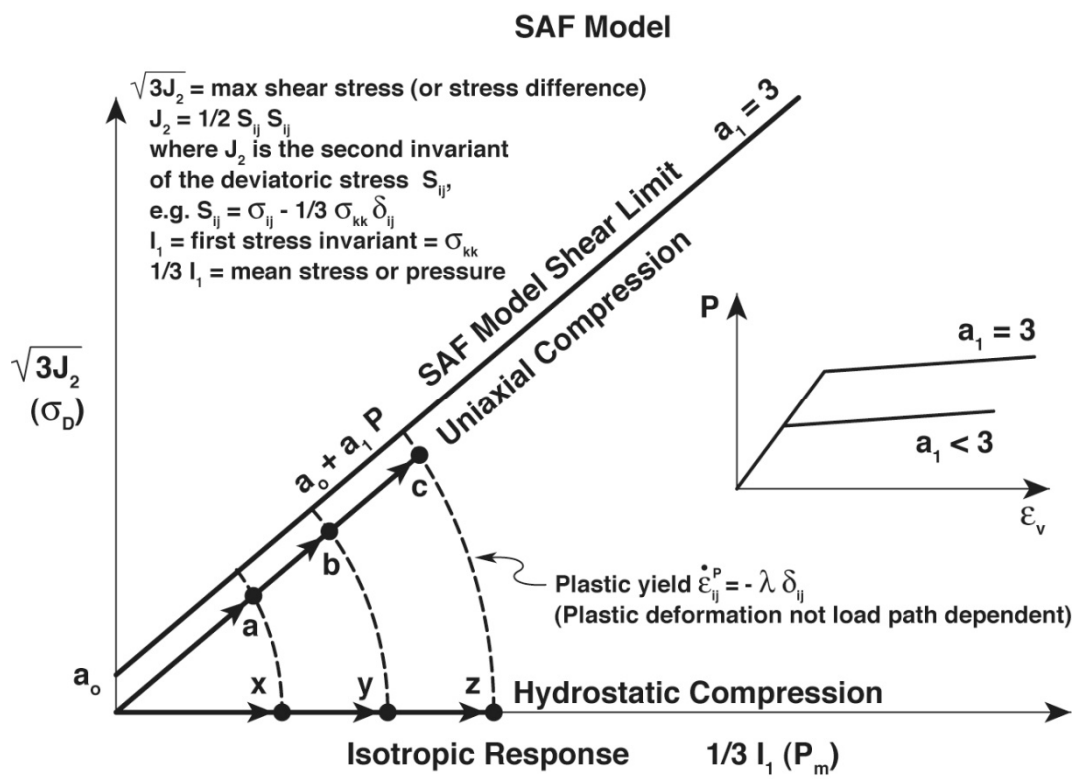

Figure 1: Illustrates the essentials of the SAF model in stress space. The ordinate is proportional to the maximum shear stress and the abscissa is the mean stress or pressure.

In order to develop a complete set of model parameters for a cap plasticity model that will allow for better simulation of waste package deformation under multi-axial states of stress, tests employing three basic load paths were required. The load paths are illustrated in Figure 2.

First, uniaxial compression tests, similar to those performed previously, are required. However, for this series of tests both axial and lateral deformations need to be determined. Second, hydrostatic compaction with direct measurement of volume change is needed to determine the behavior of the cap. This load path also has a secondary benefit of allowing an assessment of the degree of validity of the assumption of isotropy. Third, loading paths between uniaxial and hydrostatic are required to determine the slope of the shear surface and the shape of the cap. Typically these tests are done in a standard axisymmetric triaxial test configuration where a confining pressure is first applied then deviatoric stress is applied by increasing the axial load. Because the initial primary mode of plastic deformation will be the buckling of the container, an alternative load path may be used that follows a proportional loading trajectory. That is, the sample is loaded by increasing the confining pressure and axial load simultaneously in a fixed proportion. The tests described above, which are necessary for developing the required parameters for the improved cap plasticity model have been performed (Broome et al., 2014; Broome et al., 2016).

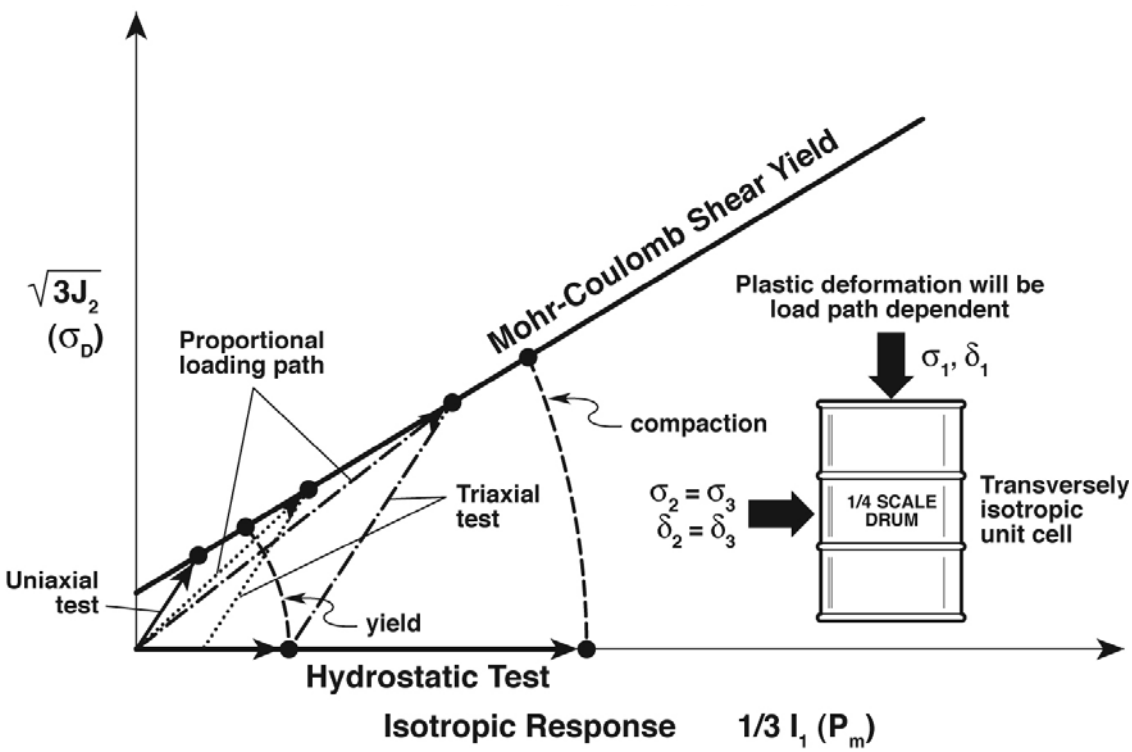

Figure 2: Graph of load paths representing uniaxial, hydrostatic, and axisymmetric triaxial tests.

2.3 Results of Recent Experiments by Broome et al. (2014, 2016)

2.3.1 ¼-Scale Waste Packages

Both the ¼-scale and full-scale tests focused on the mechanical behavior of surrogate fresh WIPP waste materials. The surrogate waste recipes used in the studies were developed based on the methodology developed by Hansen et al. (1997). The weight percent values of the materials used were modified to be in good agreement with the inventory estimates used in the most recent WIPP recertification application (CRA-2014) and have been accepted by the EPA for other WIPP model parameter determinations. For the ¼-scale tests, all three load paths described in Figure 2 are followed: uniaxial, hydrostatic, and triaxial compression. Measurements were made of axial, lateral, and volumetric strains. In some cases, the lateral strain could not be measured directly since the manner in which the containers deformed was not uniform. This led to the development of some innovative testing techniques to ensure the axial and volumetric strains were accurately measured, from which the lateral strains could be back-calculated. By themselves, the ¼-scale test results are expected to provide sufficient information to establish material properties to develop an adequately parameterized model for the waste's compaction behavior under the stress conditions at WIPP. Full-scale tests were also performed to validate, supplement, and provide information on scale-effects for these ¼-scale tests.

2.3.2 Full-Scale Waste Packages

Full-scale waste package tests which follow the load path discussed in previous sections have been performed. This complemented the ¼-scale testing, provides scale validation and a basis for evaluating the performance of a cap plasticity model in predicting the compressive behavior of waste package systems. The load paths are illustrated in Figure 2. Uniaxial compression tests were performed in which both the axial and lateral deformation were recorded as well as hydrostatic compaction tests wherein the direct measure of the volume change was captured. This new set of measurements, i.e. hydrostatic tests, pressure versus volume change, and lateral strain from known axial and volumetric strain measurements, will allow for additional scaling verification comparing ¼-scale tests to full-scale tests.

2.3.3 Degraded Waste Tests

To develop parameters for modeling room closure based on degraded waste, two basic load paths are necessary. First, hydrostatic tests were performed to understand volumetric strain versus pressure behavior. Second, triaxial compression tests with a variety of confinement pressures were performed and should allow determination of the slope of the shear surface and the shape of the cap. Triaxial testing performed by Broome et al. (2014) included several load paths. Initially the samples were loaded hydrostatically to measure the volumetric strain. Additionally, in these tests, pore pressure was also measured. The triaxial compression tests were conducted by applying a confining pressure followed by an increase in the axial load, which imposed a deviatoric stress. Lastly, uniaxial strain tests were conducted. These suites of test provide the basis and data upon which the parameters for the material models can be developed (hydrostatic tests and triaxial compression tests) and for which the model compatibility can be checked.

3 Software List

Sandia acquired software, including Sierra Mechanics Adagio (a.k.a. Solid Mechanics), Dakota, and Cubit, as well as SEACAS codes such as JAS3D will be used in the development of the analysis report. The acquired software will be qualified prior to use according to NP 19-1, *Software Requirements*. Commercial off-the-shelf (COTS) software may also be used in the development of the analysis report including, but not limited to Access®, Excel®, Grapher®, Kaleidagraph®, FLAC/FLAC3D, MATHEMATICA®, MATHCAD®, MATLAB®, or Python running on workstations. The use of any COTS application will be documented and verified per Nuclear Waste Management Procedure NP 9-1, *Analyses*, Section 2.2 as appropriate.

4 Cap Models Implemented In Sandia Codes

Possible choices of cap models implemented in various Sandia codes are, in order of increasing complexity:

- Weidlinger Cap Model (Sandler and Rubin 1979)
- Sandia Cap Model (Fossum and Fredrich 1998)
- Kayenta (Brannon et al. 2015. Originally known as the Sandia Geomodel (Fossum and Brannon 2004))

Based on preliminary scoping calculations, it is believed that the Weidlinger Cap model can be used to sufficiently capture the experimental results and be used as the basis for developing a new waste constitutive model.

5 Tasks

The tasks, responsible personnel, and estimated task schedule are summarized in Table 1. The completion dates and responsible individuals may change in the future.

Table 1: Task List and Estimated Schedule

Task	*Description*	*Guiding Document*	*Approximate Completion Date*	*Responsible Individuals*
1	Develop complete set of waste constitutive model parameters based on the hydrostatic, uniaxial, and triaxial loading tests on ¼-scale standard waste packages filled with fresh waste (Baker et al. 1980; Huerta et al. 1983; Butcher et al. 1991; Wawersik 2001; Broome et al., 2016).	AP-180 NP 9-1	29 Jun 2018	Courtney Herrick Benjamin Reedlunn

Task	*Description*	*Guiding Document*	*Approximate Completion Date*	*Responsible Individuals*
2	Develop scaling assumptions and provide a basis for evaluating the performance of the waste constitutive model in predicting the compressive behavior of standard waste package systems based on the full-scale hydrostatic and uniaxial tests (Broome et al., 2016)	AP-180 NP 9-1	29 Jun 2018	Courtney Herrick Benjamin Reedlunn
3	Include the results of hydrostatic, uniaxial, and triaxial loading tests on simulated degraded waste (Broome et al., 2014).	AP-180 NP 9-1	29 Jun 2018	Courtney Herrick Benjamin Reedlunn
4	Conduct simulations of the closure of a waste filled room to demonstrate and validate/verify the new WIPP waste constitutive model	AP-180 NP 9-1	14 Sept 2018	Courtney Herrick Benjamin Reedlunn
5	Document the results in an analysis report, "Recommendation for WIPP Waste Constitutive Model"	AP-180 NP 9-1	14 Sept 2018	Courtney Herrick Benjamin Reedlunn

6 Special Considerations

None

7 Applicable Procedures

SNL/CPG activities are conducted in accordance with the requirements specified in the DOE/CBFO Quality Assurance Program Document (QAPD), CAO-94-1012, current revision. The requirements of the DOE/CBFO QAPD, and any revisions thereto, are passed down and implemented through the SNL WIPP QA Procedures. All applicable WIPP Quality Assurance procedures will be followed when conducting these analyses.

- Training of personnel will be conducted in accordance with the requirements of NP 2-1, *Qualification and Training*.
- Analyses will be conducted and documented in accordance with the requirements of NP 9-1, *Analyses*.
- All software used will meet the requirements laid out in NP 19-1, *Software Requirements* and NP 9-1, as applicable.
- The analyses will be reviewed following NP 6-1, *Document Review Process*.

- All required records will be submitted to the WIPP Records Center in accordance with NP 17-1, *Records*.
- New and revised parameters may be created as discussed in NP 9-2, *Parameters*.

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