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One-Quarter-Scale Laboratory Crush Tests on Unconfined Waste Cans and a Confined Waste Package in Support of the Waste Isolation Pilot Plant (WIPP)

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Abstract

In 1989 1/4-scale model tests were conducted under quasi-static loading to explore the potential of laboratory experiments for evaluating computer simulations of the response of waste packages and crushed-salt backfill in the Waste Isolation Pilot Plant (WIPP). The choice of crushed salt was based on engineering considerations in the late 1980s that are superseded by the current design of the WIPP. One-quarter-scaling was applied to the dimensions of individual waste drums as well as to the distances between the walls of WIPP excavations and the outermost rows and columns of full-scale waste packages.

Experiments were performed on single cans and on one confined seven-pack of simulated waste canisters consisting of No. 12 food cans filled with simulated combustible waste. These tests had three specific objectives: (1) Comparison of the load-supporting capabilities and deformation modes of single simulated waste cans with the response of multiple waste packages that were surrounded and confined by dry crushed salt. In this case, multiple waste packages were replaced by one seven-pack of cans that could be accommodated in a laboratory experiment of manageable size. (2) Development of a small-scale experiment that would yield independent measurements to evaluate the predictive capabilities of computer simulations. (3) Generation of experimental measurements for comparison with the results of numerical analyses whose outcome is determined by the combination of geometric and structural system idealizations, boundary conditions, constitutive models, and computer algorithms.

Overall, the study confirms that laboratory tests involving a pack of seven cans filled with simulated waste surrounded and confined by crushed-salt backfill (or some other kind of backfill) constitute a viable approach to code validation.

Acknowledgement

The author thanks Michael McNamee and Brian Somerday for laboratory support. Their notes of laboratory procedures and calibrations were especially helpful for documenting experiments that were completed more than ten years ago.

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1.0 EXECUTIVE SUMMARY

Early in 1989, 1/4-scale model tests were conducted under quasi-static loading to explore the potential of laboratory experiments for evaluating computer simulations of the response of waste packages and crushed-salt backfill in the Waste Isolation Pilot Plant (WIPP). The choice of crushed salt was based on engineering considerations in the late 1980s that are superseded by the current design of the WIPP. One-quarter-scaling was applied to the dimensions of individual waste drums as well as to the distances between the walls of WIPP excavations and the outermost rows and columns of full-scale waste packages. The tests were motivated by the question about how much time was required for disposal rooms to reach a state of final consolidation.

Experiments were performed on single cans and on one confined seven-pack of simulated waste canisters consisting of No.12 food cans filled with simulated combustible waste. These tests had three specific objectives: (1) Comparison of the load-supporting capabilities and deformation modes of single simulated waste cans with the response of multiple waste packages that were surrounded and confined by dry crushed salt. In this case, multiple waste packages were replaced by one seven-pack of cans that could be accommodated in a laboratory experiment of manageable size. (2) Development of a small-scale experiment that would yield independent measurements to evaluate the predictive capabilities of computer simulations. (3) Generation of experimental measurements for comparison with the results of numerical analyses whose outcome is determined by the combination of geometric and structural system idealizations, boundary conditions, constitutive models, and computer algorithms.

Overall, the study confirms that laboratory tests involving a pack of seven cans filled with simulated waste surrounded and confined by crushed-salt backfill (or some other kind of backfill) constitute a viable approach to code validation. Tests of this or similar kind and size (27 in. or 68.6 cm diameter by about 24 in. or 61.0 cm high or possibly higher) could be repeated in the laboratory using parts that were manufactured in 1989 and kept. Shortcomings of the 1989 prototype experiment could be easily remedied. It also appears that the design and outcome of the 1989 seven-can test could guide the development of any larger tests in the WIPP involving more general waste-can arrangements and loading conditions.

The following additional major results were obtained:

The measured load bearing ability of each can in a confined 1/4-scale seven-can package subjected to predominantly axial loading was substantially greater (factor 5 or more) than the load bearing ability of isolated waste cans.

None of the No. 12 cans of the confined seven-pack of cans ruptured or exhibited lid separations. However, the experiment was carried out under quasi-static axial loading conditions inside a comparatively rigid confining ring that limited the development of lateral stresses. Greater lateral stresses are likely *in situ* as a result of horizontal room convergence in rock salt with time.

The stress distribution in crushed salt in a confined seven-pack crush test subjected to quasi-static loading was non-hydrostatic as expected in the absence of significant backfill creep. Additionally, the maximum stress across the annulus of crushed-salt backfill around the seven-pack was considerably higher than the average maximum (axial) stress supported by the more compliant seven-pack of simulated waste cans.

Relatively coarse stress measurements throughout the crushed salt backfill as well as above and below individual cans in the seven-can crush test yielded valuable data concerning the general stress field throughout the test assembly. Moreover, the shapes of the deformed cans in the seven-pack provided information about the displacement field in the crushed salt next to the seven-pack.

Realistic simulations of the behavior of waste-package and backfill systems in the WIPP probably will require single-can crush tests besides the predominantly axial loading experiments between rigid plates reported in the present and related earlier studies.

2.0 INTRODUCTION

Early in 1989, 1/4-scale model tests were conducted to explore the potential of laboratory experiments for evaluating computer simulations of the response of waste packages and crushed-salt backfill in the Waste Isolation Pilot Plant. The tests were motivated by the question about how much time was required for CH-TRU (Contact-Handled-Transuranic Waste) disposal rooms, waste packages and backfill to reach a state of final consolidation. Although this issue was raised during the design of crushed-salt backfill, it applies to any other CH-TRU waste storage configuration including the present design of waste storage drums surrounded by sacks of magnesium oxide.

Two types of experiments were carried out: (1) Individual, isolated No. 12 food cans were filled with simulated waste and crushed by loading parallel or perpendicular to the axis of the cans. (2) A seven-pack of the same kind of filled cans were buried in crushed rock salt "backfill" inside a metal confining ring representing the confinement action of a WIPP disposal room. The assembly of crushed salt and simulated waste-package was then loaded axially as measurements were made of the stress distribution at selected locations in the crushed salt backfill and underneath two of the food cans.

The choice of No. 12 food cans was based on a published comparison (Huerta et al., 1983) between the response of No. 12 food cans and full-scale waste canisters. This comparison specifically took into account some differences in the geometries of the lid closures with potential implications for the transfer of lid-failure observations from food cans to full-scale waste canisters.

Recent developments during long-term performance assessments of the WIPP have revived an interest in the earlier work and what was or could be learned from it. This report furnishes the necessary documentation in three parts. First, a brief review is provided of the rationale used for the 1989 experiments based on observations provided by Sandia staff and subcontractors during the period 1980-1989. The second part of this report describes the "recipe" for preparing simulated waste placed inside No. 12 food cans as 1/4-scale models of real 55-gal (0.21 m³) waste drums. This section also refers to laboratory records related to crush tests on individual waste cans. Although only some of these records are discussed, the combination of a video and selected data convey sufficient detail to compare single and multiple can-crush experiments and to recreate meaningful single-can crush tests in the future. The third part of the report describes a single experiment that was performed on a seven-can pack of waste and simulated backfill inside an aluminum confining ring. Essentially all of the records, including detailed calibration records, for this experiment have been recovered for a complete discussion and interpretation of results.

Records of the experiments described here were primarily taken in English units. To retain the connection between this report and the underlying 1989 laboratory records, SI units are treated as secondary and only added in parentheses.

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3.0 BACKGROUND AND OBJECTIVES OF EXPERIMENTS

The combination of ¼-scale single and multiple-confined deformation tests generally were and will be referred to as "can crush tests." The tests had three major objectives: (1) Compare the load-supporting capabilities and deformation modes of single simulated waste cans with the response of multiple waste packages that were surrounded and confined by crushed salt inside a scaled waste disposal cavity. (2) Develop a small-scale multi-can experiment that would yield independent measurements to evaluate the predictive capabilities of computer simulations whose outcome is determined by the combination of geometric and structural system idealizations, boundary conditions, constitutive models, and computer algorithms. (3) Provide experimental measurements concerning can-backfill interactions for the validation of computer simulations. It is emphasized that the scaled multi-can test of this study was not meant to eliminate larger scale, possibly full-scale *in situ* tests. Rather the test was conceived as a cost-effective first step of evaluating design procedures in a relatively short period of time (Wawersik, 2000).

Efforts to determine the mechanical response of waste packages were first coordinated by Huerta et al. (1983) for the Transportation Systems Technology Department of Sandia National Laboratories to support the analyses of transportation accidents. Complementary work was initiated in 1988 under Sandia (Procurement) Document No. 05-7501 (Butcher et al., 1990) using updated waste mixes in full-scale drum tests. Copies of this and related documents were held by WIPP staff responsible for the project.

A major result of the study by Huerta et al. was that the response of 55-gal (0.21 m³) prototype waste drums undergoing moderate amounts of deformation is well characterized in ¼-scale experiments on common No. 12 food cans (Baker et al., 1980). In essence, it was implied that ¼-scale drum tests appear to provide all the information needed for valid simulations even though Baker et al. (1980) and Huerta et al. (1983) noted some differences in the lip-closure configurations, lid and drum wall thickness, and yield and ultimate strengths of the drums and can materials.

Using the results of Huerta et al. (1983), a second drum crush study was carried out by VandeKraats and Westinghouse Electric Co. in 1987 (VandeKraats, 1987). After concluding that 55-gal (0.21 m³) drums were described adequately by the data obtained on No. 12 food cans, Westinghouse studied the influence of horizontal room closure on contact-handled waste packages. Inducing larger deformations than those considered by Huerta et al., the confinement by backfill was considered to (1) compare peak loads (resistance values) of confined with unconfined packages, (2) evaluate load transmission through backfill as indicated by the modes of deformation of the waste packages, and (3) determine whether individual drums are breached, what percentage of drums is breached, and where failed drums are located. To accomplish these objectives, VandeKraats assembled ¼-scale models containing up to 900 cans in 8-ft (2.4 m) deep, 13-ft (4.0 m) long trenches in the WIPP. Measurements made in these experiments included force applied by means of hydraulic rams and reaction loads perpendicular to the direction of active loading at selected points along the interface between the scaled waste drums and the crushed salt backfill. System deformations were measured parallel to the direction of active loading. In addition, the diameter changes of approximately 50 cans were monitored by means of beam-type displacement transducers placed inside the cans.

The studies of Huerta et al. and of VandeKraats are thorough and are well documented. The Westinghouse investigation, which is the best direct simulation of WIPP conditions, however, is restricted to dry backfill of 'pure' mine-run crushed salt and loading perpendicular to the waste-can (cylinder) axes. Therefore, although these experiments were extensive, they do not provide enough information to validate numerical analyses for more general loading conditions and attendant modes of drum collapse. Specifically, neither of the two previous studies proved that (1) systems of waste-drum packages and backfill can be modeled with constitutive data for unconfined single drums loaded parallel and perpendicular to the drum axes, and (2) final waste densities are independent of load/deformation paths.

It was inferred above that some drum characterizations were initiated under Sandia (Procurement) Document No. 05-7501 (Butcher et al., 1990). This work was awarded to Science Application International Corporation (SAIC) in parallel with the experiments that are the subject of this report. The SAIC measurements focused on (1) determinations of force-density data of several simulated waste mixes in rigid-die experiments and (2) axial crush tests of single 55-gal. (0.21 m^3) drums filled with simulated waste.

Considering the potential need for additional experimental data for validation and performance assessments, the question arose whether limited complementary measurements could be made in short-term, $\frac{1}{4}$ -scale-model tests in the laboratory. The work completed in 1989 had the goals of establishing a suitable experimental design, making multiple measurements of force, pressure, and/or deformation adequate to evaluate numerical simulations, and to identify potentially serious experimental shortcomings. Extensions of these first experiments were discussed involving other backfill and long-term loading tests in trenches in the WIPP (VandeKraats, 1987) or in a separate test frame where equivalent axial loads (about 10^6 lbs. or 4.5 MN) could be generated by means of inexpensive, compact construction-type hydraulic actuators.

4.0 SIMULATED WASTE MIXTURES

Waste mixes were categorized as metallic waste, combustible waste, and sludge. In this study combustible waste mixes were prepared using the following proportions in weight percent (Appendix 1):

Metals	9%
Paper, cloth, and wood	37%
Plastics, surgeons gloves, rubber	45%
Sorbents	9%

The metal parts consisted of 1-in (2.5-cm) to 2-in (5.1-cm) long pieces of 1/2-in (1.3-cm) steel conduit and 3/8-in (1.0-cm) copper tubing. Plastics were cut from 5/8-in (1.6-cm) to 2-in (5.0-cm) long pieces of 5/8-in (1.6-cm) polyethylene pipe, 1/2-in (1.3 cm) schedule 40 polyvinyl chloride (PVC) pipe, and plastic bottles with a wall thickness of 0.035 in. (0.09 cm). Wood waste was made of approximately 1-in (2.5-cm) wood cubes. Sorbents consisted of 50:50 mixes of Portland cement and oil sorbent (Oil-Dri). The actual weight distribution of the individual waste components used in a total of ten cans is listed in Table 1.

Note that the prescribed proportions of materials were maintained to within approximately 0.5 weight percent. Figure 1 and Appendix 4 show photographs and a detailed video of all simulated waste components before they were mixed and as they were placed into the cans.

Table 1. Simulated combustible waste mix used in single-can and seven-pack crush tests.

Item	Weight (g)									
	Can #1	Can #2	Can #3	Can #4	Can #5	Can #6	Can #7	Can #8	Can #9	Can #10
METALS										
Steel	41.9	41.4	41.2	41.5	40.9	41.6	40.9	41.4	40.8	41.6
Copper	27.1	27.0	27.3	26.5	27.1	27.1	28.1	27.6	26.9	27.7
Can & Lid	343.5	352.0	350.0	343.1	343.8	342.5	344.2	341.0	347.2	349.8
PAPER, CLOTH, WOOD										
Wood	168.6	168.9	168.2	168.9	168.5	168.4	168.4	168.6	168.2	169.2
Rags	112.4	112.4	112.4	112.4	112.5	112.5	112.5	112.5	112.5	112.6
PLASTICS										
Polyeth. Pipe	57.6	57.3	57.0	57.0	57.0	57.2	113.8	114.9	113.3	114.2
Polyethel. Bottle	114.4	114.4	114.2	114.4	114.2	113.8	57.3	57.3	56.7	57.0
PVC Pipe	136.6	136.7	136.7	136.9	136.9	136.0	135.9	136.1	136.6	136.6
Gloves	34.3	34.7	34.7	34.4	34.6	34.1	34.4	34.2	34.3	34.3
SORBENTS										
Portland Cement	34.5	34.6	34.3	34.2	34.4	34.3	34.4	34.3	34.2	34.3
Oil sorb	34.1	34.2	34.5	34.3	34.3	34.3	34.4	34.4	34.2	34.4
Total Weight	1105.0	1113.6	1110.5	1103.6	1104.2	1101.8	1104.2	1102.3	1104.9	1111.7

Figure 1. Photographs of combustible waste mixes (see Table 1 for details).

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5.0 SINGLE CAN EXPERIMENTS

Both written and visual records indicate that the can numbers 8-10 were used for single-can crush tests with loading parallel to the can axes. Cans 8 and 9 were compacted to a final height of 2.68 and 2.78 inches (6.8 and 7.1 cm), i.e., to 30% and 32% of the undeformed height. The video in Appendix 4 and Figure 2 show parts of the load-deformation test to a peak load value of 40 kip (178 kN) completed on can no. 9. For later reference, the can deformation at peak load is 5.9 in. (15.0 cm) or 68 % of the starting height. The peak load value corresponds to an average nominal stress of 1380 psi (9.5 MPa) for cans with an initial outside diameter of about 6.1 in. (15.5 cm). This value is relevant even though the machine load was transmitted primarily across the top and bottom rims (sometimes referred to as "seams") of can no 9. Existing laboratory records also indicate that an eleventh can was prepared and loaded perpendicular to the can axis. All single-can tests were completed in the 220 kip (0.98 MN) MTS (Minnesota Testing Systems Inc.) testing machine of the 6117 Geomechanics Laboratory.

Figure 2. Load-deformation curve of single-can crush tests (can #9). Frame of video record in Appendix 4.

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6.0 CONFINED SEVEN-PACK CAN EXPERIMENT

6.1 Description of Experiment

The experiments involved a circular pack of seven cans with an outside diameter of approximately 18.5 in. (47 cm). This pack was centered on a 3-inch (7.6-cm) thick aluminum base plate inside an aluminum ring with an internal diameter of 27-in. (68.6 cm) and a height of 18 in. (45.7 cm). Figure 3 shows a schematic and a photograph of this arrangement. The annulus between the perimeter of the seven-pack and the aluminum ring was 4.25 in. (10.8 cm) or approximately one fourth of the planned space between full-scale waste stacks and the ribs and back of the storage rooms in the WIPP. Hence, the experiment preserved the $\frac{1}{4}$ -scaling from 55-gal (0.21 m³) drums to No. 12 food cans that was also adhered to in the multi-can experiments by VandeKraats (1987) mentioned earlier.

The wall thickness of the aluminum ring in Figure 3 was 0.63 in. (1.6 cm). This thickness was deemed to be large enough to confine the experiment without yielding of the aluminum, yet thin enough to resolve the readings of strain gages mounted on the outside surface of the ring. The aluminum ring rested on and was bolted to the aluminum base in order to provide a secure container in which the experiment could be assembled before it was lifted and swung into a large 1,100 kip (4.9 MN) servo-controlled MTS test frame. To simulate WIPP conditions as best as possible, the stack of cans was placed directly onto the solid, flat aluminum base before crushed salt was poured around and on top of it. Friction between the crushed salt and the retaining ring was limited by a 0.01-in-thick (0.25 mm) Teflon liner (Figure 3). Load was transmitted by thick aluminum plates on top of the crushed salt and driving the entire test assembly against the upper crosshead of the load frame. Given the plate diameter of 26 in. (66 cm) and the 27 in. (68.6 cm) internal diameter of the aluminum-confining ring, the greatest achievable axial stress was between 1910 psi (13.2 MPa) and 2070 psi (14.3 MPa). These values correspond to approximately 90 percent of the lithostatic pressure at the depth of the WIPP disposal rooms.

The large external diameter of the experiment (28.25 in. or 71.8 cm) made it necessary to fabricate a new loading platen to replace the standard 15-in-diameter (38.1 cm) loading plate at the end of an 8-inch-diameter (20.3 cm) shaft of the MTS actuator. Requirements for this part were high stiffness to bending, high maneuverability, and good alignment of all parts once assembled. Substantial non-parallelism between the loading platen and the upper machine crosshead result in high bending moments perpendicular to the direction of ram loading. Such moments reduce the machine load capacity because of excessive side loads on bushings. The machine drawings produced for this project are included as Appendix 2. The crushed salt used as laboratory backfill in the seven-pack experiment was mine-run salt screened to $-3/8$ in. (-1.0 cm), effectively. Subsequent sieving in the 6117 Geomechanics Laboratory yielded the size distribution in Table 2 as determined from the sieve analysis of two samples.

Figure 3. Schematic of seven-pack crush test and photo of seven-pack placement inside aluminum confining ring.

Table 2. Sieve analysis of crushed salt used for confined seven-pack crush test.

Sample No.	Sieve Aperture (mm)	Weight (g)	Weight %
1	9.53 (0.375")	315.5	0.74
	6.36	380.7	8.98
	3.35	860.7	20.30
	2.00	699.6	16.50
	1.40	465.9	10.99
	1.00	304.9	7.19
	Fines	1494.6	35.25
	TOTAL	4237.90	99.95
2	9.35 (0.375")	22.5	22.5
	6.36	359.5	8.89
	3.35	821.1	20.31
	2.00	684.6	16.50
	1.40	494.9	10.99
	1.00	332.9	7.19
	Fines	1327.7	35.25
	TOTAL	4043.2	99.95

6.2 Instrumentation and Measurements

The experiments ultimately were designed to provide measurements and observations suitable for validating performance assessments of waste-backfill systems in the WIPP. To accomplish this, it was desirable to measure total force, total (bulk) displacement, friction losses between the crushed salt and the sides of the aluminum confining ring, and radial stress distribution as a function of height along the salt-aluminum contact. Total load in this case was determined from differential pressure measurements in the double-acting MTS actuator. The accuracy of the force measurement was 0.1 % relative to the MTS load cell normally used in the 1,100 kip (4.9 MN) MTS testing machine (Lain, 1998). The value of 0.1 % corresponds to a pressure resolution of approximately 3 psi (20 kPa). The calibration of the MTS load cell was performed according to standard ASTM E4.

Model compaction was determined by means of two wire extensometers, Model PT110, of Celesco Transducer Products Inc., with a 10-inch (25.4 cm) range mounted between the upper machine crosshead and the aluminum base of the test assembly. Model compaction was checked by measuring the position of the lower 3-inch (7.6-cm) aluminum loading plate relative to the top of the confining ring at the beginning and end of the experiment. It was planned to evaluate friction losses and radial pressures from the response of vertical and horizontal sets of standard 120-Ohm foil strain gages mounted at three heights on the outer surface of the aluminum confining ring. The precise locations of all strain gages are shown in Figure 3. Consolidation of the waste cans was determined from height and volume measurements before and after testing.

Although external measurements on the confining ring are useful, they limit the detail that may be inferred about the deformation and stress fields throughout the interior of the test assembly. Therefore, complementary post-test records of peak stress distributions were established, although crudely, by means of pressure patches under two of the cans in the seven-pack test and at fifteen locations throughout the crushed salt. The "patches" consisted of pressure sensitive films, known as Pressensor Film (Inteq Resources Corporation), between two 3/32-in (2.4 mm) thick, 0.6-inch-diameter (1.5 cm) steel disks. Peak pressure magnitudes acting normal to the faces of the pressure patches was estimated from color changes of the pressure-sensitive films. Because the fifteen pressure patches were placed normal to the vertical, horizontal/radial, and horizontal/tangential directions in the crushed salt, it was possible to estimate the stress distribution throughout the salt and under the cans. The approximate locations and positions of all pressure patches are shown in Figures 4a-c and in the video in Appendix 4. Some post-test observations indicated that the orientations of the pressure patches were not substantially altered during the test.

6.3 Calibrations and Data Acquisition

Load measurements during all crush tests were based on transducer calibrations conducted by MTS Systems Corporations. Both Celecso wire extensometers were calibrated against the calibrated stroke in another, small 22-kip (98 kN) MTS load frame in the 6117 Geomechanics Laboratory. The diametrically opposed axial strain gages at equal heights on the aluminum confining ring were averaged by placing them in opposite legs of a Wheatstone bridge. Individual radial strain measurements and axial strain averages were calibrated by means of shunt resistors in parallel with each strain gage.

Pressure patch calibrations were carried out in a small 22 kip (98 kN) MTS testing machine in the 6117 Geomechanics Laboratory (Figures 5a-b). To ensure even loading during calibrations, each patch was sandwiched between two 3/32-in.-thick (2.4 mm) rubber sheets.

The existing laboratory notes of the project staff identify most of the hardware used in the experiments including strain gages, strain gage conditioners, excitation voltages, shunt resistors, etc. All data were acquired on a PDP 11 computer. Although the associated computer records could not be located, the original test documentation includes hard-copy prints of the data, specifically, shunt resistor offsets corresponding to reference strains as well as force-strain and force-total displacement plots for loading cycles to approximately 500 and 1010 kip (2.22 and 4.5 MN) machine loads. The existing laboratory data include the original pressure patch calibrations, post-test pressure patch records, photographs of all pressure patch observations, and a number of hand-written and dated notes by the responsible staff. Relevant calibration records other than the pressure patch calibrations are retained in the laboratory records of the Geomechanics Department.

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Figure 4. (a and b) Seven-pack test assembly indicating locations and placement of pressure patches in crushed salt inside aluminum confining ring; (c) photo of cans and pressure patches at Level 2.

Figure 4. (Continued) (a and b) Seven-pack test assembly indicating locations and placement of pressure patches in crushed salt inside aluminum confining ring; (c) photo of cans and pressure patches at Level 2.

Figure 5. Color densities of pressure patches. Reference color densities for (a) low- and (b) medium-pressure sensitivities based on separate calibration tests; (c) color densities of pressure patches after the seven-pack confined crush test to peak load of 1010 kip (4.5 MN). Note: Pressure patch #9 was not used in the seven-pack crush test. Also, color densities in copies above are degraded compared to originals.

Pressure patches, Fig. 1 NPP Experiment
 Patch # = 0 → 9. Low Pressure (100-200 psi)
 Patch # = 11 → 8. High Pressure (200-3500 psi)

(c)

Figure 5. (Continued) Color densities of pressure patches. Reference color densities for (a) low- and (b) medium-pressure sensitivities based on separate calibration tests; (c) color densities of pressure patches after the seven-pack confined crush test to peak load of 1010 kip (4.5 MN). Note: Pressure patch #9 was not used in the seven-pack crush test. Also, color densities in copies above are degraded compared to originals.

Reviews of all calibrations, pre-test checks, and test records indicate conclusively one error. Inferences of shunt resistor readings for axial strain measurements on the aluminum confining ring neglected that the resolution of axial strain measurements was doubled when two diametrically opposite gages were wired into opposite legs of the same Wheatstone bridge. Therefore, the strain magnitudes shown in all plots of force versus axial strains (in percent) are twice the actual strains. This error was corrected in subsequent data analyses and does not affect the conclusions reached in this report.

6.4 Test Procedure

The execution of the confined seven-pack crush experiment consisted of the following steps. (1) After the aluminum confining ring had been instrumented with strain gages, it was placed onto and bolted to the stepped, bottom plate as indicated in Figure 3. The bolts were necessary to lift and swing the complete test assembly into the MTS testing machine. It became apparent only later that the bottom bolts also restricted the free expansion of the confining ring during loading. This restraint resulted in spurious strain gage measurements at least towards the bottom of the assembly. (2) The seven-pack of cans was centered on the bottom plate of the assembly. Note that pressure patches were placed under the cans numbered 1 and 3 (Figure 4a). (3) The confining ring was lined with a Teflon sheet, and dry crushed, sieved salt was poured around the seven-pack of cans. To simulate the placement of real backfill *in situ*, a cardboard cover was used to keep crushed salt from filling the spaces between the cans as shown in the video (Appendix 4). (4) At heights of about 3, 7, and 12 in. (2.54, 17.8, and 30.5 cm) from the bottom, 17 pressure patches were placed in the patterns shown in Figure 4b and in the photograph, Figure 4c. The pressure patches were numbered zero through 8 and 11 through 18. (5) The top surface of the crushed salt was leveled. Then the test assembly was lifted and placed inside the MTS test frame. (6) A stack of one 3-inch (7.6-cm) and one 6-inch (15.2-cm) thick aluminum loading plates was centered and placed on top of the crushed salt. The diameter of these loading plates was 26 in. (66.0 cm). The loading plates reacted directly against the flat top crosshead of the testing machine after the load cell had been removed because it had a smaller outside diameter. (7) All strain gages were connected to a Hawkeye signal conditioner and computer channels, and the functioning of all strain gages was checked with shunt resistors. (8) The test assembly was subjected to several loading cycles while the testing machine was operated in stroke control at a rate of 6 in. (15.2 cm)/hour. The total duration of the experiment was approximately 50 minutes. (9) After completion of the test, the compacted salt-can plug was pushed out of the confining ring by means of a construction type Enerpac hydraulic jack held in place by the chain and center plate depicted in Figure 6. (10) Measurements were made of the center heights of the seven deformed cans. Additionally volume measurements were made and photographs taken of some of the deformed cans (Figure 7).

Figure 6. Placement of hydraulic jack for removal of crushed-salt-can "slug" from confining ring.

Figure 7. (a) Video frame of can #9 after single-can crush tests (frame of video in Appendix 4) and (b) photograph of undeformed can and deformed cans #1 and #3 of seven-pack confined crush test.

6.5 Results of Confined Can Crush Tests

The results of the confined crush experiments are divided into force-displacement behavior of the total assembly, stress distribution throughout the simulated crushed salt backfill, and the response (load-carrying capacities, volume changes and deformation modes) of the individual cans within the seven-pack including the comparison of can response in single and confined can-crush experiments. All of these aspects are pertinent to the simulation of filled waste storage rooms in the WIPP and any comparisons between simulations and reality. Note that the clarity of some of the data plots suffer from the fact that they are reproductions of old, sometimes annotated hardcopy records because the original computer files are no longer available.

Figures 8a-b are the force displacement curves for the assembly for the two complete load/unload/reload cycles to about 500 kip and 1010 kip (2.22 and 4.5 MN), respectively. Accordingly, the total system compaction was 3.57 in. (9.1 cm), which agrees with the relative positions of components that were measured on the video images.

Table 3 lists the strains that were measured on the outside of the aluminum confining ring at the top (highest), middle and bottom positions as marked in Figure 3. Negative strains are tensile strains. All of the strains were taken from old hard copies of the force-strain curves in Appendix 3. Table 3 also includes estimates of the internal pressures (radial stresses) acting along the height of the ring. These approximate pressures were obtained by treating the confining ring as an infinitely long, uniformly pressurized thick-walled cylinder. Hence, the tangential stresses on the outside of the ring, σ_θ , were taken to be

$$\sigma_\theta = \frac{2a^2}{(b^2 - a^2)} p$$

Using elementary relations with $\sigma_r = 0$,

$$\varepsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_z) \quad \text{and} \quad \varepsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_\theta).$$

Substituting values of the outside and inside diameters of the confining ring, b and a (28.25 and 27 in. respectively; 71.8 and 68.6 cm), as well the elastic constants for aluminum 6061T6 ($E = 10.6 \cdot 10^6$ psi or 73.1 GPa and $\nu = 0.33$), it follows that

$$E\varepsilon_\theta = 21.1p - 0.33\sigma_z \quad \text{and} \quad E\varepsilon_z = \sigma_z - 6.97p,$$

or

$$p = 5.64 \cdot 10^5 \cdot (\varepsilon_\theta + 0.33\varepsilon_z)$$

Figure 8. Force-displacement records of complete load/unload/reload cycle of seven-pack assembly to about (a) 500 kip (2.22 MN; load cycle #1) and (b) 1,010 kip (4.5 MN; load cycle #2). Note scale changes and reversal of sign of axial compression between (a) and (b).

Table 3. Strain gage data and calculated pressures for aluminum confining ring used in confined seven-pack crush test. (Note: Pressure, p, given in psi; 100 psi $\approx$ 0.69 MPa and 100 kip $\approx$ 444.8 kN)

Cycle 1 (500 kip)	Top	Middle	Bottom		Top	Middle	Bottom
ϵ_{θ}	-4.36E-04	-6.93E-04	-1.05E-03	ϵ_z	4.08E-05	4.91E-04	-1.90E-04
$\epsilon_{\theta-residual}$	-5.44E-05	-1.39E-04	-2.01E-04	$\epsilon_{z-residual}$	2.90E-06	1.06E-04	-7.92E-05
p	-242	-345	-610				
p _{corrected}	-246	-391	-592				
Cycle 2 (1010 kip)							
ϵ_{θ}	-6.55E-04	-1.24E-03	-2.00E-03		4.19E-04	4.10E-04	-3.51E-04
p	-321	-681	-1320				
p _{corrected}	-361	-729	-1280				

Table 3 contains two sets of values for p. The "corrected" values are the measured axial strains, ϵ_z , multiplied by one half to correct for an error mentioned in the section Calibrations and Data Acquisition above. Residual strains are the strains recorded at the end of the first complete loading cycle to approximately 500 kip (2.22 MN) and back to zero load. The measured axial strains do not exhibit the expected increase with depth due to friction between the crushed salt and the aluminum ring. It is difficult to explain the axial strains solely by the uniformly pressurized thick-wall-cylinder simplification and by the constraints imposed by bolts that tied the confining ring to the base of the assembly. The unexplained axial tensions probably resulted in underestimates of the internal radial pressure as the assembly was loaded.

Table 4 is a compilation of pressure-patch readings at the three heights, approximately 3, 8, and 12 in. (7.6, 20.3, 30.5 cm) above the bottom of the confined can assembly (Figure 5c). These levels are referred to as Level 1, Level 2, and Level 3 (Figure 4a) in 1989 laboratory notebooks in the order in which the pressure patches were positioned during the placement of the crushed salt. Note that the pressure patches at Level 3 are located above the top of the seven-pack of cans. Moreover, the patches #4 and #16 are located directly above the pack of cans.

Table 4. Estimated stresses in crushed salt based on coloration of pressure patches. Patch numbers 0-8 were low-pressure patches with calibrated range 107-987 psi (0.74-6.81 MPa). Patch numbers 11-18 were medium-pressure patches with calibrated range 966-3266 psi (6.66-22.52 MPa). Bold-faced patch numbers indicate unambiguous readings within achievable resolution. "Saturated" implies that color density exceeded the color density of peak calibration stress. "Uneven" means that different areas of patch exhibited significant contrasts in color density. The symbols >, >>, and <, << imply that color densities were noticeably or significantly different from color of nearest applicable calibration patch. The calibration range 2170-3266 psi (14.53-22.52 MPa) for medium-pressure patches showed little difference in color densities. (Note: 100 psi $\approx$ 0.69 MPa).

Level #	Pr. Patch #	σ_r (psi)	σ_θ (psi)	σ_z (psi)	Comments
1 (lowest)	2			>>987 (saturated)	>Reading #5 Range 2170-3266 Range 550-987, uneven Range 967-1300
	13			>2170	
	8	950			
	11	1000			
2 (middle)	7			>>987 (saturated)	Range 1900-2173
	15			2100	
	6	>987			<Reading #7, similar to #5 >Reading of #16 Between readings #5 and #7 Range 1300-1790 psi
	14	$\leq$ 966			
	1		>987		
	12		1300		
3 (highest)	4			350	Range 250-450
	16			<<966	
	5		>987 (saturated)		Not as saturated as #2
	17		1000		Range 966-1300
	0	>987 (saturated)			Similar to reading #5
Under can #1	18			1000	Range 966-1300
Under can #2	3			750	Range 500-987, uneven.

Two photographs in Figure 7 indicate the modes of deformation of cans in the single-can and in the confined seven-pack crush tests. Figure 7b contains an undeformed can for comparison. The principal failure modes appear to be buckling with considerable high-mode buckling and substantially greater compaction at lower loads (average stresses) in the single-can test. Note that the cans surrounding the center can in the seven-pack crush tests also underwent bending and shearing, i.e., more complex deformations. None of the cans appeared to exhibit any holes or detached lids. Some quantitative data concerning the deformed cans are given in Table 5 with height changes and selected measurements of volume reductions.

Table 5. Height and volume reductions of $\frac{1}{4}$ -scale waste cans ($H_o = 8.625$ -in. or 21.91 cm at can center, $V_o = 250 \text{ in}^3$, i.e., $4,097 \text{ cm}^3$). nm denotes "not measured."

Can No.	Height Reduction H_f / H_o	Volume Reduction V_f / V_o
1	0.64	0.554
2	0.63	nm
3	0.64	0.497
4	0.65	0.475
5	0.64	nm
6	0.64	nm
7	0.64	0.510
8	0.30	nm
9	0.32	nm

7.0 DATA INTERPRETATION AND DISCUSSION

The results of this study should be considered within the context of the three objectives described earlier: (1) Comparison of the load-supporting capabilities and deformation modes of single simulated waste cans with the response of multiple waste packages that were surrounded and confined by crushed salt. In this case, multiple waste packages as discussed by VandeKraats (1987) were replaced by one seven-pack of cans that could be accommodated in a laboratory experiment of manageable size. (2) Development of a small-scale experiment that would yield independent measurements to evaluate the predictive capabilities of computer simulations. (3) Generation of experimental measurements for comparison with the results of numerical analyses whose outcome is determined by the combination of geometric and structural system idealizations, boundary conditions, constitutive models (for filled waste drums, crushed salt backfill, and surrounding salt mass), and computer algorithms. A review of this study naturally also brings up the question whether the experiment of a confined waste package loaded parallel to the cylindrical axis of the cans could be generalized, e.g., to more complex loading conditions between non-parallel loading platens, wet crushed-salt or some other kind of backfill.

A comparison of single and multi-can crush tests probably should include a rigorous evaluation of the boundary conditions at the ends of the cans. Because the lip of individual cans rises above the rest of the lid, laboratory loading between rigid platens implies loading across narrow rims that appears to favor early buckling. Furthermore, the initial axial stiffness of each isolated can is so low that it supported very little load until it had been compacted to less than 40% of its original height (Figures 2 and 7a). By comparison, each can in the confined seven-pack exhibited significantly higher load bearing capacities and lower buckling modes that were more uniformly distributed across the height of the cans. Assuming an average maximum vertical stress, σ_z , of approximately 1000 psi (6.9 MPa; Table 4), each can in the seven-pack supported 29,000 lbs. (129 kN) after approximately 3-in. (7.6 cm) of compaction. This compares with no more than 4,600 lbs. (20.5 kN) across isolated cans as shown in the video record of the crush test on can #9. Conversely, can #9 carried 29,000 lbs. (129 kN) only after about 5.4 in. (13.7 cm) of shortening. To arrive at a more objective comparison, however, single-can axial crush tests should be repeated between soft end caps or tubular end-caps filled with crushed salt. Consideration must also be given to what other single-can measurements are needed for the realistic numerical representation of the behaviors of individual cans under more general loading conditions.

The strain-gage readings taken on the aluminum confining ring during the seven-can crush tests proved to be less definitive than anticipated. However, this shortcoming should be easily corrected by releasing the bottom fasteners after the test assembly has been placed in the testing machine and before loading. Additionally, the interpretation of strain gage data can be improved by finding the elasticity solution for a pressurized cylinder of finite length. While axial strain gages were used primarily to resolve friction losses at the crushed-salt-Teflon-ring interface, friction can be measured more effectively in the future by recording the jack pressure needed to push the crushed-salt-can "slug" out of the confining ring at the end of the experiment as shown in Figure 6 and toward the end of the video (Appendix 4).

As expected under quasi-static conditions, i.e., in the absence of significant creep, the stress distribution in the crushed salt is non-hydrostatic. Moreover, the stress state in the top layer of crushed salt is different from the stress state in the annulus of material between the seven-pack and the aluminum confining ring. More specifically, the pressure patch measurements indicate that the vertical stress, σ_z , in the crushed salt increases from positions above the top of the cans (Figure 4) toward points next to the top or in the lower half of the annulus. Based on the data in Table 4, the average vertical stress σ_z carried by the cans is considerably lower than σ_z in the crushed-salt annulus. This agrees with the compliance measurements on single cans (e.g., Figure 2) and multi-can packages (VandeKraats, 1987) and with published data for crushed salt (Holcomb and Hannum, 1982).

The higher values of σ_z at the lower pressure-patch positions suggest that the crushed salt in the annulus was more compacted and, therefore, was likely associated with higher radial pressures between the crushed salt and the aluminum confining ring at greater depth. Such a trend is indeed indicated by the variation in $p = \sigma_r$ that is inferred by the strain-gage data in Table 3. It is also consistent with the increase in the ranges of the tangential stresses, σ_θ , in Table 4 but not with the trend in the approximate magnitudes of σ_r that were derived from the colors of the pressure patches numbers 0,6,14, etc. (Figure 4) in Table 4. No satisfactory explanation can be offered for this discrepancy except for the possibility that the radial pressure patches were placed too close to the confining ring. The clarity of eight of seventeen pressure-patch responses (bold-font gage numbers in Table 4), the agreement between some low- and medium-sensitive pressure films at the same positions, and the qualitative agreement with the pressure-patch readings for σ_z and σ_θ , however, suggest that most of the pressure-patch observations are credible.

Inspection of the deformed seven-pack and dimensional measurements at the end of the experiment yield indications of the crushed-salt displacements next to the cans, shape changes of the waste cans as well as measurements of the height and volume reductions of the cans (Table 5). All of this information may be compared with the results of computer simulations. The can data may also be used to verify the applicability of measurements on 1/4-scale No. 12 food cans filled with simulated waste (in this case: combustible waste mixes). Note that the tilting of the top of can #9 (Figure 7a) was typical for all cans surrounding the center can #1 (Figure 3). Using the undeformed dimensions and the after-test volume of can #1, the mean final diameter of this symmetrically compacted center can is 5.65 in. (14.35 cm) compared with its pre-test value of 6.08 in. (15.44 cm). None of the cans ruptured or exhibited lid separations. As noted previously, however, Baker et al. (1980) made the observation that the lid-closures of No. 12 food cans and of 55 gal (0.21 m³) waste drums are different which suggests caution in the transfer of lid-failure observations from food cans to full-scale waste canisters. It is unknown to what extent VandeKraats et al. (1987) considered this possibility in their report on lid-failures in multi-can crush tests in trenches in the WIPP.

It was a major concern during the design of the seven-can crush test that the test assembly might not be loaded uniformly. In the end, remarkably uniform loading was suggested by the facts that the extensometer (displacement) readings along two diametrically opposed gage lengths on the confining ring agreed to within 1.1%. Nevertheless, caution is needed in setting

up any future experiment by means of the existing parts because the diameter of the various loading plates is only 26 in. (66.0 cm). This leaves only 0.5 in. (1.3 cm) tolerance between the pistons and the inside of the aluminum confining ring which should never touch each other.

The seven-can crush tests described in this report is the first of its kind, and therefore, no data exist to demonstrate that these measurements are representative. To explore the validity of the observations, the following, admittedly very approximate calculations can be performed. Based on the pressure patch data in Table 4, the average stress acting on each can of the seven-pack is between 900-1000 psi (6.2-6.9 MPa). Table 4 also indicates that σ_z throughout the crushed-salt annulus is at least 2200 psi (15.2 MPa) toward the bottom of the assembly. Summing the resulting forces acting on the seven-pack and on the crushed-salt annulus yields $8.75 \cdot 10^5$ to $9.85 \cdot 10^5$ lbs. (3.9-4.4 MN) without friction losses. This force compares favorably with the greatest applied test load of $1.01 \cdot 10^6$ lbs. (4.5 MN), a difference of less than 13%. Admittedly, the apparent resultant force compares less favorably with the applied load at the Level 3 in Figure 4.

In 1989, when various single-can and multiple-can crush tests had been or were being performed, the WIPP program had only limited capabilities for realistic code simulations. Based on recent communications, these numerical capabilities have been advanced substantially. In addition, several series of crushed-salt property measurements were used to develop a new constitutive model for crushed salt describing both quasi-static and long-term material behaviors (e.g., Holcomb and Hannum, 1982; Weatherby, 1993; Callahan, 1998). It appears that the present measurements during a seven-pack crush experiment furnish an adequate amount of observational and quantitative data for a comparison of code simulations and physical system response. It also appears, that some failings of the present tests could be easily overcome and, therefore, it is recommended that the seven-can crush test be considered among viable options for future performance-assessment and validation studies. There is no reason why this test could not be extended to other types of backfill including magnesium oxide. Alternatively, a taller aluminum confining ring would permit the placement of can packages perpendicular to the loading direction (VandeKraats, 1987). The experience gained in this test may also be helpful in developing a larger test in the WIPP; perhaps making use of the trench that was used in the large $\frac{1}{4}$ -scale crush test by VandeKraats et al. (1987).

Baker et al. (1980) pointed out that the closure seams of 55 gal. (0.21 m^3) waste drums and No. 12 food cans differ in ways that could affect the behavior of $\frac{1}{4}$ -scale models undergoing large deformations. Specifically, these differences might determine at which point the lids of waste drums and cans might pop loose leading to changes in drum/can load bearing ability and stiffness. Lid separations were quite common in the scaled in-WIPP experiments by VandeKraats (1987) in which can packages were loaded perpendicular to the can axes. No lid separations occurred either in the present single-can crush tests or in the seven-can crush experiment with external loading parallel to the can axes. However, note that both types of experiments were performed quasi-statically and that the seven-can test involved only relatively small lateral loading induced by crushed-salt movement inside the comparatively rigid aluminum containment ring (Figure 7b). Further valuable information about the comparative responses of full-scale waste drums and $\frac{1}{4}$ -scale cans might be obtained by a review of the single-drum crush

tests that were conducted by SAIC under the 1989 Sandia (Procurement) Document No. 05-7501 (Butcher et al., 1990).

8.0 SUMMARY AND CONCLUSION

Early in 1989, 1/4-scale model tests were conducted to assess the potential of laboratory experiments and to generate measurements for evaluating computer simulations of waste packages surrounded by crushed salt in the WIPP. The choice of crushed salt was based on engineering considerations in the late 1980s that are superseded by the current design of the WIPP. However, the general approach to evaluating the performance of waste disposal systems remains applicable.

One-quarter-scaling was applied to the dimensions of individual waste drums as well as to the distances between the walls of WIPP excavations and the outermost rows and columns of full-scale waste packages. This report documents the foregoing exploratory tests that were completed more than ten years ago. The report includes a brief description of earlier and concurrent work concerning the characterization of different waste forms, 55-gal. (0.21 m³) drum behavior, and the evaluation of scaled model experiments.

Overall, the study confirms that laboratory tests involving a pack of seven cans filled with simulated waste surrounded and confined by crushed-salt backfill constitute a viable approach to code validation. Tests of this or similar kind and size (27 in. or 68.6 cm diameter by about 24 in. or 61.0 cm high or possibly higher) could be repeated in the laboratory using parts that were manufactured in 1989 and kept. Shortcomings of the 1989 prototype experiment could be easily remedied. It also appears that the design and outcome of the 1989 test could guide the development of any larger tests in the WIPP involving more general waste-can arrangements and loading conditions.

Major results were as follows:

1. The measured load bearing ability of each can in a confined 1/4-scale seven-can package subjected to predominantly axial loading was substantially greater (factor 5 or more) than the load bearing ability of isolated waste cans. However, early collapse of isolated cans may have been favored by loading along the rims of the cans as opposed to distributed loading.
2. None of the cans of the seven-pack ruptured or exhibited lid separations. However, Baker et al. (1980) noted several differences that exist in the lid closures and wall characteristics between 55-gal. (0.21 m³) waste drums and No. 12 food cans, which might limit the transfer of lid-failure observations from food cans to full-scale waste canisters.
3. The stress distribution in crushed salt in a confined seven-pack crush test under quasi-static loading conditions was non-hydrostatic as expected in the absence of significant backfill creep. Additionally, the maximum stresses across the annulus of crushed-salt backfill around the seven-pack were considerably higher than the average maximum (axial) stress supported by the more compliant seven-pack of waste cans.
4. Relatively coarse stress measurements throughout the crushed salt backfill as well as above and below individual cans in the seven-can crush test yielded valuable data concerning the stress field throughout the test assembly. Moreover, the shapes of the deformed cans in the seven-pack provided information about the displacement field in the crushed salt next to the seven-pack.
5. Difficulties encountered in the conduct of the seven-can crush test and in post-test interpretations of some measurements are deemed to be correctable. In spite of these shortcomings, the single prototype test of 1989 provides a variety of independent

measurements that could be used immediately to evaluate the predictive accuracy of computer simulations of waste packages and crushed salt backfill in the WIPP. Stress measurements by means of pressure-sensitive films probably could be improved if they were placed between metal disks thinner than the 3/32-in. (2.4 mm) thick disks used in this study.

The 1989 results were obtained by means of a mix of materials prescribed by WIPP staff as representative of combustible wastes in full-scale, 55-gal. (0.21 m³) waste drums. Obviously, the particular mix used influenced the force-deformation behavior of the scaled waste-can and waste-package experiments described in this report. Consideration must also be given to what single-can crush tests will be needed besides axial crush tests for realistic numerical simulations of the behaviors of individual cans in multi-can packages.

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Appendix 1

Prescribed Mixes for Combustible Waste Simulants

Figures referred to in this appendix were not part of the available notes.
Descriptions are copies of best available original records.

Notes provided by
J. H. Butcher, Experi-
mental Programs
Division, 6832

Combustible Waste

The state of an average drum of combustibles was estimated by summing the weight of each component and finding its average value:

Type of Container	DOT-17C (55 gallons) with 90 mil liner ⁷
Weight of Drum Contents (drum liner not included)	88.1 ± 50.0 lbs
wt% Metals	9%
wt% Paper, Cloth, and Wood	37%
wt% Plastics, Surgeons Gloves, Rubber	45%
wt% Sorbents	9%
Drum weight	64.5 lbs
Weight of liners + other components	17.0 lbs ⁸
Average Gross Weight	169.6 lbs ⁹

The amount of each component in combustible waste is shown graphically in Figure 3. To create simulated combustible waste components, we propose to mix materials representative of the items listed in Table 4, until their combined weight is equal to the average weight of the drums. If the average weight of a collection of drums containing combustible waste differs from the average gross weight quoted above, we will simply adjust the weights of the various components in proportion to the difference between drum weights.

In reviewing the results for combustible waste, the uncertainty of ± 50.0 lbs in the average weight of the drum contents is large. In addition, a histogram of how this weight is distributed among the various drums, in Figure 4, shows that the cause of the discrepancy is a wide variation of weights from drum to drum.

7. Rocky Flats Plant Standard SX-200, "Standards for DOT-17C 55 Gal. Drum".

8. Normally this quantity should be the difference between the weight of the drum contents plus the weight of the drum and the measured gross weight of the drum. Estimation in this manner was not possible for combustibles, because of several obvious discrepancies in gross drum weights, so that this value is assumed to be the weight of the 90 mill polyethylene liner.

9. The value of average gross weight calculated from the data was 162.2 lbs

TEST AND MATERIAL SUMMARY

MATERIAL NO.	TEST NO.	MATERIAL DESCRIPTION	MATERIAL TYPE
1	15	Polyethylene bottles, sml and lrg (cut)	Plastics
1	22	Polyethylene bottles, sml and lrg (cut)	Plastics
2	07	Phillips Marlex PE Beads	Plastics
2	08	Phillips Marlex PE Beads	Plastics
① 3	12	40% bottles, 40% PVC, 20% gloves by wt.	Plastics
3	26	40% bottles, 40% PVC, 20% gloves by wt.	Plastics
4	23	50% Marlex beads, 50% cut PC by wt.	Plastics
4	27	50% Marlex beads, 50% cut PC by wt.	Plastics
5	05	Sawdust (Mixed pine and fir)	Fiber
5	06	Sawdust (Mixed pine and fir)	Fiber
6	10	Pine wood cubes (1" dim.)	Fiber
6	24	Pine wood cubes (1" dim.)	Fiber
② 7	11	60% wood cubes, 40% rags by wt.	Fiber
7	30	60% wood cubes, 40% rags by wt.	Fiber
8	13	Oil-Dri ("SORB-ALL")	Sorbents
8	21	Oil-Dri ("SORB-ALL")	Sorbents
9	09	Vermiculite	Sorbents
9	20	Vermiculite	Sorbents
④ 10	16	Portland cement	Sorbents
10	25	Portland cement	Sorbents
③ 11	14	Various metal parts, 1" dim	Metals
11	28	Various metal parts, 1" dim	Metals
12	17	Various metal parts, 3" dim	Metals
12	29	Various metal parts, 3" dim	Metals
13	18	Moist sand/Dry cement (layered)	Sludge
13	32	Moist sand/Dry cement (layered)	Sludge
14	19	Crushed salt under 3" metal	

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Appendix 2

Drawings for Loading Plate(s) for Seven-Pack Laboratory Crush Test

Note: Drawings are cutouts of reduced originals.

NOTES:

1. GENERAL REQUIREMENTS AND DRAWING INTERPRETATIONS ARE DEFINED IN 8000000.
2. MATL: 1000 TO 1000 FTREL.
3. CADMIUM PLATE PER QQ-P-416, CLASS 2, TYPE II.

▲ WITH PART NUMBER PER 801000, CLASS C-E WITH 100 INCH DIMENSIONS. LOCATE APPROX 45 INCHES

REPORT ON COMPL. ACTION	DATE			
IN 22002-000	NO. 1	REPORTED BY	REPORTED	DATE
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NOTES:

1. GENERAL REQUIREMENTS AND DRAWING INTERPRETATIONS ARE DEFINED IN 9600000.
2. MATL: 1020 TO 1030 STEEL.

PART NUMBER		REVISIONS		DATE	OWN	APD
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R14053-000	A	ALBION 2552/ANALYSIS	6232			WFW

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Appendix 3

Force-Strain Plots for Two Loading Cycles of Seven-Pack Confined Crush Test

Note: Axial strains are larger by factor 2 than actual strains (see text for explanation). Plots are copies of best available original records.

cycle #1

Appendix 4

Video of 1/4-Scale Single-Can and Seven-Pack Crush Tests (Available Only on Request – WPO#52168)

Note: Essential information on the video has been incorporated into the main body of the report.

Conceptual Vertical Sediment Flume Design Review Panel - Process Flow

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