MCC

Materials Characterization Center

DWPF Canister Impact Testing and Analyses for the Transportation Technology Center

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December 1988

**Prepared for the U.S. Department of Energy
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DWPF CANISTER IMPACT TESTING AND ANALYSES
FOR THE TRANSPORTATION TECHNOLOGY CENTER

R. K. Farnsworth
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

A legal weight truck cask design has been developed for the U.S. Department of Energy by GA Technologies, Inc. The cask will be used to transport defense high-level waste canisters produced by the Defense Waste Processing Facility (DWPF) at the Savannah River Plant. The development of the cask required the collection of impact data for the DWPF canisters. The Materials Characterization Center (MCC) performed this work under the guidance of the Transportation Technology Center (TTC) at Sandia National Laboratories. Two full-scale DWPF canisters filled with nonradioactive borosilicate glass were impacted under "normal" and "hypothetical" accident conditions.

Two canisters, supplied by the DWPF, were tested. Each canister was vertically dropped on the bottom end from a height of either 0.3 m or 9.1 m (for normal or hypothetical accident conditions, respectively). The structural integrity of each canister was then examined using helium leak and dye penetrant testing. The canisters' diameters and heights, which had been previously measured, were then remeasured to determine how the canister dimensions had changed.

Following structural integrity testing, the canisters were flaw leak tested. For transportation flaw leak testing, four holes were fabricated into the shell of canister A-27 (0.3 m drop height). The canister was then transported a total distance of 2069 miles. During transport, the waste form material that fell from each flaw was collected to determine the amount and size distribution of each flaw release.

For pressurized flaw leak testing, four holes were drilled into each canister shell. The holes were then closed, and the internal plenum of each canister was pressurized to a predetermined level. Each hole was then opened, allowing the canister to depressurize. During depressurization, any waste form particles exiting the design basis flaw were collected to determine the amount and size distribution of each release.

Upon completing flaw leak testing, each canister was disassembled to determine the total mass and size distribution of the waste form fines. Of

particular interest was the total amount of respirable fines (those with diameters less than 10 μm) and dispersable fines (those with diameters less than 20 μm).

The results of the canister structural tests showed that neither of the canister shells was breached by the impact. The results also showed that the change in canister dimensions caused by the 9.1-m impact was five to seven times that caused by the 0.3-m impact. This was due to the higher impact energy for the 9.1-m impacted canister, which was 30 times that of the 0.3-m impacted canister.

During transportation flaw leak testing, between 0.1 and 260 mg of glass particles came out of each hole in the 0.3-m impacted canister. However, only 0.1 to 12.3 mg of the released glass particles were smaller than 20 μm in diameter. Even less waste form material (1.2 and 2.9 mg, all of it smaller than 20 μm) exited the holes during pressurized flaw leak testing of the 0.3-m impacted canister.

The 9.1-m impacted canisters did not undergo transportation testing. During pressurized flaw leak testing, 79 to 333 mg of waste form material exited each fabricated hole of the 9.1-m impacted canister. However, only 1.1 to 11.4 mg of the glass exiting each hole was smaller than 20 μm in diameter, and 0.8 to 3.0 mg was smaller than 10 μm in diameter. The results also showed that a combination of dry sieving, light scattering particle size analysis, and scanning electron microscopy (SEM) analysis was best for determining the size distribution of fine material collected from each flaw.

Upon disassembling canister A-10 (9.1-m impact), it was determined that 532 g (0.031 wt%) of the waste form was less than 20 μm in diameter, and 239 g (0.014 wt%) was less than 10 μm in diameter. This compares with values of 149 g (0.009 wt%) and 61 g (0.004 wt%) for canister A-27 (0.3-m impact). The results also tend to support contentions that the fines in the 9.1-m impacted canister were primarily created by the impact, while the fines in the 0.3-m impacted canister were primarily created before impact. Finally, the results show that significant amounts of respirable and dispersable fine

material are not accounted for by ordinary disassembly operations, and that methods described in this report need to be used for estimating the amount of these fines.

The data will be used to support the design and licensing of high-level waste (HLW) shipping casks for DWPF canisters. However, the results should only be used in determining an order of magnitude estimate of the amount of fine particles present in an actual HLW canister, as well as their size distribution and potential for release. If more precise estimates are required, additional canister test data will be needed.

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INTRODUCTION

A legal weight truck cask design has been developed for the U.S. Department of Energy by GA Technologies, Inc. The cask will be used to transport defense high-level waste (HLW) canisters produced by the Defense Waste Processing Facility (DWPF) at the Savannah River Plant. The development of the cask required the collection of impact data for the DWPF canisters. The Materials Characterization Center (MCC) performed this work under the guidance of the Transportation Technology Center (TTC) at Sandia National Laboratories. Two full-scale DWPF canisters filled with nonradioactive borosilicate glass were impacted under "normal" and "hypothetical" accident conditions. Following impact, the DWPF canisters and their simulated waste forms were evaluated using the impact performance procedures developed by the MCC. The procedures were used to determine

- the structural integrity and dimensional changes of the canisters after impact
- the mass and size distribution of waste form fines that are released under specified transport and pressurization conditions
- the mass and size distribution of waste form fines that are present in each canister after impact.

Mass and size distribution data from these tests are necessary to support the use of a single containment cask for possible shipment of DWPF test canisters to the Waste Isolation Pilot Plant (WIPP). Single containment may be acceptable if the canister contains respirable waste form fines (material with a diameter less than 10 μm) that have less than 20 Ci of plutonium isotopes (McClure et al. 1985). In addition, GA Technologies, Inc. (under the direction of the TTC) needs data on the amount, location, and ease of release for the respirable fines in the canister. The data will be used to establish the cask-seal leak rate levels needed for the cask Safety Analysis Report for Packaging (SARP). Finally, tests need to be performed on these full-scale canisters of simulated waste to show that hypothetical accident condition impacts do not breach the waste canister. This requirement is needed to show the integrity of the canister during a transportation accident.

The purpose of this report is to document the impact test results for two DWPF canisters. These canisters were fabricated from 304L stainless steel and were filled with a continuous pour of frit 165 at the reference rate of 240 lb/h. Brief descriptions of the impact tests that were performed on each canister are reported. In addition, the significance of the results is discussed, along with any limitations regarding their use.

The following sections present conclusions and recommendations, the procedure followed in the canister drops, the procedures used to determine the integrity of the canisters following the impact testing, the results of integrity testing, the results from transportation flaw leak testing of the normal condition DWPF canister, the results from pressurized flaw leak testing of both DWPF canisters, and the results of size distribution analyses of the glass fines present in each of the impacted canisters.

CONCLUSIONS

Two simulated DWPF HLW canisters were vertically dropped on their bottom ends from two different drop heights. The effect of each impact on the HLW canister's containment performance was then evaluated under a number of different test conditions. Based on this work, a number of conclusions have been drawn. These conclusions are presented below.

- The structural shell integrity of both DWPF HLW canister simulants was not affected during either impact. This was verified by helium leak and dye penetrant testing of both of the canisters in the area of each impact. The results are consistent with previous impact tests.
- Changes in canister dimensions accompanying an impact are directly related to the amount of impact energy that each canister encounters. A canister with higher impact energy will have a larger diameter increase in the impact area, and a greater decrease in overall canister height than a canister impacted at a lower energy.
- Nearly all of the particles released during transportation and pressurized flaw leak testing from the normal condition canister's impact area had a diameter smaller than 20 μm . However, the total amount released was less than 0.02% of the total amount of fine particles smaller than 20 μm in the canister.
- The total amount of glass material released during pressurized flaw leak testing of the hypothetical accident condition canister (9.1-m impact) was an order of magnitude greater than the amount released from the normal condition canister (0.3-m impact). However, the amount of particles smaller than 20 μm that were released from the 9.1-m impacted canister was approximately the same as that released during pressurized flaw leak testing of the 0.3-m impacted canister.
- The use of dry sieving, light scattering particle size analysis, and scanning electron microscopy (SEM) analysis provides a better estimate of particle size distribution during pressurized and transportation flaw leak release testing than does use of a 1.5- to 15- μm aerodynamic particle sizer, or of SEM analysis alone.
- Glass fines in the DWPF canisters are caused by fracturing of the glass during cooling, and the energy imparted to the glass by the impact. The total amount of respirable fines present in the 9.1-m impacted canister is approximately four times greater than the amount of fines in the 0.3-m impacted canister. Also, the glass fines in the 9.1-m impacted canister were concentrated in the bottom portion of the canister (the section in which the canister's

"impact zone" was located). The glass fines in the 0.3-m impacted canister are fairly evenly distributed throughout the canister. This indicates that, for the 9.1-m impacted canister, most of the respirable fines were caused by the canister impact; for the 0.3-m impacted canister, most of the respirable fines were probably caused by fracturing of the glass during cooling.

- Significant amounts of glass fines were found to adhere to the enclosure and sleeving material in which the canister was held during disassembly operations. The use of sample coupons of the plastic sleeving material and plexiglass enclosure was necessary for estimating the mass and size distribution of these glass fines.

EXPERIMENTAL TECHNIQUES, RESULTS AND DISCUSSION

This section describes each of the tests performed and presents the results. Impact performance testing proceeded in the following order.

Two DWPF canisters were dropped on their bottom ends in a vertical orientation. Different drop heights were specified for each canister by the TTC to establish different canister conditions. For the "normal condition" canister, the drop height was 0.3 m (1 ft). For the hypothetical accident condition canister, the drop height was 9.1 m (30 ft).

The dimensions of each canister shell were measured at various positions before and after impact. This was necessary to determine the change in canister dimensions caused by the impact. The canisters were also helium leak and dye penetrant tested after impact to determine whether the impacts had caused the canister shell to breach.

After the above evaluations, the impacted canisters were tested, to determine the amount and size distribution of waste form fines released during transport or under pressure from holes drilled in each canister shell. Transportation flaw leak testing was only performed on the 0.3-m impacted canister. Pressurized flaw leak testing was performed on both of the DWPF canisters, however.

After flaw leak testing, both canisters were disassembled to determine the amount and size distribution of waste form fines present in each impacted canister. Included in the disassembly was a measured estimate of the amount and size distribution of waste form fines adhering to the disassembly enclosure surfaces during canister disassembly operations.

CANISTER IMPACTING

Canister impacting was performed as summarized below. Each canister was dropped vertically on its bottom end from a pre-designated height. Previous studies (Slate, Pulsipher, and Scott 1985) have shown that a center of gravity drop over a bottom corner produces a higher concentration of waste form fines than vertical bottom drops on HLW canisters. However, the use of a vertical drop orientation provides a better simulation of the actual

canister impact if a drop were to occur while the canister is housed in a shipping cask. Tests have shown that the cask cavity housing the canister is not distorted during a 9-m impact, even if the filled shipping cask was impacted in an orientation where the cask's center of gravity was directly over its impacted corner. As a result, the impact energy transferred from the cask to the canister will be distributed evenly over the bottom canister surface.

Two full-scale DWPF canisters, filled with simulated HLW glass, were provided for this testing by the DWPF. Prior to impacting, the canisters were examined for any major imperfections on the surfaces. None were observed. The pre-impact lengths and the pre-impact diameters at various positions near the bottom of each canister were then measured. These measurements were needed to determine the change in canister dimensions that would result from each impact (see Canister Integrity Evaluations). Finally, each canister was weighed:

- canister A-27 - 2153 kg (4746 lb)
- canister A-10 - 2203 kg (4856 lb).

Two different drop heights were used. For a normal condition canister, a 0.3-m drop height was specified to simulate the type of impact expected during normal cask handling. This condition was set by the TTC. For the hypothetical accident condition, the 9.1-m drop height was specified to simulate the canister impact from a worst-case hypothetical accident inside a loaded cask. The hypothetical accident condition was defined by 10 CFR 71.73 of the United States Code of Federal Regulations.

Canister A-10 was chosen for the 9.1-m impact because of its heavier weight. Canister A-27 was chosen for the 0.3-m impact. Using the canister weights and calculated impact velocities, the resultant impact energies were determined for each canister. The calculated impact velocities and energies imparted to each canister are listed in Table 1.

In preparing for impact, the canisters were lifted by rigging a metal sling around the canister, then attaching it to a pelican release device. The pelican release device was used to release the canister without causing

TABLE 1. Calculated Impact Velocities and Impact Energies for Each DWPF Canister

<u>Canister No.</u>	<u>Canister Weight, kg</u>	<u>Drop Height, m</u>	<u>Impact Velocity, m/s</u>	<u>Impact Energy, kJ</u>
A-27	2153	0.3	2.4	6.4
A-10	2203	9.1	13.4	196.4

any extraneous motion. The release was triggered by pulling a cord that was attached to the latching ring. After the canisters were rigged, they were lifted off the impact pad and a level was used to verify the vertical orientation. The canisters were then raised to their prescribed heights and dropped. Two cameras, using high-speed film and videotape, recorded each drop.

Figure 1 shows canister A-27's orientation before impact. Upon impact, the canister rocked back and forth for a short period of time but did not fall over. The rocking motion was probably caused by an uneven release of the pelican hook, which imparted motion to the canister upon release. To mitigate this effect during canister A-10's 9.1-m drop, the pelican hook was slightly modified.

Figure 2 shows canister A-10's orientation before impact. The impact orientation of canister A-10 was more vertical than that of A-27, as evidenced by its initial bounce. Although the canister did fall over after subsequent bounces, the secondary nature of the impact should have had a negligible effect on the impact performance tests.

CANISTER INTEGRITY EVALUATIONS

After the canisters were impacted, tests were performed to evaluate the effect of each impact on canister shell dimensions and integrity. The diameter of each canister was measured at various circumferential positions near the bottom of the canister. In addition, the height of each canister was also measured at various circumferential positions. These measurements were compared with the pre-impact measurements to determine how the canister

FIGURE 1. Orientation of Canister A-27 During 0.3-m Impact

FIGURE 2. Orientation of Canister A-10 During 9.1-m Impact

dimensions were changed by the impact. Afterward, each canister was helium leak and dye penetrant tested to determine whether any canister welds had failed as a result of the impact. Results from each test are discussed below.

Dimensional Analysis of Impact Zone

To prepare the canisters for dimensional analysis, a vertical reference line was drawn from the top to the bottom of each canister. Placement of this line was arbitrary, and was only done to provide a reference point for each diameter and height measurement. A total of 20 different diameter measurements and 4 different height measurements were then taken for each canister. Each dimensional measurement location was described in terms of its circumferential angle from a reference line drawn longitudinally on the canister, and (for canister diameters) the distance from the bottom of the canister. The dimensional measurement locations for the 20 diameter measurements and 4 height measurements are given in Table 2.

Canister dimensional measurements, at the locations given in Table 2, were measured before and after impact. In addition to each measurement, canister shell temperature was also recorded at each diameter and height location. The temperature measurements were necessary to correct the diameter and height measurements to an arbitrary standard of 25°C. The linear thermal expansion coefficient of $1.73 \times 10^{-5}/^{\circ}\text{C}$ for 304L stainless steel was used to correct each measurement.

Tables 3 and 4 show the change in dimensions for the diameter heights of each canister before and after impact. Included in each table is the percentage change in each dimension. As shown in the tables, the increase in

TABLE 2. Shell Locations for Canister Height and Diameter Measurements

<u>Measurement</u>	<u>Angle from Longitudinal Reference Line</u>	<u>Distance from Bottom of Canister, cm</u>
Canister Diameter	0°, 45°, 90°, 135°	2.5, 3.8, 5.1, 7.6, and 10.2
Canister Height	0°, 90°, 180°, 270°	Not Applicable

TABLE 3. Change in Dimensions of Canister A-27 (0.3-m Impact)

Canister Diameters	Angle From Vertical Reference Line			
	0°	45°	90°	135°
2.5 cm from bottom	-0.170 cm (0.3%)	+0.046 cm (0.08%)	+0.061 cm (0.1%)	+0.262 cm (0.4%)
3.8 cm from bottom	+0.079 cm (0.1%)	+0.020 cm (0.03%)	+0.025 cm (0.04%)	+0.086 cm (0.1%)
5.1 cm from bottom	+0.018 cm (0.03%)	+0.015 cm (0.03%)	+0.020 cm (0.03%)	+0.043 cm (0.07%)
7.6 cm from bottom	+0.048 cm (0.08%)	-0.003 cm (0.004%)	+0.018 cm (0.03%)	+0.066 cm (0.1%)
10.2 cm from bottom	+0.036 cm (0.06%)	+0.003 cm (0.004%)	-0.008 cm (0.01%)	+0.023 cm (0.04%)
Canister Height	Angle From Vertical Reference Line			
	0°	90°	180°	270°
	0.00 cm (0.0%)	0.00 cm (0.0%)	-0.16 cm (0.05%)	-0.32 cm (0.1%)

TABLE 4. Change in Dimensions of Canister A-10 (9.1-m Impact)

Canister Diameters	Angle From Vertical Reference Line			
	0°	45°	90°	135°
2.5 cm from bottom	+1.19 cm (2.0%)	+1.17 cm (1.9%)	+1.24 cm (2.1%)	+1.17 cm (1.9%)
3.8 cm from bottom	+1.52 cm (2.5%)	+1.50 cm (2.5%)	+1.52 cm (2.5%)	+1.42 cm (2.3%)
5.1 cm from bottom	+1.65 cm (2.7%)	+1.75 cm (2.9%)	+1.78 cm (2.9%)	+1.52 cm (2.5%)
7.6 cm from bottom	+1.57 cm (2.6%)	+1.68 cm (2.8%)	+1.63 cm (2.7%)	+1.47 cm (2.4%)
10.2 cm from bottom	+1.19 cm (2.0%)	+1.37 cm (2.3%)	+1.24 cm (2.0%)	+1.27 cm (2.1%)
Canister Height	Angle From Vertical Reference Line			
	0°	90°	180°	270°
	-0.64 cm (0.2%)	-1.43 cm (0.5%)	-1.59 cm (0.5%)	-0.79 cm (0.3%)

diameter for the 0.3-m impacted canister (A-27) was 0 to 0.26 cm (0% to 0.4%); that for the 9.1-m impacted canister (A-10) was 1.2 to 1.8 cm (1.9% to 2.9%). Canister impacting also caused a decrease in height of 0 to 0.32 cm (0% to 0.1%) for canister A-27 (0.3-m impact) and 0.6 to 1.4 cm (0.2% to 0.5%) for canister A-10 (9.1-m impact). The change in canister dimensions accompanying each impact is directly related to the amount of impact energy encountered by each canister.

Helium Leak and Dye Penetrant Testing

Following dimensional analysis, each canister was tested to verify the post-impact integrity of its welds. This step was performed by standard helium leak and dye penetrant test methods. These procedures, along with their results, are described below.

Helium leak testing was performed on the bottom portion of each canister using the hood method. Initially, a plastic hood was sealed around the bottom portion of each canister, above its weld. Helium was then bled into a

2.5-cm-diameter hole in the canister plenum. The helium was allowed to flow from the plenum space to a 2.5-cm-diameter fabricated hole approximately 20 cm from the canister bottom. The flow was necessary to establish that enough helium would be present in the canister bottom to use helium leak testing. The presence of helium at a flow rate greater than $10^{-6} \text{ cm}^3/\text{s}$ in the sealed hood would indicate that a leak was present in that portion of the canister shell. However, a helium flow rate of $10^{-6} \text{ cm}^3/\text{s}$ was not detected in the plastic hood of either canister.

Dye penetrant testing was performed on all of the canister welds in and out of the impact region. The test results showed no evidence of failure in the weld areas of the two canisters. Combined with the helium leak test results, these tests confirm the post-impact weld integrity of both canisters.

TRANSPORTATION FLAW LEAK TESTING

Transportation flaw leak testing was performed on the canister that had been dropped from a height of 0.3 m. This test was designed to determine the mass and size distribution of glass fine material that could exit a design flaw in a HLW glass-filled canister while the canister was being transported over a distance of 2000 miles. The canister filled with simulated HLW glass was tested to simulate the fine release from actual HLW canisters with design flaws less than or equal to the surface area of a 0.28-cm-diameter hole.

Procedure

Four 0.28-cm-diameter holes were end milled in the OWPF canister's shell. Three of the holes were located in the canister impact area, at the bottom of the canister; a fourth hole was located in the canister plenum area, above the glass. The holes were positioned in these areas to provide worst-case estimates of the mass and size distribution of fines released from potential canister flaws. Glass releases from holes in the impact area were expected to contain a large percentage of fines smaller than $20 \mu\text{m}$. Glass releases from the canister plenum were expected to be greater than the amount released from flaws in the canister's impact area, but the number of particles smaller than $20 \mu\text{m}$ was anticipated to be fewer. To try to maximize

the release of fines from the canister impact area, the three impact area holes were positioned in those areas that appeared to have experienced the greatest impact deformation.

A longitudinal reference line was then drawn on the canister to ensure correct orientation of the "flaws" during transport. The canister would be transported in a horizontal position with the reference line at the base of the canister and the flaws located at 15° and 30° left of the base line and 30° to the right of the base line. An additional hole was milled in the plenum area above the glass.

To minimize glass disturbance, the holes were fabricated by using a 0.28-cm-diameter end mill. Each design flaw in the impact area was end milled until only a fraction of the canister shell remained. The remaining shell material was then picked out as foil, using dental picks. During hole fabrication, it was found that the canister's reversed flange bottom had an uneven internal ridge, caused by its fabrication process. As a result, the glass was disturbed slightly during hole fabrication by the deeper required end milling of the holes. The disturbance was minimal, however, and probably resulted in only a slight increase in the mass of released fine material and a slight decrease in the size distribution of released fine material. This decrease in particle sizes should provide a conservative worst-case estimate of the actual amount and size distribution of fines released from a 0.28-cm-diameter hole.

Glass fines released from each design flaw during transport were collected on pre-weighed 0.3- μm filters held in specially fabricated filter assemblies. The use of these filters allowed for the collection of all released fine material greater than 0.3 μm , but prevented the formation of a dead air space in the collection area (since the back of the filter was open to the environment). The presence of dead air spaces in the collection area can inhibit fine releases during transport. The loss of fines smaller than 0.3 μm was insignificant for our purposes.

Following filter assembly attachment to each hole, the test canister was packaged in a wooden box that protected the four attached filter assemblies during transport. The canister was placed horizontally in the box with the

new reference line on the underside of the canister. This orientation allowed the loosened glass material to fall out of each canister hole. The canister package was then placed on the bed of a tractor trailer that had leaf spring shock absorbers. This type of shock absorber was expected to provide a rougher ride than most trailers outfitted with standard air bag shock absorbers.

The canister was transported from the Hanford Site to Cheyenne, Wyoming, and back, a total distance of 2069 miles over four days. The canister package was primarily transported over interstate freeways, although a small portion of the trip was over state highways. During its transport, the trailer encountered 26 miles of road construction and at least 40 miles of poor road conditions. The canister package reached a maximum elevation of 8640 ft during its transport. This travel route is consistent (if not conservative) with the transportation route expected for shipment of DWPF canisters to the WIPP.

Following transport, the filters and collected fines were removed from each filter holder and weighed to determine the mass of waste form material released from each filter. The size distribution of the collected fine material on each impact area filter was then determined using SEM analysis. This analysis allows for counting and estimation of the size distribution of particles on each filter. However, this analysis was made difficult by the sparseness of material present on each filter (see Figure 3). Because of the scarcity of material, it was decided to analyze a random sample of 100 to 200 particles on each impact area filter before determining the particle size distribution. Because only a small portion of each filter was analyzed, there was a potential for missing a few large particles that, if present, might constitute a significant portion of the weight of material collected. However, since all of the measured particles were found to be smaller than 10 μm , any error in this method would provide a conservative estimate of the mass of respirable fines released.

For the filter located in the plenum area, more material was collected during transport than could be analyzed using SEM analysis alone. For this filter, dry sieving and light scattering particle size analysis was used to

FIGURE 3. SEM Photograph of a Typical Transportation Flaw Leak Test Filter (Flaw No. 4, 93X Magnification)

determine the size distribution of the loose particulate material that could be poured from the filter. The material remaining on the filter was then analyzed by SEM, and the results were combined with the dry sieving and light scattering analyses to give a complete size distribution.

Results

Upon its return to PNL, the canister was removed from its package, and the filters were removed from their assemblies. During transport, two of the three straps that banded the canister to its package were broken. However, the four filter assemblies on the canister were undamaged. The filters and collected glass were weighed to determine the total material collected from each hole. The amounts of glass material released from the four holes are shown in Table 5.

The hole from which the greatest amount of fines was released, 260 mg, was located in the canister plenum. The mass of waste form material released from the three impact area holes was 0.1, 10.9, and 12.3 mg. The amount of

TABLE 5. Weight of Glass Fine Material Collected During Transportation Flaw Leak Testing

Flaw No.	Position on Canister	Amount Released, mg
1	Canister plenum, 4 in. above glass surface	260
2	Impact area, 15° left of vertical	0.1
3	Impact area, 30° left of vertical	10.9
4	Impact area, 30° right of vertical	12.3

material released from each impact area hole was affected by the amount of fines exiting each hole before the hole became clogged. For flaws 3 and 4, it appears that much, if not most, of the fine material in the hole proximity was released before clogging occurred. For flaw 2, however, very little material was released before plugging occurred.

The size distributions of glass material released from each design flaw (determined by SEM and light scattering for the plenum filter and by SEM for the impact area filters) were combined with the weights of glass material collected to give the size distribution results shown in Table 6. As shown by the size distribution results, the plenum filter was the only location from which a significant mass of particles larger than 20 μm was released. Although one or two particles larger than 75 μm were present on the filter

TABLE 6. Size Distribution of Fines Collected During Transportation Flaw Leak Testing

Flaw No.	Total Amount Collected, mg	Size Distribution, mg			
		>75 μm	20-75 μm	<20 μm	<10 μm
1	260	257.75	1.03	1.14	0.56
2	0.1	0 ^(a)	0	0.1	0.044
3	10.9	0	0	10.9	10.9
4	12.3	0	0	12.3	12.3

(a) One or two particles >75 μm were seen; however, these were not counted because of a SEM imaging problem.

used to collect material from flaw 2, they were not among those particles whose dimensions were analyzed and are thus not indicated in the table. As previously discussed, this results in a conservative estimate of the amount of <20- μ m material.

Results from this test show that the release of glass material from a canister flaw would be greatest if the flaw was in the canister plenum area. Releases in this area are an order of magnitude greater than the amount released from the impact areas. However, the amount of respirable glass fines (fines less than 20 μ m in diameter) released from the design flaw in the plenum area is much smaller than the amount of respirable fines released from flaws in the impact area.

PRESSURIZED FLAW LEAK TEST

Pressurized flaw leak testing was performed on both of the impacted canisters. The pressurized flaw leak test was designed to determine the mass and size distribution of glass fine material that would exit a design flaw in a pressurized, previously impacted HLW canister. Hole diameters and internal pressures for each canister condition were as specified by the TTC. For the hypothetical accident condition canister (9.1-m impact), the prescribed flaw was equivalent to a hole with a diameter of 0.95 cm, and the specified canister pressure was 3.0 psig. For the normal condition canister (0.3-m drop height), the prescribed flaw diameter was 0.28 cm, and the specified internal pressure was 2.0 psig.

Procedure

To prepare the canisters for testing, four holes were end milled into the shell wall of each canister. The holes were positioned in the bottom 7.5 cm of each canister wall. Prior to end milling the holes in canister A-27, the four flaws that were fabricated in the canister for transportation flaw leak testing were welded closed. This was necessary to prevent transportation flaws from influencing the waste form releases during pressurized flaw leak testing. The new holes in canister A-27 were at least 7.5 cm away from any of the holes that were used for transportation flaw leak testing, in order to prevent the holes from being located in an area where the waste

form had been disturbed. The holes were placed in the areas on the canisters' bottom surfaces that visually appeared to have the greatest damage. The approximate locations of the canister holes are shown in Figure 4.

After design flaw fabrication, 1.3-cm-diameter, 5-cm-long, stainless steel tubes were welded over the flaws. Each tube was connected to a simulated leak valve and discharge assembly. This assembly consisted of a calibrated pressure gauge, a standard 1.3-cm-diameter gate valve, and a flared discharge tube. The simulated leak valve and discharge assembly was designed to monitor the pressure at the canister design flaw and control the release of that pressure in a manner that allowed for collection of the released glass material on a filter assembly similar to that used for the transportation flaw leak testing.

To supply the internal canister pressure, a hole was drilled into the upper plenum of each canister, and a stainless steel tube was welded over the opening. A pressure gauge, gate valve, and low-pressure regulator assembly were attached to the tube and connected through a two-stage regulator to a cylinder of breathing air. Each canister was then placed in a horizontal position. Each canister flaw was oriented in a vertical downward direction during pressurized flaw leak testing.

FIGURE 4. Circumferential Locations for Design Flaws on Canisters A-27 and A-10

For mass determinations, a 90-mm, 0.8- μ m-pore filter was positioned directly under the discharge tube. To ensure that all of the released glass particles were collected, a manifold of vacuum pumps with an adjustable flow rate was used to cause a flow rate through each filter. The flow rate through the filter was set at a level that corresponded to the maximum flow rate anticipated from each design flaw during pressure release. In addition, the filter, holder, and discharge tube were surrounded by a clean air shroud. This procedure was necessary to ensure that the only particles collected on the filter were glass particles from the canister, not dust particles from the air.

Each canister was then pressurized to the predetermined level. The canister pressure was verified by the pressure gauges at all of the flaw sites. After waiting a few minutes to ensure that no significant leaks existed in the assemblies, the vacuum flow rate was set to its predetermined level, and the clean air shroud was set at a level at or beyond the sampler flow rate. The gate valve for the particular hole was then opened, and the canister was allowed to depressurize. After depressurization, the gate valve was closed, the filter and collected material were removed, and the canister was rotated to position the next flaw for testing. The filters used in each test were pre-weighed and reweighed after collection to determine the amount of material collected on each filter.

For particle size determinations, an aerodynamic particle sizer (APS) was initially used. The APS is an electronic device capable of measuring the aerodynamic diameter of individual aerosol particles between 0.5 and 15 μ m. The APS was placed directly below the discharge assembly of hole 3 of canister A-27. Following pressurization of the canister, the gate valve was opened to allow canister depressurization. Sampling was continued until the pressure in the canister was 0 psig. The measured amount was then compared with a background sample taken immediately after testing to arrive at the estimated size distribution. Measurement of the size distribution from a design flaw, using an APS, cannot be done in conjunction with any measurement of mass release. As a result, it was planned that two of the four design flaws on each canister would be used for mass determinations, and the other two design flaws would be used for particle size determinations.

Three of the four holes in canister A-27 (0.28-cm-diameter flaw, 2 psig) were pressurized flaw leak tested. Two of the holes were evaluated for mass determinations (using filter assemblies), and one was evaluated for particle size determinations (using the APS). The fourth design flaw was not tested, since its pressure gauge indicated that it had not responded to canister pressurization. The choice of a second mass determination rather than a second size distribution determination was expected to provide the more useful data.

After determining the size distribution from flaw 3 of canister A-27, the APS pump would not function, probably because a relatively large particle became stuck in the capillary tubing. As a result, a new method for measuring particle size distribution was needed for pressurized flaw leak testing of canister A-10 (0.95 cm diameter, 3 psig). It was decided to use the same procedure previously used to determine the particle size distribution of material exiting the plenum design flaw during transportation flaw leak testing of canister A-27. This procedure involved dry sieving and light scattering analysis of the loose particles collected on a filter, followed by SEM analysis of the material remaining on the filter (see the section on Transportation Flaw Leak Testing). Use of this procedure allowed for mass and size distribution determinations from the same hole, as well as a size distribution analysis of particles greater than 15 μm (which could not be analyzed by the APS).

Results

Table 7 shows the mass and size distribution of fines released during pressurized flaw leak testing from each of the fabricated holes in canister A-10 (9.1-m impact, 0.95-cm flaw diameter, 3 psig). The results show significantly different mass and size distributions for each hole. The significant differences for each hole point to the variable nature of fracture and release in the canister. The incomplete size distribution results shown for hole 3 were caused by equipment problems encountered during light scattering analysis of the sieved pan fraction (particles smaller than 75 μm in diameter).

TABLE 7. Mass and Particle Size Distribution of Fines Released During Pressurized Flaw Leak Testing of Canister A-10

Hole No.	Amount Released, mg	Size Distribution Analysis, mg			
		<149 μm	<74 μm	<20 μm	<10 μm
3	208.9	7.68	2.03	<1.09 ^(a)	<0.82 ^(a)
5	106.8	27.17	10.05	5.38	1.59
6	332.9	47.06	17.74	11.43	3.04
7	79.2	13.24	11.14	8.73	1.75

(a) Incomplete light scattering analysis.

The SEM analyses that were performed on the canister A-10 filters showed a significant variation in particle density between filters (compare Figures 5 and 6). Based on these results, it appears that the use of dry sieving and light scattering analysis of the loose particles from each filter must be combined with SEM analysis of the remaining particles on the filter. This inclusion will provide better size distribution results than the use of SEM analysis alone, dry sieving and light scattering analysis alone, or the use of an APS (provided enough material is present for dry sieving and light scattering analysis).

Table 8 shows the mass and estimated size distribution of fines released from two of the four design flaws during pressurized flaw leak testing of canister A-27 (0.3-m impact, 0.28-cm flaw diameter, 2 psig). The masses determined for each flaw were 1.2 mg and 2.9 mg, respectively. These values were within the range of masses released from the impact area flaws of canister A-27 during transportation flaw leak testing (see Table 6).

The particle size distribution for canister A-27 was determined by using the APS on hole 3 of the canister. A more accurate determination of the size distribution of released fines could have been made if additional particle size distribution analyses were available. However, the amount of released material was small enough that any inaccuracies associated with the size distribution analysis may be of no consequence.

FIGURE 5. SEM Photograph of a Sparsely Loaded Pressurized Flaw Leak Test Filter (hole 7, canister A-10, 279X magnification)

FIGURE 6. SEM Photograph of a Densely Loaded Pressurized Flaw Leak Test Filter (hole 5, canister A-10, 279X magnification)

TABLE 8. Mass and Particle Size Distribution of Fines Released During Pressurized Flaw Leak Testing of Canister A-27

<u>Hole No.</u>	<u>Amount Released, mg</u>	<u>Size Distribution Analysis, mg</u>	
		<u><20 μm</u>	<u><10 μm</u>
1	2.9	2.9	1.9
2	1.2	1.2	0.78

The particle size distribution observed by the APS exhibited a bimodal distribution, with peaks at 15 μm and approximately 1 μm . This bimodal distribution is not in accordance with previous log normal size distributions (Slate, Pulsipher, and Scott 1985) and should be examined further. Results from the APS size distribution analysis for hole 3 showed that 65 wt% of the released material was smaller than 10 μm . Since the APS could not measure particle diameters larger than 15 μm , the percentage of released material smaller than 20 μm was assumed to be 100%. This size distribution will provide a conservative estimate of the actual size distribution of material released from a normal condition canister.

The particle size distributions for the two design flaws shown in Table 8 were calculated by determining the mass of material released from each hole and multiplying them by the size distribution percentages given above. The mass of fines smaller than 10 μm that were released from the two design flaws was calculated to be 1.9 and 0.78 mg, respectively. These values are similar to the values given for canister A-10 (0.8 to 3.0 mg), even though the total mass of material released from the holes in canister A-27 was 60 to 100 times less than the canister A-10 totals.

CANISTER DISASSEMBLY AND PARTICLE SIZE ANALYSIS

The final activity performed on the two DWPF canisters was to disassemble each canister and determine the amount and size distribution of glass particles present inside each canister. The canisters were disassembled in sections, starting with the bottom 61 cm and moving up in 46-cm increments. The sectional disassembly of the canisters is used to determine whether the fines that are present in the canister are primarily caused by canister

cooling or by canister impact. This is done by determining the particle size distributions found in each canister's bottom section, relative to other sections.

Procedures

To prepare the canister for disassembly, the canister shell was arc cut in a pattern that divided the canister into five sections. When completed, each canister section was held to the adjacent canister section(s) by four small tabs, spaced 90° apart. Each canister section, upon being removed from the rest of the canister, was held together by only two small tabs.

Each canister section was removed from the rest of the canister by grinding off the four small tabs holding the sections together, then using a spreading device to push the sections apart. To prevent the loss of any glass particles during this operation, a plastic sleeve was first taped to both of the canister sections. After the sections were apart, the spread sleeve was bundled together and taped in the middle, then cut. The removed canister section was then placed in a disassembly tray. In the disassembly tray, the two remaining tabs holding the section together were ground off. Care was taken to prevent metal grindings from falling in the disassembly tray and being mistaken for glass fines. The disassembly tray was then moved to the screening station.

At the screening station, a large plexiglass enclosure was placed over the canister section and tray, and the canister sections were removed from the glass. All of the glass fragments within a particular canister section were then separated into an oversize (greater than 4 mesh) and undersize (less than 4 mesh) fraction. This was done by passing all glass fragments smaller than 7.5 cm in diameter over a shaking 4 mesh screen. After screening each section, the oversize and undersize fractions were weighed.

The undersize fraction was coned and quartered a number of times to reduce the mass of undersize material to a sievable size (200 g). This material was then sieved for 15 minutes, using standard 10-in.-diameter sieves. The sieves used, along with their respective sizes, are shown in Table 9. After sieving, the glass particles present in each sieve tray were weighed. The total undersize fraction was then divided by the total amount of sieved

TABLE 9. Screen Sizes Used During Sieving Operations

<u>Screen Identification</u>	<u>Sieve Size, μm</u>
12 mesh	1680
20 mesh	840
40 mesh	420
100 mesh	149
200 mesh	74
325 mesh	44
pan	<44

glass to arrive at a reduction ratio for the coning and quartering operation. The mass of each sieve fraction was multiplied by this ratio to arrive at the estimated amount of glass particles of each size fraction in each canister section.

To determine the size distribution of fine particles smaller than 44 μm , light scattering analysis of a representative portion of the pan fraction was used. Upon measuring each particle diameter, the particle was counted in one of 24 different size ranges from 1.5 to 67.5 μm . After light scattering analysis was complete, a population and volumetric size distribution are determined. The use of light scattering analysis aided in the determinations of the mass and size distributions of fine glass particles smaller than 44 μm that were in the canisters.

The above procedures were carried out on all five sections of each canister. Upon completing the canister disassembly and particle size analysis for each canister, the results from each section were added together to get the total uncorrected amount and size distribution of glass particles present in each canister. However, to improve the results, corrections needed to be included to account for the amount of material adhering to the sleeving material and canister disassembly enclosure surfaces after canister disassembly and oversize screening operations.

To estimate the amount of adhering material, twelve 2.5-cm-diameter coupons were punched out of the plastic sleeve used for disassembly of the first section of each canister. These plastic coupons were then weighed.

The total weight was compared with twelve 2.5-cm-diameter coupons from an unused plastic sleeve to determine the weight of glass fines present on the coupons. The total surface area of sleeve material used on each canister was then divided by the total surface area of the 12 coupons to arrive at a ratio for estimating the amount of fines lost during canister disassembly. This ratio was then multiplied by the determined fine weight present on the 12 coupons from the first sleeve of each canister. The resultant amount was the estimated amount of fine material unaccounted for during disassembly operations. Size distribution analysis of the sleeve samples was performed on four of the sleeve coupons from canister A-10. The average size distribution from the four samples was used to determine the size distribution of fine material from both canisters. This will provide a conservative estimate of the particle size distribution of fines adhering to the other sleeves during disassembly.

The amount and size distribution of fine material adhering to the disassembly enclosure after oversize screening operations was estimated using 4-in.² plexiglass coupons attached to each interior surface of the plexiglass enclosure. After each canister had been completely screened, the pre-weighed coupons were removed from each surface and reweighed to determine the amount of fine material collected on each coupon. The total area of each interior surface of the enclosure was then divided by the coupon area to arrive at a reduction ratio for each coupon. The determined weight of fine material collected on each plexiglass coupon was then multiplied by the reduction ratio for its surface to arrive at an estimated amount of fine material present on each enclosure surface. The estimated amounts on each surface were then added together to determine the total amount of material lost during oversize screening operations. Particle size distributions were determined for each plexiglass coupon from oversize screening of the first canister (canister A-10), using SEM analysis. The results were then applied to the determined weights of both canisters. As with disassembly correction, this should provide a conservative estimate of the size distribution of particles adhering to the enclosure during disassembly of both canisters.

The total amount and size distribution of glass particles present in each canister were determined by summing up the amounts and size distributions measured for each canister section with the amounts that were determined based on the sleeve and disassembly coupon analyses. The total masses of fine material smaller than 10 μm and 20 μm in each canister were of primary importance in evaluating each canister.

Results

Differences in particle size distribution were observed for the two canisters. For canister A-10 (9.1-m impact), the glass fragments tended to be much smaller than the canister fragments from canister A-27 (0.3-m impact). Differences in particle sizes were primarily due to the different impact conditions experienced by each. As a result, disassembly of canister A-10 was made difficult by the large amount of undersized material present in the canister. This was particularly noticeable for the bottom section of canister A-10, where over 64 kg of particles smaller than 4 mesh were collected. Disassembly of canister A-27, however, was encumbered by the extremely large sizes of some of the glass fragments, which attained volumes up to 27 liters (70 kg) apiece and were difficult to remove from the shell. The bottom section of canister A-10 also exhibited a slight adhesion between the glass and the metal shell, increasing the difficulty of its canister disassembly. Reasons for the occurrence of adhesion in canister A-10 and not in A-27 are not known. However, the different filling histories of the canisters is probably a factor.

Particle size distributions for canister A-10 (0.3-m impact) are shown in Table 10. Included in the row identified as "CORRECT." is an estimation of the mass and size distribution of fine material adhering to the surfaces of the plexiglass enclosure and the plastic sleeving material. The canisters were disassembled in sections, with Section A representing the bottom 61 cm of each canister and Sections B, C, D, and E representing the other sections of the canister, which were cut at 46-cm intervals. The results of the particle size distribution gave a total of 239 g for particles smaller than 10 μm , and 532 g for particles smaller than 20 μm . The amount of fines smaller than 10 and 20 μm that were estimated on the canister sleeves and

TABLE 10. Particle Size Distribution of the Glass in Canister A-10
(9.1-m impact)

Section/ Weight, kg	Size Distribution								
	<4 msh, kg	<1680 μ m, kg	<840 μ m, kg	<420 μ m, kg	<149 μ m, kg	<74 μ m, g	<44 μ m, g	<20 μ m, g	<10 μ m, g
A / 430	64.2	30.2	13.7	7.11	2.18	873	343	302	111
B / 307	16.0	6.02	2.35	1.06	0.306	124	44.3	34.8	11.2
C / 341	10.4	3.74	1.27	0.559	0.177	82.5	25.1	9.52	2.17
D / 410	18.2	9.13	4.96	2.78	0.951	365	117	49.8	12.8
E / 211	10.0	5.40	3.05	1.70	0.524	207	71.1	71.1	69.1
<u>CORRECT.</u>	<u>0.099</u>	<u>0.099</u>	<u>0.099</u>	<u>0.099</u>	<u>0.099</u>	<u>99.0</u>	<u>99.0</u>	<u>65.0</u>	<u>32.2</u>
TOTAL/ 1699	119	54.6	25.4	13.3	4.24	1750	699	532	239

plexiglass enclosure was 13 wt% and 12 wt% of the total amount. The primary influence on the amount of fines present in the canister is the 9.1-m impact. This is supported by the fact that 54 wt% and 57 wt% of the fines smaller than 10 and 20 μ m in diameter were present in the bottom 61 cm of the canister.

Table 11 shows the particle size distribution in canister A-27, which had been impacted under normal conditions (0.3 m impact). Estimations of the mass and size distribution of material that adhered to the plexiglass enclosure and plastic sleeving material are accounted for in the row marked "CORRECT." The results from the disassembly of canister A-27 show that 61.1 g of particles smaller than 10 μ m and 149 g of particles smaller than 20 μ m were present in the canister. The mass of fine particles smaller than 10 μ m and 20 μ m in canister A-27 was only 26% and 28% respectively, of that for canister A-10. Of that amount, only 4% and 7% were from the bottom section, and 38% and 32% were from estimation of the amount of material lost on the

TABLE 11. Particle Size Distribution of the Glass in Canister A-27,
(0.3-m Impact)

Section/ Weight, kg	Size Distribution								
	<4 msh, kg	<1680 μ m, kg	<840 μ m, kg	<420 μ m, g	<149 μ m, g	<74 μ m, g	<44 μ m, g	<20 μ m, g	<10 μ m, g
A / 407	7.60	2.72	1.07	476	145	66.1	21.6	10.8	2.67
B / 620	6.20	2.63	1.25	644	212	93.8	42.3	24.4	6.43
723 (b&c combined)									
C / 7.00	7.00	2.93	1.36	685	229	102	34.1	13.5	3.26
D / 275	5.60	2.38	1.13	603	202	77.9	30.0	18.1	4.51
E / 262	5.10	2.19	1.09	612	229	98.3	38.3	34.9	21.0
<u>CORRECT.</u>	<u>0.0708</u>	<u>0.0708</u>	<u>0.0708</u>	<u>70.8</u>	<u>70.8</u>	<u>70.8</u>	<u>70.8</u>	<u>47.6</u>	<u>23.2</u>
TOTAL/ 1667	31.6	12.9	5.97	3090	1090	509	237	149	61.1

canister sleeve and plexiglass enclosure. The high percentage of fines in both canisters that adhered to the canister sleeves and plexiglass enclosure shows the importance of procedures that are used to estimate the amount of this material. The reduction in the total amount of respirable and dispersible fines (fines smaller than 10 and 20 μm in diameter) and the reduced percentage of respirable fines found in the bottom of the canister A-27 are primarily based on the reduced impact force associated with the 0.3-m impact.

As reported in the section on procedures, above, determination of the size distribution was performed using SEM analysis. The typical particle densities present on the plastic sleeve and plexiglass enclosure coupons were much greater than the typical particle densities of the flaw leak test filters (see Figures 7 and 8). As a result, better size distributions could be taken for each coupon.

FIGURE 7. SEM Photograph for a Typical Plastic Sleeve Coupon (279X magnification)

FIGURE 8. SEM Photograph for a Typical Plexiglass Enclosure Coupon (279X magnification)

Comparison with Previous Data

Table 12 shows a comparison of the canister disassembly data for canister A-10 (9.1-m impact) and canister A-27 (0.3-m impact) with disassembly data for two similarly impacted canisters. As shown in the table, the amount of respirable fine material (less than $10\text{ }\mu\text{m}$) is approximately 65% greater in canisters A-10 and A-27 than in canisters E-18 and B-35. Although correction factors were used in the present data (to account for material adhering to the disassembly enclosure surfaces), the differences between the two data sets would still be significant if the correction factors were not included. The difference between the two data sets are probably due to three factors. First, there may be differences between the thermal histories experienced by the different canisters. This would affect the amount of glass fines that are present due to fracturing of the glass during cooling. Second, substantial variations in canister-to-canister fines content may be expected even among canisters that are nominally "the same." Third, the data reflect the variability in test results (particularly long-term variability) that is inherent in any type of experimental work.

TABLE 12. Comparison of Canister A-10 and A-27 Particle Size Distributions with Previous Impact Data

Canister Ident.	Impact Height, m	Size Distribution				
		<4 mesh	<1680 μm	<44 μm	<20 μm	<10 μm
A-10	9.1	118.9 kg	54.6 kg	699.4 g	532.5 g	238.7 g
(E-18) (a)	9.1	63.4 kg	27.8 kg	307.2 g	262.1 g	145.3 g
A-27	0.3	31.6 kg	13.0 kg	237.1 g	149.3 g	61.1 g
(B-35) (a)	0.3	52.3 kg	24.4 kg	275.1 g	106.6 g	36.9 g

(a) MCC data taken in 1985 (previously unpublished).

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