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QUARTER-SCALE MODELING
OF ROOM CONVERGENCE EFFECTS
ON CH TRU DRUM WASTE EMPLACEMENTS
USING WIPP REFERENCE DESIGN GEOMETRIES

DOE/WIPP 87-012

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NOVEMBER 1987

WASTE ISOLATION PILOT PLANT
Prepared for the Department of Energy
under Contract DE-AC04-86AL31950

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EXECUTIVE SUMMARY

The rock salt at the Waste Isolation Pilot Plant (WIPP) repository depth of 2150 feet slowly creeps or deforms plastically into excavated areas. In the case of a waste storage room, the walls, floor and roof creep so that eventually the opening is resealed and the waste materials are entrapped. The WIPP Reference Design for disposal of contact-handled (CH) waste calls for the waste packages to be emplaced three high and five across along the length of the waste rooms with screened salt backfill placed wall to wall over and around the waste stack.

Because the waste packages are not sufficiently strong to resist the stresses in the rock, they will deform and possibly be breached by the loads exerted by the strata. The Department of Energy (DOE) has made provisions for and has agreed to retrieve any radioactive wastes emplaced during a five-year Operations Demonstration period, if it cannot be demonstrated that permanent disposal at the WIPP site is viable. Therefore, reliable predictions of the condition of the waste packages through time become important for two major reasons. First, it is important to be able to anticipate the conditions expected to be encountered, should retrieval become necessary, both from an operational and a personnel safety point of view. Second, it is necessary to be able to demonstrate the ability to retrieve waste in a safe manner should it become necessary. Note that to properly address the second point, it is necessary to be able to model the condition of the stack at the time of retrieval.

The purpose of this study was to investigate the effect of horizontal room convergence on CH waste packages emplaced in the WIPP Reference Design geometry (rooms 13 feet high by 33 feet wide, with minus 3/8 inch screened backfill emplaced over and around the waste packages) as a function of time.

Planning proceeded in November of 1986 based on direction given by WIPP Management and Operating Contractor Engineering and Operations Departments to investigate the following:

1. Whether or not load would be transmitted through the salt backfill to the waste stack,
2. If load will be transmitted through the backfill to the stack, predict the nature and extent of damage to the waste stack, and
3. Whether drums will be breached and, if so, what will be the percentages and of location of those drums breached.

Because the CH Mock Demonstration is scheduled to be performed in September 1987, less than a year from the inception of this work, emphasis was placed on timeliness. Three options to accomplish the work were identified: (1) full-scale physical modeling; (2) computer modeling; and (3) reduced-scale physical modeling. Reduced-scale modeling was chosen because of time and cost constraints. Because most of the waste is expected to arrive at WIPP in 55-gallon drums bound together as 6-packs, all studies were performed using scale-model drums.

A quarter-scale model was selected for further study as a model based on previous work done by M. Huerta (1983) in support of a Sandia National Laboratories transportation modeling study. A test plan was developed to proceed in a stepwise fashion: (1) confirm the quarter-scale mode with Huerta's data; (2) compare full- and quarter-scale data for both single drums and for 6-packs confined with backfill to further confirm the model; and (3) execute quarter-scale room-size tests in the Reference Design geometry if the model proved valid for each preliminary step.

The initial preliminary test series to confirm the quarter-scale models with Huerta's data indicated that the models tested were up to 20% stiffer than those Huerta used. Although the data from the two sources did not match perfectly, the correlation between the two was sufficient to justify further testing using salt backfill with the models.

The second preliminary test series consisted of empty single quarter-scale cans and full-scale drums confined in a fixture with backfill and loaded laterally across the drum diameter. Only the quarter-scale tests were performed in this phase. The tests indicated that load was transmitted by the backfill and that the models were substantially strengthened through the sidewall support offered by the backfill; approximately six times as much load was required to crush single cans confined with backfill as cans not confined.

The third preliminary test series consisted of crushing individual 6-packs, both full- and quarter-scale, in a confining fixture with backfill surrounding them. The drums and cans were empty. Scale comparisons of the two test types indicated a close correlation between the two to near the peak load. Through monitoring the confining fixture on the full-scale tests, it was determined that the out-of-plane stresses were as much as 80% of those directly behind the loading plate. Full-scale drums breached during testing at an average of 2.1 inches of rim diameter deformation with a range of 1.0 to 2.9 inches.

Because of good scale correlation from the preliminary data, two room-scale tests were performed using the quarter-scale models. The two tests had identical geometry using 150 6-packs (900 cans) emplaced in a quarter-scale WIPP Reference Design geometry (three 6-packs high by 5 across) with a reduced length (only about 50 feet of the room length was modeled as opposed to the 300 feet design length). Backfill was emplaced around, but not over the cans. Load was applied with load-indicating jacks located behind the simulated walls. As the walls were displaced and converged on the simulated room, crush was monitored on the top of the stack visually and was monitored remotely by instrumentation installed in 30 of the cans placed in the stack. Also, consolidation of the backfill was monitored at each layer depth at one location. The first test consisted entirely of empty cans and the second test was a random distribution having 50% empty cans and 50% cans filled with loose salt.

Based on these two tests the following predictions were made with regard to full-scale 6-packs emplaced in the Reference Design geometry:

1. Load will be transmitted completely through the stack within the first five years after waste emplacement. All drums in all 6-packs will be affected.

2. Virtually all drums will show some deformation eight years after emplacement.
3. Some drums may breach before the eighth year after emplacement has elapsed. These breaches may occur at any location in the stack, but the most likely location for breach is near the storage room center.
4. Based on criteria developed during testing, it is predicted that 1% of the drums emplaced will be breached after 8 years. Using a simple extrapolation format, after 15 years, approximately 12% of the drums are predicted to be breached; this figure may be larger.

Although the inclusion of CH boxes in the waste stack was not addressed by testing, it is noted that boxes received on site for demonstration to date are structurally reinforced and should be able to resist more pressure due to lateral loading by backfill than the drums. If this is the case, then boxes may not deform until any drums placed adjacent to them have crushed somewhat. If the project proceeds toward using drums and boxes in backfilled storage rooms, it will be beneficial to perform a detailed structural analysis for the various box designs and examine their interaction with the drums.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
Title Page	1
Executive Summary	2
Table of Contents	5
List of Tables	5
List of Figures	6
Introduction	9
Background on Scale Modeling	12
General Concepts for Testing	12
Preliminary Testing - Confirmation of Model	14
Single Can Unconfined Tests - Quarter Scale (T1)	16
Single Can Confined Tests - Quarter Scale (T2)	18
6-Pack Confined Tests - Quarter Scale (T3)	21
6-Pack Confined Tests - Full Scale (T5)	24
Single Drum Confined Testing - Full Scale	29
Room Scale Testing - Use of the Model	29
General	29
Room Scale Test - Empty Drum Simulation (T6)	36
Room Scale Test - Simulated Waste Test (T7)	43
Discussion of the Implications of the Room-Scale Tests	44
Conclusions	51
References	53
Appendix 1: Strain Gaged Beams - Theory and Application	
Appendix 2: Model Numbering and Layout	
Appendix 3: Test 5 Confining Fixture - History and Development	
Appendix 4: Plots of Strain Gaged Beam Data from Tests 6 and 7	
Appendix 5: Graphical Presentation of Crush in Tests 6 and 7	

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
1	Model Dimensions	16
2	T6 (Quarter Scale, Room Geometry - 100% Empty Models) - Summary of Model Deformation by Layer	39
3	T7 (Quarter Scale, Room Geometry - 50% Simulated Waste Filled, 50% Empty Models) - Summary of Model Deformation by Layer	46

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
1	Reference Design Storage Area Room Dimensions	11
2	Quarter- and Full-Scale Lateral Force-Displacement Results	13
3	Lateral Force Versus Displacement for Full-Scale Drums . .	15
4	Force Versus Displacement for Lateral Quarter-Scale Tests .	15
5	T1 Tests (Single, 1/4 Scale, Unconfined) With Huerta Data .	17
6	T1 (Single, 1/4 Scale, Unconfined) - Beam Displacement Versus Platen Displacement	17
7	T2 (Single, 1/4 Scale, Confined) Test Confining Fixture . .	19
8	T2 (Single, 1/4 Scale, Confined) Load Versus Displacement Data	20
9	T1 and T2 (Single, 1/4 Scale) Confined/Unconfined Plot Comparisons	20
10	T2 (Single, 1/4 Scale, Confined) - Quarter-Scale Models After Testing	22
11	T2 (Single, 1/4 Scale, Confined) - Beam Displacement Versus Platen Displacement	22
12	T3 Configuration of Single 6-Pack Confined Preliminary Testing	23
13	T3 (6-Pack, 1/4 Scale, Confined) Load Versus Displacement Data	25
14	T3P30 6-Pack (1/4 Scale, Confined) in Test Fixture After Loading	25
15	T3P30 6-Pack (1/4 Scale, Confined) Bottom View After Testing	25
16	T3 (6-Pack, 1/4 Scale, Confined) - Beam Displacement Versus Platen Displacement	26
17	Test 5 (6-Pack, Full Scale, Confined) Geometry	28
18	Crush Monitoring Device for Full Scale Preliminary Testing	28
19	T5P30 6-Pack (Full Scale, Confined) Breach After Testing .	30

LIST OF FIGURES
(Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
20	T5 (6-Pack, Full Scale, Confined) Load Versus Displacement Data	30
21a	T5P10A (6-Pack, Full Scale, Confined) Plot of Individual Drum Crush	31
21b	T5P20 (6-Pack, Full Scale, Confined) Plot of Individual Drum Crush	31
21c	T5P30 (6-Pack, Full Scale, Confined) Plot of Individual Drum Crush	32
22	Scale Comparison of T3 and T5 (6-Pack, Full and Quarter Scale, Confined)	32
23	Loading Geometry for Tests 6 and 7 (1/4 Scale, Room Geometry)	34
24	Instrumentation Locations for Tests 6 and 7 (1/4 Scale, Room Geometry)	35
25	T6 (1/4 Scale, Room Geometry, Empty Models) - Top Rim Crush Data	38
26	T6 (1/4 Scale, Room Geometry, Empty Models) - Top Wall Crush Data	38
27	T6 (1/4 Scale, Room Geometry, Empty Models) - Bottom Rim Crush Data	38
28	T6 (1/4 Scale, Room Geometry, Empty Models) - Bottom Wall Crush Data	38
29	T6 (1/4 Scale, Room Geometry, Empty Models) - Average Plate Displacement Versus Backfill Consolidation	41
30	T6 (1/4 Scale, Room Geometry, Empty Models) - Convergence Versus Total Load	42
31	T6 (1/4 Scale, Room Geometry, Empty Models) - Convergence Versus Total Load Versus Time	42
32	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Top Rim Crush Data	45
33	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Top Wall Crush Data	45

LIST OF FIGURES
(Continued)

<u>Figure</u>	<u>Title</u>	<u>Page</u>
34	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Bottom Rim Crush Data	45
35	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Bottom Wall Crush Data	45
36	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Contour Plot of Severe Crush Occurrences	47
37	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Average Plate Displacement Versus Backfill Consolidation	48
38	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Convergence Versus Total Load	49
39	T7 (1/4 Scale, Room Geometry, Random Waste Model) - Convergence Versus Total Load Versus Time	49

INTRODUCTION

The WIPP is research and development facility being developed by the DOE to demonstrate safe disposal of defense program radioactive wastes in the underground salt beds of southeastern New Mexico. Of the total 6.4 million cubic feet of waste that is predicted to be received at WIPP, roughly 80% is expected to arrive in 55-gallon drums bound together in "6-pack" configurations¹. These 6-packs will be two drums wide and three drums long similar to the way canned soft drinks are packaged for sale. The 6-packs will be bound with either steel banding or "stretch wrap" (a polyethylene film) around the drum sides*.

When these 6-packs arrive at the WIPP site, they will be transported underground for emplacement in rooms mined out of the thick salt beds. Several 6-packs will be lowered at a time on the waste handling hoist to the repository level, where they will be transported to the storage rooms and then stacked to economically optimize the amount of waste placed in each mined area. After a waste room is filled it will be sealed with bulkheads.

The WIPP salt formations are considered to be extremely stable geologically and, thus, an excellent location for a waste repository. In addition, when areas are excavated at the repository depth of 2150 feet, the strata will creep or deform plastically and will close into these excavated openings over time, resealing and entrapping the waste materials. During this resealing stage, the salt rock will act much like an irresistible force and will tend to crush 6-packs and breach individual drums. This is of no consequence if the panels are properly sealed. However, DOE has made provisions for and has agreed to retrieve any waste emplaced during the five-year Operations Demonstration period following the first shipment if it cannot be demonstrated that permanent disposal is viable. If a decision is made to retrieve, then it is anticipated to take an additional two to ten years beyond the five-year emplacement and storage period to remove the waste (primarily depending on the number of shifts worked per day). If breaching occurs during this time period, retrieval will be complicated by the presence of the freed radioactive particles and by the necessity of removing them.

Placement of backfill over and around the waste stack is considered to be a part of the emplacement reference design which was developed by Bechtel National, Inc., the Architect/Engineer for the project, and is noted in their Design Validation Final Report (DVFR)*. Previous to the modeling effort reported in this paper, the lack of knowledge about how stress is transmitted to the stack through backfill was of concern both from the standpoint of the actual five-year Operations Demonstration and possible subsequent retrieval and from the standpoint of adequately modeling the stack for mock demonstration

*It is the writer's understanding that the planned use of 6-packs and of backfill is presently being evaluated by the Department of Energy. This report evaluates the current Reference Design (DOE-WIPP-86-010) and does not address any design changes nor does it speculate on any impacts due to them.

of retrieval capabilities. Information was needed in a timely manner (1) to effect any design changes necessary from an operational standpoint before actual emplacement of waste and (2) to guide the planning and performance of a mock retrieval demonstration that is representative of conditions anticipated at the time of retrieval.

This report outlines the short-term program which used quarter-scale models to simulate how standard 55-gallon drums emplaced as 6-packs in the Reference Design configuration react to lateral loading by the room walls due to creep closure. This work was performed in support of the Westinghouse Waste Handling Engineering and Waste Handling Operations groups to provide data and information primarily for their work in the five-year Operations Demonstration phase of waste emplacement and in their work with the CH TRU Mock Retrieval Demonstration at WIPP. The information obtained in these tests may also be useful in the areas of continuing operation, development, and design validation.

The reference emplacement configuration for CH waste in drums is 6-packs stacked five wide, three high, along the length of the rooms. The WIPP Reference Design calls for the storage rooms to be 33 feet wide by 13 feet high by approximately 300 feet long, and includes using minus 3/8 inch screened salt backfill placed over and around the stack. Typical dimensions for the Reference Design are shown in Figure 1.

Particular to the Mock Demonstration setup, it is necessary to simulate the condition of the stack at the time of retrieval. Information helpful in setting up the demonstration includes the configuration of the stack: the nature of drum crushing, prediction of the percentage of breached drums, changes in the positioning or geometry of individual drums and 6-packs, and the integrity of the 6-pack units.

This information is not only useful for the Mock Demonstration, but when considering convergence as a function of time, it is useful as an operational tool to support the continued development and validation of the WIPP design. For example, knowledge of the number and location of breached drums which may be encountered during retrieval will help calculate realistic radiation dosage calculations for the waste handlers working in the retrieval operation. This information, in turn, can help guide the planning of how to retrieve waste, should it become necessary.

Previous to performing any work, several options were identified to enable the gathering of information concerning backfill performance and to predict stack configuration. These included both full-scale and reduced-scale physical modeling, and computer modeling. Scale modeling was the most appealing option due to the ability to rapidly bring a test on line. Finite element computer codes existed which could be modified to use on this particular problem; however, a constitutive relationship for waste-stack behavior is not yet developed and validated. The deployment of the scale modeling work discussed herein should help to develop some of these relations. Although computer codes were not viable for the testing discussed here, they probably can now be utilized to explore design changes, possibly as the most inexpensive and most timely option.

EXPLANATION

- (1) Height of waste packages stacked three high: 9'-7 1/2" for boxes; 9'-0" for six-packs.
- (2) Salt cover: 1' to 2'; level of salt is maintained at 10'-8" above the floor.
- (3) Ventilation space: 1'-4" minimum until room or panel is filled and plugged.
- (4) Salt creep allowance: 1'-0" roof; 4 1/2" each wall (assumed to be adequate for 5 years).
- (5) Construction tolerance: +6". The contractor must maintain the minimum room dimensions.
- (6) Backfilling conveyor clearance: 2'-4" above waste packages.
- (7) Headroom: 12'-0" for CH boxes and RH transporter.
- (8) Waste package width: 6'-2 1/2" for boxes; 6'-1 1/2" for six-packs.
- (9) Stacking tolerance: 2 1/2" between waste packages.
- (10) Salt backfill: 8 3/4" between waste packages and wall.

FIGURE 1. Storage Area
Room Reference Design Dimensions (after Bechtel, 1986, ref. 1)

BACKGROUND ON SCALE MODELING

Some work with scale models has been previously performed. In his 1983 Sandia report² developed in support of transportation accident modeling, Huerta tested full-scale models using 55-gallon drums as well as quarter-scale models using #10 and #12 food type cans and eighth scale models using #300 cans. Various tests were performed on the models; however, of particular interest to WIPP participants are the lateral static crush test results, since this is the expected initial loading configuration of CH drums in the waste panels.

The models in the Sandia test were crushed by unconfined, uniaxial loading between steel platens. Tests were performed on empty models as well as models containing simulated combustible waste materials and sludge. Lateral displacement was recorded as a function of the lateral force applied to the model. Scaled plots of force versus displacement comparing the data collected from the full-scale and each reduced scale model indicates an excellent correlation between the full-scale and the quarter-scale using #12 cans (Figure 2).

A further literature search has not revealed any other work using scale models to simulate 55-gallon drums. In a telephone conversation³, Huerta added that, to his knowledge, no further work has been done employing the use of scale models.

GENERAL CONCEPTS FOR TESTING

Full-scale modeling is a desirable method of modeling the effects of convergence in the waste panels because the model is to the actual scale of the waste emplacement and, therefore, should most closely simulate conditions found in the stack. However, it was recognized that to do full-scale testing a large testing area is necessary, construction is labor intensive, and a large energy input is needed to load a test stack (Huerta showed that a load of approximately 15 kips was necessary to crush a single empty 55-gallon drum and it was believed that the addition of salt backfill would 'strengthen' the drums by providing confining pressure). These needs equated to time and money constraints which were prohibitive for the required information identified in the introduction.

It should be noted that Sandia National Laboratories has full-scale simulated CH TRU tests (using 55-gallon drums configured into 6-packs and stacked into partial room geometries) in the WIPP underground at this time. The test area is designated as Room T. The Room T tests will address the effect of rib loading on backfilled emplacements of full-scale drums. However, this test and the evaluation of its data is limited by the rate at which room convergence occurs. The information produced by these tests will be of use at a later date.

To address the questions and problems posed and to aid in making informed decisions regarding the Operations Demonstration in a timely manner, it was decided to use reduced scale models. This decision was based on the belief that reduced scale modeling was a relatively reliable, inexpensive method to simulate the loading conditions expected in the waste panels. Huerta's good correlation in the results between the full-scale and the quarter-scale models was encouraging. It was believed that the use of #12 cans as quarter-scale

FIGURE 2. Comparison of Quarter- and Full-Scale Lateral Force-Displacement Results Using the No. 12 Model Cans (after Huerta, 1983, ref. 2)

models not only would reduce costs, but also reduce the time which was required to acquire data. Since the test area and energy constraints were substantially reduced (33' x 13' x 300' rooms reduce to 8.25' x 3.25' x 75' models [a scaling factor of 4] and the approximate crush force of 15,000 lb. [after Huerta] for a single 55-gallon drum reduces to 934 lb. for a quarter-scale model [a scaling factor of 16]), a larger focus on the test room was possible by using more drums. However, there were no data on the correlation between full- and quarter-scale models of multiple drum emplacements or the influence of backfill. In addition, it was recognized that the effects of gravity could not be adequately scaled and therefore the base friction of a reduced scale model is lowered. Some initial confirmatory testing was necessary to ensure that the most important correlations were intact when these physical changes are made to the models.

Plans were made to proceed in a stepwise fashion; confirming a quarter-scale model with Huerta's data, comparing full- and quarter-scale data for both single drums and for 6-packs confined with backfill to further confirm the model, and finally executing quarter-scale room size tests in the reference geometry if the model proved valid for each preliminary step.

It is noted that waste containers other than 55-gallon drums will be used to ship CH transuranic wastes to WIPP. The most common container type used other than the 55-gallon drums will be steel boxes of various sizes. The behavior of these containers under crushing conditions was not tested here because of the smaller volumes of waste to be shipped in them and because of the desire to minimize the number of variables. Future tests, including scale model test, could employ them.

It should be recognized that the construction of #12 cans and 55-gallon drums is different. Although there is some difference in the rings or beads in the drum walls, the most prominent difference is in lid attachment. The lids of 55-gallon barrels are attached by positioning a clamping ring around the lid and drum head and securing the ring with a nut and bolt; the lids on #12 cans are secured by crimping the lid to the can walls. When lateral uniaxial compression is applied at a constant crush rate, a noticeable decrease in the required loading is observed when the lid begins to separate from the drum wall of a 55-gallon drum (Figure 3). No such decrease is noted in the #12 cans (Figure 4). Since the lid separation on the 55-gallon drums occurs consistently at a 2-2.5 inch (8-10%) lateral crush, it is believed that lid separation can be inferred in a #12 can at a 1/2-5/8 inch (again, 8-10%) lateral crush. Lid separation alone may not release any radioactive particles, since it is anticipated that waste will be shipped to WIPP encapsulated by a plastic bag, a plastic liner, and finally the steel drum. However, since the drum is the strongest component of the container system, the possibility of release or breach is greatly increased. In any given drum emplacement configuration, releases may be conservatively modeled if lid separation (or a 8-10% crush of quarter-scale models) is considered to be breach.

PRELIMINARY TESTING - CONFIRMATION OF MODEL

Preliminary testing was performed to determine if the scaling relationships were valid between the quarter-scale and full-scale drums. In order to use

FIGURE 3. Lateral Force Versus Displacement for All Full-Scale Drums Tested (after Huerta, 1983, ref. 2)

FIGURE 4. Force Versus Displacement for the Lateral Quarter-Scale Crush Tests with No. 12 Cans (after Huerta, 1983, ref. 2)

the previously acquired data, it was necessary to confirm that the materials used in the proposed tests compared favorably with Huerta's. Since Huerta used the standard DOT 17-C barrels which are to be used at WIPP, no preliminary testing of individual full-scale drums was performed. However, the available reduced-scale models (food cans) have varying standards so, it was necessary to select cans of similar construction (dimensions and material properties) to those Huerta used. Conversations with D. Stenberg⁴, who worked with Huerta on the previous test, revealed that the cans used in the Sandia experiment came from a dealer who could not now guarantee consistency between purchase lots, much less guarantee that the cans bought by Sandia for the 1983 experiment were replicated⁵. A different supplier (Container Supply Company) was selected that could provide #12 cans with similar dimensions and physical characteristics (primarily beading of the sides) as the cans used by Sandia. Table 1 presents dimensional data for the models. These cans were used in all quarter-scale tests.

TABLE 1
Model Dimensions

MODEL	RIM DIAMETER (in.)	HEIGHT (in.)	MATERIAL THICKNESS (in.) (Top, Bottom, Side)
D.O.T. 17-C Drum	23.85	34.81	.0598
Quarter Scale of D.O.T. 17-C	5.69	8.70	.0150
Huerta's #12 Can	6.15	8.75	.0125
Container Supply's #12 Can	6.17	8.75	.0125

Single Can Unconfined Tests - Quarter-Scale (Test Designation: T1)

These tests were performed to verify that the model's loading characteristics were comparable to Huerta's. In addition, these first tests were used to help prove the usefulness of the beam/strain gage displacement instrumentation (See Appendix 1 for discussion of this instrumentation).

Individual empty cans were placed between the platens of a load testing machine (MTS Corp., 600 kip capacity) at New Mexico Institute of Mining and Technology and were loaded at the rate of 0.5 inch/minute through a stroke of 1.5 inches. (For consistency and ease of analysis all the cans were placed such that the wall seam faced the loading surface in this and all tests). Data were collected in both digital and analog form for load on and displacement of the platens and for the extreme fiber strain on the instrumented beams installed in the base of each can (one in the load direction and one transverse to the load direction).

Figure 5 shows a plot of load versus displacement for the three cans used in (test designation) T1 along with the plot of Huerta's results for empty cans.

FIGURE 5. T1 Tests with Huerta Data
Combination Plot - Displacement Versus Load

FIGURE 6. T1 - Beam Displacement Versus Platen Displacement

In general, the load plotted as a function of displacement is somewhat lower for Huerta's data than for the data collected in T1. Although data from the two sources does not match perfectly, the correlation between the two was sufficient to justify further testing using crushed salt backfill with the models.

The strain gaged beams performed well in each test. Figure 6 shows plots of platen displacement versus the displacement as measured by the changing chord length and, therefore, the strain in the beams for each test. Note that at approximately 0.6 inch displacement, the beam placed in T1P3 in the direction of loading diverges from the other two curves; this may be explained by the 'capture' of one or both of the beam ends by the crushing can (the beam end was transformed from a pivoting end to a fixed end). Except for a short lag which may be attributed to an initial flattening of the can rim, the strain gaged beams located in the direction of loading predicted crush (based on platen displacement) reasonably well. The beams located transverse to load all were lengthened during loading indicating some minor ovaling of the instrumented end of the can.

Both the loading side and the reaction side of each can was flattened equally with little or no damage noted in the midsection. This is consistent with damage noted in photos of Huerta's work.

Single Can Confined Test - Quarter-Scale (Test Designation: T2)

The next step in investigating the modeling relationships was to test a single quarter-scale model surrounded by backfill in lateral loading in a confining fixture. To reduce some of the uncertainty due to the addition of backfill, it was decided to load metal to metal (platen-can-platen) instead of platen-backfill-can-backfill-platen. The backfill used was quarter-sized from the Reference Design of minus 3/8 inch screened backfill to minus #8 (#8 = 0.093 inch). Although scaling the maximum grain size does not necessarily scale grain size distribution, strength, or material properties, the scaling down was necessary to allow the backfill to "run" through the small clearances between the quarter scale models and to reduce point loads.

A confining fixture was constructed that allowed vertical loading of the can side while simulating the light confinement of gravity through use of a spring loaded plate located at the can top. In each test an empty can was placed on its side in the fixture; the can bottom was in direct contact with the confining fixture leaving a 3 inch (1/4 of the 1 foot of backfill placed over the stack in the reference design) clearance between the can top and the spring loaded plate. Can wall clearances were 5/8 inch maximum to be left between 6-packs as noted in the reference design). The #8 backfill was then placed to the level of the highpoints on the rims and finally the loading plate was installed to be in contact with the can and the surrounding backfill (Figure 7).

As with T1, the rate of displacement was 0.5 inch per minute through a stroke of 1.5 inches. Figure 8 shows a plot of platen displacement versus load for the three tests performed in T2. Peak load was approximately 6 times greater in T2 compared with T1 for the same platen displacement. Figure 9 shows a

FIGURE 7. T2 Confining Fixture With Can and Backfill Emplaced

FIGURE 8. T2 Load/Displacement Data
Combination Plot of T2P1/T2P2/T2P3
Conf. Single Cans (Plot Date: 6/16/87)

FIGURE 9. T1 and T2
Confined/Unconfined Plot Comparisons
Single Can Testing (Plot Date: 6/16/87)

comparison of T1 and T2 load versus displacement data. Note the differences in the loading characteristics in the two tests: the T1 loading increased gradually to a peak load of about 1000 lb. at 0.8 inch platen displacement and holds at that peak through the 1.5 inch stroke of the test; the T2 loading increased much more rapidly to a peak of 5000-7000 lb. at a displacement of about 0.3 inch, then dropped off by about a third of the peak by the 0.4 inch displacement mark, and finally held steady or increased through the remainder of the test.

Inspection of the cans after the test show that two of the cans took on a "heart" shape in cross-section (Figure 10). The apex of the heart is associated with the loading surface and the can seam, with little or no damage associated with the opposite (restraining) wall. The heart shape most certainly affected readings on the strain gaged beams placed in the loading direction by causing odd seating of the beam. Beams acted upon in this manner overestimate crush.

The displacements measured by the strain gaged beams are shown in Figure 11. The beams installed longitudinal to loading indicate that can crush is roughly the same as platen displacement for the first quarter to half inch, but is greater when considered past this early time indicating the effect that the heart shape has on the instrumentation. The beams installed transverse to load indicate the tendency for the can to become oval, much like those shown in T1 during early loading, but as loading progresses for that process to reverse as the backfill collapses the can walls. Several jumps are observed in the otherwise smooth, predictable data plots of T2 (T2P1, T2P3) for the beam installed in the direction transverse to loading. These jumps indicate a rapid, nearly instantaneous increase of the chord length of the beam. This may be attributed to the beam reseating in a slightly different location. This phenomena was later noted in beams installed in the direction of loading in cans in T3 (P21 and P31).

6-Pack Confined Test - Quarter-Scale (Test Designation: T3)

Quarter-scale 6-packs were prepared to model the full-scale 6-packs that are expected to be used to ship waste to WIPP. Three 6-packs were prepared using empty cans, one with scaled wood framing similar to that to be included in the full-scale and two without. All three were stretch-wrapped with the same wrap used on the full-scale drums, although the quarter-scale models were wrapped only three times compared with approximately twelve times for the full-scale. (In actual operation, the stretch wrapper when set for 9 wraps, actually wraps the bottom 18" of full-scale 6-packs nine times, then spirals the wrap up to the top 18" and wraps that portion nine times, and finally spirals back down to the base and stops. Although the rate at which the spiral proceeds up the sides can be varied, it is felt that the equivalent number of wraps averaged over the 6-pack is about twelve⁶. Hence, the quarter-scale figure for 12 is the modeled 3 wraps.)

As with T2, a steel confining fixture was constructed. Figure 12 illustrates the basic geometry of the fixture and a 6-pack. Clearances were similar to those in T2: the base of the 6-pack was in contact with the confining fixture; there were 3 inches between the top of the 6-pack and the spring loaded plates;

FIGURE 10. T2 Quarter-Scale Models After Testing

FIGURE 11. T2 - Beam Displacement Versus Platen Displacement

FIGURE 12. Configuration of Single 6-Pack Confined Preliminary Testing

there was 5/8 inch between the 6-pack walls and the confining fixture. Some difficulty was encountered in placing the two 6-packs that had no wood framing installed because of the tendency for the cans to offset vertically with respect to one another (rim jumped over rim because of the pressure exerted by the stretch wrap). Care was taken during installation to ensure that this offsetting did not occur prior to initial loading. Again, as with T2, minus #8 screened salt backfill was emplaced around and over each 6-pack.

Single strain gaged beams were placed in three cans of each 6-pack. All were installed in the base of the cans to react in the direction of loading. The three cans were in series on the left side of the 6-pack with respect to loading plate. See Appendix 2 for can numbering and layout.

The platen displacement rate was 0.5 inch per minute and total stroke was 4.5 inches. Figure 13 plots load as a function of platen displacement for all three tests.

Crush was almost completely confined to the first two cans (those closest to the loading surface) in each row of the 6-pack. The third can in each row showed only superficial rim damage (Figures 14 and 15). The most severe crush tended to occur at the interface between the first and second cans, followed by the loading-plate/can interface, the interface between the second and third cans, and finally the interface between the third can and the fixture. Figure 16 shows individual can crush as a function of platen displacement as monitored by the strain gaged beams in each can. Although not easily discernable in the plot, beams in T3P13, T3P23, and T3P33 (the cans located furthest from the loading platen), plot on top of each other with near zero displacement.

During loading the spring-constrained 'top' plates were displaced by the pressure in the backfill up to 2 inches. The backfill was kept from running out of the fixture by placing plastic wrap inside the fixture at the gaps previous to loading.

Note that load versus displacement plots for tests in T2 and T3 are quite similar; it took about the same peak load to crush a 6-pack as it took to crush a single can in the test geometries used.

6-Pack Confined Tests - Full-Scale (Test Designation: T5)

These tests were conducted in the underground at WIPP in a nominally 14 foot wide drift. This location was chosen in order to readily load the models by reacting off of the ribs (walls) of the underground openings; surface locations would have necessitated construction of a substantial reaction frame. A three sided (two opposing walls and a floor) open box fixture was constructed with wood to laterally confine the backfill.

Testing was accomplished by placing a 6-pack, consisting of empty drums, into the confining fixture, installing steel strongbacks in the mouths of each open end in contact with the 6-pack, then backfill (minus 3/8" crushed salt to model the reference design) was added to the box to fill the voids around the drums. The 6-packs were then crushed by applying force to the strongback with load

DISPLACEMENT (in.)
FIGURE 13. T3P10/T3P20/T3P30
Confined Six-Pack Tests

FIGURE 14. T3P30 6-Pack in Test
Fixture After Loading

FIGURE 15. T3P30 Cans Bottom
View After Testing

FIGURE 16. T3P10/T3P20/T3P30
T3 - Beam Displacement Versus Platen Displacement

indicating hydraulic jacks based on one rib while the opposing strongback reacted off of the opposite rib through a steel pipe assembly. Figure 17 illustrates the test configuration.

Displacement of the loading face was measured with respect to the walls of the confining fixture manually at four locations. (Steel tapes with 1/16 inch resolution were attached to each wall of the confining fixture at the high and low points of the loading plate.) The crush of the tops of individual drums was monitored by manually measuring displacement from stringlines attached to the confining fixture walls which were initially positioned at the drum interfaces. Crush near the bottom of individual drums was monitored by displacement of a wire attached to the wall of each drum 4 inches above the base, running horizontally across the drum in the direction of loading through an eyehook, then running vertically upward through a 1-inch hole in the lid. This arrangement is illustrated in Figure 18.

Four tests were performed in this configuration; actual performance of each test took two days with the setup left under load at night. The long time period was necessary due to the time required to reset the loading jacks from time to time. The confining fixture failed to hold the lateral pressure transferred to it by the backfill in both the first and second tests (T5P10 and T5P10A). Appendix 3 outlines the construction of and modifications to the confining fixture during these two tests. As a result of the modifications and with the installation of strain gages onto the fixture, data on the lateral pressure exerted by the backfill was collected. This data indicated that substantial stress was transmitted to the fixture walls by the backfill; engineering calculations show that lateral stress to be approximately 60-80% of the stress directly behind the loading plate near peak loading. This analysis is also presented in Appendix 3.

Three of the four test 6-packs had nominal 2 x 2 inch framing installed between the drums and the fourth had none. The 6-pack with no framing (T5P20) behaved much like the quarter-scale 6-packs with no framing in that vertical offsetting of individual drums occurred. This 6-pack was installed in the confining fixture so that there was no offsetting previous to loading; however, as soon as loading began, the individual cans were observed to offset. This offsetting produced no large variation from the data collected in the other tests.

Test T5P10 was an abbreviated test and was not run until a peak load was reached because of the failure of the confining fixture. In the three other tests, however peak loads were reached and drums were breached. In each of these three tests, two drums breached or their lids became partially dissociated from the drum. The location of the breached drums was the same for each test; with respect to the loading plate, those breaching were the first drum on the right and the second drum on the left. In comparison, these tests showed that the drum furthest away from the loading plate had more than the superficial rim damage observed in the quarter-scale 6-pack tests, but that major damage was still confined to the first, two drums in each row nearest the loading plate.

Failure in both the drum tops and bottoms can be best described as a buckling of the surfaces. The tops buckled in a single location approximately midway

FIGURE 17. Test 5 Geometry

FIGURE 18. Crush Monitoring Device for Full-Scale Preliminary Testing

across the lid and then bowed up dramatically (Figure 19). The drum bottoms buckled in accordion fashion at multiple locations across their surfaces. Of those drums that were breached in T5, the average crush (measured at the drum tops) was 2.1 inches in a range of 1.0 to 2.9 inches.

Figure 20 shows a plot of load versus loading-plate displacement for all three completed tests. Figure 21a, b, and c shows deflection in individual drums as a function of loading plate displacement and notes the point where an opening (breach) between the lid and drum occurs. An examination and comparison of the T5 and T3 data for load versus loading plate displacement show good correlation up to peak load. (Figure 22 - The scale conversion for T3 is Displacement x 4 and Load x 16.)

Single Drum Confined Testing - Full-Scale (Test Designation: T4)

Although testing on single full-scale drums was planned as a part of this testing, it was decided not to proceed for multiple reasons. Based on the quarter-scale data comparison between single cans and 6-packs confined with backfill, it was apparent that 60-80 tons peak force would be necessary to crush a drum. This was a concern from the standpoints of constructing a confining fixture strong and inflexible enough to withstand the expected stresses, location of the hydraulic jacks in very close proximity to each other which would complicate operation and safety, and construction of a stable reaction assembly for the relatively small loading area across the approximately 10 feet of remaining drift to the opposite rib. Since there was a good correlation between the T3 and T5 data at the early time loading, it was determined that although data for single drums in a confined test might be informative, that it was not essential to further validate the relationship between the full- and quarter-scale models. So tests on full-scale confined models, originally designated T4, were not performed.

ROOM SCALE TESTING - USE OF THE MODEL

General

The good correlation of the data collected from the single 6-pack tests, particularly during the pre-peak portion of the load versus displacement plots, encouraged use of the quarter-scale models in a room scale geometry. This testing was performed in the WIPP underground. Two different tests were proposed and performed. The first was performed with empty cans, while the second was a random distribution having 50% empty cans and 50% cans filled with loose salt.

It was believed that empty drums would present a worst-case scenario with regard to resistance to drum crush and attendant breaching while simplifying the test analysis by maximizing homogeneity and reducing the total number of variables. The second test introduced simulated waste into the problem to more closely model the expected waste stack contents.

In these tests each can was numbered sequentially and was accounted for accordingly. Appendix 2 provides numbering information and geometric layout for all cans in these tests. The tests consisted of laterally loading backfilled

FIGURE 19. T5P30 6-Pack After Testing

FIGURE 20. T5P10A/T5P20/T5P30
T5 - Plot of Load Versus Displacement

Note: T5P10A plot shows peaks only; no regression due to unloading is presented.

FIGURE 21a. T5P10A Plot of Individual Drum Crush

FIGURE 21b. T5P20 Plot of Individual Drum Crush

FIGURE 21c. T5P30 Plot of Individual Drum Crush

FIGURE 22. Scale Comparison of T3 and T5
 (T3 [Load x 16] and [Displacement x 4])

6-packs stacked three high and five across in accordance with the WIPP Reference Design. There were ten 6-packs stacked along the simulated room length; one end was lightly restrained by backfill, and the other was restrained by a rigid steel boundary wall bolted to the floor. This configuration was chosen because it was believed that it would accurately model response to rib convergence both for the open end of a test room and for the main portion of the stack away from the end effects. No consideration was given to the possibility of slabbing, floor heave, or anomalous geologic behavior. Figure 23 shows the general configuration of the tests.

The test geometry modeled the interstices between individual 6-packs and between 6-packs and ribs by reducing the spans and material thicknesses to one quarter their full-scale size (3 inches between the 'rib' and first 6-pack, 5/8 inch between 6-pack ends, no space between 6-pack sides). Minus #8 sieved salt backfill was placed around, but not over, the stack to the appropriate dimensions. (It was not placed over the stack because it was believed that a greater benefit could be received from the observation of the top layer during testing and because to properly scale the weight of fill, approximately 94 lb. would be required over each can; the geometrical quarter-scale of 3 inches of fill over the stack would yield only about 6% of this.) This is a variance from the Reference Design considered to be insignificant.

During actual waste emplacement it is planned that 6-packs will be emplaced on 80 mil polyethylene slip sheets with 1/2 inch plywood separator sheets placed on top (integrally wrapped with the 6-pack). In the quarter-scale room tests both the separator sheets and slip sheets were included with appropriate reductions in all dimensions to quarter-scale. All 6-packs were stretch wrapped three times using the same polyethylene material which is used on the full-scale containers. No internal framing was used on individual 6-packs since there did not appear to be any substantial difference between those 6-packs with and those without framing.

Room closure was simulated by loading a steel strongback located on each side of the test with load indicating hydraulic jacks. The strongback extended a length of 12 feet on each side of the test stack. Jacking occurred at three, approximately equally spaced points on each side. Load was transferred to the test stack by loading a horizontal jack onto a vertical I or H Beam, which distributed its load to several horizontal channel beams, that, in turn, loaded a 1/4 inch steel plate acting as the rib (sidewall) of the room. The strongback was placed on the same plywood base used for the simulated room floor. Movement of the steel plates or "ribs" loaded the stack and was monitored and measured with steel tapes from ramset nails shot into the ribs at twelve locations. Section BB in Figure 23 illustrates the test geometry.

Individual can crush was monitored during the test in the simulated waste drums by 30 strain gaged beams installed in cans at selected locations in the stack. Figure 24 shows the location of strain gaged beams within the stack geometry.

The change in thickness of the backfill between the loading plate and the first can was monitored at each layer adjacent to the strain gage array located near the center of the test. This was accomplished by cutting holes in the channels

FIGURE 23. Loading Geometry for Simulated CH TRU Waste Room (Tests 6 and 7)

LEGEND

B	Backfill Thickness Gage	(Quantity - 3)
S	Beam-Strain Gage Assembly	(Quantity - 30)
D	Loading Plate Displacement Point	(Quantity - 12)

FIGURE 24. Instrumentation Locations for Simulated
CH TRU Waste Room (Tests 6 and 7)

and plate at the proper locations (Figure 24) and slipping a dial gage probe through a thin-walled casing to contact the can surface. The dial gage was attached to the channel. These gages had a resolution of 0.001 inch.

During execution of the tests the simulated ribs were displaced by 1/4 inch increments (or 1/2 inch total convergence increments) in order to collect data on an interval approximately simulating a year of room convergence. Bechtel's analytical wall to wall, steady-state closure prediction of a 13 x 33 foot storage room in an infinite number of 13 x 33 foot rooms predicts a 2 inch closure per year⁷. Total convergence in the quarter-scale tests was limited to approximately 4 inches or 8 years of simulated convergence. (Initial direction was to model 7 years convergence in the CH Mock Demonstration; after this testing was complete, but before compilation of the data, indications were that a 15-year figure may be used in the Mock Demonstration.) At the end of each increment, data was collected on 'rib' displacement, load, individual can crush, and change in thickness of the backfill (through the dial gages). The top layer of the stack was tracked by photographing against a one-foot string grid positioned initially along the 6-pack interfaces.

After test completions, the three layers were removed one at a time. Photographs were taken of the final disposition of each layer against the same stringline grid as was used as an aid to track changes in the top layer during loading. The layers were then removed a 6-pack at a time. Each can was visually examined and deformations in the upper and lower portions of its wall and its upper and lower rims were measured with an outside micrometer and were recorded; if no damage was visually identifiable at a particular location, a measurement was not taken, but a "no damage" note was recorded.

Room Scale Test - Empty Drum Simulation (Test Designation: T6)

Test 6 (T6) was performed over a two-day period in March of 1987. Due to the small (1/4 inch) increments of displacement on the model ribs, one could not observe crush occurring in individual cans during loading, but close inspection of the top layer after each successive convergence increment yielded the following general observations:

1. After the second displacement increment (approximately 1 inch of total convergence or 2 years modeled) vertical offsetting of the cans due to overriding each other at the rims was prevalent at all locations.
2. After the third displacement increment (approximately 1.5 inches of total convergence or 3 years modeled), the first deformation of rims and can walls was noticed. Again, deformation was taking place in all locations.
3. Some displacement or pop-out of individual cans and 6-packs from their original locations was noted after the fifth or sixth modeled year at the open end of the stack. This displacement was first noticed in the end row of 6-packs and became more pronounced through succeeding increments, being observed up to four to five 6-pack rows into the stack at the end of the test. The greatest movement occurred in the

center of the end row (up to approximately 2 inches from the original location) and decreased in an apparently linear fashion both inward from the end toward the stack center and toward each of the walls.

Plots of the displacements of the beam/strain gage instrumentation reveal that none of the instrumented cans were undergoing substantial crushing through the first modeled year (approximately 1/2 inch convergence increment). However, after the second modeled year, 10 of the 30 beams show a reaction to load as measured by a displacement of greater than or equal to 0.01 inch. Of these 10 beams, nine are located in the gage array near the center of the test geometry and one was located in the gage array at the end of the stack. Even at this early point in the model's history, it is apparent that load was being transmitted through the stack. Examination of the data produced by this instrumentation shows that the array near the middle of the stack had larger deflections; this is consistent with the fact that there is more confinement in that location. Comparisons of the data in the same layer of the stack array indicate that there may be more crush manifest in the middle cans in the 6-packs than in the end cans. Vertical comparisons show consistency in the data for different layers, indicating that the greater confinement due to depth had little or no effect on the model. Plots of the displacement data for the instrumented cans are presented in Appendix 4.

The data collected by measuring the deformations of individual cans indicate that load was transmitted through all portions of the stack and that virtually every can was deformed somewhere on its surface. Of the 900 cans in the test, 859 (greater than 95%) were deformed in at least one location on their surface. Of the 41 having no visible damage, 32 were located in 6-packs adjacent to the steel confining (or rigid) wall. (For presentation of the raw data and a graphical representation for the location of the undamaged cans, see Appendix 5.) The confining wall is recognized as an artificial constraint that could, and evidently does, affect the test data. It is not believed that the edge effects of the confining wall in the model are representative of the situation expected to be found in a waste room; a more realistic prediction of damage may be reached by ignoring cans in the immediate vicinity of the wall. (If the first row of 6-packs is mathematically removed, leaving the test with 9 undamaged cans out of 810, the percent damage approaches 99%.) Figures 25-28 summarize the occurrences of rim and wall deformation measured in T6. Note that in all cases the majority of cans showed less than 0.01 inch of deformation and in a single case is more than 1 inch of deformation noted.

For ease in data analysis and in graphical representation, the data were categorically divided into three groups: cans showing no visual deformation, those showing minor deformation, and those showing severe deformation. The division of the latter two groups was chosen as a 5.9 inch diameter for rim data (a 0.275 inch deformation of the 6.175 inch manufactured diameter) and as a 5.6 inch diameter for wall data (a .450 inch deformation of the 6.050 manufactured diameter). Table 2 presents a summary of the number of cans in each category by layer location. A graphical representation of each layer showing the categorized cans is presented in Appendix 5.

All degrees of crush were found in virtually every location of the stack. The notable exception was the lack of severely crushed cans next to the confining

FIGURE 25. T6 - Top Rim Crush Data

FIGURE 26. T6 - Top Wall Crush Data

FIGURE 27. T6 - Bottom Rim Crush Data

FIGURE 28. T6 - Bottom Wall Crush Data

TABLE 2

T6 - Summary of Model Deformation by Layer

Count of Cans With No Visible Deformation

	Total	Top Layer	Middle Layer	Lower Layer
Top Rim	449 (50%)	195 (65%)	141 (47%)	113 (38%)
Bottom Rim	402 (45%)	137 (46%)	125 (42%)	140 (47%)
Upper Wall	166 (18%)	77 (26%)	41 (14%)	48 (16%)
Lower Wall	297 (33%)	91 (30%)	107 (36%)	99 (33%)

Count of Cans With Minor Deformations

	Total	Top Layer	Middle Layer	Lower Layer
Top Rim	447 (50%)	103 (34%)	159 (53%)	185 (62%)
Bottom Rim	473 (53%)	150 (50%)	171 (57%)	152 (51%)
Upper Wall	716 (80%)	212 (71%)	257 (86%)	247 (82%)
Lower Wall	579 (64%)	199 (66%)	186 (62%)	194 (65%)

Count of Severely Deformed Cans

	Total	Top Layer	Middle Layer	Lower Layer
Top Rim	3 (0%)	1 (0%)	0 (0%)	2 (1%)
Bottom Rim	24 (3%)	12 (4%)	4 (1%)	8 (3%)
Upper Wall	17 (2%)	10 (3%)	2 (1%)	5 (2%)
Lower Wall	23 (3%)	9 (3%)	7 (2%)	7 (2%)

Plot date: 10/28/87

Note: Can #614 was not measured and is not included in the above data.

wall and in the lightly constrained end row of each layer. There were no major differences noted in the manner crush occurred between the different layers of the stack; however, some variation in the number or percentage of cans indicated by the degree of crush did occur between the layers (Table 2 - note top rim figures for no deformation and minor deformation). Damage appeared to occur in two distinctly separated manners. Where cans were in contact with other cans, damage to their rims and on their walls near the rims was prevalent. When wall damage was observed away from the rims, it was noted that the deformation was associated with the backfill between the 6-packs. No damage was found on the walls of cans facing the loading walls and no damage was found on any surface not associated with forces applied in the loading direction. The damage of the rims and walls near the rims can be attributed to metal to metal point loading by one or both rims of adjacent cans and the other wall damage may be attributed to loading by the backfill on the walls.

Associated with the noted deformations is consolidation of the backfill. Figure 29 illustrates this by plotting the change in the distance between the loading wall and the first can in each layer (location is shown in Figure 24) as a function of wall displacement. The initial span of 2.5 to 3 inches was reduced by a range of approximately 3% to approximately 7% through loading. The fact that the dial installed to monitor the middle layer indicated more displacement than the others may be attributed to bowing of the steel strong-back about the load point of the adjacent hydraulic jack which was located vertically nearest to the middle layer of the model. (Note that this possibility was not visually confirmed in either T6 or T7.) The dial installed at the lower layer may have indicated the second most displacement because of a combination of the confining effect of the walls and floor due to friction on their surfaces and the weight of the upper layers.

Load data were also collected during testing. Figure 30 shows convergence as a function of total load summed from all six jacks. The reduction in load corresponding to 2.8 inches of convergence is associated with an overnight cessation of testing while leaving the test configuration under load. Figure 31 shows a plot of the same data with respect to time.

It should be noted that the test setup held substantial stored elastic strain energy. After testing was complete, the jacks were slowly unloaded and each wall rebounded approximately a half inch. This stored energy and the strain associated with it are not accounted for in the post-test deformation measurements and, therefore, affect the prediction of crush and breach in a non-conservative manner. The 0.8 inch divergence of the walls (from 3.7 inches to 2.9 inches), resulting from the unloading of the jacks, may be a rough indicator of the amount of stored elastic strain energy present. If it is assumed that the backfill has no rebound, then it may be implied that before unloading and subsequent measurement of the cans, that the cans actually have 28% $([0.8/2.9]*100)$ more deformation at the last load increment than after unloading. (This information should be used as an indicator only. When the jacks were unloaded in the room-scale tests, the hydraulic bleedoff valves were left open until the jack was moveable. In some cases the jacks had to be removed to keep them from falling out of their positions and possibly being damaged by the fall or injuring those working around them. The removal of the jacks allowed the walls to further diverge and, thus, an unrealistically high amount of stored strain energy is implied. This is especially true for T7.)

FIGURE 29. T6 - Backfill Consolidation-Plate Displacement Versus Gage Displacement

FIGURE 30. T6 - Plot of Convergence Versus Total Load
(Plot Date: 6/24/87)

FIGURE 31. T6 - Plot of Convergence Versus Total Load
With Respect to Time (6/24/87)

Room Scale Test - Simulated Waste Test (Test Designation: T7)

In this test the configuration remained the same as in T6 except that 450 of the 900 cans were filled with loose run-of-mine crushed salt to simulate waste. The numbers of the cans that received the simulated waste were selected by programming a Hewlett-Packard model 71-B computer to generate a pseudo-random number sequence given a randomized seed from its clock function. The number generation was limited to numbers between 1 and 900. The first 450 non-repeated numbers were designated to receive simulated waste. The test layout, including locations of the drums loaded with simulated waste, is included as part of Appendix 2.

Test layout and location of instrumentation was the same as T6 with the exception that the strain gaged beams were installed in the tops of the cans instead of the bottoms. Those cans receiving both simulated waste and beams were filled with salt only to three quarter depth. In T7, not quite as much fill was used to constrain the end of the stack as was used in T6; fill sloped on its angle of repose from the top of the stack to a level near the bottom.

Observations during T7 were similar to those noted above for T6. Vertical offsetting of individual cans was noted at the end of the second increment (approximately year 2), but first deformation was not observed until the fourth (approximately year 4). Pop-out of the cans toward the lightly constrained end was perhaps a little more pronounced in this test than in T6, probably due to less confinement, and it was noticed at the same time that first deformation of cans was observed (the fourth increment). However, it progressed into the stack and toward the walls approximately the same distance as seen in T6.

Plots of the displacements of the beam/strain gages are generally similar to and have the same ranges as those in T6, although in T7, three of the gages indicated large increases of beam deflection during the last displacement increment. Since there were no unusual circumstances associated with these jumps and since two of the gages were located in the same horizontal location (one in the top layer and one in the middle layer) it is believed that the data are valid and are the result of crush in the stack. Plots of the displacement data for the instrumented cans are presented in Appendix 4.

The data collected by measuring the various can diameters are similar to that collected in T6, although more severe crush was noted in the second test. Crush was not particular to either the filled or unfilled cans except for the case of severe wall crush. Although one might intuitively expect much more damage in the unfilled cans this is not substantiated here or by Huerta's data for crush of this magnitude in #12 cans loaded laterally with various simulated waste materials inside. This is probably because during the early crush the simulated wastes used in the models offer little or no resistance; however, as crush tends toward severe the simulated waste consolidates and begins to resist. If a large quantity of the CH waste drums received at WIPP are substantially stiffer than the models, more severe crush may be observed sooner in adjacent drums than predicted by the model.

In Test 7, 39 cans (4%) were free from any visually detected damage and 34 of these were in the first 6-pack row next to the confining wall. Figures 32-35 summarize the occurrences of rim and wall deformation measured in Test 7.

Table 3 presents a summary of the occurrences of the three categories of crush using the same criteria for classification as was used in T6. For the graphical representation of the three categories of crush for each layer, the reader is again referred to Appendix 5. As with Test 6, all degrees of crush were found in virtually every location of the stack and damage appeared to occur in the same manner. In the categories of upper and lower rim and lower wall there were only slightly fewer severely deformed cans which had fill in them compared with those without. In the upper wall category, none of the 23 severely deformed cans had any fill in them. These observations support the theory that the simulated waste (crushed salt in this case) resists the crush force somewhat, reducing the severity of the crush and probably transferring the load to adjacent cans and increasing the crush manifest in them.

Since the same criteria were used to designate cans with no crush, moderate crush, and severe crush as was used in T6, it is interesting to note a three-fold increase in the number of severe crush occurrences (from 67 to 189). Figure 36 is a contour plot of occurrences of severe crush by location of individual 6-packs without consideration for location of the deformation on the can or layer location of the 6-pack. This figure shows that apart from end effect, most of the severe crush occurs in the central portion of the stack away from the boundary conditions imposed by the walls. This may be attributable to a combination of the thicker backfill pad at the walls or to a confining effect resulting from friction between the wall surfaces and the adjacent material (the same effect noted previously with regard to the location of most of the totally undamaged cans near the rigid wall).

The data collected from the dial gages monitoring the consolidation of the backfill between the wall and the first can were also consistent with that collected in T6; the reduction in the span ranged from approximately 1% at the lower layer to approximately 8% at the middle layer. The plot of consolidation versus layer displacement is presented in Figure 37.

Figures 38 and 39 present the plot of load versus displacement and load versus displacement as a function of time for Test 7. The total load required to complete 4 inches of convergence between the walls was approximately the same as in T6 (T6 - 62 tons, T7 - 69 tons). No major differences were noted in the load versus displacement data for the two tests. (The unload portion of the plots is not considered because of difficulties encountered in collecting the data - discussed above.)

DISCUSSION OF THE IMPLICATIONS OF THE ROOM-SCALE TESTS

It is apparent that load was transmitted completely through the modeled stack in both T6 and T7. Based on the visual observations of the top layer in both tests and on the data collected from the 30 instrumented cans in each test, it is predicted that this will occur within five years (implying that the drums first emplaced in the first waste panel will be under load before the end of the five-year Operations Demonstration period).

FIGURE 32. T7 - Top Rim Crush Data

FIGURE 33. T7 - Top Wall Crush Data

FIGURE 34. T7 - Bottom Rim Crush Data

FIGURE 35. T7 - Bottom Wall Crush Data

TABLE 3

T7 - Summary of Model Deformation by Layer

Count of Cans With No Visible Deformation

	Totals			Top Layer			Middle Layer			Lower Layer		
	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111
Top Rim	347 (39%)	130	217	153 (51%)	51	102	106 (35%)	43	63	88 (29%)	36	52
Bottom Rim	380 (42%)	176	204	135 (45%)	62	73	133 (44%)	55	78	112 (37%)	59	53
Upper Wall	175 (19%)	109	66	93 (31%)	63	30	53 (18%)	33	20	29 (10%)	13	16
Lower Wall	228 (25%)	75	153	92 (31%)	29	63	76 (25%)	23	53	60 (20%)	23	37

Count of Cans With Minor Deformations

	Totals			Top Layer			Middle Layer			Lower Layer		
	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111
Top Rim	517 (57%)	299	218	140 (47%)	91	49	187 (62%)	92	95	190 (63%)	116	74
Bottom Rim	452 (50%)	255	197	149 (50%)	83	66	138 (46%)	75	63	165 (55%)	97	68
Upper Wall	702 (78%)	341	361	195 (65%)	83	112	242 (81%)	104	138	265 (88%)	154	111
Lower Wall	611 (68%)	356	255	184 (61%)	109	75	200 (67%)	107	93	227 (76%)	140	87

Count of Severely Deformed Cans

	Totals			Top Layer			Middle Layer			Lower Layer		
	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111	Total	W/ F111	W/O F111
Top Rim	36 (4%)	21	15	7 (2%)	4	3	7 (2%)	2	5	22 (7%)	15	7
Bottom Rim	69 (8%)	19	50	16 (5%)	1	15	30 (10%)	7	23	23 (8%)	11	12
Upper Wall	23 (3%)	0	23	12 (4%)	0	12	5 (2%)	0	5	6 (2%)	0	6
Lower Wall	61 (7%)	20	41	24 (8%)	8	16	24 (8%)	7	17	13 (4%)	4	9

Plot date: 10/28/87

FIGURE 36. T7 - Contour Plot of Severe Crush Occurrences

FIGURE 37. T7 - Backfill Consolidation-Plate Displacement Versus Gage Displacement

FIGURE 38. T7 - Plot of Convergence Versus Total Load
(Plot Date: 6/24/87)

FIGURE 39. T7 - Plot of Convergence Versus Total Load
With Respect to Time (6/24/87)

A static analysis of a single drum located in the bottom layer of the stack can also be used to examine the forces in the stack and the tendency for load to be transmitted throughout. Vertical loading due to the overburden of drums and backfill is only about 2,000 lb., based on 550 lb. drum weight with backfill over the stack top having a density of 120 pcf. Assuming a friction factor of 0.3 (probably conservative) between the drums and the floor, lateral movement should occur whenever the lateral loading difference exceeds about 600 lbs. Given the near irresistible force being exerted by the ribs, and T5 data indicating that it takes about 30-tons force applied through backfill across the cross-sectional area of a drum to cause breach, the 600 lb. sliding resistance figure will be easily exceeded.

Using T6 and T7 as predictors, virtually every drum in the stack will show some deformation eight years after emplacement. Here, it is also interesting to examine the physical model of the space between the ribs. At the time of emplacement, the approximately 33-foot span of a waste room is taken up by 15 drums with diameters of 24 inches each with the remaining 3 feet containing backfill with about 40% initial porosity. If a 30-ton load applied across the drum's cross-sectional area is required to cause breach (compare with T5 data), the equivalent pressure is about 70 psi. Salt backfill is capable of transmitting this pressure at a porosity greater than about 35%⁸. If it is assumed that the backfill is not pushed out of the top of the stack in any quantity, the backfilled space need only be reduced from the original 3 feet to 2.77 feet or by 2.8 inches. This reduction can take place in less than 2 years time. For time forward until retrieval, the creep must be taken up by the drums. Since Huerta showed that there was little difference in pre-breach force/displacement relationships for unconfined drums with various types of fillers or simulated waste, it may be assumed that all drums in the stack will have about the same stiffness initially. With a similar stiffness, if all drums should deform by the same amount and if it takes 2 inches of lateral displacement to breach a drum, then first breach would occur in year 18.

An argument that first breach will not occur until year 18 is weak. Based on the above rough analysis, it would be more appropriate to state that the latest time that first breach could occur is year 18. Work with the models in T6 and T7 indicates that the room model does not act in a simple and uniform manner; the amount of stress and, therefore, deformation varies with regard to individual can and 6-pack location within the modeled waste room. From the deformation data collected in T6 and T7, first breach may be expected before year 8 in some drums. An examination of the T7 data (because it is believed to be a better prototype of the actual waste rooms than T6) indicates three cans exceeded 0.5 inch of top rim deformation, which equates to 2 inches in the full scale; 14 other cans exceeded 0.5 inch of top wall deformation. Assuming that all of the cans having greater than 0.5 inch top rim deformation and half of the cans having greater than 0.5 inch top wall deformation breach, then ten breaches, or 1%, are predicted by the T7 model after 8 years. Simplistically applying a factor of 15/8 to the T7 data to linearly approximate 15 years of convergence (the currently projected retrieval period) and using the above criteria, indicates that 72 drums, or approximately 8% ($\% = [(38 + [68/2]) / 900 * 100]$) of the total, would be breached.

Fewer occurrences of severe crush are associated with the ends of the modeled rooms than in the main or central portion of the rooms (Figure 36). Furthermore, cans located in the end areas make up a large portion of the test model, but only a small percentage in the proposed waste rooms. This discrepancy may be dealt with by assuming that end effects are confined to the three rows of 6-packs at each end of the model and only the four center rows of 6-packs are used for analysis. After 8 years 1% breach will have occurred ($0 \text{ Top Rim, } 10 \text{ Top Wall...}\% = \frac{[0 + [10/2]]}{360} \times 100$), but after 15 years 12% are predicted to breach ($23 \text{ Top Rim, } 38 \text{ Top Wall...}\% = \frac{[23 + [38/2]]}{360} \times 100$).

Note that if 12% of the drums are breached at the time of retrieval, an average of more than five breached drums will be encountered in each layer of the stack face. Based on observations in the room-scale tests these breaches may occur at any location on the face. In addition, one should also recognize that the linear 15/8 term, used to extrapolate the model data to 15 years, is probably conservative since plots of load versus early deformation are generally approximated by a power curve ($y = ax^b$, where $b > 1$). Not enough information has been collected to statistically use this relationship with any degree of confidence.

CONCLUSION

Through a series of preliminary test it has been shown that there exists a scale relationship between lateral load versus displacement for D.O.T. 17-C drums and #12 food type cans both in single unconfined and 6-pack confined configurations prior to breaching. This relationship has been applied in room-scale tests, configured in a reduced-scale WIPP Reference Design geometry using 6-packs. Based on the T6 and T7 room-scale tests, the following predictions can be made with regard to full-scale 6-packs emplaced in the Reference Design geometry:

1. Load will be transmitted completely through the stack within the first five years after emplacement. All drums in all 6-packs will be affected.
2. Virtually all drums will show some deformation eight years after emplacement.
3. Some drums may breach before eight years after emplacement has elapsed. These breaches may occur at any location in the stack, but the most likely location for breach is near the storage room center along its axis.
4. Based on criteria developed during testing, it is predicted that after 8 years 1% of the drums emplaced will be breached. Using a simple extrapolation format, after 15 years, approximately 12% of the drums are predicted to be breached and this figure may be larger because of conservatism in the assumptions.

Although the inclusion of CH boxes in the waste stack was not addressed by testing, it should be noted that those received on site for demonstration to date are structurally reinforced and should be able to resist more pressure

due to lateral loading by the backfill than the drums. If this is the case, then boxes may not deform until any drums emplaced adjacent to them have crushed somewhat. If the project proceeds toward usage of drums and boxes in backfilled storage rooms, it will be beneficial to perform a detailed structural analysis for the various boxes and examine their interaction with the drums.

The predictions of drum damage and breach discussed herein should be useful in performing future work with regard to personnel dosages and overpack considerations if retrieval becomes necessary. However, those performing work of this nature, particularly if further extrapolations are applied, are encouraged to recognize the limitations of the model and respond to them in a conservative manner.

REFERENCES

1. Bechtel National, Inc., Waste Isolation Pilot Plant Design Validation Final Report, DOE-WIPP-86-010, October 1986.
2. Michael Huerta et. al., Analysis, Scale Modeling, and Full-Scale Tests of Low-Level Nuclear Waste Drum Response to Accident Environments, SAND80-2517-TTC-0315 (Albuquerque, NM: Sandia National Laboratories, January 1983).
3. Telephone conversation with Michael Huerta, October 28, 1986.
4. Telephone conversation with Duane Stenberg, October 28, 1986.
5. Telephone conversation with Jim Eck, Westinghouse Purchasing, November 24, 1986.
6. Telephone conversation with Tod Burrington, Westinghouse Waste Handling Engineering, November 20, 1986.
7. Bechtel National, Inc., Waste Isolation Pilot Plant Design Validation Final Report, DOE-WIPP-86-010, October 1986, Figures 12-22.
8. IT Corporation, Assessment of Crushed Salt Consolidation and Fracture Healing Processes in a Nuclear Waste Repository in Salt, BMI/ONWI-546, November 1984, Figures 2-9.

APPENDIX 1
BEAM/STRAIN GAGE THEORY AND APPLICATION

THEORY

Given straight steel beams of constant cross section and an axis of symmetry (ASI 1095 spring steel beams sheared to ≈ 6.10 – 6.15 inches long, ≈ 1 inch wide, that were 0.020 inch thick were used in this project), when bending is forced by buckling the beam through application of axial end loading, stresses develop in the beam parallel to its length. Maximum stresses are manifest on the outer or skin surface (that surface furthest away from the neutral axis) in accordance with the flexure formula for beams:

$$\sigma_{\max} = (Mc/I)$$

(Popov, eqn. 5-1)*

where $\sigma_{\max}$ is maximum stress
M is moment
c is the distance from the neutral axis to the most remote fiber
I is moment of inertia

Since beams bend in a parabolic shape, maximum stress takes place at the point of the maximum curvature, which coincides with the origin of the parabola and midpoint of the beam. Applying the stress/strain relationship for elasticity implies that maximum strain occurs at the same point.

With this in mind, a Micro Measurements Group, Inc. EP-08-250-BG-120 strain gage was applied at the midpoint of each beam using M-bond adhesives. Type curves for each beam were developed by:

1. Placing the beam on a flat surface and calipering the beam for length and zeroing a strain indicator (Vishay) connected with a 3-wire quarter bridge circuit.
2. Placing the beam in a vise so as to be slightly buckled (strain gage on the convex side).
3. Calipering the vise opening (beam chord distance) and reading the strain manifest in the gage.
4. Incrementally closing the vise and recording chord distance and strain readings to ≈ 3 inches of closure.
5. Plotting strain (ϵ) versus beam chord distance (CL) and fitting data using regression analysis for

$$\epsilon = a(CL)^b$$

where a and b are constants determined by the regression.

*Popov, E. P., Mechanics of Materials. Englewood Cliffs, NJ: Prentice-Hall, 1976.

APPLICATION

After determining constants for the type curves for each strain gaged beam, they were installed and used as follows:

1. Zeroed the strain reading on an unloaded, flat lying beam.
2. Installed the beam into the can to be tested.
3. Recorded the strain reading.
4. Ran the wiring out of the can through a hole drilled at 45° to the loading direction at the can midsection. Sealed the can.
5. Zeroed the strain reading, if possible, and recorded that reading. If not possible, recorded an arbitrary initial strain reading.
6. Recorded subsequent strain readings during testing.
7. Calculated strain for the test by adding initial strain (or installed strain) to the subsequent change in strain recorded during the test.
8. Calculated beam chord length by applying the constants from the derived type curve along with the calculated strain readings.

Figure A1-1 illustrates the data collection setup with vise, beam, and strain indicator. Figure A1-2 shows two beams installed in a can being prepared for testing in the T1 test series.

Figure A1-1

Figure A1-2

APPENDIX 2
MODEL NUMBERING AND LAYOUT

PRELIMINARY TESTING: CAN NUMBERING AND LAYOUT

Can Designation	Beam/ Strain Gage	Single Can	6-Pack	Unconfined	Confined	Location w/respect to Loading Plate	Remarks
T1P1	X(2)	X		X		N/A	#12 Can
T1P2	X(2)	X		X		N/A	#12 Can
T1P3	X(2)	X		X		N/A	#12 Can
T2P1	X(2)	X			X	N/A	#12 Can
T2P2	X(2)	X			X	N/A	#12 Can
T2P3	X(2)	X			X	N/A	#12 Can
T3P11	X		X		X	Top Left	#12 Can
T3P12	X		X		X	Middle Left	#12 Can
T3P13	X		X		X	Lower Left	#12 Can
T3P14			X		X	Near Right	#12 Can
T3P15			X		X	Middle Right	#12 Can
T3P16			X		X	Far Right	#12 Can
T3P21	X		X(w/ framing)		X	Near Left	#12 Can
T3P22	X		X(w/ framing)		X	Middle Left	#12 Can
T3P23	X		X(w/ framing)		X	Far Left	#12 Can
T3P24			X(w/ framing)		X	Near Right	#12 Can
T3P25			X(w/ framing)		X	Middle Right	#12 Can
T3P26			X(w/ framing)		X	Far Right	#12 Can
T3P31	X		X		X	Near Left	#12 Can
T3P32	X		X		X	Middle Left	#12 Can
T3P33	X		X		X	Far Left	#12 Can
T3P34			X		X	Near Right	#12 Can
T3P35			X		X	Middle Right	#12 Can
T3P36			X		X	Far Right	#12 Can

PRELIMINARY TESTING: DRUM NUMBERING AND LAYOUT

Drum Designation	Crush Gage	Single Drum	6-Pack	Unconfined	Confined	Location w/ respect to Loading Plate	Remarks
TSP11	X		X(w/ framing)		X	Near Left	55 Gallon Drum
TSP12	X		X(w/ framing)		X	Middle Left	55 Gallon Drum
TSP13	X		X(w/ framing)		X	Lower Left	55 Gallon Drum
TSP14			X(w/ framing)		X	Near Right	55 Gallon Drum
TSP15			X(w/ framing)		X	Middle Right	55 Gallon Drum
TSP16			X(w/ framing)		X	Far Right	55 Gallon Drum
TSP11A	X		X(w/ framing)		X	Near Left	55 Gallon Drum
TSP12A	X		X(w/ framing)		X	Middle Left	55 Gallon Drum
TSP13A	X		X(w/ framing)		X	Far Left	55 Gallon Drum
TSP14A			X(w/ framing)		X	Near Right	55 Gallon Drum
TSP15A			X(w/ framing)		X	Middle Right	55 Gallon Drum
TSP16A			X(w/ framing)		X	Far Right	55 Gallon Drum
TSP21A	X		X		X	Near Left	55 Gallon Drum
TSP22	X		X		X	Middle Left	55 Gallon Drum
TSP23	X		X		X	Far Left	55 Gallon Drum
TSP24			X		X	Near Right	55 Gallon Drum
TSP25			X		X	Middle Right	55 Gallon Drum
TSP26			X		X	Far Right	55 Gallon Drum
TSP31	X		X(w/ framing)		X	Near Left	55 Gallon Drum
TSP32	X		X(w/ framing)		X	Middle Left	55 Gallon Drum
TSP33	X		X(w/ framing)		X	Far Left	55 Gallon Drum
TSP34			X(w/ framing)		X	Near Right	55 Gallon Drum
TSP35			X(w/ framing)		X	Middle Right	55 Gallon Drum
TSP36			X(w/ framing)		X	Far Right	55 Gallon Drum

TEST NO. 6 : CAN NUMBERING AND LAYOUT

LOWER LAYER

PLAN VIEW

283	286	289	292	295	298	301	304	307	310	313	316	319	322	325	328	331	334	337	340

SECTION AA

5/27/87

Beam/Strain Gage Devices Were Installed
In The Following Numbered Cans:

T6P122
T6P158
T6P182
T6P218
T6P241
T6P242
T6P243
T6P277
T6P278
T6P279

Note: Can Designations Are T6P### For This Test.

TEST NO. 6 : CAN NUMBERING AND LAYOUT

MIDDLE LAYER

PLAN VIEW

503	506	509	512	515	518	521	524	527	530	533	536	539	542	545	548	551	554	557	560

SECTION AA

5/21/82

Beam/Strain Gage Devices Were Installed
In The Following Numbered Cans:

T6P422
T6P458
T6P482
T6P518
T6P541
T6P542
T6P543
T6P577
T6P578
T6P579

Note: Can Designations Are T6P### For This Test.

TEST NO. 6 : CAN NUMBERING AND LAYOUT

UPPER LAYER

Beam/Strain Gage Were Installed
In The Following Numbered Cans:

T6P722
T6P758
T6P782
T6P818
T6P841
T6P842
T6P843
T6P877
T6P878
T6P879

PLAN VIEW

843	846	849	852	855	858	861	864	867	870	873	876	879	882	885	888	891	894	897	900

SECTION AA

3/21/87

Note: Can Designations Are T6P### For This Test

TEST NO. 7: CAN NUMBERING AND LAYOUT

LOWER LAYER

PLAN VIEW

SECTION AA

5/21/87

Beam/Strain Gage Devices Were Installed
In The Following Numbered Cans:

T7P122
T7P158
T7P182
T7P218
T7P241
T7P242
T7P243
T7P277
T7P278
T7P279

Note: Shaded Numbers Denote Cans Receiving Simulated Waste.

Can Designations Are T7F### For This Test.

TEST NO. 7 : CAN NUMBERING AND LAYOUT

MIDDLE LAYER

Bean/Strain Gage Devices Were Installed
In The Following Numbered Cans:

T7P422
T7P458
T7P482
T7P518
T7P541
T7P542
T7P543
T7P577
T7P578
T7P579

PLAN VIEW

SECTION AA

3/21/87

Note: Can Designations Are T7P### For This Test.

Shaded Numbers Denote Cans Relieving Simulated Waste.

TEST NO. 7 : CAN NUMBERING AND LAYOUT

UPPER LAYER

Beam/Strain Gage Were Installed
In The Following Numbered Cans:

T7P722
T7P758
T7P782
T7P818
T7P841
T7P842
T7P843
T7P877
T7P878
T7P879

PLAN VIEW

643	646	649	652	655	658	661	664	667	670	673	676	679	682	685	688	691	694	697	900

SECTION AA

5/21/87

Note: Can Designations Are T7P### For This Test
Shaded Numbers Denote Cans Receiving Simulated Waste

APPENDIX 3

TEST 5 CONFINING FIXTURE HISTORY AND DEVELOPMENT

The fixture used to confine both drums and backfill for the full-scale preliminary tests underwent a series of changes and alterations which may have affected the test data in the T5P10 and T5P10A tests. It is because of the possible effects on the data that this detailed account of the fixture's construction and its subsequent alteration is presented.

The fixture was originally designed in the fall of 1986 (previous to conceptualization of the quarter-scale modeling idea) to aid in the crushing of empty full-scale 6-packs for use in the CH Mock Demonstration. There were no plans to use backfill to perform this task. The fixture was offered for use in the preliminary work of the scale model tests, both as a time and money saver, and because the preliminary model testing would produce crushed 6-packs thought to be more like those deformed in the CH room because of the inclusion of backfill. Although there were some concerns about the amount of space that would be left on each side of a 6-pack (≈ 10.5 inches), construction proceeded in parallel with the development of the test plan. Figure A3-1 illustrates the original design plans.

Initially, it was planned to use the two large RH handling fork trucks as "im-moveable" objects to load against, simply by backing them into the open ends of the fixture and loading the 6-pack and surrounding backfill with load indicating hydraulic jacks through a steel strongback off of the counterweights. However, after performing the quarter-scale preliminary work, it was apparent that it would take approximately six times as much force to crush a confined 6-pack as an unconfined single drum. This meant that, based on Huerta's unconfined single drum data, it would take over 100,000 lb. of laterally applied force to reach peak loading. The fork trucks would easily be moved by this magnitude of force.

Based on this information, permission was sought and received to relocate the test underground where loading could be reacted off of the rigid salt rock walls. The fixture was downloaded in pieces and reassembled underground. The legs were removed and the floor and lower cross beams were embedded in crushed salt for support. A 6-pack was installed and backfill emplaced, then testing commenced.

In the first test, T5P10, after approximately 2.5 inches of loading plate displacement, the center right (with respect to load) vertical beam failed in shear because of pure beam bending due to the out of plane stresses transmitted by the backfill. Figure A3-2 illustrates this failure. This test was ended at this point; peak load at failure was 39.5 tons.

Since some buckling of the lids was observed previous to the failure and load was nearing the range believed to cause breaching, it was believed that only minor changes were necessary to facilitate breach and an associated reduction in applied load. This proved to be incorrect. All of the vertical beams were replaced with solid beams (without countersunk lag bolt holes) of the same size and length as originally designed. In addition, the horizontal beams running over and under the fixture were shortened and attached in-line with the vertical beams with bolts and steel straps. The most important change was the reduction of the inside width of the fixture to 53 inches (leaving a 2.5-inch space on each side of an installed 6-pack--scaling the same as the quarter-scale confining fixture). Figure A3-3 illustrates the new configuration.

The first test was begun again, redesignated as T5P10A. The vertical beam failed at the same location as in T5P10 in exactly the same manner. Average loading plate displacement was 3.3 inches and load was recorded as 39 tons after the failure. Knowing that approximately 25% more strength could be gained by simply reducing the length of the vertical beams, it was decided to unload, remove opposing beam pairs, and shorten them while leaving the other beams in place. By doing this, the test was able to proceed with a time delay and with a slightly wider ($\approx 1/2$ inch was required to allow the beams to slip back in) opening between the walls. Figure A3-4 illustrates the new configuration.

T5P10A was continued until the front left vertical beam failed as the others had. Total average loading plate displacement was 4.1 inches; load immediately after the failure was recorded as 54 tons. Again, the vertical beams were replaced in pairs while leaving the others in place to hold the test configuration together. This time the verticals were replaced with 12-inch steel beams. A modification of the steel straps was also necessary and was performed. A strain gage was installed at the midpoint of one of the middle vertical beams and strain in it was monitored throughout the rest of this test and the remaining tests. Figure A3-5 illustrates the new configuration.

T5P10A was continued until the bolt securing the base of the middle right vertical beam to the lower horizontal beam pulled through the horizontal wood beam by shearing out the plug. Total average loading plate displacement was 5.9 inches; total load recorded immediately after the failure was 56 tons. With the information recorded from the strain gage installation and by performing a static analysis of the structure, it was calculated that the wall which had the instrumented beam had a ≈ 58 psi stress applied to it at the same time the loading plate had a total of 68 tons applied to it (≈ 70 psi). This means that approximately 80% of the loading plate pressure was being transmitted to the sidewalls. (The strain gage leads became debonded during T5P20, but similar calculations performed for T5P30 indicated 60% of the loading plate stress was transferred to the sidewalls at peak loads.)

The confining fixture underwent an extensive structural analysis after the T5P10A failure and was reinforced one final time using the above, stress information. Figure A3-6 illustrates the final configuration, which was used for both T5P20 and T5P30 without further incident.

FIGURE A3-1. CH TRU Mock Demo Six-Pack/Box Fixture

FIGURE A3-2. Vertical Beam Failure

PLAN VIEW

SIDE VIEW

END VIEW

FIGURE A3-3

PLAN VIEW

SIDE VIEW

END VIEW

CONSTRUCTION:

WALLS: 6 X 6 NOM. DOUG. FIR NO. 1
1/2 IN. PLYWOOD

FLOOR: 1 IN. PARTICLE BOARD

VERTICAL MEMBERS: 6 X 6 NOM. DOUG. FIR NO. 1

HORIZONTAL MEMBERS: 6 X 6 NOM. DOUG. FIR NO. 1

CONNECTORS: 1.25 IN. BOLTS
1/4 IN. STEEL STRAPS

FIGURE A3-4

CONSTRUCTION:

WALLS: 6 X 6 NOM. DOUG. FIR NO. 1
1/2 IN. PLYWOOD

FLOOR: 1 IN. PARTICLE BOARD

VERTICAL MEMBERS: S12 X 40.8 STEEL BEAM

HORIZONTAL MEMBERS: 6 X 6 NOM. DOUG. FIR NO. 1

CONNECTORS: 1.25 IN. BOLTS

1/4 IN. STEEL STRAPS

FIGURE A3-5

CONSTRUCTION:

WALLS: 6 X 6 NOM. DOUG. FIR NO. 1
1/2 IN. PLYWOOD

FLOOR: 1 IN. PARTICLE BOARD

VERTICAL MEMBERS: S12 X 40.8 STEEL BEAM

HORIZONTAL MEMBERS: C6 X 10.5 CHANNELS

CONNECTORS: 1.25 IN. BOLTS

1/4 IN. STEEL STRAPS

FIGURE A3-6

APPENDIX 4

PLOTS OF BEAM/STRAIN GAGE DATA FROM TESTS 6 AND 7

T6 - Bottom Layer, Row Comparison in Cans
P122/P182/P241/P242/P243

T6 - Bottom Layer, Row Comparison in Cans
P158/P218/P277/P278/P279

T6 - Middle Layer, Row Comparison in Cans
P422/P482/P541/P542/P543

T6 - Middle Layer, Comparison in Cans
P458/P518/P577/P578/P579

T6 - Top Layer, Row Comparison in Cans
P722/P782/P841/P842/P843

T6 - Top Layer, Row Comparison
P758/P818/P877/P878/P879

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T6 - Vertical Comparison of Crush in Individual Cans

T7 - Bottom Layer, Row Comparison in Cans
P122/P182/P241/P242/P243

APPENDIX 4
Page 9 of 16

T7 - Bottom Layer, Row Comparison in Cans
P158/P218/P277/P278/P279

T7 - Middle Layer, Row Comparison in Cans
P422/P482/P541/P542/P543

APPENDIX 4
Page 10 of 10

T7 - Middle Layer, Row Comparison in Cans
P458/P518/P577/P578/P579

T7 - Top Layer, Row Comparison in Cans
P758/P818/P877/P878/P879

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

APPENDIX 4
Page 15 of 16

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

T7 - Vertical Comparison of Crush in Individual Cans

APPENDIX 5

GRAPHICAL PRESENTATION OF CRUSH IN TESTS 6 AND 7

LOWER LAYER

LEGEND

☐ CAN WITH SOME VISUALLY IDENTIFIED CRUSH

☒ CAN WITH NO VISUALLY IDENTIFIED CRUSH

PLAN VIEW

243	246	249	252	255	258	261	264	267	270	273	276	279	282	285	288	291	294	297	300

SECTION AA

5/16/87

Note: Can designations are T6P234 for this test.

MIDDLE LAYER

PLAN VIEW

[illegible]

SECTION AA

5/16/87

UPPER LAYER

LEGEND

- CAN WITH SOME VISUALLY IDENTIFIED CRUSH
 ⊗ CAN WITH NO VISUALLY IDENTIFIED CRUSH

PLAN VIEW

643	644	649	652	655	658	661	664	667	670	673	676	679	682	685	688	691	694	697	900

SECTION AA

5/16/87

Note: Can Designations Are T6P### For This Test

TEST NO. 7: CANS WITH NO CRUSH AT ANY LOCATION

LOWER LAYER

LEGEND

- CAN WITH SOME VISUALLY IDENTIFIED CRUSH
 ⊗ CAN WITH NO VISUALLY IDENTIFIED CRUSH

PLAN VIEW

243	244	249	252	255	258	261	264	267	270	273	276	279	282	285	288	291	294	297	300

SECTION AA

5/16/87

Note: Can designations are T7P### for this test.

UPPER LAYER

LEGEND

- CAN WITH SOME VISUALLY IDENTIFIED CRUSH
 ● CAN WITH NO VISUALLY IDENTIFIED CRUSH

PLAN VIEW

601	606	609	612	615	618	621	624	627	630	633	636	639	642	645	648	651	654	657	660
661	666	669	672	675	678	681	684	687	690	693	696	699	702	705	708	711	714	717	720
721	726	729	732	735	738	741	744	747	750	753	756	759	762	765	768	771	774	777	780
781	786	789	792	795	798	801	804	807	810	813	816	819	822	825	828	831	834	837	840
841	846	849	852	855	858	861	864	867	870	873	876	879	882	885	888	891	894	897	900

SECTION AA

5/10/87

Note: Can designations are T7P### for this test.

TEST NO. 7: CANS WITH NO CRUSH AT ANY LOCATION

MIDDLE LAYER

LEGEND

- CAN WITH SOME VISUALLY IDENTIFIED CRUSH
 ● CAN WITH NO VISUALLY IDENTIFIED CRUSH

PLAN VIEW

501	506	509	512	515	518	521	524	527	530	533	536	539	542	545	548	551	554	557	560
561	566	569	572	575	578	581	584	587	590	593	596	599	602	605	608	611	614	617	620

SECTION AA

5/11/87

UPPER LAYER

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. ≈ 6.175")
- ⊘ CRUSH DIAMETER > 5.9"
- CRUSH DIAMETER ≤ 5.9"

PLAN VIEW

843	844	849	852	855	858	861	864	867	870	873	876	879	882	885	888	891	894	897	900

SECTION AA

6/22/87 jcu

Note: Can designations are T6P### for this test.
All diameters are outside diameters.
Can T6P614 was not measured.

TEST NO. 6 : LOWER RIM CRUSH

UPPER LAYER

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. ≈ 6.175")
- ⊘ CRUSH DIAMETER > 5.9"
- CRUSH DIAMETER ≤ 5.9"

PLAN VIEW

843	844	849	852	855	858	861	864	867	870	873	876	879	882	885	888	891	894	897	900

SECTION AA

6/22/87 jcu

LEGEND

NO VISUALLY IDENTIFIED CRUSH (DIA. $\approx 6.05^{\circ}$)

CRUSH DIAMETER >5.6"

CRUSH DIAMETER $\leq 5.6"$

PLAN VIEW

[illegible]

SECTION AA

12287

Note: Can designations are T6P### for this test.
All diameters are outside diameters.
Can T6P614 was not measured.

UPPER LAYER

LEGEND

NO VISUALLY IDENTIFIED CRUSH (DIA. $\approx$ 6.05")

CRUSH DIAMETER 15.6"

CRUSH DIAMETER ($\approx 3.6"$)

PLAN VIEW

[illegible]

SECTION AA

62287

PLAN VIEW

[illegible]

SECTION AA

4/22/80

Note: Can designations are T6P### for this test.

All crush diameters measured are outside diameters

TEST NO. 6: BOTTOM RIM CRUSH

MIDDLE LAYER

PLAN VIEW

[illegible]

SECTION AA

4/22/67 JCN

MIDDLE LAYER

301	304	307	310	313	316	319	322	325	328	331	334	337	340	343	346	349	352	355	358
361	365	369	371	374	377	380	383	386	389	392	395	398	401	404	407	410	413	416	419
403	396	389	382	375	368	361	354	347	340	333	326	319	312	305	298	291	284	257	260
361	364	367	370	373	376	379	382	385	388	391	394	397	400	403	406	409	412	415	418
362	365	368	371	374	377	380	383	386	389	392	395	398	401	404	407	410	413	416	419
363	366	369	372	375	378	381	384	387	390	393	396	399	402	405	408	411	414	417	420
421	424	427	430	433	436	439	442	445	448	451	454	457	460	463	466	469	472	475	478
422	425	428	431	434	437	440	443	446	449	452	455	458	461	464	467	470	473	476	479
423	426	429	432	435	438	441	444	447	450	453	456	459	462	465	468	471	474	477	480
441	444	447	450	453	456	459	462	465	468	471	474	477	480	483	486	489	492	495	498
442	445	448	451	454	457	460	463	466	469	472	475	478	481	484	487	490	493	496	499
443	446	449	452	455	458	461	464	467	470	473	476	479	482	485	488	491	494	497	500
501	504	507	510	513	516	519	522	525	528	531	534	537	540	543	546	549	552	555	558
502	505	508	511	514	517	520	523	526	529	532	535	538	541	544	547	550	553	556	559
503	506	509	512	515	518	521	524	527	530	533	536	539	542	545	548	551	554	557	560
541	544	547	550	553	556	559	562	565	568	571	574	577	580	583	586	589	592	595	598
542	545	548	551	554	557	560	563	566	569	572	575	578	581	584	587	590	593	596	599
543	546	549	552	555	558	561	564	567	570	573	576	579	582	585	588	591	594	597	600

[illegible]

4/27-87 jdv

All crush diameters measured are outside diameters.

MIDDLE LAYER

[illegible]

6-27-57 JMW

LOWER LAYER

[illegible]

4-10-67 p.

NO VISUALLY IDENTIFIED CRUSH (DIA. $\geq 6.175"$)
CRUSH DIAMETER $\geq 5.9"$
CRUSH DIAMETER $\geq 5.9"$

LOWER LAYER

287	286	285	282	280	259	261	264	267	270	273	276	279	282	285	288	291	294	297	300

4-22-57

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. $\geq 6.175"$)
CRUSH DIAMETER $\geq 5.9"$
CRUSH DIAMETER $\geq 5.9"$

TEST NO. 6: TOP WALL CRUSH

LOWER LAYER

APPENDIX 5
Page 9 of 15

PLAN VIEW

SECTION AA

4' 2" 57 30"

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. = 6.05")
- ◐ CRUSH DIAMETER > 5.6"
- CRUSH DIAMETER ≤ 5.6"

Note: Can designations are T6P### for this test.
All diameters noted are outside diameters.

TEST NO. 6: BOTTOM WALL CRUSH

LOWER LAYER

PLAN VIEW

SECTION AA

6/12/87

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. = 6.05")
- ◐ CRUSH DIAMETER > 5.6"
- CRUSH DIAMETER ≤ 5.6"

UPPER LAYER

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. = 6.05")
- CRUSH DIAMETER >5.6"
- CRUSH DIAMETER <=5.6"

PLAN VIEW

803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900
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SECTION AA

1/30/87 jdv

Note: Can designations are T7P### for this test.
All diameters are outside diameters.

TEST NO. 7 : LOWER WALL CRUSH

UPPER LAYER

LEGEND

- NO VISUALLY IDENTIFIED CRUSH (DIA. = 6.05")
- CRUSH DIAMETER >5.6"
- CRUSH DIAMETER <=5.6"

PLAN VIEW

803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900
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SECTION AA

1/30/87 jdv

[illegible]

4/22/87 jpv

MIDDLE LATER

[illegible]

4/30/87 jdv

LOWER LAYER

001	004	007	010	013	016	019	022	025	028	031	034	037	040	043	046	049	052	055	058
002	025	028	031	034	037	040	043	046	049	052	055	058	061	064	067	070	073	076	079
003	006	009	012	015	018	021	024	027	030	033	036	039	042	045	048	051	054	057	060
081	084	087	090	093	096	099	102	105	108	111	114	117	120	123	126	129	132	135	138
062	065	068	071	074	077	080	083	086	089	092	095	098	101	104	107	110	113	116	119
063	066	069	072	075	078	081	084	087	090	093	096	099	102	105	108	111	114	117	120
121	124	127	130	133	136	139	142	145	148	151	154	157	160	163	166	169	172	175	178
122	125	128	131	134	137	140	143	146	149	152	155	158	161	164	167	170	173	176	179
123	126	129	132	135	138	141	144	147	150	153	156	159	162	165	168	171	174	177	180
181	184	187	190	193	196	199	202	205	208	211	214	217	220	223	226	229	232	235	238
182	185	188	191	194	197	200	203	206	209	212	215	218	221	224	227	230	233	236	239
183	186	189	192	195	198	201	204	207	210	213	216	219	222	225	228	231	234	237	240
241	244	247	250	253	256	259	262	265	268	271	274	277	280	283	286	289	292	295	298
242	245	248	251	254	257	260	263	266	269	272	275	278	281	284	287	290	293	296	299
243	246	249	252	255	258	261	264	267	270	273	276	279	282	285	288	291	294	297	300

283	286	289	292	295	298	261	264	267	270	273	276	279	282	285	288	291	294	297	300

4/30/87 jpw

LOWER LAYER

[illegible]

4/30/67 JCV

LOWER LAYER

- NO VISUALLY IDENTIFIED CRUSH(DIA. $\leq 6.03"$)
- ▨ CRUSH DIAMETER $> 5.6"$
- CRUSH DIAMETER $\leq 5.6"$

PLAN VIEW

SECTION AA

6/30/87 jmv

Note: Can designations are T7P### for this test.

All diameters noted are outside diameters.

LOWER LAYER

- NO VISUALLY IDENTIFIED CRUSH (DIA = 6.05")
CRUSH DIAMETER >5.6"
CRUSH DIAMETER <=5.6"

PLAN VIEW

SECTION AA

4-79-87 JCU