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Analysis, Scale Modeling, and Full-Scale Tests of Low-Level Nuclear-Waste-Drum Response to Accident Environments

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MASTER

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Analysis, Scale Modeling, and Full-Scale Tests of Low-Level Nuclear-Waste-Drum Response to Accident Environments

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Abstract

This report describes extensive full-scale and scale-model testing of 55-gallon drums used for shipping low-level radioactive waste materials. The tests conducted include static crush, single-can impact tests, and side impact tests of eight stacked drums. Static crush forces were measured and crush energies calculated. The tests were performed in full-, quarter-, and eighth-scale with different types of waste materials. The full-scale drums were modeled with standard food product cans. The response of the containers is reported in terms of drum deformations and lid behavior. The results of the scale model tests are correlated to the results of the full-scale drums. Two computer techniques for calculating the response of drum stacks are presented.

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Analysis, Scale Modeling, and Full-Scale Tests of Low-Level Nuclear Waste Drum Response to Accident Environments

Introduction

Sandia National Laboratories (SNL) is involved in various programs investigating the transportation of nuclear materials. One form of material for which transportation systems are being evaluated is Contact-Handled Transuranic Waste (CH-TRU). One method of transporting this material is in special 208-litre (55-gallon) drums which are included in the International Atomic Energy Agency category of Type A packagings. These drums are normally carried in large numbers inside a second container. In a hypothetical accidental impact of the outer container, the interior drums will interact and be subjected to crush environments where the forces are predominantly lateral. The present work characterizes the crush response of individual drums and the dynamic impact response of single drums and drum stacks. The information acquired will allow the accurate modeling of a cargo of drums inside a second container and the prediction of cargo damage.

The purposes of this study are to determine

- The static crush resistance of individual drums
- The response of single drums and drum stacks to impact environments
- The adequacy of commercial food product cans as models in predicting the response of the full-scale prototypes to static and dynamic environments
- The utility of computer programs to predict drum response to dynamic impact environments.

To achieve these purposes, we conducted numerous static and dynamic tests of full-scale prototype drums and of scale models. The dynamic tests included impacts of single drums as well as of single columns stacked eight drums high.

Computer models used included dynamic finite-element and lumped-parameter models with computer programs previously developed at SNL. In this report, we compare results of prototype and scale model tests with results of the computer models.

Full-Scale Static Crush Tests

Introduction

The first phase of the test program involved quasi-static crush tests of drums filled with combustible or simulated sludge waste. The crush tests were conducted at the SNL static test facility using a universal testing machine equipped with large flat plates. Twelve full-scale drum tests were conducted in the lateral and four in the longitudinal (axial) direction. For each variety of drum contents, load deflection characteristics were measured.

Drum Description

Features of the type of full-scale test drums used throughout this evaluation are illustrated in Figure 1. All drums were obtained from the Rocky Flats facility to insure that the correct hardware for transporting this material was used in all tests. The drums are designated DOT-17C and have a capacity of 208 litre (55 gallon). The metal thickness throughout is 16-gauge steel, 1.52 mm (0.0598 in.) thick. The drum is nominally 61 cm (24 in.) in diameter and 86 cm (34 in.) tall. This design utilizes a rigid polyethylene liner and a light polyethylene plastic inner bag. The metal drum lid is held in place with a clamping ring secured with a nut and bolt (Figure 1). Waste material is first loaded into the light polyethylene bag and placed inside the liner. The top of the bag is then gathered, taped shut, and checked for outside contamination. If no contamination is found, the liner lid is then installed. This lid snaps into place after an adhesive has been applied and is then banded with a circumferential stainless steel strap. The metal drum head is then installed using a gasket and adhesive. The clamping ring is positioned and secured with a nut and bolt.

Figure 1. Typical Drum Waste Package With Rigid Polyethylene Liner and Plastic Bag

Static Test Procedure

A 2.67×10^6 N (600,000-lb) capacity machine equipped with rigid surfaces large enough to cover the drums was used for the full-scale crush tests (Figure 2). Plots of crush force vs head deflection were obtained from recording equipment fixed to the test machine. Documentary photographs were taken of the pretest and posttest setup and test specimens. Time-lapse motion pictures were also taken from two cameras in fixed positions with exposure rates synchronized at one frame per second. The head speed of the test machine was set to crush the containers at a rate of 1.3 cm (0.5 in.) per minute. The maximum crush of the drums was arbitrarily limited to be about half the drum diameter or approximately 30 cm (12 in.) for a side crush and about 38 cm (15 in.) for an end crush test.

The crush tests were conducted with empty drums and with drums containing either simulated combustible or sludge waste in different amounts. The combustible waste consisted of washroom and lunchroom

types of trash, moist hand towels, rubber gloves, broken glass from laboratory equipment and pop bottles, beverage cans, small metal objects, and paper sheets. Two densities of simulation sludge were used. The light sludge contained pea-sized fragments of crushed rock, sand, and oil dry (a lightweight clay particle material) to adjust the material density. The dense sludge was simulated with Rocky Flats soil. A small amount of water was added to the content to produce the desired total package weight. The containers were about 80% full. Twelve tests were conducted, two of each in the following configurations:

- Lateral, combustible waste, 90 kg (200 lb) nominal gross weight
- Lateral, simulated sludge, 230 kg (500 lb nominal gross weight)
- Lateral, empty
- Lateral, simulated sludge, 320 kg (700 lb) nominal gross weight
- Axial, empty
- Axial, simulated sludge, 320 kg (700 lb) nominal gross weight

Figure 2. Test Setup for the Full-Scale Lateral Crush Tests

Lateral Static Test Results

The first eight tests were conducted in the lateral configuration with force-displacement curves recorded up to about 25 cm (10 in.) of crush. Drums filled with combustible waste were tested first. Figure 3 illustrates different stages of crush ranging from 13 to 30 cm (5 to 12 in.) in a typical lateral test. In the tests, the removable drum head deformed outward and folded along a horizontal centerline as shown in Figure 3 and more clearly in Figure 4, which illustrates the posttest condition of the drum. As can be seen in this latter figure, the drum lid opened widely during crush. Typically, the lid separated at a crush of between 5.3 and 6.1 cm (2.1 and 2.4 in.) and a force of between 7.78×10^4 and 9.56×10^4 N (17.5×10^3 and 21.5×10^3 lb). At this point, the lid pulled out from under the sealing band, an event that was clearly detectable.

The force-displacement results for the first two drums tested are shown in Figure 5. These drums were filled with combustible waste and had a gross nominal weight of 90 kg (200 lb). As can be seen, the load rises fairly uniformly with displacement up to a displacement value of 6.3 cm (2.5 in.) and then takes a sudden

drop followed by a more gradual increase with displacement. The sudden drop in force occurred at the point of drum lid separation and clamp ring slippage. At this point, the head end of the drum loses a considerable amount of stiffness and the load drops. As can be seen from Figure 5, there was some variation in load necessary to cause lid separation between the first two drums tested (numbers in the figures indicate test numbers) with the average load value being about 8.89×10^4 N (20×10^3 lb). The two drums containing simulated sludge and having gross weights of 227 kg (500 lb) showed more consistency in the force causing lid separation (Figure 6). With these, lid separation occurred at a force of approximately 7.78×10^4 N (17.5×10^3 lb) and at about the same displacement. Empty drums (Figure 7) behaved in basically the same manner up to the point of lid separation; however, the subsequent crush force for the empty drums was much lower and remained essentially constant. The drums containing the denser sludge (Figure 8) and having gross weights of 318 kg (700 lb) did not behave significantly different than those containing the lighter sludge.

Figure 3. Typical Stages of Crush in a Lateral Full-Scale Crush Test

Figure 4. Posttest Condition of a Full-Scale Drum Following a Lateral Crush Test

Figure 5. Lateral Force vs Displacement for Combustible-Waste-Filled Full-Scale Drums

Figure 6. Lateral Force vs Displacement for Light-Density-Sludge-Filled Full-Scale Drums

Figure 7. Lateral Force vs Displacement for Empty Full-Scale Drums

Figure 8. Lateral Force vs Displacement for Dense-Sludge-Filled Full-Scale Drums

From the curves derived from the tests (Figure 9) one can see that the drums containing the simulated combustible waste were the stiffest and the empty ones were the softest. Curves for the drums containing simulated sludge fell in between without a significant difference between the light and heavy sludge. The point of lid separation occurred very consistently at the same load and displacement for all the drums except the second (containing combustible waste), which exhibited lid separation at a somewhat higher force (Figure 9).

The amount of energy or work associated with a drum deformation is equal to the area under the

force-displacement diagram. This quantity was calculated for all tests; the results for the lateral configuration are illustrated in Figure 10. This figure shows that the empty drums took the least energy, followed by the group containing sludge. The drums containing combustible waste clearly took the most energy—with the second drum, which experienced the late lid separation, taking considerably more than the first one. The energy required to laterally crush a drum 25 cm (10 in.) varied from a low of about 13550 N-m (120,000 in.-lb) to a high of about 20340 N-m (180,000 in.-lb).

Figure 9. Lateral Force vs Displacement for All Full-Scale Drums Tested

Figure 10. Energy vs Displacement for the Full-Scale Drums Tested Laterally

Axial Static Test Results

The last four drums (Nos. 9-12) were tested in an axial mode. The same equipment was used, but the drums were compressed through a distance of 38 cm (15 in.) instead of 30.5 cm (12 in.) and data were plotted through 30.5 cm (12 in.) of crush. The behavior of drum 9 at various stages of crush to 38 cm (15 in.) was typical of the axial tests (Figure 11); the lids remained in place, and none of the drums showed any sign of splitting at any point.

The force-displacement results for these tests (Figure 12) show that plastic deformation began at a load of about 6.80×10^4 N (15×10^3 lb). The crush force then remained fairly constant, with the drums containing the sludge (nominal gross weight of 320 kg) exhibiting a higher force level. At about 15.2 cm (6 in.) of crush, the filled drums began showing a rapid increase in force which is commonly referred to as a "lock up" condition. At 30.5 cm (12 in.) the filled drums had a crush force of about 3.55×10^5 N (80×10^3 lb); higher, by about a factor of 4, than the empty drums which maintained a fairly constant crush force.

As with the lateral tests, curves illustrating the deformation energy were generated from the force displacement data (Figure 13). The two drums with the force-displacement simulated sludge produced practically identical results and took considerably more energy to crush.

Table 1 summarizes the 12 tests, indicating the contents, the exact gross weight, the point of lid failure, and the energy required to crush the drum 25 cm (10 in.).

Discussion

These results indicate that a lateral crush force level of about 80.0×10^3 N (18,000 lb) is sufficient to cause visible initiation of drum lid separation, suggesting that leak tightness is probably lost at some prior lower load. It was postulated that the amount of energy required (about 2825 N-m (25,000 in.-lb) can be converted into kinetic energy to roughly compute the necessary drop height to initiate drum lid separation. Assuming negligible strain rate sensitivity, the results of this calculation indicate that a drum with a gross weight of 230 kg (500 lb) requires 130 cm (50 in.) and that one with a gross weight of 320 kg (700 lb) requires only 90 cm (36 in.). The calculation is very approximate because an impact situation is different from a quasi-static crush environment. It is presented, however, to give the reader a feeling for the energy required to initiate lid separation in terms of container drop height as based on static crush data. In later sections, we compute the energy required under dynamic conditions.

A lid separation does not necessarily mean loss of contents, because the rigid liner and the polyethylene bag provide additional containment. No contents were lost in any of the static crush tests.

Table 1 shows that the crush energies for the lateral and axial cases are quite comparable at 25 cm (10 in.) of crush. On the average, the axial crush took $\sim 10\%$ more energy.

Figure 11. Full-Scale Drum at Progressive Stages of Axial Crush

Figure 12. Force vs Displacement for Full-Scale Drums Tested Axially

Figure 13. Crush Energy vs Displacement for the Full-Scale Axial Tests

Table 1. Summary of Full-Scale Static Crush Tests

Test No.	Orientation	CONTENTS		LID SEPARATION		Energy to Crush 25 cm (10 in)	
		Type	Gross Weight kg (lbs)	Force N (lbs)	Defl. cm (in)	N-m (in-lb)	
1	Lateral	Comb. Waste	94 (207)	79174 (17,800)	6.6 (2.6)	18642 (165,000)*	
2	Lateral	Comb. Waste	94 (207)	96076 (21,600)	6.8 (2.7)	22596 (200,000)*	
3	Lateral	Sim. Sludge	234.5 (516)	78729 (17,700)	6.3 (2.5)	16947 (150,000)	
4	Lateral	Sim. Sludge	233.6 (514)	80064 (18,000)	7.1 (2.8)	16947 (150,000)	
5	Lateral	Empty	-- --	76060 (17,100)	5.1 (2.0)	14122 (125,000)	
6	Lateral	Empty	-- --	81398 (18,300)	6.6 (2.6)	14122 (125,000)	
7	Lateral	Sim. Sludge	310.4 (683)	80953 (18,200)	6.6 (2.6)	17512 (155,000)*	
8	Lateral	Sim. Sludge	313.2 (689)	80953 (18,200)	7.1 (2.8)	16947 (150,000)*	
9	Axial	Empty	-- --	No Failure	NA	16947 (150,000)	
10	Axial	Empty	-- --	No Failure	NA	12427 (110,000)	
11	Axial	Sim. Sludge	325.4 (716)	No Failure	NA	22596 (200,000)	
12	Axial	Sim. Sludge	312.2 (687)	No Failure	NA	22596 (200,000)	

*Estimated

Scale Model Static Crush Tests

Introduction

One of the objectives of this evaluation was to examine the accuracy of using commercially available food product cans to model the response of the prototype drums described in the previous section. If commercially available cans prove to be adequate models, then these can be used in subscale experiments involving the overpack containers and vehicle systems at a great savings in time and expense. This section will describe static crush tests of cans that are approximately one-eighth and one-quarter scale models of the full-scale drums. Thirty-eight crush tests were conducted using a procedure similar to that used with the full-scale drums. The results of these tests are compared below to the scaled results of the prototype drums.

Scale Model Description

The 208-litre (55-gallon) prototype drums can be closely scaled dimensionally to a one-fourth and one-eighth scale using standard cans. This requires food product cans commercially designated No. 12 and No. 300, respectively. A No. 10 can is also a close approximation of a one-quarter scale model. A complete model analysis for this problem is presented in Reference 1.

Figure 14 illustrates some of the models used. Table 2, a tabulation of the scaled prototype and commercial can dimensions, shows that although the No. 10 can is ~19% short, the other dimensions are within 8%. The No. 12 can scales well in the height and diameter dimensions, but is ~16% low in material thickness. The No. 300 can, a one-eighth subscale model, agrees very well in the height and diameter dimensions, but is ~19% high in material thickness.

A significant deviation between the models and the prototype occurs in the way the lid is attached. As described previously, the full-scale drums utilize a clamping ring secured with a nut and bolt to keep the lid in place. All the model lids were placed on the cans with a commercial canning machine using a crimp joint. (Early in the program some cans were purchased full of foodstuff that was removed through a small hole which was resealed.) In this study it was decided not to try to duplicate the clamping ring but to see how well the data correlated using unmodified tin cans. Also, no attempt was made to model the rigid liner or the polyethylene bag.

Figure 14. Illustration of One-Eighth and One-Quarter Scale Can Models

It was recognized that the food product can material probably did not have the same stress-strain properties as the prototype. Tensile specimens obtained from both the model and prototype materials¹ revealed that the properties of the No. 12 and No. 300 cans were about the same, with an average yield stress of 379.1 mPa (55 ksi). The full-scale material was found to have the much lower value of 220.6 mPa (32 ksi). The possibility of heat-treating the models to reduce the yield strength was investigated² and found to be feasible. However, no models were heat-treated for this test series.

Table 2 shows that the No. 12 can appears to be the best model. The height and diameter dimensions are close, whereas the material thickness is low; however, the thin wall should be offset by its higher yield stress. The No. 300 can scales well in the diameter and height dimensions, but has a high material thickness.

This condition is further aggravated by a high value in material yield stress. The No. 10 can scales well except in the height dimension. It also has the problems of too high a yield stress. As a check on their adequacy as scale models, these cans were subjected to crush tests similar to those conducted with full-scale drums.

Table 2. Comparison of Prototype and Model Dimensions

Container	Dimensions, cm (in)		Material Thickness, cm (in)		
	Diameter	Height	Top	Bottom	Side
Prototype (17-C)	60.58 (23.85)	88.42 (34.81)	0.152 (0.0598)	0.152 (0.0598)	0.152 (0.0598)
Prototype Scaled to 1/4	14.46 (5.693)	22.10 (8.70)	0.0381 (0.015)	0.0381 (0.015)	0.0381 (0.015)
No. 10 Can	15.62 (6.150)	17.78 (7.00)	0.0381 (0.015)	0.0381 (0.015)	0.0356 (0.014)
% Error	+8.02	-19.5	0.0	0.0	-6.5
No. 12 Can	15.62 (6.150)	22.22 (8.75)	0.0317 (0.0125)	0.0317 (0.0125)	0.0317 (0.0125)
% Error	+8.02	0.54	-16.79	-16.79	-16.79
Prototype Scaled to 1/8	7.57 (2.98)	11.05 (4.35)	0.019 (0.0075)	0.019 (0.0075)	0.019 (0.0075)
No. 300 Can	7.49 (2.95)	11.28 (4.44)	0.0226 (0.0088)	0.0226 (0.0088)	0.0226 (0.0088)
% Error	-1.05	+2.08	+18.94	+18.94	+18.94

Procedure

Scale-models were tested in a universal testing machine equipped with thick steel plates. Traces of crush force as a function of head displacement were monitored by recording equipment for each test. The test setup for a one-eighth scale test is shown in Figure 15. The procedure was similar to that followed for the full-scale drums, except that the test machine was smaller.

The test series was begun with No. 10 cans because they were readily available. Some of these were purchased with food stuff, then emptied, filled with simulated contents, resealed, and tested. One No. 10 can purchased with ground coffee was tested full as well as one No. 300 can with cat food. As soon as

commercially manufactured empty cans with unattached lids became available, they were used in the test program.

In all, 21 quarter- and 17 eighth-scale models were tested; Tables 3 and 4 summarize test conditions. First, a group of nine quarter-scale models (No. 10 cans) was tested laterally. This series was followed by six axial quarter-scale model tests (No. 12 cans). Then five more lateral quarter-scale tests were conducted (No. 12 cans). The one-eighth scale tests all used No. 300 cans. In this series, seven cans were first tested laterally, followed by six axially, and finally four laterally. Weights as well as contents are given in Tables 3 and 4.

Figure 15. Experimental Setup for the Scale Model Static Crush Tests

Table 3. Summary of Quarter-Scale Container Model Static Tests

Test No.	Can No.	Gross Weight gm (lb)	Contents Simulated	Crush Orientation
1	10	1497 (3.29)	Comb. Waste	Lateral
2	10	1410 (3.10)	Comb. Waste	Lateral
3	10	2722 (5.99)	Light Sludge	Lateral
4	10	2750 (6.06)	Light Sludge	Lateral
5	10	1690 (3.72)	None (contained ground coffee)	Lateral
6	10	328 (0.72)	Empty	Lateral
7	10	324 (0.71)	Empty	Lateral
8	10	2954 (6.51)	Light Sludge	Lateral
9	10	2853 (6.28)	Light Sludge	Lateral
10	12	376 (.828)	Empty	Axial
11	12	378 (.833)	Empty	Axial
12	12	1451 (3.20)	Comb. Waste	Axial
13	12	1430 (3.15)	Comb. Waste	Axial
14	12	4972 (10.95)	Dense Sludge	Axial
15	12	4966 (10.94)	Dense Sludge	Axial
16	12	380 (0.8)	Empty	Lateral
17	12	377 (0.83)	Empty	Lateral
18	12	1424 (3.14)	Comb. Waste	Lateral
19	12	1425 (3.14)	Comb. Waste	Lateral
20	12	4971 (10.95)	Dense Sludge	Lateral
21	12	4971 (10.95)	Dense Sludge	Lateral

Table 4. Summary of One-Eighth Scale Container Model Static Tests

Test No.	Can No.	Gross Weight gm (lb)	Contents Simulated	Crush Orientation
1	300	188 (0.41)	Comb. Waste	Lateral
2	300	188 (0.41)	Comb. Waste	Lateral
3	300	445 (0.98)	Light Sludge	Lateral
4	300	446 (0.98)	Light Sludge	Lateral
5	300	509 (1.12)	None (contained cat food)	Lateral
6	300	64 (0.14)	Empty	Lateral
7	300	64 (0.14)	Empty	Lateral
8	300	72 (0.16)	Empty	Axial
9	300	73 (0.16)	Empty	Axial
10	300	187 (0.41)	Comb. Waste	Axial
11	300	176 (0.39)	Comb. Waste	Axial
12	300	621 (1.36)	Dense Sludge	Axial
13	300	615 (1.35)	Dense Sludge	Axial
14	300	73 (0.16)	Empty	Lateral
15	300	72 (0.16)	Empty	Lateral
16	300	630 (1.39)	Dense Sludge	Lateral
17	300	620 (1.36)	Dense Sludge	Lateral

Four types of simulated contents were tested to correspond to the full-scale tests. The simulations were as follows:

- Empty
- Simulated combustible waste, 90-kg (200-lb) drum
- Simulated light sludge waste, 230-kg (500-lb) drum
- Simulated dense sludge waste, 320-kg (700-lb) drum)

In each case, the contents were scaled for weight and not for volume. The contents were the same as had

been used for the prototype drums and the material was actually taken from the full-scale drums.

Results

Quarter-Scale Models

Figure 16, a test sequence using a quarter-scale can, illustrates typical results. Figure 17 illustrates a typical axial sequence. Unlike the prototype containers, the lids on the models remained in place and did not separate.

Figure 16. Lateral Crush Sequence for a Quarter-Scale Test

Figure 17. Axial Crush Sequence for a Quarter-Scale Test

Figure 18, which illustrates the force-displacement results for the first nine quarter-scale tests that used No. 10 cans, shows that Tests 3, 4, and 5 deviated significantly from the rest. The reason for the difference is that these models were packed full. In the case of Nos. 3 and 4, they were packed full of light density simulated sludge; No. 5 contained ground coffee. Tests 8 and 9, run with the same material but packed to only 80% of full volume, produced a significant difference. The crush force level for this series of cans was between 4448 and 8896 N (1000 and 2000 lb) until ~50% crush, at which point the cans with contents started to stiffen. Figure 19 illustrates results for the second group of quarter-scale cans (No. 12) tested laterally. These results correspond to Tests 16 through 21 in Table 3. The figure shows that the crush forces for these models were somewhat lower than the previous ones which used the shorter No. 10 can. Test 20 appears to be anomalous because it showed a significant force rise before reaching a 50% crush value. The model used in Test 21, which had identical contents, showed a much lower force at high-crush values.

Figure 18. Force vs Displacement for the Lateral Quarter-Scale Crush Tests With No. 10 Cans

The results for the axial-quarter scale tests (Figure 20) revealed that the models had a peak buckling load of ~8896 N (2000 lb) which dropped to ~4448 N (1000 lb) as the can crushed. Tests 14 and 15, which contained the dense sludge, stiffened up considerably after about a 25% crush. The empty cans (Tests 10 and 11) crushed at a nearly constant level without any increase in load.

Figure 19. Force vs Displacement for the Lateral Quarter-Scale Crush Tests With No. 12 Cans

Figure 20. Force vs Displacement for the Axial Quarter-Scale Crush Tests

As with the full-scale tests, the force-displacement curves were integrated to obtain plots of the work or crush energy. The results for the quarter-scale lateral tests using the No. 10 cans are shown in Figure 21. Excluding Tests 3, 4, and 5, which had the abnormally high crush forces due to a pressure buildup in the container, the work to crush these No. 10 cans fell in the range of 337 to 450 N-m (3000 to 4000 in.-lb). Figure 22 illustrates the results for the lateral crush tests using the No. 12 cans. These models displayed lower crushing energy levels that fell in the range of 225 to 340 N-m (2000 to 3000 in.-lb). In axial tests

with No. 12 cans, contents made a very large difference in crush energies (Figure 23). The models containing dense sludge took by far the most energy and required ~ 565 N-m (5000 in.-lb) to crush 6.4 cm (2.5 in.).

Figure 21. Crush Energy vs Displacement for the Lateral Quarter-Scale Crush Tests With the No. 10 Cans

Figure 22. Crush Energy vs Displacement for the Lateral Quarter-Scale Tests With No. 12 Cans

Figure 23. Crush Energy vs Displacement for the Axial Quarter-Scale Tests

One-Eighth-Scale Models

The one-eighth-scale tests were also conducted in three phases (see Table 4). The first seven tests were conducted in a lateral mode with cans having different contents or empty. The next six models were then tested in an axial mode and the final four models were tested laterally. Test results for these three test groups are explained below. Figure 24 illustrates the force displacement results for the first seven lateral tests. The models containing the light simulated sludge (Nos. 3 and 4) started stiffening up considerably after about a 25% crush. The rest of the models crushed at a fairly constant rate of ~ 2225 N (500 lb). Figure 25 illustrates the results for the second group of one-eighth-scale models crushed laterally, which are very similar to those of Figure 24. The models containing dense simulated sludge (Nos. 16 and 17) showed a sharp increase in crush force after about a 25% crush. The rest maintained a fairly constant crush force of ~ 2225 N (500 lb). The results for the axial tests are illustrated in Figure 26. Initial buckling loads were ~ 4448 N (1000 lb). The models then crushed at a fairly uniform load of ~ 3110 N (700 lb) except for the models containing simulated sludge which started locking up at about a 25% crush.

Figure 24. Force vs Displacement for the First Group of Eighth-Scale Models Tested Laterally

Figure 25. Force vs Displacement for the Second Group of Eighth-Scale Models Tested Laterally

The energy or work associated with these one-eighth-scale crush tests is illustrated in Figures 27 and 28. The first of these illustrates crush energies for all the lateral tests. The reason for the anomaly of container No. 3 is not known, but this data should probably be disregarded. The rest of the models took a crush energy < 110 N-m (1000 in.-lb) for a 50% crush. Figure 28 illustrates the crush energies for all the axial tests (Tests 8 through 13 in Table 4). There was not much deviation between tests, although the cans filled with sludge took more energy than the empty ones or the ones filled with combustible waste. The energy absorbed in crushing the cans 3.2 cm (1.25 in.) or $\sim 30\%$ of their height was of the order of 85 N-m (750 in.-lb) or less.

Figure 26. Force vs Displacement for the Eighth-Scale Models Tested Axially

Figure 27. Crush Energy vs Displacement for the Eighth-Scale Models Tested Laterally

Figure 28. Crush Energy vs Displacement for the Eighth-Scale Models Tested Axially

Comparison of Prototype and Model Test Results

Introduction

In this section the prototype results of the full-scale static-crush tests will be compared with the subscale model static-crush tests. This comparison will include the force-deflection characteristics and the energies required to crush the container. The comparison will be illustrated by banding the scale model data and superimposing dotted lines to represent the scaled prototype results.

Quarter-Scale Models

The model results of Figures 18 and 19 have been banded and are presented in Figures 29 and 30 with the typical scaled prototype results superimposed. Figure 29 represents the results obtained with the No. 10 cans (the tests considered invalid are removed). The scale model results for up to ~ 4 cm (1.6 in.) of deformation, which represents more than a 25% crush, are in excellent agreement with the prototype results. At larger deformations, the No. 10 cans overpredicted the crush force somewhat (Figure 29). The results of the model tests with the No. 12 cans (Figure 30) are in better agreement. With the No. 12 cans, the agreement is quite good through the entire range of crush. Figure 31 compares the axial force-displacement results of prototype and model tests using the No. 12 cans. The models greatly overpredicted the initial buckling force. The agreement in crush levels after the containers have passed the initial buckling stage is excellent for empty containers. The models, however, underpredicted the axial force in the sludge-filled containers at large deformations. For example, Figure 31 shows that at deformation levels > 15 cm (6 in.) on the prototype, the model results underpredicted the force level.

The lateral crush energies for the quarter-scale models are compared to scaled prototype results in Figures 32 and 33. The No. 10 cans (Figure 32) slightly overpredicted the crush energies, especially in the large deformation range. The crush energies of the No. 12 can models are in excellent agreement with the prototype energies (Figure 33).

Figure 34, comparing axial crush energies, shows that the agreement in crush energies in this mode is not as good as in the lateral case. However, there is still very reasonable correlation.

Figure 29. Comparison of Quarter- and Full-Scale Lateral Crush Test Results Using the No. 10 Model Cans

Figure 30. Comparison of Quarter- and Full-Scale Lateral Force-Displacement Results Using the No. 12 Model Cans

Figure 31. Comparison of Quarter- and Full-Scale Axial Force-Displacement Results Using the No. 12 Model Cans

Figure 32. Comparison of Quarter- and Full-Scale Lateral Crush Energies Using the No. 10 Model Cans

Figure 33. Comparison of Quarter- and Full-Scale Lateral Crush Energies Using the No. 12 Model Cans

Figure 34. Comparison of Quarter- and Full-Scale Axial Crush Energy

One-Eighth-Scale Models

Results for model crush forces compared to the prototype results using the No. 300 cans are presented in Figures 35 and 36. The results from the lateral tests (Figure 35) indicate that these models greatly overpredict the force level at all stages of crush. It is estimated that the model crush forces were generally high by about a factor of 2.5. The results from the axial tests (Figure 36) also indicate that the No. 300 cans greatly overpredicted the crush forces. As with the results from the quarter-scale tests, the initial buckling load was overpredicted but to a greater degree. The disagreement between model and prototype for these tests ranged roughly within a factor of 2 to 3.

Figure 35. Comparison of Eighth- and Full-Scale Lateral Force-Displacement Results

Figure 36. Comparison of Eighth- and Full-Scale Axial Force-Displacement Results

Figures 37 and 38 illustrate the crush energy results for the lateral and axial cases, respectively. The crush energy results from these models were quite high, as could have been predicted from the force results.

Figure 37. Comparison of Eighth- and Full-Scale Lateral Force-Displacement Results

Figure 38. Comparison of Eighth- and Full-Scale Axial Crush Energy

For a visual comparison, Figure 39 illustrates an eighth-, quarter-, and full-scale container crushed proportionately. Although the deformation patterns are very similar, the models cannot simulate the lid behavior.

Figure 39. Posttest Comparison of Eighth-, Quarter-, and Full-Scale Containers Tested Laterally

Discussion

The results presented in this section indicate that for lateral static conditions, the prototype drums can most accurately be modeled with No. 12 cans. These commercially available containers closely approximate not only the height and diameter of the prototype drums but also the crush force and energy absorption characteristics. The low material thickness of this model is compensated by a higher material yield stress. The No. 10 cans, while agreeing in material thickness, have a large height inaccuracy and differ more from the prototype results. The No. 300 cans closely approximate a one-eighth scale model in diameter and height. The material thickness of this can, however, is $\sim 19\%$ high. This discrepancy, coupled with the fact that the model material is much stronger, leads to large errors in crush force and energy absorption characteristics for quasi-static conditions.

Agreement in the axial test results was not as good as in the lateral tests. The largest discrepancy occurred in the peak buckling loads. All the models greatly overpredicted the buckling load of the prototype. The best results were obtained with the No. 12 can, which also produced the best results for the lateral tests. This model gives reasonably good axial results when compared to an empty, full-scale container. The comparison of test results for the sludge-filled cans did not produce results that were as good as the results for the empty containers, indicating that the discrepancy is probably in modeling the contents. The quarter-scale No. 12 can appears to be the best model for the prototype drums.

Full-Scale Impact Tests

Introduction

After the quasi-static test series was completed, a series of full-scale impact tests followed. In this series, single empty drums and drums containing heavy and light simulated sludge were dropped from heights of up to 36.5 m (120 ft). The impacts were all in the lateral mode, with achieved impact velocities ranging up to 94 km/h (58 mph). In addition to the single-drum drops, stacks of 1×8 drums containing heavy

sludge were also dropped from heights of 9.1 m (30 ft). This section describes the tests and the resulting drum deformations.

Procedure

All tests were conducted at SNL's Coyote drop test facility. The containers were suspended from a cable spanning the canyon and dropped onto an essentially rigid target consisting of a large 10-cm (4-in.)-thick armor plate backed by 250 tons of concrete. A support beam and guide wires were used to assure that the axis of the drum remained parallel to the target at impact (Figure 40). The drums were attached to a support saddle on the beam with wire rope. The support beam was then raised to the desired height and the hoist cable was severed by an explosive cutter. The support beam was then allowed to free-fall, guided by a slidertube-guide wire assembly at each end of the beam. At a height of 2.4 m (8 ft) above the target, the support beam triggered a second explosive cutter that released the drum from the support saddle. The support beam was stopped 1.8 m (6 ft) above the target (note rubber bumpers in Figure 40), while the drum continued to free-fall toward the target. In total, 17 single drums were tested. Of these, six were empty and the rest contained simulated sludge. The tests conducted and deformation results are presented in the following section.

The 1×8 stacks were drop-tested at the same facility. The 320-kg (700-lb) nominal-weight drums were held in the vertical configuration by a special frame constructed from heavy steel plate and angle plate (Figure 41). The frame was designed to keep the drums in a vertical orientation, but not to prevent vertical drum motion within the frame. During a test, the assembly was lifted so that the bottom of the frame was 9.1 m (30 ft) above the target. It was then released and allowed to free-fall, unguided, onto the target. Two of these tests were conducted using 320-kg (700-lb) nominal weight drums. In one of the tests, a block of polyurethane foam, designation FR-6703, 91 cm (36 in.) thick was placed under the frame to determine any mitigation effects.

All tests had extensive high-speed film coverage to record the container impact velocity, orientation, and dynamic response.

Figure 40. Photograph of the Drop Test Facility

Results

For the single-drum drop tests, results will be described in terms of measurements on the deformed drums and qualitative observations. The basic measurements made on the drums are illustrated in Figure 42, which also indicates the original drum dimensions. Table 5 includes the results from the 17 single-drum drops. The worst damage was observed in Test 31, which used the heaviest drum and the highest impact velocity of the drums tested with contents. The empty drums exhibited less deformation for the same impact velocity; however, the difference was surprisingly low, considering the much higher kinetic energy of the filled drums—an observation that is discussed below.

The diametral changes in the head end (the original diameter minus dimension A) ranged from 1.24 to

7.27 cm (0.49 to 2.87 in.). The largest deformation occurred in Test 31 where a 340-kg (748-lb) drum was impacted at 71.0 km/h (43.9 mph). The smallest deformation occurred in Test 4B, which was an empty drum impacted at 37.8 km/h (23.4 mph).

In some of the tests, the drum lid separated and in others it did not. Table 6 lists the diametral change, D , in the drum as well as the kinetic energy content in each test and a statement indicating whether or not the lid failed. Lid failure is defined as slippage of the C-clamp at any point in the drum circumference. As can be seen, lid failure occurred in relatively few cases. The inner plastic bag was broken only in Test 31 and remained intact in all the others. This includes drum 33 and 34 which were also dropped from the maximum height. Rupture of the inner bag resulted in a slight loss of contents from drum 31. No contents were lost from any of the other drums tested.

Table 5. Summary of Full-Scale Impact Test Results

Test No.	Weight, kg (lbs)	Drop Height m (ft)	Impact Vel. km/hr(mph)	Deformations*, cm (in)			
				A	B	C	D
25	232 (510)	6.4 (21)	38.88 (24.05)	58.57 (23.06)	55.54 (21.87)	22.86 (9.00)	27.94 (11.00)
26	312 (686)	6.4 (21)	42.03 (26.00)	57.78 (22.75)	55.24 (21.75)	22.86 (9.00)	26.67 (10.50)
27	234 (515)	9.1 (30)	47.09 (29.13)	57.15 (22.50)	54.12 (21.31)	30.48 (12.00)	30.48 (12.00)
28	320 (705)	9.1 (30)	47.25 (29.23)	56.51 (22.25)	53.97 (21.25)	27.94 (11.00)	30.48 (12.00)
29	317 (698)	13.4 (44)	57.47 (35.55)	54.91 (21.62)	53.16 (20.93)	35.56 (14.00)	35.86 (14.12)
30	319 (702)	17.4 (57)	65.10 (40.27)	54.61 (21.50)	52.37 (20.62)	39.37 (15.50)	38.73 (15.25)
31	340 (748)	20.7 (68)	70.97 (43.90)	50.80 (20.00)	50.16 (19.75)	46.35 (18.25)	42.54 (16.75)
33	308 (678)	20.7 (68)	70.97 (43.90)	54.61 (21.50)	49.83 (19.62)	35.56 (14.00)	45.72 (18.00)
34	325 (714)	20.7 (68)	70.48 (43.26)	53.16 (20.93)	50.80 (20.00)	41.91 (16.50)	35.56 (14.00)
35	312 (687)	17.4 (57)	64.95 (40.18)	55.24 (21.75)	52.37 (20.62)	39.37 (15.50)	39.37 (15.50)
36	311 (685)	13.4 (44)	58.20 (36.00)	56.18 (22.12)	53.34 (21.00)	32.38 (12.75)	33.65 (13.25)
4B	27.5 (60.5)	6.4 (21)	38.31 (23.7)	59.38 (23.38)	57.30 (22.56)	12.70 (5.00)	17.14 (6.75)
5B	27.5 (60.5)	9.1 (30)	46.07 (28.50)	58.57 (23.06)	55.88 (22.00)	19.05 (7.50)	22.86 (9.00)
1B	27.5 (60.5)	13.7 (45)	56.13 (34.72)	58.42 (23.00)	56.31 (22.19)	21.59 (8.50)	26.67 (10.50)
2B	27.7 (61.0)	18.3 (60)	67.70 (41.88)	57.78 (22.75)	55.72 (21.94)	25.40 (10.00)	30.48 (12.00)
6B	27.5 (60.5)	20.7 (68)	69.64 (43.08)	56.36 (22.19)	54.61 (21.50)	27.94 (11.00)	31.11 (12.25)
3B	27.5 (60.5)	36.6 (120)	94.19 (58.26)	54.61 (21.56)	53.97 (21.25)	34.29 (13.50)	36.83 (14.50)

*See Figure 42 for definitions.

Figure 41. Test Arrangement for the 1×8 Drop Tests

Figure 42. Original Dimensions and Idealized Deformed Shaped for the Full-Scale Drums

Table 6. Full-Scale Drum Impact Test—Diametral Deformations

Test No.	D,* Cm (in)	Lid Failure	Kinetic Energy, N-M (ft-lb)	
25	2.06 (.81)	No	13359.0	(9852.0)
26	2.84 (1.12)	No	29968.0	(15463.0)
27	3.48 (1.37)	No	19758.0	(14571.0)
28	4.19 (1.65)	No	36929.0	(20084.0)
29	5.71 (2.25)	Yes	39884.0	(29413.0)
30	6.02 (2.37)	Yes	51472.0	(37959.0)
31	9.83 (3.87)	Yes	65179.0	(48067.0)
33	6.02 (2.37)	No	59078.0	(43568.0)
34	7.47 (2.94)	Yes	60415.0	(44554.0)
35	5.38 (2.12)	No	50148.0	(36982.0)
36	4.44 (1.75)	No	40139.0	(29601.0)
4B	1.24 (0.49)	No	1536.0	(1133.0)
5B	(0.81)	No	2221.0	(1638.0)
1B	(0.87)	No	3296.0	(2431.0)
2B	(1.12)	No	4837.0	(3567.0)
6B	(1.68)	No	5076.0	(3743.0)
3B	(2.31)	No	9285.0	(6847.0)

*D is the change in diameter measured perpendicular to the flat.

To convey the magnitudes of drum deformation, some idealized deformed shapes have been sketched (Figure 43) using dimensions from Table 5. The idealized shape was obtained by averaging the deformed dimensions on both ends of the drum and keeping the drum circumference constant. These deformed shapes are typical of what was observed at the drum ends. In severe tests with heavy drums, the drum cross-sections removed from the ends assumed more of a triangular shape caused by a high pressure of the sludge material against the sides of the drum. This can clearly be seen in Figure 44, a posttest photograph of the drum from the most severe test. This figure also shows how the lid separated from the body of the drum and how the liner prevented spillage of contents. Figure 45, a bottom view of the drum, shows the buckling that occurred as well as the assumed D-shape that corresponds to Figure 43(d). Figure 46 illustrates drums from the series of empty drums impacted at different velocities. The most severely damaged drum corresponds to the test wherein the drum impacted at 94.2 km/h (58.3 mph).

Some attempts have been made to establish deformation patterns based on impact velocity and kinetic energy. Data listed in Table 5 were used to generate the plots of Figures 47 and 48. In Figure 47, the length of the flat (using the average of both ends of the drum) divided by the drum diameter was plotted against the impact velocity. Notice that the empty drums generate a fairly smooth curve. The drums filled with sludge showed more scatter, but a clear trend is still discernible. An interesting point with regard to the filled drums is that the drums with the low-density sludge, which were quite a bit lighter, caused a slightly greater deformation at the same impact velocity. Also interesting is the fact that the difference in deformation between the empty and filled drums is relatively small when considering the large differences in kinetic energy of the systems.

Figure 48 is a plot of the deformed drum diameter divided by the original diameter plotted against the impact velocity. This parameter shows a fairly clear pattern. Again, the filled drums exhibited more deformation; however, the difference between the empty and filled drums was not extremely great, especially at the lower impact velocities. Of interest is the fact that

Figure 43. Idealized Deformed Shapes for Some Full-Scale Single-Drum Drop Tests

the light sludge drums produced deformations that were virtually the same as those produced by the heavier drums. This same parameter plotted as a function of kinetic energy at impact gives fairly linear relationships for the same contents (Figure 49). The behavior is significantly different with differing contents (including no contents at all). For example, to achieve a d/D value of 0.9 (meaning that the compressed diameter is 90% of the original value) requires roughly four times more kinetic energy when the drum contains sludge than when it is empty.

Figure 44. Side View of a Full-Scale Drum Tested With Dense Sludge

Figure 45. End View of a Full-Scale Drum Tested With Dense Sludge

Figure 46. Full-Scale Drums Tested Empty

Figure 47. l/D vs Impact Velocity for Full-Scale Drums

Figure 48. d/D vs Impact Velocity for Full-Scale Single-Drum Drop Tests

Figure 49. d/D vs Kinetic Energy for Full-Scale Single-Drum Drop Tests

Two stacks of drums were also impact-tested to obtain data of drum interaction as might occur in a large cargo container. The resulting impact velocities were 48.5 km/h (30.0 mph) for the first test and 46.9 km/h (29.0 mph) for the second test, which utilized a foam block for energy mitigation. Both times the impacts were at very close to a square orientation. The first stack, which was tested without foam, remained vertical. The second stack tipped over after crushing the foam. In both tests most of the individual drums underwent rather severe deformations.

Figure 50 illustrates how the drums of the first stack compressed significantly. After test, the compressed height of the stack was $\sim 70\%$ of the undeformed height. Through measurements made of the average elevation of the drum interfaces, the idealized deformed shape of Figure 51 was constructed. The lower six drums sustained about the same deformation, $\sim 60\%$ of their original height. The seventh drum was deformed to $\sim 75\%$ of its height, and the top drum underwent a very minor, almost undetectable, deformation.

Figure 52 illustrates the drum stack from the second test just before impact and after impact in a tipped-over condition. The foam block is clearly visible before impact, as it is in its posttest, thoroughly crushed, condition. However, the condition of the drums after the impact was almost identical to the first test. Again the drums crushed to $\sim 70\%$ of their original height. Figure 53 illustrates the idealized deformed shape. The deformation of these drums was almost identical to those of the first test and very slightly more severe: The total crush was a few centimeters greater, and the top drum was slightly more deformed.

In neither of the drum stack tests was the frame significantly deformed nor did it inhibit vertical drum motion.

Discussion

The test results have shown that these containers can take very significant impacts without loss of material. These dynamic tests have also shown that the drums behave differently under dynamic conditions. The static force-displacement data described in the Full-Scale Static Crush section would indicate that the drum deformation in the dynamic impact tests would have been much greater based on the drum kinetic energy. A rough comparison can be made by considering the crush energies observed in the static tests (Figure 10). For example, the energy necessary to statically crush a sludge-filled drum 10 cm (4 in.) is

$\sim 5.65 \times 10^3 \text{ N}\cdot\text{m}$ ($50.0 \times 10^3 \text{ in}\cdot\text{lb}$). For a comparison, one can consider the drum of Test 31, which had a diametral change of 9.8 cm (3.87 in.). (Although this impact and the static crush are not the same configuration, one would expect that for a given diametral change the energy required in each case would not be greatly different.) This drum impacted at a velocity of 71.0 km/h (43.9 mph) and an impact kinetic energy of $6.5 \times 10^4 \text{ N}\cdot\text{m}$ ($5.76 \times 10^5 \text{ in}\cdot\text{lb}$)—a difference of

more than an order of magnitude in the required energy. Clearly, there is a significant dynamic effect in the system.

The data from the stack tests can be used to make a similar comparison. In this case, the comparison is more direct since the configuration of a drum being crushed by drums on both sides is closer to the static crush situation than it is in the single-drum impact case.

Figure 50. Posttest Photograph of the First 1×8 Full-Scale Drum Stack

Figure 51. Idealized Deformed Shapes for the First 1x8 Full-Scale Test

Figure 52. Photograph of the Second 1×8 Full-Scale Drum Stack

Figure 53. Idealized Deformed Shapes for the Second 1×8 Full-Scale Test

If one considers the first 1×8 drop test, where the impact velocity was 48.3 km/h (29.9 mph), the total kinetic energy of the system, excluding the frame, is 2.322×10^5 N-m (2.055×10^6 in.-lb). This energy caused the first six drums to crush an average of 21.9 cm (8.64 in.), the seventh one 9.6 cm (3.8 in.), and the eighth one a negligible amount. From Figure 10 we can calculate the total static crush energy to be $\sim 6.667 \times 10^4$ N-m (5.9×10^5 in.-lb). The dynamic case then required more energy by a factor of ~ 3.5 . Clearly, this configuration also shows the presence of a strong dynamic effect.

The results of Figure 49 indicate that aside from kinetic energy considerations, the contents have a significant effect on drum behavior. These results indicate that the light sludge has a different effect than the heavy sludge, although the amount of data is very limited for the light sludge. Clearly then, the drum deformation cannot be predicted by considering only the kinetic energy of the system. The drum contents are quite important because different materials absorb varying amounts of energy.

Scale Model Impact Tests

Introduction

As with the full-scale experiments, a large number of single drum drop experiments were conducted with both one-eighth and quarter-scale models. The quarter-scale models used the No. 12 cans and, as before, all eighth-scale experiments used No. 300 cans. In total, 23 quarter-scale single-can drop tests were performed, and 29 tests were conducted with the eighth-scale cans. Tests with 1×8 stacks were also conducted with quarter-scale cans at impact velocities ranging from 40 to 48 km/h (25 to 30 mph). Eleven of these tests were conducted, some including foam blocks to test the impact mitigation at the bottom of the stack.

Procedure

The procedure used with the scale-model tests was basically the same as that used with the full-scale hardware. However, because of difficulties encountered in obtaining normal (square) impacts with the models, cables were used to guide the models into the target (Figure 54).

Eyelets were fastened to the containers through which taut cables leading to the target were passed. This system worked quite well, and it did not appear that the guide system influenced the response of the container. The same procedure was used with the 1×8 stacks, as is illustrated in Figure 55, which shows a suspended model system at the test site. In total, 11 of these tests were conducted at impact velocities ranging from 40 to 50 km/h (25 to 31 mph). The first tests were conducted with cans containing combustible waste; the following 10 tests were of cans containing the heavy sludge material. Eight tests had 23-cm (9-in.)-thick foam blocks. Measurements made of the deformed drum stacks were similar to those for the full-scale tests.

Results of the scale-model tests are presented in the next section. These will later be compared to the full-scale results.

Results

Table 7 lists results of the quarter-scale tests using the same measurements that were made on the full-scale drums. Tests to simulate drums filled with heavy sludge, light sludge, and combustible waste were conducted. The impact velocities ranged from ~ 39 to 73 km/h (24 to 45 mph). The containers filled with the dense sludge exhibited the largest deformations and those filled with combustible waste the least. Figure 56 illustrates the quarter-scale model tested under the most severe conditions in its posttest configuration. In this figure, the guideline and eyelets also can be seen clearly. The remainder of the quarter-scale cans underwent similar deformations but to a lesser degree.

Figure 54. Test Arrangement for the Scale-Model Tests

Figure 55. Test Arrangement for the 1×8 Model Drop Tests

Table 7. Summary of Quarter-Scale Drop Test Results

Test No.	Weight, kg (lbs)	Drop Height, m (ft)	Impact Vel. km/hr (mph)	Deformations*, cm (in)			
				A	B	C	D
43	4.940 (10.868)	7.01 (23.0)	40.61 (25.12)	14.16 (5.575)	14.37 (5.660)	11.11 (4.375)	9.68 (3.812)
44	4.984 (10.964)	7.01 (23.0)	42.45 (26.26)	13.90 (5.475)	14.47 (5.700)	11.43 (4.500)	8.89 (3.500)
45	1.432 (3.150)	7.01 (23.0)	41.04 (25.39)	15.02 (5.915)	15.02 (5.915)	6.85 (2.700)	6.35 (2.500)
46	1.431 (3.148)	7.01 (23.0)	38.71 (23.95)	14.98 (5.900)	14.98 (5.900)	6.60 (2.600)	7.36 (2.900)
47	3.545 (7.799)	7.01 (23.0)	41.17 (25.47)	14.56 (5.734)	14.56 (5.735)	7.62 (3.000)	8.63 (3.400)
49	3.552 (7.814)	7.83 (25.7)	43.89 (27.15)	14.42 (5.680)	14.51 (5.713)	9.49 (3.740)	9.34 (3.678)
50	4.984 (10.964)	7.83 (25.7)	44.13 (27.30)	14.43 (5.684)	14.23 (5.603)	9.65 (3.800)	11.17 (4.400)
48	3.554 (7.818)	7.83 (25.7)	44.79 (27.71)	14.60 (5.750)	14.23 (5.605)	8.61 (3.390)	7.87 (3.100)
53	1.448 (3.185)	7.83 (25.7)	43.87 (27.14)	14.98 (5.900)	15.03 (5.920)	6.88 (2.710)	6.88 (2.710)
51	5.010 (11.022)	7.83 (25.7)	44.63 (27.61)	14.41 (5.675)	14.19 (5.590)	8.87 (3.495)	9.84 (3.875)
52	1.448 (3.185)	7.83 (25.7)	43.87 (27.14)	15.03 (5.920)	14.98 (5.900)	6.50 (2.560)	6.29 (2.480)
243	1.427 (3.139)	13.25 (43.5)	53.64 (33.18)	14.75 (5.810)	14.81 (5.832)	7.94 (3.127)	7.76 (3.058)
244	1.423 (3.131)	13.25 (43.5)	54.90 (33.96)	14.81 (5.832)	14.70 (5.790)	7.83 (3.084)	8.12 (3.199)
245	4.975 (10.945)	13.25 (43.5)	55.77 (34.50)	13.97 (5.500)	14.21 (5.595)	10.98 (4.325)	9.36 (3.686)
246	4.922 (10.828)	13.25 (43.5)	57.48 (35.56)	13.77 (5.422)	13.78 (5.429)	11.70 (4.607)	10.90 (4.292)
247	4.972 (10.938)	17.22 (56.5)	65.83 (40.72)	13.42 (5.286)	13.59 (5.353)	12.04 (4.743)	11.35 (4.472)
248	4.955 (10.901)	17.22 (56.5)	65.05 (40.24)	13.45 (5.298)	13.46 (5.303)	12.24 (4.822)	11.74 (4.623)
249	1.435 (3.157)	17.22 (56.5)	66.21 (40.96)	14.62 (5.757)	14.66 (5.773)	8.60 (3.387)	8.19 (3.227)
250	1.436 (3.159)	17.22 (56.6)	61.46 (38.02)	14.64 (5.765)	14.62 (5.758)	8.25 (3.250)	8.49 (3.344)
251	1.431 (3.148)	21.79 (71.5)	66.46 (41.11)	14.55 (5.732)	14.59 (5.748)	8.68 (3.419)	8.39 (3.304)
252	1.426 (3.137)	21.79 (71.5)	69.43 (42.95)	14.56 (5.736)	14.56 (5.734)	8.82 (3.471)	8.29 (3.263)
253	4.967 (10.927)	21.79 (71.5)	74.60 (46.15)	13.33 (5.249)	13.42 (5.284)	12.49 (4.919)	12.45 (4.905)
254	4.947 (10.883)	21.79 (71.5)	72.10 (44.60)	13.39 (5.275)	13.39 (5.275)	12.82 (5.050)	11.92 (4.695)

*See Figure 42 for definitions.

Figure 56. End View of a Quarter-Scale Model Drop-Tested With Dense Sludge

Figure 57 illustrates a plot of the ℓ/D parameter as a function of impact velocity. As can be seen, the heavy sludge models clearly deformed more than the models filled with the light combustible waste. The deformations for the light sludge fell somewhere in between. Similar results are observed when the d/D parameter (Figure 58) is examined. With this parameter, however, there was less apparent difference between the heavy and light sludge-filled models. The models filled with combustible waste behaved almost like the full-scale drums that were tested empty. The trends exhibited by the quarter-scale model deformations appear very similar to those of the full-scale

container; detailed comparisons will be made later in the report.

Table 8 includes results for the one-eighth scale single-can drop tests. Again, the same measurements were made on the models. As with the quarter-scale models, these were tested with two types of simulated sludge and with combustible waste to simulate full-scale drums with nominal weights of 320, 230, and 90 kg (700, 500, and 200 lb).

The impact velocities for these models ranged from ~ 39 to 65 km/h (24 to 40 mph).

Table 8. Summary of One-Eighth Scale Drop Test Results

Test No.	Weight, kg (lbs)	Drop Height, m (ft)	Impact Vel. km/hr (mph)	Deformations*, cm (in)			
				A	B	C	D
49	623.0 (1.370)	7.28 (23.91)	41.54 (25.70)	7.122 (2.804)	7.066 (2.782)	4.165 (1.640)	3.888 (1.531)
53	445.0 (0.979)	7.28 (23.91)	42.03 (26.00)	7.170 (2.823)	7.264 (2.860)	3.586 (1.412)	3.175 (1.250)
50	620.0 (1.364)	8.00 (26.25)	46.88 (29.00)	7.013 (2.761)	6.911 (2.721)	4.707 (1.735)	4.412 (1.737)
54	444.0 (0.976)	8.00 (26.25)	46.88 (29.00)	7.191 (2.831)	7.086 (2.790)	3.507 (1.381)	3.914 (1.541)
51	178.0 (0.391)	8.00 (26.25)	49.30 (30.50)	7.313 (2.879)	7.266 (2.861)	2.971 (1.170)	3.070 (1.209)
52	181.0 (0.398)	8.00 (26.25)	47.69 (29.50)	7.264 (2.860)	7.259 (2.858)	3.302 (1.300)	3.302 (1.300)
55	447.0 (0.983)	8.00 (26.25)	45.75 (28.30)	7.201 (2.835)	7.099 (2.795)	3.530 (1.390)	3.708 (1.460)
56	622.0 (1.368)	8.00 (26.25)	44.13 (27.30)	7.081 (2.788)	7.084 (2.789)	3.886 (1.530)	3.886 (1.530)
479	184.0 (0.404)	7.01 (23.00)	43.13 (26.68)	7.157 (2.850)	7.150 (2.815)	3.208 (1.263)	3.065 (1.207)
480	187.0 (0.411)	7.01 (23.00)	45.88 (28.38)	7.239 (2.850)	7.226 (2.845)	3.235 (1.274)	2.821 (1.111)
481	452.0 (0.994)	7.01 (23.00)	44.36 (27.74)	7.094 (2.793)	7.061 (2.780)	3.756 (1.479)	3.512 (1.383)
482	452.0 (0.994)	7.01 (23.00)	44.65 (27.62)	4.579 (2.803)	4.442 (2.749)	3.436 (1.353)	3.987 (1.570)
483	626.0 (1.377)	7.01 (23.00)	46.72 (28.90)	6.982 (2.749)	6.995 (2.754)	4.216 (1.660)	4.241 (1.670)
484	636.0 (1.399)	7.01 (23.00)	42.48 (26.28)	6.946 (2.735)	7.038 (2.771)	4.147 (1.633)	3.690 (1.453)
765	621.0 (1.366)	7.31 (24.00)	40.95 (25.33)	6.969 (2.744)	7.051 (2.766)	4.084 (1.608)	3.837 (1.511)

Table 8 (cont)

Test No.	Weight, kg (lbs)	Drop Height, m (ft)	Impact Vel. km/hr (mph)	Deformations*, cm (in)			
				A	B	C	D
766	618.0 (1.359)	7.31 (24.00)	41.53 (25.69)	6.982 (2.749)	6.987 (2.751)	4.015 (1.581)	4.008 (1.578)
767	185.0 (0.407)	7.31 (24.00)	39.73 (24.58)	7.272 (2.863)	7.216 (2.841)	2.875 (1.132)	2.484 (0.978)
768	182.0 (0.400)	7.31 (24.00)	39.73 (24.58)	7.241 (2.851)	7.264 (2.860)	2.364 (0.931)	2.473 (0.974)
769	622 (1.368)	9.29 (30.50)	46.65 (28.86)	6.898 (2.716)	6.962 (2.741)	4.366 (1.719)	3.716 (1.463)
770	619 (1.361)	9.29 (30.50)	46.09 (28.51)	6.901 (2.717)	6.949 (2.736)	4.310 (1.697)	3.916 (1.542)
771	180 (0.396)	9.29 (30.50)	44.91 (27.78)	7.226 (2.845)	7.216 (2.841)	2.921 (1.150)	2.700 (1.063)
772	184 (0.404)	9.29 (30.50)	44.84 (27.74)	7.239 (2.850)	7.193 (2.832)	2.697 (1.062)	2.748 (1.082)
773	620.0 (1.364)	14.63 (48.00)	58.81 (36.38)	6.774 (2.667)	6.794 (2.675)	4.373 (1.722)	4.206 (1.656)
774	620.0 (1.364)	14.63 (48.00)	56.50 (34.95)	6.781 (2.670)	6.680 (2.630)	4.526 (1.782)	4.495 (1.770)
775	187.0 (0.411)	14.63 (48.00)	52.62 (32.55)	7.160 (2.819)	7.157 (2.818)	3.154 (1.242)	3.302 (1.300)
776	185.0 (0.407)	14.63 (48.00)	51.28 (31.72)	7.180 (2.827)	7.175 (2.825)	3.012 (1.186)	3.068 (1.208)
777	610.0 (1.342)	17.67 (58.00)	63.84 (39.49)	6.723 (2.647)	6.705 (2.640)	4.978 (1.960)	4.562 (1.769)
778	620.0 (1.364)	17.67 (58.00)	64.06 (39.63)	6.799 (2.677)	6.662 (2.623)	4.706 (1.853)	4.856 (1.912)
779	182.0 (0.400)	17.67 (58.00)	58.11 (35.95)	7.152 (2.816)	7.152 (2.816)	3.368 (1.326)	2.976 (1.172)

*See Figure 42 for definitions.

Figures 59 and 60 are the deformation results for the eighth-scale tests plotted in the same fashion as the data for the quarter- and full-scale tests. Again the ℓ/D parameter showed more scatter, but the dense sludge drums again exhibited significantly more deformation than the models filled with combustible waste and slightly more than the light-sludge-filled models. The d/D parameter results (Figure 60) were very similar to those obtained with the quarter-scale tests. Again, this parameter showed considerably less scatter than the ℓ/D parameter.

Figure 61 illustrates a typical result of the 1×8 drum stack tests. This particular test was conducted with a foam block attached to the frame. In this case, the foam block was partially compressed and pieces of foam had spalled. Damage to the foam blocks used in the tests ranged from very slight to total disintegration. In all tests, measurements of the posttest can interfaces were made at two points for each location (Figure 62) and averaged. The results of the 11 tests conducted are tabulated in Table 9 and schematically illustrated in Figure 63. Only the results of Test 1 differed significantly, because the first test was conducted with very light (combustible waste) cans and was impacted at a lower velocity. In all subsequent tests conducted with the dense waste sludge, the stacks were compressed to heights between 79 and 88 cm (31 and 34.5 in.), which is about 63% to 79% of their original height. The impact velocities for these drum stacks ranged from 42.3 to 49.9 km/h (26.2 to 30.9 mph). In all cases, the top drum was almost completely undamaged. The amounts of deformation imparted to the rest of the drums in the stack are illustrated in Figure 63. In general, the first six drums in the stack were deformed to $\sim 50\%$ of their original diameter. The seventh drum in the stack underwent deformations that were somewhat smaller, with a deformed diameter $\sim 75\%$ of the original dimension.

A preliminary examination of these results indicates that insertion of a foam block under the stack to mitigate the impact did not significantly affect the drum response. This perhaps can be better demonstrated by analyzing the deformed drum stacks in terms of impact velocity. These results have been arranged as a function of impact velocity in Figure 64. These data indicate that encasing (constraining) the foam with plywood slightly influenced the results as Tests 8, 9, and 10 showed a trend of less deformation than Tests 6 and 11 which were done with an unconstrained stiff foam and with no foam at all. Tests 4, 5, and 7, conducted with basically the same foam blocks, show an unexpected trend of less deformation with increasing impact velocity, which is not realistic. Further comments regarding these data are made in the Discussion section.

Discussion

The single-drum drop tests with the two sizes of scale models produced very comparable results, especially when deformation is examined in terms of the d/D parameter. These data have been assembled in Figure 65, including results from both the eighth- and quarter-scale tests. As can be seen, when similar tests are compared, the results agreed very well. The cans filled with combustible waste produced diametral deformations that ranged up to $\sim 5\%$ at impact velocities up to ~ 65 km/h (40 mph). The dense sludge cans deformed substantially more, with deformations ranging up to $\sim 12\%$ at the same impact velocities. Figure 65 also reveals that, in terms of this parameter, the difference between the eighth- and the quarter-scale results was quite small—of the order of 3%.

The ℓ/D parameter (Figures 57 and 59) produced results that had more scatter than the d/D parameter. The assembled data for all the scale-model single-can drop tests in terms of the ℓ/D parameter is shown in Figure 66. Here differences between the eighth- and quarter-scale were much more pronounced, with the quarter-scale models exhibiting proportionately larger flattened areas.

Some of the scatter in the ℓ/D data is certainly attributable to difficulties in accurately measuring the length of the flat, ℓ . In most cases, there was no pronounced line where the flat intersected the cylindrical portion of the can and considerable judgment had to be exercised in making the measurement. Considering this problem, the d/D parameter is probably a better indicator of damage.

The 1×8 can stack drops, performed with quarter-scale cans, produced results which were very similar to those observed with the full-scale tests, and some quantitative comparisons will be made in a later section. The 1×8 tests indicated that the inclusion of a 23-cm (9-in.) foam block on the end of the model drumstack did not significantly affect the results (Figures 63 or 64). The reason for the minimum or nil effect of the foam is that the foam "locked up" too quickly to prevent crush-up of the drums. To significantly affect drum damage, a softer foam would have to be used, and to provide the necessary energy absorption capability, the thickness of the foam block would have to be increased to an impractical dimension.

The next section will quantitatively compare full-scale and scale-model results.

Figure 57. l/D vs Impact Velocity for the Quarter-Scale Models

Figure 58. d/D vs Impact Velocity for the Quarter-Scale Models

Figure 59. l/D vs Impact Velocity for the Eighth-Scale Models

Figure 60. d/D vs Impact Velocity for the Eighth-Scale Models

Figure 61. Posttest Condition of a Quarter-Scale 1×8 Stack

Figure 62. Illustrations of Measurements Made on the 1×8 Model Drum Stacks

Table 9. Results for the 1×8 Quarter-Scale Drop Tests

TEST NO.	DEFORMED DIMENSIONS, cm (in)								IMPACT VEL. km/hr (mph)	TOTAL CAN WEIGHT kg (lbs)	FOAM TYPE	FOAM CRUSH STRENGTH MPa (Psi)
	A	B	C	D	E	F	G	H				
1	12.06 (4.75)	24.13 (9.50)	37.46 (14.75)	51.43 (20.25)	65.40 (25.75)	80.01 (31.50)	95.25 (37.50)	110.49 (43.50)	40.2 (24.90)	11.44 (25.17)	None	--
2	8.48 (3.34)	16.51 (6.50)	24.13 (9.50)	34.29 (13.50)	43.96 (17.31)	55.40 (21.81)	70.64 (27.81)	86.03 (33.87)	42.3 (26.18)	39.81 (87.58)	None	--
3	8.89 (3.50)	16.99 (6.69)	25.70 (10.12)	35.08 (13.81)	44.75 (17.62)	56.82 (22.37)	71.12 (28.00)	86.51 (34.06)	47.0 (29.11)	39.83 (87.63)	6602	.172 (25)
4	9.37 (3.69)	17.45 (6.87)	25.22 (9.93)	34.29 (13.50)	43.00 (16.93)	54.12 (21.31)	67.77 (26.68)	83.00 (32.68)	44.6 (28.83)	39.82 (87.61)	6703	.344 (50)
5	9.75 (3.84)	18.64 (7.34)	28.47 (11.21)	38.58 (15.19)	48.71 (19.18)	60.15 (23.68)	73.66 (29.00)	89.05 (35.06)	47.4 (29.33)	39.82 (87.61)	6703	.344 (50)
6	9.98 (3.93)	18.24 (7.18)	25.55 (10.06)	34.29 (13.50)	42.70 (16.81)	52.22 (20.56)	64.77 (25.50)	80.01 (31.50)	47.6 (29.48)	39.90 (87.78)	6704	.689 (100)
7	8.81 (3.47)	16.58 (6.53)	25.25 (9.94)	34.29 (13.50)	44.60 (17.56)	56.41 (22.21)	70.48 (27.75)	86.77 (34.16)	47.2 (29.18)	39.79 (87.53)	9503	.344 (50)
8	10.39 (4.09)	18.49 (7.28)	26.67 (10.50)	35.86 (14.12)	44.91 (17.68)	55.88 (22.00)	68.83 (27.10)	84.91 (33.43)	48.7 (30.14)	39.90 (87.80)	9505*	.689 (100)
9	9.60 (3.78)	18.41 (7.25)	26.90 (10.59)	35.38 (13.93)	44.68 (17.59)	56.18 (22.12)	70.08 (27.59)	85.90 (33.82)	48.1 (29.77)	39.88 (87.74)	6703*	.344 (50)
10	9.83 (3.87)	17.60 (6.93)	25.47 (10.03)	34.29 (13.50)	42.93 (16.90)	53.49 (21.06)	66.67 (26.25)	81.99 (32.28)	49.9 (30.91)	39.83 (87.63)	9503*	.344 (50)
11	8.96 (3.53)	17.22 (6.78)	24.13 (9.50)	32.69 (12.87)	41.10 (16.18)	50.39 (19.84)	63.32 (24.93)	78.74 (31.00)	48.2 (29.8)	39.82 (87.60)	None	--

*Plywood encased

Figure 63. Deformed Drum Stack Heights for the 1x8 Quarter-Scale Impact Tests

Figure 64. Drum Stack Height vs Impact Velocity for the 1x8 Quarter-Scale Impact Tests

Figure 65. d/D vs Impact Velocity for the Eighth- and Quarter-Scale Can Drop Tests

Figure 66. l/D vs Impact Velocity for the Eighth- and Quarter-Scale Single-Can Drop Tests

Comparison of Prototype and Scale-Model Impact Test Results

Introduction

A review and comparison of the impact test results of the full-scale and the subscale tests, for both the quarter- and eighth-scale models, are contained in this section. The comparisons will include both the single container and the 1×8 stack drop tests. The principal bases for comparisons will be the d/D and ℓ/D parameter results that were presented in previous sections.

Quarter-Scale Models

The d/D parameter indicated excellent correlation between the quarter- and the full-scale single drum impact tests. The results for containers filled with dense sludge will be reviewed first. Figure 67 includes the results for both the full- and quarter-scale tests. At impact velocities up to 18 m/s (59 ft/s) (40 mph) it is estimated that the results agreed within $\sim 3\%$ to 4% . At higher velocities, the scatter was only slightly greater.

Figure 68 compares the empty full-scale drums to models filled with combustible waste, and includes results of full- and quarter-scale light sludge drums.

Figure 67. Comparison of d/D vs Impact Velocity for the Dense-Sludge-Filled Quarter- and Full-Scale Single-Drum Drop Tests

The results for the models filled with combustible waste agreed very well (within $\sim 2\%$) with the empty full-scale drum tests. Fewer data points were available for the light sludge tests. However, the available data correlated extremely well (within $\sim 2\%$).

Figures 69 and 70 compare results for the same series of tests in terms of the ℓ/D parameter. These measurements produced considerably more scatter. In all cases, the value of the ℓ/D parameter was higher for the models, indicating that in general the models developed larger flats upon impact than the full-scale containers.

Visual inspection of the models and prototypes also indicated great similarity in results (see especially Figures 45 and 56, which are photographs of full- and quarter-scale models filled with sludge and impacted at a high velocity). The damage looks very similar—even down to the wrinkle patterns on the container bottom.

The prototype and scale-model results for the 1×8 stack tests also correlated very well. Figures 50 and 61 reveal qualitative similarities of drum deformations. Figure 71 gives a more quantitative comparison. Here the quarter-scale results of Figure 63 have been normalized with respect to the original drum stack height and replotted with the full-scale results added at the end. Agreement between the model data and the full-scale results was quite good, the average of the model results for the deformed drum stack heights deviating from the full-scale results by no more than $\sim 2\%$.

Figure 68. Comparison of d/D vs Impact Velocity for Quarter- and Full-Scale Drums

Figure 69. Comparison of ℓ/D vs Impact Velocity for Quarter- and Full-Scale Drums

Figure 70. Comparison of ℓ/D vs Impact Velocity for Quarter-Scale Combustible Waste and Full-Scale Empty Drums

Figure 71. Normalized Stack Height for the Quarter- and Full-Scale 1×8 Drum Stack Drop Tests

One-Eighth-Scale Models

In this section, the eighth-scale test results are compared to the full-scale results in a manner similar to the quarter-scale test comparisons. Figure 72 illustrates that the eighth-scale results for the d/D parameter correlated well with those for the full-scale dense sludge containers. Figure 73 illustrates the d/D parameter results for empty full-scale cans and eighth-scale models filled with combustible waste. Also included in this figure are results for full-scale and model containers filled with light sludge. As with the quarter-scale tests, the eighth-scale models containing combustible waste agreed very well with the full-scale empty drums. There was also very good agreement between the light sludge containers.

Figures 74 and 75 compare the ℓ/D parameter for the one-eighth-scale data with full-scale results. Again, the ℓ/D parameters contained more scatter than the d/D parameter, as was also observed with the quarter-scale cans.

Figure 76 shows typical posttest conditions for the eighth-, quarter-, and full-scale containers after drop-testing.

Figure 72. Comparison of d/D vs Impact Velocity for Eighth- and Full-Scale Dense-Sludge-Filled Single-Drum Drop Tests

Figure 73. Comparison of d/D vs Impact Velocity for Eighth- and Full-Scale Single-Drum Drop Tests

Figure 74. Comparison of l/D vs Impact Velocity for Eighth- and Full-Scale Single-Drum Drop Tests

Figure 75. Comparison of l/D vs Impact Velocity for Combustible-Waste-Filled Eighth-Scale and Empty Full-Scale Drums

Figure 76. Photograph of Eighth-, Quarter-, and Full-Scale Containers After Drop-Testing

Computer Analysis of Impact Tests

Introduction

This section describes computer models that were formulated to predict the response of low-level waste drums to impact environments. The models incorporated data from the full-scale static crush tests described previously. Results of the computer simulations are presented in this section and later compared to results of actual full-scale and scale-model impact tests.

Two different computer programs (codes) representing two different approaches were used for the computer analyses. First, a lumped-parameter modeling approach was tried and then a dynamic finite-element method was used. Both of these models utilized previously existing general purpose SNL codes.

The lumped-parameter model utilized the program SHOCK,³ which solves the second-order differential equations of motion associated with a spring-mass system. The spring elements can be nonlinear and can incorporate hysteresis effects. This feature makes the code usable for simulating large plastic deformations. Construction of a SHOCK model is relatively fast, requiring a minimum amount of setup and computer time. Deformation information provided by this model, however, is limited to the radial crush of each drum in a 1×8 array, impacting at a given velocity. As presently configured, this model cannot be used to analyze a single drum impact.

The second computer code employed was HONDO II,⁴ a two-dimensional, dynamic, finite-element code for predicting the large deformation response of solids. The capabilities of this code include a sliding interface option that allows the modeling of either single- or multiple-drum arrays. This code also has the feature of being able to provide a visual representation of the deformed drum shapes when coupled with a post-processor. It was used to analyze both single- and multiple-drum drop tests.

Lumped-Parameter Model

Model Description

The lumped-parameter model was constructed by first assuming that the spring-mass representation of each drum remained the same regardless of its position in the stack. It was then assumed that the behavior of each drum in the stack was a function of the mass and stiffness of the drum and its position in the

stack. With these assumptions and the data obtained from the full-scale static crush tests, a lumped-parameter model of the system was constructed. Figure 77 shows a schematic representation of the model of an eight-high stack of drums. Each container was modeled with two couplings representing the stiffness of the drum, and a coupling representing the stiffness of the contents. Also, the mass in the model was separated into the mass of the drum and the mass of the contents. This "unit cell" was repeated for each drum in the stack being modeled. Details of the derivations of the various model parameter values are provided in Appendix A.

Figure 77. Schematic Illustration of the Lumped-Parameter Model for a 1×8 Stack

The output from the SHOCK code includes plots of displacement-time, velocity-time, and acceleration-time for each mass. The output also includes the load in each coupling and coupling lengths as functions of time. These data are then interpreted, in terms of drum damage, by the analyst. The SHOCK results were used as a measure of maximum crush. The static crush tests had shown that the drums exhibit ~ 3.8 cm (1.5 in.) of springback after crush. This was subtracted from the SHOCK results for drums exhibiting large deformations before plotting the data.

Results

Figure 78 illustrates deformation results for a stack of eight drums dropped from 9 m (30 ft). The model predicted that the first six drums would deform approximately the same amount ($\sim 45\%$ on the diameter) and that the seventh drum from the bottom would deform only about half this amount. As described previously, springback was subtracted from drums undergoing large deformation. In Figure 78, 3.8 cm (1.5 in.) was subtracted from the calculated deformation for the first seven drums before plotting. This lumped-parameter model predicted no damage for the top drum in the stack.

Figure 78. Lumped-Parameter Model Results for a 1×8 Drum Stack 9-m Drop Test

Finite Element Model

Model Description

To simplify the drum impact problem, drums were modeled as solid uniform cylinders and some average material properties were determined. The static crush data were used for determining the drum properties by selecting a typical force-displacement curve for a drum. HONDO II requires that Young's modulus, yield stress, hardening modulus, Poisson's ratio, and material density be input to the model. These parameters were estimated for the model by the method detailed in Appendix B.

The model was tested by first using it to simulate a static crush test. A schematic of this model is shown in Figure 79. The loading was applied as a pressure to the top surface of the platen, which was modeled as a very rigid plate. The applied pressure was allowed to vary with time as a ramp function going from 0 to 16 N/cm² (0 to 23.3 psi) in 3.75 s. The peak pressure was

equivalent to a load of 111,000 N (25,000 lb) on the drum (see Appendix B).

Figure 79. Finite-Element Mesh for a Drum Crush Analysis

The same basic model was then used in a 1×8 drop test configuration. It was used to simulate impact velocities corresponding to drop heights of 6.4 and 9.1 m (21 and 30 ft). Figure 80 shows the finite-element model for the 1×8 configuration. The impact was simulated by giving all the nodes in the model an initial velocity of either 11.3 or 13.4 m/s (441 or 527 in./s) in the direction of the rigid boundary. Each drum face was treated as a sliding interface, allowing forces to be transmitted between drum surfaces.

Results

The results of static crush analysis indicated a peak deflection of about 20.3 cm (8 in.) as indicated in Figure 81, which shows the deformed mesh. This deformation is within the range of the observed behavior in the static crush tests. The single-drum model therefore gave a reasonable value for the amount of deformation that a drum would sustain, given a slowly applied load of 11.4×10^4 N (25,000 lb).

ACTUAL TEST CONFIGURATION

Figure 80. Finite-Element Mesh for a 1x8 Drum Stack Simulation

Figure 81. Deformed Mesh From the Static Crush Finite-Element Analysis

Figure 82 shows the results for the analyses of the 1x8 drop tests; analyses indicate that in both cases the drum stacks would be severely crushed. For the 6.4-m (21-ft) drop, the HONDO results indicate that the drum stack is compacted ~40% and ~45% when dropped from 9 m (30 ft). The results also indicate that the second through the seventh drums are crushed by about the same amount. The first drum in the stack crushed ~25% more than the middle drums, and the top drum crushed only a slight amount.

Figure 82. Deformed Finite-Element Meshes for a 6.4-m (21-ft) and a 9.1-m (30-ft) Drum Stack Drop Tests

Comparison of Computer Analyses to Test Results

To gain an overall picture, the results obtained using the two analyses techniques described above are compared to results from a full-scale and quarter-scale 1x8 drop test. The diametral crush of each drum is plotted as a function of drum location in the stack.

The drum crush, as predicted by analysis and obtained from full- and quarter-scale drop tests of 1x8 arrays, is plotted against the drum position in the stack in Figure 83. (The drum positions are numbered consecutively from 1 to 8 starting at the bottom.) The figure indicates that the lumped-parameter model closely predicts the crush of all eight drums. The finite-element model, on the other hand, overpredicts

the damage to the first, seventh, and eighth drums, but is reasonably close for those numbered two through six. The difference in the two models arises for two reasons.

Figure 83. Comparison of Computer Analysis and Test Results for a 1x8, 9-m Drum Stack Drop Test

First, there are three sections of the drum force-deflection curve (or stress-strain curve for the HONDO model), which must be modeled to reasonably simulate the drum response. These include the section prior to buckling of the lid, the portion between lid buckling and the point at which the contents begins to carry part of the load ("lock up"), and the region after lock up. While all three portions of the curve can be included in the lumped mass model, only the first two can be used in the finite-element model. The deflection of the first drum is consequently over-predicted by the latter model.

The second reason for the discrepancies in the model predictions is that the drums respond differently in an impact environment than they do in a crush environment.

In an impact, only those portions of the drum that are near the target surface are affected by inertial loads from the contents. The rest of the drum experiences inertial loads due to its own weight only. However, because these are small, the diametrical reduction of the drum is small. On the other hand, the entire drum structure is subjected to large loads in a crush environment. Although a solid uniform cylinder can be made to simulate the drum response to one or the other of these environments, it is not possible to simulate both with the same model. If the cylinder is made to simulate the drum response to crush, it will be too soft in an impact. On the other hand, if the cylinder simulates the drum response in an impact, it will be too stiff when subjected to a crush environment. The material properties for the cylinder of the

finite-element model were based on a crush environment (see Appendix B). Therefore, near the top of the stack (drums 7 and 8) where the environment is more like that of impact than a crush, the cylinder is too soft and the damage is overpredicted. The lumped-parameter model can more appropriately account for these effects and more closely simulate the drum response throughout the stack.

While the drums can be more accurately modeled using a more detailed finite-element analysis, doing so is very expensive because of the thin sheet metal construction of the waste containers. The additional expense of further refining the finite-element model is not really justified, since the two models discussed herein would be sufficient for most applications. For example, the existing model can be used in a finite-element analysis to assess the effects of the drums on a transport vehicle. In addition, one can obtain reasonably accurate predictions of drum crush by utilizing the lumped-parameter model, which has been shown to closely parallel full-scale results.

Discussion

It is perhaps appropriate to discuss repeatability of the test results to give more meaning to the comparisons between analytical and test results. Several methods of measuring damage to the drums were attempted, but the most useful was determining the diametral crush resulting from the impact. However, because the drums have three protruding ribs and a clamp ring, they tend to randomly slide relative to each other when drop-tested in stacks or arrays. Hence some of the drums would have the stiff lid and clamp ring pushing against the flexible bodies of adjacent drums. This causes the damage to be very irregular, so the technician must determine an average crush. This, in turn, is a significant source of error, making the measured crush vary from test to test by several centimeters. Therefore, the analytical predictions cannot reasonably be expected to agree with test results closer than to within 3 to 4 cm (1 to 1.5 in.).

Conclusion

In lateral crush testing, full-scale drums took a peak force of ~79,900 N (18,000 lb) before lid separation occurred. After lid separation, the force typically dropped ~22,000 N (5000 lb), and subsequent behavior (including stiffening of the drum) was dependent on contents. The interior drum linings prevented spillage of material and no contents were lost in any of the tests.

Axially, the full-scale drums took a peak force of $\sim 88,800$ N (20,000 lb) to initiate buckling. Empty drums crushed at fairly constant force levels, while sludge-filled drums stiffened up considerably. Lid separation was not observed in the static axial tests.

The quarter-scale No. 12 cans closely simulated the full-scale containers in the static lateral crush tests. In these same tests, the No. 10 can models simulated the full-scale drums well in early stages of crush; however, they proved to be too stiff at higher deformations. The eighth-scale models (No. 300 cans) were too stiff, by about a factor of 2, in these same tests.

In the axial static tests, all the can models greatly overpredicted the peak buckling force. Aside from the initial force peak, however, the No. 12 quarter-scale model predicted the crush level quite well for empty full-scale drums. The agreement was not good for sludge-filled containers; however, this is probably due to inaccuracies in modeling the contents.

The quarter-scale No. 12 can is considered a very good model for the full-scale containers in static tests. The second quarter-scale model (the No. 10 can) is less accurate, but still judged acceptable. The eighth-scale, No. 300 cans, were too stiff by about a factor of 2 in both the lateral and axial static directions. The single-container impact tests indicated that the heavy drums filled with dense sludge deformed the most. With the most severe test impact velocity, which was 19.8 m/s (65 ft/s), the d/D parameters (compressed diameter/original diameter) went as low as 0.85, meaning that the drums underwent a diametral deformation of 15%. This parameter was found to be the most consistent for comparing damage demonstrating much less scatter than the ℓ/D parameter (length of flat/original diameter). That drum contents greatly influenced the results of the impact tests was demonstrated by the fact that drum damage was found to be not only a function of the kinetic energy but of the contents as well. When drums with similar contents were compared, however, it was found that the d/D parameter was linear with kinetic energy.

The full-scale drum stack tests indicated that a 9-m (30-ft) drop with sludge-filled drums caused the stack to compress to $\sim 70\%$ of its original height. In these tests, the first six drums compressed to $\sim 65\%$ of their original diameter, the seventh drum to $\sim 85\%$, and the top drum sustained only a very minor deformation. The addition of a 1-m (3-ft) rigid foam block to the bottom of the stack made an insignificant difference in results.

Agreement between the scale models and the full-scale single drum impact tests was excellent when the data was compared in terms of the d/D parameter. The quarter-scale models (No. 12 can) also quite accurately simulated the full-scale drum stack tests.

For the quarter-scale models, the d/D parameter results as well as the compressed container stack height were within $\sim 4\%$. The eighth-scale single-can drop data, in terms of the d/D parameter, was within $\sim 5\%$ of the full-scale results. Therefore, the eighth-scale models worked well under dynamic but not under quasi-static conditions.

The dynamic tests revealed that both the full-scale and scale-model containers behaved in a much different manner under the dynamic impact conditions than in the quasi-static tests. Quasi-static stiffness data, therefore, cannot be used directly to develop mathematical models. However, by using the assumptions outlined in Appendices A and B, satisfactory analytical models can be developed.

Drum stack impacts can be simulated by computer, either by use of a lumped-parameter or a finite-element program. Both techniques give reasonable results and each can predict the amount that individual drums in a stack will crush. The lumped-parameter model requires much less computer time and is therefore less expensive. For the analysis of drum stack impacts, it is the more practical method. If only a single container is to be analyzed, the finite-element model must be used. These computer models for drums can be coupled to a model of an outer container to predict the internal response of the drums.

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APPENDIX A

Details of the Lumped-Parameter Model

The details of the lumped-parameter model shown in Figure 77 are given in this appendix. The model is constructed of mass points connected by couplings (springs), which can be either linear or nonlinear. The couplings can also be defined to load and unload along different paths to simulate a hysteresis effect. Once the coupling masses and initial conditions are defined, the SHOCK code solves the equations of motion associated with the model.

The eight-high stack was simulated using eight identical "cells". A typical cell, shown in Figure A1, consisting of three couplings and two masses, represents one drum. The mass, M , represented the mass of the contents and had a value of 290 kg (640 lb m); M_2 , the mass of the drum, had a value of 27.2 kg (60 lb m). Couplings 1 and 3, representing drum stiffness, are defined in Figure A2. Figure A3 shows the definition of coupling 2, the contents stiffness.

Figure A1. Unit Cell of the Lumped-Parameter Model

The definition of the drum stiffness was obtained from full-scale, static crush data. The contents stiffness was estimated, but a sensitivity study showed that the overall behavior varied only slightly with different representations of contents stiffness. The impact mass was fixed, and all other masses were given an impact velocity equal to the impact velocity of the test being simulated. Hysteresis couplings were used to simulate the crush up and permanent deformation of the drums.

If the behavior of the drum stack with a foam energy absorber is to be analyzed, an additional coupling has to be added between the bottom "cell" and the fixed mass. An appropriate load-deflection curve would be input for this extra coupling.

Figure A2. SHOCK Coupling for the Drums

Figure A3. SHOCK Coupling for the Contents

APPENDIX B

Details of the Finite-Element Model

The full-scale drums have several features (see Figure 1) that make development of an exact model very difficult: The lid, the bottom, the three intermediate ribs, the thin sheet metal construction, and the fact that the drums are only partially filled. Because of these difficulties, it was decided to model the drums as solid uniform cylinders and determine average material properties for the whole system.

To determine the average properties, use was made of the static crush data presented in the Full-Scale Static Crush Tests section. Figure B1 is a curve taken from Figure 9 that is considered to be representative of all the tests. The sharp drop-off in the force observed in this figure, at ~ 7 cm (2.75 in.) displacement, corresponds to the time at which the lid separated. This phenomenon was observed in all the crush tests and always occurred at about the same deflection. Consequently, it was felt that lid separation could be used as a failure criterion. That is, when a drum has been crushed 7 cm (2.75 in.) it can be assumed that the lid has separated from the body.

Figure B1. Typical Force-Deflection Curve for the Side-On Static Crush of a 55-Gallon Drum

HONDO II, the finite element computer program used, requires that the modulus and Poisson's ratio be input to describe the drums. Material type 6, a finite strain elastic-plastic and a strain hardening material,

was selected to describe the drums in the HONDO Computer Program. The analysis was done assuming a plane strain situation. In order to determine material properties, the force-deflection curve of Figure B1 had to be transformed into a stress-strain curve. To do this, some area that was representative of the actual area being stressed had to be found. It was felt that a reasonable estimate of the average stress area might be obtained by finding the area of a rectangular block that had the same volume, height, and length as the drums. The idealized drum and a block of the same volume are shown in Figure B2. The unknown dimension of the block, the width, could then be solved for by setting the volume of the block equal to the volume of the cylinder as follows:

$$H \times L \times W = \frac{\pi H^2}{4} \times L \quad \text{or} \quad W = \frac{\pi H}{4},$$

where L is the length of the drum and block, H is the height of the block and diameter of the drum, and W is the width of the block.

In round numbers, the drums are 61 cm (24 in.) in diameter and 91.4-cm (36-in.) long. Using H equal to 61 cm (24 in.), W is found to be 47.9 cm (18.8 in.) and the assumed stress area is 4378 cm² (678 in.²). Again, this procedure is nothing more than a means to obtain some representative average stress area. Using this area and the identities

$$\sigma = \frac{P}{A}, \quad \epsilon = \frac{\delta}{L},$$

where P and δ are the force and deflection as taken from Figure B1, A is equal to 4378 cm² (678 in.²) and L is 61 cm (24 in.). The stress-strain curve is developed and shown in Figure B3. The curve has been fitted with two straightline segments, one representing the elastic portion of the curve and the other representing the plastic portion. The straightline approximations are made so that the area under the actual curve is about the same as the area under the bilinear approximation. Young's modulus is then taken to be equal to the slope of the elastic portion of the curve, or 4.0 MPa

(580 psi), and the hardening modulus is taken as the slope of the plastic portion of the curve, or 0.31 MPa (45 psi). The yield stress, by inspection, is 0.10 MPa (15 psi), and Poisson's ratio is taken arbitrarily as 0.3.

Figure B2. Rectangular Block and Cylinder of Equivalent Volume

Figure B3. Stress-Strain Curve for Drum Material Model

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