MCC-15: WASTE/CANISTER ACCIDENT TESTING AND ANALYSIS METHOD

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ABSTRACT

The Materials Characterization Center (MCC) at the Pacific Northwest Laboratory (PNL) is developing standard tests to characterize the performance of nuclear waste forms under normal and accident conditions. As part of this effort, the MCC is developing MCC-15, "Waste/Canister Accident Testing and Analysis." MCC-15 is used to test canisters containing simulated waste forms to provide data on the effects of accidental impacts on the waste form particle size and on canister integrity. The data are used to support the design of transportation and handling equipment and to demonstrate compliance with repository waste acceptance specifications.

This paper reviews the requirements that led to the development of MCC-15, describes the test method itself, and presents some initial results from tests on canisters representative of those proposed for the Defense Waste Processing Facility (DWPF).

THE NEED FOR STANDARDIZED ACCIDENT TESTS

As part of the Department of Energy's effort to implement an integrated waste management system, each organization that will produce, transport, store, or dispose of high-level waste (HLW) has issued separate draft acceptance specifications for the waste they will be handling. These specifications address: 1) the physical and chemical condition of the canister and waste form, 2) limitations on the canister and waste form, and 3) performance under specified conditions. The MCC is currently compiling these specifications and defining the test and material or data collection technique for each specification. As part of this effort, the MCC created MCC-15 to meet specific requirements on the impact performance of waste-filled canisters:

- The Transportation Technology Center (TTC) needs data on the impact performance of DWPF canisters to support their use of a single containment cask for shipping test canisters to the Waste Isolation Pilot Plant (WIPP) repository. Single containment is acceptable if the canister contains respirable waste form fines (particles smaller than 10 μm) that have less than 20 Ci of plutonium isotopes.[1]

- GA Technologies, Inc. (under the direction of the TTC) needs data on the amount, location, and ease of release of respirable fines in the canister as a basis to establish cask-seal leak rate levels. This information will eventually be part of the cask safety analysis report.

- The three major repository sites have prepared draft waste acceptance specifications[2,3] that include the requirement that accidental impacts do not breach waste canisters or create waste form fines beyond a certain quantity. Compliance must be shown by testing full-scale canisters of simulated waste.

- Waste producers and the Monitored Retrievable Storage Program may need canister impact data for their facility safety analyses.

BACKGROUND ON WASTE CANISTER IMPACT TESTING

For years the nuclear industry has subjected nuclear material containers to impact tests because accurate analytical predictions of the impact damage are very difficult to make. PNL has effectively used this testing approach to help develop suitable canisters for high-level waste forms. Staff at PNL have conducted impact tests on canisters containing simulated borosilicate waste glass since 1975.[4-7] A variety of canisters were dropped from heights ranging from 1 to 32 m using several impact orientations.

Early tests[4,5] were conducted to quantify the effects of canister size, material, and fabrication method on impact performance. Later testing efforts[6,7] focused on the canister designed for the DWPF and provided detailed data on canister damage and on the particle size distribution of the DWPF glass. This combined testing experience is the foundation for the MCC-15 impact test method.

MCC-15 TEST METHOD

Formal development of MCC-15 was begun in 1984 to provide impact performance data to support transportation studies. The current version of the test method is described below. A sampling of both full- and quarter-scale results is also presented. Work will continue on the development and use of this method and it will eventually be submitted to the Materials

Review Board (MRB) for extensive peer review. The MRB has the responsibility within DOE to review and approve key materials tests and data to ensure that they are adequate for their intended purposes. The formal relationship between the MCC and the MRB has been described previously.[8]

Scope

The purpose of the MCC-15 test method is to provide statistically valid data on canister integrity, canister deformation, and waste form particle size distribution following a free drop impact under standard transportation accident conditions. Other accident events such as fire or the mitigating effects of the cask are not considered. The test method can accommodate expected quality assurance requirements.

Due to the limited range of experimental experience with MCC-15, it is currently restricted to right-circular ductile-metal canisters that are smaller than 0.65 m in diameter and 4 m in length. The nonradioactive waste form must be brittle, continuous, and homogeneous. These restrictions do not prevent testing most proposed waste forms and canisters. Normally test canisters are produced according to reference process conditions.[9] The test method identifies the information that must be recorded for each canister to support interpretation of the results. The basic impact conditions that must be used are described in the method, although some latitude in the test conditions is allowed to accommodate special data requirements.

Test Preparation

MCC-15 allows flexible test matrices that can be tailored to meet different test objectives, which can range from screening different canister designs to showing compliance with specifications. Once the objectives for the test are established the test matrix can be defined and the necessary preparation steps can begin.

Usually the test matrix is designed for collection of data on canister integrity and on waste form damage that would be suitable to show compliance with transportation or disposal specifications. These data require that the canisters be produced by the reference process so that they accurately represent actual waste-filled canisters. Specific production records must be collected and the canisters must be carefully characterized by measuring the weight, determining the center of gravity, measuring overall dimensions, and applying strain circles. Strain circles are nominally 5 mm in diameter and are arranged in an orthogonal They are etched onto the surface of the canister in regions that will be deformed by the impact. Changes in dimensions of the circles as a result of impact deformation are used to calculate surface strain. These data can be used in separate analyses to evaluate the structural condition of the canister.

The different impact conditions and the number of canisters to be tested must be established. Some regulations state that the canister must be tested under the conditions causing the most damage to the waste form and to the canister. Generally, different orientations and conditions must be tested to determine which is most severe. Critical conditions include drop orientation, canister filling procedure, canister temperature during the test, and canister material.

Once the test conditions are selected, the number of replications for each set of conditions must be established to provide the necessary level of confidence in the data. Waste form data are of particular concern because the data must be expressed in terms of ranges and distributions of occurrence and interpretation must be in terms of probabilities. The ultimate statement describing the waste form condition usually has the following form: a level of confidence that a certain high percentage of canisters contain less than X wt% of waste form particles below a critical size. For example, the final statement from a test series might read: There is 90% confidence that 95% of all canisters contain less than 0.01 wt% of waste form particles smaller than 10 μm effective diameter. The exact values used are normally selected by the experimenter. MCC-15 includes a procedure to estimate the number of replications needed to attain the level of confidence desired, based on the variability of the data (i.e. standard deviation), the amount of waste form allowed below the critical particle size (usually set by the regulations), and statistical tables. Once the test matrix is defined, the canisters are then dropped and evaluated in three steps: 1) measure deformation, 2) check for leaks, and 3) determine the waste form particle size distribution.

Impact Testing

The steps to drop the canister are carefully delineated in the MCC-15 test method. Each canister is positioned over the impact pad and accurately oriented using special rigging. The canister is released from the crane by a special mechanism that will not impart motion to the canister. The design requirements for a suitably unyielding impact pad are defined in MCC-15. The pad shall consist of reinforced concrete topped with a steel plate that is at least 0.15 m thick. The pad must weigh at least 10 times the weight of the canister and be placed on suitably compacted soil. The pad can also include a vertical cylindrical steel penetrator with a diameter of 0.15 m. The penetrator must meet regulatory requirements[10] and be firmly attached to the pad.

The canister is raised to a height of 9 m and then released. The impact event is recorded with high-speed film (at least 500 frames per second) and still photographs. After the impact, the film is reviewed to verify that the canister hit the pad at the expected orientation. The impact procedure when using a penetrator is similar but the drop height is reduced to 1 m. No provision is included to collect waste form fines that may be released from a breached canister because existing specifications do not address a waste form release. Only the quantity of fines and canister integrity are specified. MCC-15 also includes a detailed discussion of the safety measures that should be observed during all handling and dropping operations.

Canister Integrity

Two different types of data are collected on the canister after it is dropped: 1) canister deformation and 2) canister integrity (i.e. leak tightness). Deformation is quantified by measuring the gross changes in canister shape and by measuring the changes in the strain circles. These data must be used with physical data on the canister material in an analytical evaluation to establish the structural condition of the canister. For example, the analysis can show the margin of allowable deformation remaining before canister failure might occur.

An example of actual deformation data is shown in Figs. 1 and 2. The data were taken by the MCC on a reference DWPF canister that was dropped 9 m onto the top nozzle at an angle of 6 degrees from vertical.[6] Figure 1 shows the axial and hoop strains and Fig. 2 shows the change in the shape of the top. Strain levels measured to date on DWPF reference canisters have been less than 20%, which is significantly below the 55% strain level at which 304L stainless steel typically starts to fail.[11]

The canister integrity measurements are designed to show directly whether there is a breach or crack in the canister. A helium leak test is performed on the canister using the hood method in ASME Section V Article 10. Essentially, the method shows whether helium placed around the outside of the canisters can leak into the evacuated interior. Calibrated leaks (2.2×10^{-8} atm-cc/sec) are used to verify that the detection system is adequate. DWPF canisters tested to date have been leak tight to the sensitivity of available detectors, (4.5×10^{-10} atm-cc/sec)/scale division. A leak rate of 1×10^{-5} atm-cc/sec has been proposed as the acceptable level in draft transportation and disposal specifications. A dye penetrant examination is made of the damaged zones according to ASME Section V Article 6. This step is included to show whether there are any nonpenetrating cracks. No cracks have been observed in the DWPF canisters that have been tested.[6]

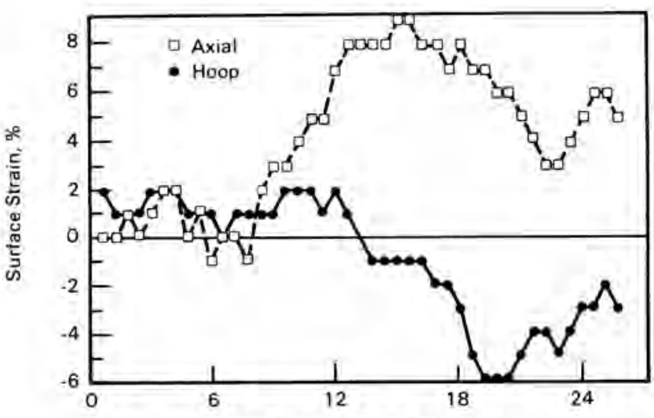

Fig. 1. Surface Strain Along Axial Trace on DWPF Canister Top.

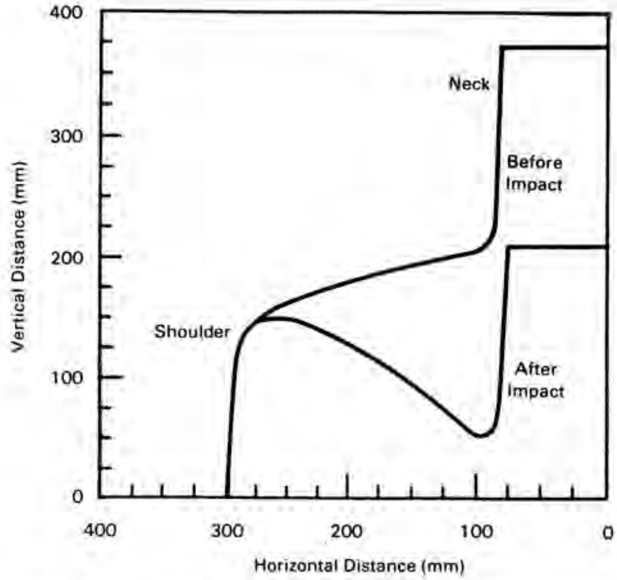

Fig. 2. Gross Shape Change of DWPF Canister Top.

Waste Form Damage

The canister is disassembled, and the waste form is removed to determine the particle size distribution. The canister is separated into manageable sections by a technique that avoids cutting the waste form. The sectioning process is designed to minimize the creation of new fines and to contain the existing ones within plastic sheeting. The waste form from a section is transferred to a gyratory 4 mesh (5 mm) screen that is completely enclosed to contain all the air-dispersible fines (particles smaller than 200 µm). The purpose of this first screening step is to separate all particles smaller than 5 mm (usually about 10 wt%) from the majority of the waste form so an accurate size distribution down to about 1 µm can be determined.

The second screening operation uses a set of six 200-mm-diameter sieves. The sieving operation is designed to minimize the creation of new fines and to prevent loss of fines. The particles that pass through the 75-µm sieve are sized by one of several instruments which have been reviewed by Jardine et al.[12] and which were all found to produce essentially similar results. The operation of several of these instruments involves placing the waste form particles into a liquid for counting. Isopropyl alcohol is recommended in the case of borosilicate glass because it will not alter the particle size and shape as water will. Due to the large quantity of waste form that is involved, the final screening and sizing steps are performed on carefully selected samples. MCC-15 also outlines the accuracy and calibrations required for scales and sizing devices. Steps are included to help quantify the possible loss of material and the precision of the data.

MCC-15 includes a prescribed format for presentation of the particle size data. Existing draft specifications call for data on the amount of particles below a certain size. Therefore, the cumulative mass of material below a certain size is plotted as a function of particle size. The ranges of sizes and amounts cover several orders of magnitude, so log scales must used. Mecham and coworkers[13] have observed that the data from borosilicate waste glass impact tests can be plotted as lognormal probability distributions. The significance of plotting the data in this way is that if a straight line is produced, the distribution can be represented by just two parameters. This allows extrapolation beyond the normally limited range of experimental data and more accurate interpolations within the range. An example of how the data are treated is included in the section below on experimental results.

EXPERIMENTAL RESULTS FROM MCC-15 TESTING

The MCC-15 test method has been used several times to verify that it is workable and to obtain data on DWPF canisters. Two separate tests were conducted using MCC-15 with one full-scale canister and with thirty-four quarter-scale canisters. The initial results from the full-scale test and the final results from the quarter-scale test are presented.

Full-Scale Test

During the summer of 1984 one full-scale prototypic DWPF canister was tested using the MCC-15 test method. The purpose of this test was to demonstrate the workability of MCC-15 and to compare MCC-15 results with results from similar past impact tests[6,7] that did not use all the techniques found in MCC-15.

The test canister was filled according to the DWPF reference process and shipped to PNL by common carrier. The canister was prepared and then dropped 9 m onto the bottom corner at an angle that placed the center of gravity over the corner. Canister integrity was examined by the method described above. No leaks or cracks were detected and deformation was within the data scatter observed in past tests.[6,7]

The canister and glass were divided into five equal segments prior to the sizing operations. The sectioning process consisted of two operations. First, a circumferential cut was made in the canister wall. Second, the two resulting canister segments were pulled apart, with the glass parting along preexisting fracture surfaces. The glass particles were sized according to the procedure described in the section on waste form damage. All of the glass in the bottom damaged section was sieved at one time, which is a departure from the practice used in past tests of sizing the impact-damaged material separately. This change was made because identifying the extent of the impact-damaged glass was subjective and the results were easily misinterpreted.

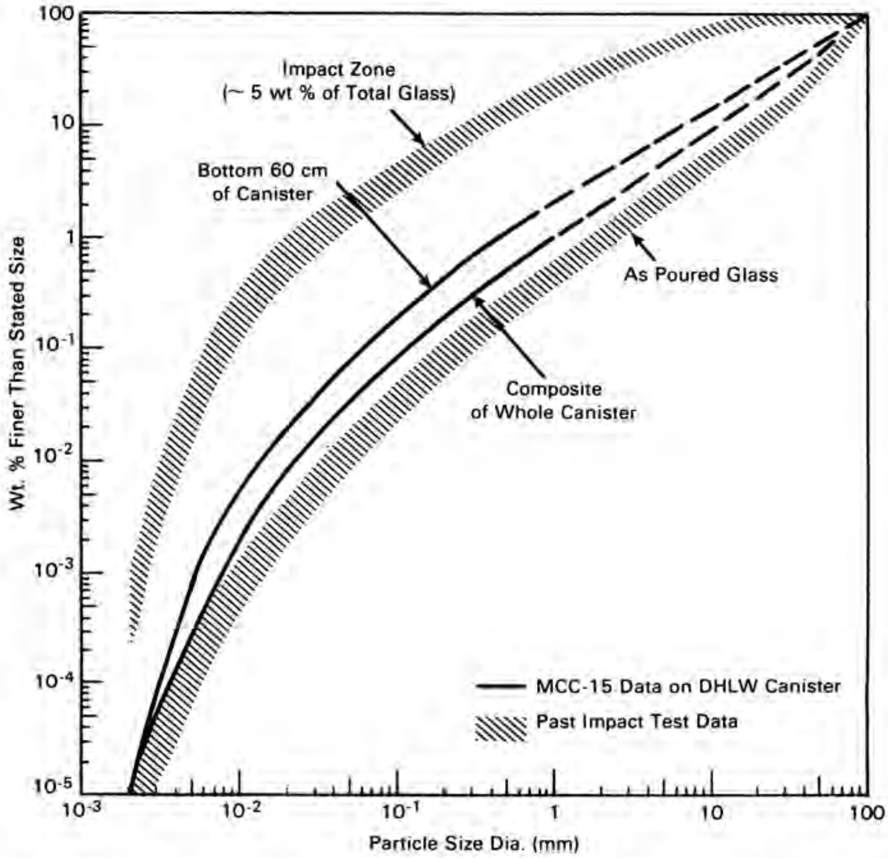

Fig. 3. Particle Size Distribution of Glass from the Full-Scale DWPF Canister.

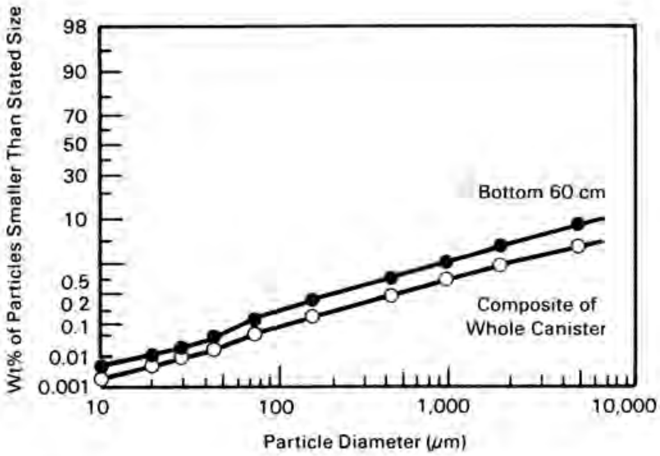

Fig. 4. Lognormal Plot of Particle Size Distribution of Glass from the Full-Scale DWPF Canister.

The measured particle size distribution is plotted using a log scale in Fig. 3 and a lognormal probability scale in Fig. 4. Figure 3 shows the distribution over the entire size range and also includes the combined data from past tests. The MCC has concluded from the similarity of data that impact performance is not sensitive to small changes in the test parameters or glass composition. Figure 4 shows that the results are very nearly lognormal. Because other tests have produced lognormal distributions, Fig. 4 suggests that MCC-15 was successful in measuring the majority of glass fines in the canister.

The canister contained about 50 g of particles smaller than 10 μm, which is the size of interest in transportation regulations. This value is a factor of 240 below the proposed maximum limit for transporting DWPF glass in a single-containment cask.[1,9]

A statistical evaluation of all full-scale data on DWPF canisters will be made to estimate the variability of the glass particle size data. This estimate will be used to design future tests for demonstrating compliance of prototypic DWPF canisters with transportation specifications.

Quarter-Scale Test

Some of the impact performance specifications require that the canister, impact orientation, and canister temperature used in the test result in the most severe damage. In order to determine what the most severe conditions are, a series of tests at different conditions must be performed. The number of canisters needed for the necessary replications for each condition to determine the worst case can be quite large and possibly exceed available testing resources. Therefore, the MCC is using scaled canisters to reliably identify the most severe conditions in a practical way.

Specifically, the MCC performed a statistically designed test using quarter-scale DWPF canisters to determine the most severe conditions for a full-scale test program. The full-scale program will provide data on DWPF canister impact performance to support design of the defense HLW shipping cask. The variables investigated in the quarter-scale effort included canister temperature, impact orientation, and glass-filling conditions. Regulations[10] define the temperature range for testing to be -30 to 40°C, although the DWPF canister is predicted to be about 90°C during transport in the cask. Therefore, -30 and 90°C were selected as the two test temperatures. Four impact orientations were selected: flat impact on the bottom, center of gravity over the bottom corner, a 12-degree incline above horizontal to give a "slap-down" effect, and flat impact on the side. The process variable determined to most likely affect glass performance was the glass filling rate, because it directly affects glass bulk density. Ideally, the filling rate should be scaled to match the linear fill rate in the reference process. However, due to melter pouring limitations, the filling rates used were twice and four times the proper scaled rate. These faster rates result in more glass cracking during filling, which will produce conservative impact results. In addition, the relative effect of filling rate was still discernible because two rates were used.

A test matrix was developed to evaluate the effects on glass damage of these variables independently and in combination. Sixteen unique combinations were identified using these variables. Two replicates for each combination were desired, so 32 canisters were necessary. Two control canisters were filled at the two rates but were not impacted.

The canisters were impacted and analyzed by the MCC-15 test method with only a few modifications to accommodate the small canister size. Glass particle size data were placed in a computer database and statistical calculations and manipulations were performed. Since transportation regulations focus on the quantity of material below 10 μm, that fraction was chosen for detailed statistical analysis.

The first statistical analyses performed on measured values of the sub-10-μm fraction were not definitive. Clear correlations between some of the independent variables and the quantity of fines were not possible. It was also evident from plots of the size distributions that the data deviated significantly from a lognormal distribution for sizes smaller than 44 μm. As shown in Fig. 5, which uses probits to quantify the cumulative mass fraction, this deviation was consistently below the lognormal extrapolation of the curve. (A probit is the inverse of the standard normal cumulative distribution.) The deviation indicated that less material was measured than would have been predicted using lognormal relationships that are typical for glass impact data. This deviation was attributed to the loss of some material during handling and errors in the final sizing step. The loss occurred because the absolute quantity of the fines is very small relative to the total glass quantity and, as a result, the particles are difficult to collect and contain.

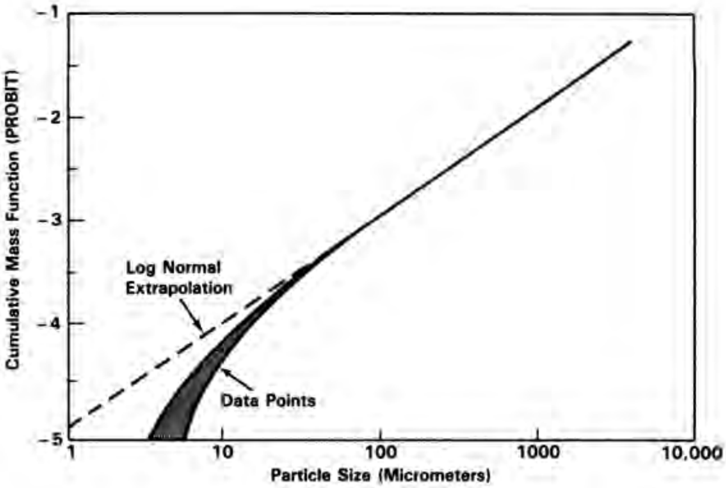

Fig. 5. Comparison of Measured and Extrapolated Particle Size Distributions from Quarter-Scale DWPF Canisters.

A second set of statistical analyses were performed using values for the quantity of sub-10 μm material predicted from extrapolating the straight portion of the curve. The experimental data support a 95% confidence level that this portion of the curve is lognormal. In this case there was a clear correlation between impact orientation and the quantity of fines produced. Figure 6 shows that the corner drop orientation was the worst, the end drop was slightly less damaging, and the side and slap-down conditions were significantly less damaging. There was no indication that temperature or canister fill rate affected the amount of sub-10-μm particles in any significant way.

Quarter-scale data can indicate the relative effects of variables but cannot be used directly to predict the behavior of full-scale canisters. The canister size will probably have some effect on the absolute quantity of fines and the fracture mechanisms. This possibility will be tested before the statistical statements derived from this experiment can be applied without question to the full-scale case. However, the MCC believes that the potential for significant size-related effects is extremely small. A wide range of full and quarter-scale impact tests yield approximately the same proportion of sub-10-μm material, indicating that the scaling factors are not large. Therefore, future full-scale tests will drop prototypic canisters at ambient temperatures onto the bottom corner to provide worst-case data.

CONCLUSIONS AND RECOMMENDATIONS

The MCC has prepared MCC-15 as the standard method for testing the impact performance of full-scale waste-filled canisters. MCC-15 has undergone one round of reviews by TTC, DOE, and Savannah River and is being revised to include review comments and information from ongoing research. Experimental experience to date shows that MCC-15 is workable and able to produce the types of data required to satisfy waste acceptance specifications.

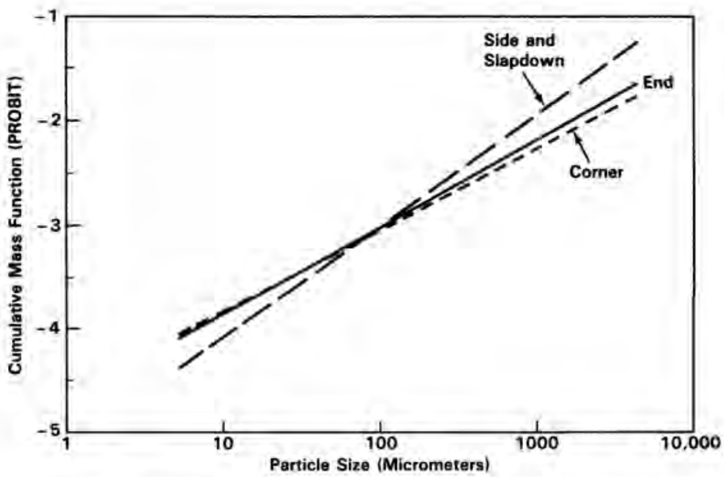

Fig. 6. Effect of Impact Orientation on Glass Particle Size Distribution in Quarter-Scale DWPF Canisters.

The MCC is planning to complete development of MCC-15 and submit it to the MRB for formal consideration. It will be integrated with other full-scale test methods as they are developed. The MCC is also planning to continue using MCC-15 to test canisters produced by the different DOE waste form producers.

The impact tests that have been performed indicate that current canister designs should adequately meet all expected specifications. Testing should continue when designs change substantially or new specifications are proposed.

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