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Civilian Radioactive Waste Management System
Management & Operating Contractor

WASTE PACKAGE FILLER MATERIAL TESTING REPORT

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REVIEW CONCURRENCE

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Discipline	Reviewer	Signature	Date
Waste Package Design	T. W. Doering	T. W. Doering	7.29.96
Waste Package Engineering Development (PCG)	W. E. Wallin	J Balchak for W. E. Wallin	7-30-96

Document is being revised to clarify that the Holometrix thermal conductivity data is to be considered unqualified data. Other limited changes have been made for clarification purposes.

1. PREFACE

As part of the Mined Geologic Disposal System Waste Package Development design activities, it has been determined that it may be beneficial to add material to fill the otherwise free spaces remaining in waste package after loading high-level nuclear waste. The use of filler material will benefit criticality control in spent nuclear fuel waste packages, by the moderator displacement method. Another objective of adding filler would be to enhance long term containment and isolation by inhibiting release of radionuclides, for both the cases of spent nuclear fuel and of high-level waste glass.

This *Waste Package Filler Material Testing Report* presents results of a development test program for placement of filler material within a loaded waste package containing spent nuclear fuel assemblies. Two simulated/dummy nuclear fuel assemblies were fabricated to support this filler placement test program. Additionally, experimental determination of selected physical properties was performed for the candidate filler materials, as needed to support the Management and Operating Contractor (M&O) Waste Package Development design activities.

The development testing constitutes a portion of the *Waste Package Engineering Development Task Plan* (Ref. 1); specifically the Waste Package Internal Filler Material Task. The *Waste Package Engineering Development Task Plan* is written to the requirements of the *Waste Package Implementation Plan* (Ref. 2). This Testing Report has been prepared by the M&O Waste Package Development Department in accordance with QAP-3-5, *Development of Technical Documents* (Ref. 3).

The results reported herein describe results of a most successful test program. Test objectives were fully met; placement of the selected steel shot filler material resulted in all cases in excess of 94 percent fill of available free space around/within the simulated nuclear fuel assembly resting within the test fixture, versus the stated minimum acceptable fill of 85 percent. Additionally, selected physical properties of the steel shot filler material were obtained, including bulk density, material density, bulk material angle of repose, and bulk material thermal conductivity over a temperature range up to 350°C.

2. OBJECTIVE

The objective of this document, the *Waste Package Filler Material Testing Report*, is to describe the testing methods employed during the Waste Package Filler Material Test program, and to report the test results and recommendations. The purpose of the development program as described in the *Spent Nuclear Fuel Waste Package Filler Testing Technical Guidelines Document* (TGD) (Ref. 4) was to determine procedures necessary to accomplish a high percentage fill of available free space upon addition of filler material to a spent nuclear fuel (SNF) waste package for geologic disposal. The development program has been conducted to obtain technical information needed to support the Mined Geologic Disposal System (MGDS) waste package development program design activities.

3. SCOPE

The range of development activities entailed the building of two dummy pressurized water reactor (PWR) fuel assemblies, and construction of a transparent test fixture to simulate a single cell of a PWR waste package spent nuclear fuel basket. Each of the dummy fuel assemblies was tested in turn; each assembly was placed into the test fixture and a series of tests were performed involving placement of small-diameter steel shot into the simulated basket cell. In addition, experimental determination of certain physical properties of the shot filler material were made, including filler material bulk thermal conductivity, bulk density, and bulk material angle of repose. The actual filler testing was performed at Framatome Cogema Fuels in Lynchburg, VA.

4. ISSUES/BACKGROUND

This section discusses filler materials in general. However, the filler testing program reported herein specifically addresses filler placement testing of only steel shot filler material. The rationale for the choice of steel shot as the test filler material is based on an assessment of the attributes of iron/steel shot in comparison to alternative materials (see the following list of technical objectives). Those attributes include ease of handling and placement (spherical shot will "flow" quite readily), commercial availability, low cost, cathodic protection, and chemical buffering. The choice of steel shot is not exhaustive or exclusive. It is based on engineering judgement. The basis for this decision is contained in the *Initial Review/Analysis of Thermal and Neutronic Characteristics of Potential MPC/WP Filler Materials* (Ref. 5).

4.1 Issues

Use of waste package filler materials would help in achieving several technical objectives; specific materials would achieve some or all of the following:

1) Criticality control: moderator displacement by means of a substantial reduction of waste package internal free space, to minimize the amount of water that could enter the waste package in the event of repository flooding and breach of the waste package containment barriers

2) Chemical buffering for radionuclides in the event of water intrusion into the waste package upon breach of the containment barriers

3) Cathodic protection by selection of a filler material having the highest electrochemical activity in comparison to other materials present in the waste package, in the event of water intrusion into the waste package upon breach of the containment barriers

4) Function as mechanical packing to inhibit movement (collapse) of other materials internal to the waste package (fuel rods, fuel pellets, and/or basket materials; or high-level waste glass canisters)

5) For SNF, improve thermal conductance, which would improve heat transfer and decrease fuel rod cladding temperatures

The use of filler material remains a waste package design option yet to be decided; however, the primary motivation would be that of criticality control for SNF and/or chemical buffering in general. If used for chemical buffering, it would be used in most/all waste packages; if used for criticality control, it would be expected that filler would be added only to selected packages depending on specific waste content. Addition of filler material to sealed spent fuel (SF) canisters, such as a Multi-Purpose Canister (MPC), would require that the SF canister be cut open after arrival at the repository, filler added, and, if required, the canister would then be resealed by welding. Adding filler to SF canisters would require that such additional capability be added to the surface facility. The use of filler material would increase waste package weight and cost.

Filler material for (optional) use within high-level waste glass waste packages has yet to be chosen; however, the preliminary choice would be a copper-based shot material. Present knowledge suggests that iron-based materials would be unsuitable, as such material would promote the dissolution of the glass and consequential release of radionuclides from the glass matrix. Use of filler within high-level waste glass waste packages is not under consideration at this time.

4.2 Background

The use of filler material within an SNF waste package and/or a high-level waste glass waste package, versus only filling the free space with an inert gas, is an issue yet to be decided. The choice will be determined by the benefits or penalties related to use of such filler materials, derived from engineering studies and performance analysis assessments that have yet to be performed.

Filler material development activities are directed specifically to the SF canisters and uncanistered fuel (UCF) waste packages (collectively referred to as SNF waste packages), and included material (steel shot) placement including infiltration and uniformity of distribution around the in-place SNF assemblies within the basket, measurement of filler material effective thermal conductivity over a range of temperatures, and determination of filler bulk density. Free spaces within high-level waste glass waste packages would be large, open, and readily accessible; thus, no filler placement testing was to be performed for that type of waste package. Procedures developed and lessons learned from this SNF waste package filler placement testing would also be of use for the high-level waste glass waste packages, in the eventuality that filler material should be used for those waste packages.

Filler material development work would be applicable to both the UCF waste package and canistered SF engineering development activities. Filler material, if used, would be added only at the repository. In the case of the canistered SF, the canister would have to be cut open, filler added, and, if required, resealed. In the case of the UCF waste package, filler would be added following loading of the SNF assemblies. A manner of measuring the quantity of filler material would be required to establish that placement of the proper total quantity of filler had been accomplished.

Selection of candidate filler materials must consider the effects that the presence of that material can have upon the SNF fuel rod cladding temperatures, as compared to having the free space filled with only an inert gas. This concern would include the brief interval of filler material placement, as well as the extended waste disposal containment period. A brief, modest excursion above fuel cladding temperature limit because of filler material placement may not cause consequential cladding damage, as damage potential depends on a time-at-temperature integrated effect, in addition to the absolute temperature.

Desirable attributes of candidate filler materials would include ability to displace water from the waste package/canister interior free spaces, chemical buffering of radionuclides, provide cathodic protection, higher thermal conductivity, inertness in the waste package internal environment before possible water intrusion, ease and rapidity of filler emplacement including assurance of attaining minimum acceptable percent free space fill, lower density, naturally plentiful, and inexpensive for the required material purity.

A preliminary study was performed during fiscal year (FY) 1994 to determine the potential impact of using steel shot filler material in an MPC or UCF waste package, *Initial Review/Analysis of Thermal and Neutronic Characteristics of Potential MPC/WP Filler Materials* (Ref. 5). The investigation examined both thermal effects and criticality control potential (due to moderator displacement), based on the large (21 PWR) multibarrier waste package design case. Preliminary thermal investigations of the effect of steel shot filler material indicated that waste package internal thermal conductance may be improved compared with only helium gas fill; however, that could not be definitively stated as no valid source was found for iron/steel shot bulk thermal conductivity.

The preliminary criticality control investigations (Ref. 5) indicated results utilizing steel shot for moderator displacement could not achieve the needed level of criticality control, for the assumed conservative design basis fuel (fresh fuel, no burnup). A more recent analysis, *21 PWR Assembly MPC Waste Package Criticality Analysis* (Ref. 6), superseding the previous analysis, shows that criticality control can be achieved using steel shot as filler material. Further, more rigorous, evaluations will be performed in the future in the course of waste package final design evolution: 1) to incorporate shot bulk thermal conductivity measurement test results from this testing program, and 2) reassessment of the worst-case criticality control assumptions (no burnup credit, no neutron absorber materials, and sudden catastrophic breaching and flooding of the waste package) based on Performance Analysis assessment of the probability of such an extreme occurrence.

5. REQUIREMENTS

5.1 Program Level Requirements

Program level requirements are identified in the *MGDS Requirements Document* (MGDS-RD) (Ref. 7), Section 3.7.3.3.G.2. Technical requirements applicable to the waste package filler material development task are as identified in the *Engineered Barrier Design Requirements Document* (EB-DRD) (Ref. 8), Sections 3.7.B and 3.7.1, and assumptions stated in the *Controlled Design Assumptions Document* (CDA) (Ref. 9), Section 5.4.2.4.

5.2 QA Requirements

The Quality Assurance (QA) program is applicable to the Waste Package Filler Material Testing development task. The waste package has been identified as an item on the MGDS *Q-List* (Ref. 10) by direct inclusion by the Department of Energy. A QAP-2-3 (Ref. 24) classification analysis has not yet been performed. Further, an NLP-2-0 *Determination of Importance Evaluation* (DIE) (Ref. 25) is not applicable to the design of the waste package. The work associated with the MGDS waste package filler material development activity is identified in the QAP-2-0 Activity Evaluation entitled *Engineering Development* (Ref. 11). This QAP-2-0 evaluation determined such activities to be subject to the requirements of the *Quality Assurance Requirements and Description* (QARD) (Ref. 12). In addition, the applicable procedures to this task are identified in the QAP-2-0 evaluation. The technical document was prepared in accordance with the *Technical Document Preparation Plan For Waste Package Filler Material Testing Report* (TDPP) (Ref. 13).

6. TECHNICAL APPROACH

The development testing was conducted by Framatome Cogema Fuels of Lynchburg, VA under their QA program approved by *Supplier Evaluation Report* (SER) (Ref. 14). The technical approach for the filler material testing is described in the *Spent Nuclear Fuel Waste Package Filler Testing Technical Guidelines Document* (Ref. 4) and further described in Section 7 of this document.

7. TEST PROGRAM DESCRIPTION

The performing organization for the preparation and execution of the filler placement testing was Framatome Cogema Fuels (FCF) of Lynchburg, chosen because they could produce the two dummy nuclear fuel assemblies that are essential to performance of the prescribed development testing. FCF was allowed to use alternate materials to build the dummy simulated fuel assemblies, provided the dimensions of the assembly remained the same. FCF Lynchburg built the dummy fuel assemblies on the standard fuel assembly production line.

To perform the filler placement testing, the test fixture was to be oriented in an upright position; the test program involved only this position, and excluded any required testing in an inclined or horizontal position. As such, the test fixture support rig did not need to have facility to enable tilting the test fixture.

Waste Package Engineering Development personnel were in attendance and provided assistance in the conduct of all filler testing activities performed at FCF Lynchburg.

FCF was permitted to subcontract secondary testing activities as appropriate; the bulk thermal conductivity testing was subcontracted to a unqualified commercial test laboratory.

Raw data measurements for this testing program include both SI and English units. Weights were in the form or force measurements; however, in this report, pounds will be referred to as weight, and kilograms will be referred to as mass. Results and conclusions will be in SI units; however, tallies of raw data and intermediate calculations in English units will omit accompanying SI units.

7.1 Dummy Fuel Assembly Description

Two dummy fuel assemblies were fabricated. They are the 15x15 B&W Mark-B design, and the 17x17 B&W Mark-BW replacement for the Westinghouse design. The dummy assemblies were fabricated on the FCF assembly line, and are physically equal to the production fuel assemblies except slightly lighter in weight.

The Mark-B 15x15 dummy fuel assembly is the same as the B&W fuel assembly except the fuel tubes are replaced with solid stainless steel rods and the 16 guide tube assemblies were modified. The guide tube assemblies have two slots cut through the very bottom of the tubing to allow the shot to drain out of the guide tube assemblies at the conclusion of the filler placement tests.

The Mark-BW 17x17 dummy fuel assembly is the same as the B&W replacement for the Westinghouse design except the fuel tubes are replaced with solid stainless steel rods and the 24 guide thimble assemblies were modified. The guide thimble assemblies have two slots cut through the bottom of the tubing to allow the shot to drain out of the guide tube assemblies at the conclusion of the filler placement tests.

7.2 Test Fixture Description

The simulated SNF basket was fabricated from nominally 3/4 in. thick Lexan (polycarbonate) side plates. The inside square dimension is nominally 8.81 in. ±0.05 in. (223.8 mm ±1.3 mm) and the height is nominally 180.00 in. ±0.06 in. (4572 mm ±1.5 mm). One side is removable and the structure is not designed to be watertight. There are no openings or plugged openings in the side walls and no top or cover. The bottom plate (metal) has a "funnel like" slope, drain hole, and a 3 in. ball valve attached to allow draining of the shot. The source for the test fixture dimensions is the *Initial Summary Report for Repository/Waste Package Advanced Conceptual Design* (Ref. 15) which details the UCF waste package tube type basket design current dimensions.

The test fixture was mounted on an elevated stand to allow draining of the shot, and is fitted with structural support brackets. Two compressed air-driven rotating ball vibrators are used; one affixed to the support stand, and the other mounted on one side of the test fixture about half way up. The test fixture mounted on its stand was installed in the bottom of a 12 ft deep pit area at the FCF Commercial Nuclear Fuel Plant.

7.3 Shot Description

Shot is produced by atomizing molten metal, in which the droplets assume nearly spherical shape before solidification. Shot size may be as high as 6 mm (~1/4 in.) with current production hardware. The product is normally graded into various sizes. Newer production techniques are available to produce quite small shot (~0.4 mm and smaller) with more uniform size distribution, improving yield within the nominal size range.

To avoid any tendency of separation of various size shot within the waste package free space, it is likely that shot size will be limited to a fairly narrow grading size band (apropos the question of why the larger nuts rise to the top of the can during handling). Production cost of the graded shot would depend somewhat on the ability of the process to provide a reasonable yield in that size range, as the rejected shot would have to be recycled back into the process. It is recognized that mixed grade shot provides a denser bulk material (~10%) which reduces bulk interstitial void space; however, there is no plan at present to pursue examination of mixed grade shot unless further reduction of free space is recommended for reasons of neutronics (criticality control via moderator displacement technique).

The Society of Automotive Engineers (SAE) has specifications for shot screenings; Table 7.3-1 is an excerpt from Table 1 of Reference 16. Typically, any specified shot size number has 3 or 4 combinations of screen sizes, each with a related percentage of shot which must pass or not pass through. The central two screen sizes bound the bulk (75%-80%) of the shot in that SAE size; and the average of the two screen sizes would be roughly the nominal shot size. For SAE Specification J444 size numbers of S230 and larger, the ratio of the central two screen sizes is approximately 1.4. For shot sizes below S230, the ratio of the central two screen sizes is closer to 1.7, indicating that actual shot size would vary more widely than for size S230 and above.

The two different graded shot sizes utilized in the filler material placement testing are listed in Table 7.3-1; SAE Shot Size S230 (the smaller shot, nominally about 0.7 mm diameter) and Size S330 (the larger shot, nominally about 1 mm diameter), although both sizes are actually quite small. These sizes were established by the TGD (Ref. 4). One-ton lots of each shot size were procured from Metaltec Steel Abrasive Co., each lot contained in a 55-gallon steel drum. The shot composition is Metaltec's commonly-used bainite shot, which is basically a low carbon steel, rather than the alternative near-pure iron ferrite shot material mentioned in the TGD. Quality Control Certification (QCC) sheets from Metaltec Steel Abrasive Co. are included in Appendix A.

Table 7.3-1. Selected Graded Shot Size Distributions

SAE J444 Specification Tolerances: Shot Size S330	Screen Opening (mm)	SAE J444 Specification Tolerances: Shot Size S230	Screen Opening (mm)
All Pass No. 14 Screen	1.40	All Pass No. 18 Screen	1.00
5% Max on No. 16 Screen	1.18	10% Max on No. 20 Screen	0.850
85% Min on No. 20 Screen	0.850	85% Min on No. 30 Screen	0.600
96% Min on No. 25 Screen	0.710	97% Min on No. 35 Screen	0.500
Ratio of mid-range screen sizes	1.4	Ratio of mid-range screen sizes	1.4

7.3.1 Bulk Density Test Results

The producer of the steel shot used in the testing (Metaltec) indicated that graded shot bulk density could be expected to be in the range of 4.8 g/cm^3 (g/cc). Assuming a low carbon steel density of about 7.85 g/cc, this would indicate a void fraction of about 39 percent. Test results obtained indicated slightly lower bulk density, with void fraction ranging from 38-40 percent.

Bulk density was determined for two conditions: 1) the loose as-poured condition, which would correspond with poured placement of shot into a waste package, and 2) a slightly more dense condition produced by vibrating the shot, corresponding to settling of the bulk shot as may be expected to occur while transporting a waste package underground.

Small scale bulk density testing was conducted by filling a 100 ml graduated container with loose shot and calculating the net weight. This testing was repeated a number of times, with both shot sizes. Some of these same samples were then vibrated, and the volume reduction was recorded (a lowering of the level within the graduated container). Several techniques were employed to vibrate the test samples, including placing the sample on the test fixture stand while the filled test fixture was being vibrated (one of the vibrators was affixed to the test stand), placement on vibrating machinery in the facility, and lastly by hand-induced vibration (tapping the sides and bottom of the container). In each case, vibrating continued until no more settling and consolidation of the sample could be observed.

Results of the bulk density testing are presented in Tables 7.3-2 and 7.3-3. As may be seen from the averages of the test values, bulk densities are nearly equal for the two different shot sizes. Average vibrated bulk density values were 2 to 2.5 percent higher than the loose density values. Computed standard deviation of the measured values is in the range of 1 percent or less for all cases; this appears to be quite good in light of the fact that measured volume in the 100 ml graduated container could only be read to the nearest ½ percent.

Table 7.3-2. Steel Shot Bulk Density - As-Poured Condition

Small Shot, Size S230			Large Shot, Size S330		
Mass kg	Volume ml	Density g/cc	Mass kg	Volume ml	Density g/cc
0.4600	100.0	4.600	0.4600	100.0	4.600
0.4700	100.0	4.700	0.4650	100.0	4.650
0.4550	100.0	4.550	0.4650	100.0	4.650
0.4565	100.0	4.565	0.4585	100.0	4.585
0.4635	100.0	4.635	0.4650	100.0	4.650
0.4634	100.0	4.634	0.4595	100.0	4.595
0.4635	100.0	4.635	0.4605	100.0	4.605
			0.4608	100.0	4.608
			0.4590	100.0	4.590
	average	4.617		average	4.615
	std. dev.	0.0505		std. dev.	0.0273
	std. dev. %	1.1		std. dev. %	0.6

Table 7.3-3. Steel Shot Bulk Density - Vibrated Condition

Small Shot, Size S230			Large Shot, Size S330		
Mass kg	Volume ml	Density g/cc	Mass kg	Volume ml	Density g/cc
0.4600	98.0	4.694	0.4600	97.5	4.718
0.4565	98.0	4.658	0.4595	99.0	4.641
0.4635	98.0	4.730	0.4605	97.0	4.747
0.4634	97.0	4.777	0.4608	97.0	4.751
0.4635	97.0	4.778	0.4590	97.5	4.708
	average	4.727		average	4.713
	std. dev.	0.0525		std. dev.	0.0441
	std. dev. %	1.1		std. dev. %	0.9

Material density tests were also performed for the steel shot. The Metaltec QCC sheets indicate "% Irregular Voids, Hollows" as being ≤5%. The material chemistry listed on the QCC sheets is similar to A 516 low carbon steel; density of A 516 is 7.85 g/cc (Ref. 17). The testing was performed by reweighing some of the foregoing samples after adding water to fill the interstitial space between the shot particles (water density, Ref. 18). Material density was then calculated by:

material density = shot mass ÷ { container volume - [mass water added ÷ water density] }

The average measured material density for the smaller shot was 2.5 percent less than A 516 density, and the large shot was 4.5 to 5 percent less than A 516 density, as presented in Table 7.3-4. These values indicate porosity in accordance with the manufacturer's specified value (namely, ≤5%), with the small shot exhibiting somewhat less porosity than the larger shot.

Table 7.3-4. Steel Shot Material Density

Small Shot, Size S230					Large Shot, Size S330				
Mass kg	Volume ml	Water Added, kg	Water Density,g/cc	Material Density,g/cc	Mass kg	Volume ml	Water Added, kg	Water Density,g/cc	Material Density,g/cc
0.4780	100.0	0.0375	0.9984	7.655	0.4585	100.0	0.0385	0.9986	7.462
0.4825	100.0	0.0370	0.9984	7.665	0.4650	100.0	0.0380	0.9986	7.506
					0.4575	100.0	0.0385	0.9986	7.446
(Water @ 19 C)			average	7.660	(Water @ 18 C)			average	7.471
			std. dev.	0.0075				std. dev.	0.0315
			std. dev. %	0.1				std. dev. %	0.4

7.4 Filler Placement Test Description

The objective of the filler placement testing was demonstration of a specified minimum percentage filling within the free space of a single simulated PWR waste package basket cell. In general, free spaces within a waste package will not be permitted which would be inaccessible to gravity placement of filler material, with the waste package oriented vertically, especially if the purpose of the filler material is moderator displacement to aid in criticality control. Design of the waste package spent fuel basket and other internal structures must not preclude attaining 85 percent minimum percentage free volume fill, with the waste package oriented vertically, based on loose as-poured filler bulk density.

Free volume (free space) is defined as the waste package internal volume less displacement volume of all objects therein. Percentage fill refers to the needed volume of bulk shot to fill the stipulated percentage of free space; it does not refer to or include the interstitial void space within the bulk shot. The equation for total void space is:

void fraction = { 1.0 - [fraction fill] × [1.0 - bulk shot void fraction] }

For example, assuming a case of 85 percent fill, 4700 kg/m^3 shot, and 7850 kg/m^3 solid material density, void fraction equals { 1.0 - [0.85] × [4700/7850] } = 0.49.

The test fixture was made of transparent plastic material, constructed full scale to accommodate each of the two dummy PWR SNF assemblies. The test material was limited to commercially available graded steel shot free of surface scale. The two shot sizes used for the testing program were SAE J444 Size S330 and Size S230, which have mid-range screen sizes of 0.850-1.18 mm and 0.600-0.850 mm, respectively. Material composition was obtained from the manufacturer, and actual screen pass/no pass of samples were certified from the manufacturer for the particular batch supplied for this testing.

Filler placement testing began with the first available dummy fuel assembly, the B&W 15x15 Mark-B. Filler placement testing was conducted under ambient temperature conditions. A weight method was used to measure the quantity of shot placed into the test fixture, based on the total of incremental quantities placed. Both the test fixture empty volume and the simulated SNF assembly displaced volume were determined, so as to have an accurate prediction of available free space volume. The volume of each dummy assembly was determined by a combination of physical measurements and analysis; the summation of component volumes calculated by dividing actual component weights by appropriate material density values. The as-built test fixture inside dimensions were measured at several locations along the fixture length to determine average cross-sectional area and to calculate volume. These methods were approved by Waste Package Engineering Development prior to conducting the filler testing. Computation of the volumes from the measured data is summarized in Table 7.4-1. Volume of a production B&W Mark-B4 fuel assembly was obtained from the BR-100 Final Design Report (Ref. 19, p. II 3.6-98) as being 4911 ±16 in.^{3} (0.0805 ±0.0003 m^3, a value which corroborates the displaced volume calculated for the dummy Mark-B fuel assembly).

The following subsections discuss test setup, test activities, and results and observations. Subsequent to performing fill tests Nos. 1 and 2, Waste Package Engineering Development personnel in attendance made the decision to alter the test procedure for tests Nos. 3 though 8. Results of both tests Nos. 1 and 2 had demonstrated that nearly inconsequential amounts of shot remained within the test fixture/fuel assembly upon gravity-draining the fixture. Thus, following the loose fill tests (the odd-numbered tests), draining and subsequently refilling the fixture preparatory to the vibration testing (the even-numbered tests) simply had the effect of performing the loose fill test twice; results from tests Nos. 1 and 2 demonstrated this was not a necessary or profitable expenditure of time and resources.

In each case, the test fixture was filled to the 168 in./14 ft (4.267 m) level (to a scribed line, 12 in. below the top edge of the fixture). A steel pail was used; the incremental quantity of shot was weighed in the pail, and then poured by hand into the top of the test fixture. The quantity remaining in the final pail-full after reaching the proper fill level was deducted from the total, and the incremental quantities were summed for the total placed.

Table 7.4-1. Test Fixture and Fuel Assembly Volumes

Physical Test Results	Volume, (m^3)
Test Fixture, full length, 15 ft (4.572 m) (includes funnel/drain)	0.2311
Test Fixture, to fill-level scribe mark, 14 ft (4.267 m) (includes funnel/drain)	0.2158
B&W Mark-B 15x15 Dummy Fuel Assembly	0.0812
B&W Mark-BW 17x17 Dummy Fuel Assembly	0.0778
Net to 14 ft level, with Mark-B 15x15 Dummy Fuel Assembly	0.1346
Net to 14 ft level, with Mark-BW 17x17 Dummy Fuel Assembly	0.1380

The test fixture was fitted with a 3-in. ball valve on the bottom to facilitate gravity draining of the shot; this design feature performed quite successfully. The shot was incrementally weighed as is was drained from the fixture; a quantity of shot was drained into the pail, which was weighed as it was removed from the test pit and returned to bulk storage. Once all shot was removed that could be removed by gravity draining, the ball valve was closed and the test fixture vibrated with the attached vibrators. The vibrating caused a portion of the residual shot to be dislodged and fall to the bottom; vibration was terminated when it appeared that little/no more shot was to be dislodged, and the dislodged quantity was weighed and temporarily segregated for later examination. Visual observations and photographic records were made throughout the filling and draining processes.

Based on the records of the incremental quantities added for filling and removed during draining, the residual quantities remaining after draining were quite small. Visual observations showed that the bulk of this small residual was resting on the flat-surfaced area of the test fixture bottom plate (41 percent flat area, as 59 percent of the bottom plate area was machined to be a funnel).

As discussed in the individual test results, the quantities trapped up in the fuel assembly were very small, even before vibration was applied. Visual observations showed that a few particles of the larger shot could be caught and retained at isolated spots in the fuel assembly spacer grids upon draining; however, it was also obvious that bulk quantities of both the larger and smaller shot sizes readily passed through the spacer grid assemblies, and only a few particles were being caught and retained within the spacer grids.

Of course, a waste package is not designed to be drained. The purpose of focussing on residual shot in the fuel assembly is that this information gives quantitative insight into the size of unfilled pockets as may occur beneath overhangs, etc. The observation that some particles of the larger shot can be retained by the spacer grids does illustrate that shot of that size is larger than some of the apperatures existing in isolated areas of the spacer grid. That being the case, there exists the potential for corresponding small unfilled pockets within or beneath such areas. Although the foregoing remarks be true, for the shot sizes employed in this filler placement testing, the volume of these small unfilled pockets can be shown to be inconsequentially small.

Cleanout of the test fixture/fuel assembly was performed each time a different shot size was to be used. The test fixture two-piece front panel was removable, enabling test personnel to gain access to the fuel assembly for complete cleanout of any residual shot remaining in the assembly, and to sweep out the bottom of the test fixture. Cleanout equipment employed included a compressed air hose and the test fixture installed vibrators. Following gravity draining of the test fixture, a mallet was used to jar the test fixture and thus augment the installed vibrators during the test step involving vibratory recovery of residual shot.

The filling and draining tests performed have demonstrated that placement of small diameter shot may be readily accomplished, utilizing material with reasonably high density and having a relatively smooth hard surface. Based on the demonstrated test results, fill percentage within the fuel basket cells may be expected to exceed 96.5 percent if the smaller Size S230 shot is used, and to exceed 93 percent if the larger Size S330 shot is used (these figures based on test results summarized in Table 8-1; calculated as average fill percent less twice the standard deviation). Either of these figures considerably exceeds the minimum required 85 percent figure; however, the minimum figure applies to the basket as a whole, rather than just the cells for the fuel assemblies. Nonetheless, the minimum figure should be easily attainable, given appropriate access to other free spaces existing within a waste package fuel basket.

7.4.1 Fill Test No. 1

7.4.1.1 Instructions

Filling with the smaller shot shall be tested first, to minimize the possibility of significant quantities of shot being temporarily trapped and not recovered upon draining the shot from the test fixture. Upon completion of a test fixture fill (level full to a line one foot from the top, loose fill, no vibration applied), perform and record in writing visual observations around the perimeter of the test fixture, supported with photographic record where anomalies are observed. Although the perimeter observations may indicate seemingly complete filling by the shot, a comparison of the quantity of shot placed versus the quantity expected to be placed shall be recorded (based on measured free space volume multiplied by the previously measured density of loose shot).

Following the preceding filler placement test (no test fixture vibration allowed in that part of the test), the fixture shall be gravity drained (again, no test fixture vibration allowed) of shot. Upon completion of gravity draining, close the bottom valve and empty the bull hose of any residual shot. Then reopen the bottom valve and vibrate the test fixture a short time; catch the quantity of dislodged shot in a separate container, and assuming it is a small quantity, segregate this shot for possible future examination. Visually examine the test fixture post-vibration to determine if any shot can be seen which has not been dislodged and discharged from the test fixture. If deemed necessary to allow for closer examination of residual shot retention, the assembly may be partially withdrawn from the test fixture for inspection. This eventuality is thought to be especially unlikely for this test, due to beginning the testing series with the smaller shot size.

7.4.1.2 Observations and Results

A measured total of 1332.4 lb (604.4 kg) of small size shot was emplaced in the loose condition. A measured total of 1328.6 lb (602.6 kg) of shot was removed by gravity draining. Vibrating the empty test fixture drained another 2.2 lb (1.0 kg) which was segregated for later examination; by difference, the inferred quantity of residual shot remaining after empty vibration was 1.6 lb (0.7 kg). Some small amount was seen to remain on the flat ledge of the bottom plate. The vibrators (one attached to the stand and one on the test fixture) did not impart enough vibratory energy to the test fixture to essentially clear the bottom plate of residual shot. Only 0.8 lb (0.4 kg) was removed by the installed vibrators; jarring the test fixture with the mallet increased the total recovered by vibration to 2.2 lb (1.0 kg). The following paragraphs discuss the residual on the bottom plate, which is estimated to be ≤1 lb after vibration. Visual observations confirmed that the fuel assembly was virtually free of trapped shot.

The shot interface against the transparent test fixture front panel at the end of gravity draining was measured as being 1 1/4 in. and 1 3/16 in. in the two corner locations, and 3/16 in. at midspan (see picture page A8). This data implies about a 27° angle of repose for this residual shot resting on the bottom plate. The amount of residual shot as might be expected to rest on the test fixture bottom plate following gravity draining is analytically estimated as 1.9 lb (0.9 kg) for a 27° angle of repose.

Half of that material was discharged due to vibration (the shot interface against the test fixture inner surface was observed to fall by half). Thus, almost half of the 2.2 lb (1.0 kg) discharged by vibration came from the residual resting on the test fixture bottom plate, which would leave approximately 1 lb resting on the bottom plate after vibrating the empty test fixture. Considering that half of the shot dislodged by vibrating came from that piled on the test fixture bottom plate, it was not unexpected that the segregated shot appeared to be the same as the bulk material; therefore, the segregated shot was returned to bulk storage. It should be noted that the residual removed following vibration (test fixture cleanout) was measured for test No. 2, and that quantity was 1.0 lb, thus corroborating the analytical estimate.

The residual values mentioned above are in the range of few-tenths of percent, illustrating a very high percentage recovery of the shot even before vibrating to enhance recovery. The ratio of measured weight removed to measured weight added is (1328.6 + 2.2 + ~1.0) ÷ 1332.4 = 0.9995, or within 0.05% in this case, which is evidence of the accuracy of the weight measurements. Some later fill tests record slightly more weight removed than added; however, the values are so small as to easily be within measurement accuracy. A discussion of fill test measurement accuracy may be found in Appendix A.

Loose as-poured bulk density within the test fixture for Fill Test No. 1 was:

$$604.4 \text{ kg} \div (0.1346 \text{ m}^3 \times 1000) = 4.490 \text{ g/cc}$$

This value is about 2.8 percent below the loose as-poured test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-2).

7.4.2 Fill Test No. 2

7.4.2.1 Instructions

The next test is a repeat of test No. 1, except that the test fixture will be vibrated following initial loose fill. First fill full to the top, loose fill, measuring total weight of shot added. After vibration, add and accurately measure the quantity necessary to again bring the level full to the top (if that quantity is small, subsequent vibrating to settle the newly added filler may be dispensed with). The total weight of filler placed in this test may be compared to the weight from the prior test (No. 1; same shot size but loose placement). Utilizing this ratio of vibrated-to-loose shot placement, as compared to the similarly determined bulk material density ratio, will give a good indication as to the amount of free space that existed during the loose placement filler placement test (free space that would probably not have been visible upon exterior visual examinations). Previous material testing will have established the ratio of vibrated-to-loose shot density. Assuming at this point that no surprises emerge from these two tests, it would be expected that the filler placed in the vibrated test would quite nearly equal the predicted fill quantity calculated from the measured free space volume multiplied by the previously measured density of vibrated shot.

Repeat the test fixture shot draining procedure from test No. 1. In the case of anomalous results from any of this testing, collaborative consultation with Waste Package Engineering Development shall be conducted to expand upon this test procedure to attempt to clarify the test results. If the fill testing results are as expected, then the segregated shot quantities that resulted from final draining of the test fixture may be returned to the bulk. Otherwise, it may be decided to do a screening test of the segregated shot quantities to compare size population to that of the bulk material.

7.4.2.2 Observations and Results

A measured total of 1343.8 lb (609.5 kg) of small size shot was emplaced in the loose condition. The test fixture was then vibrated for a period of about 30 minutes (see picture page A7), following which 36.8 lb (16.7 kg) of shot was added to bring the level back to the fill line, for a measured total of 1380.6 lb (626.2 kg) emplaced for the vibrated condition. A measured total of 1379.2 lb (625.6 kg) of shot was removed by gravity draining. Vibrating the empty test fixture drained another 2.0 lb (0.9 kg) which was segregated for later examination. Another 1.0 lb (0.5 kg) of residual shot was removed from the test fixture following the test during cleanout before changing to the larger shot size. The final total measured quantity removed was 1382.2 lb (627.0 kg). By difference, the inferred quantity of residual shot was a negative 1.6 lb (0.7 kg). The segregated shot was returned to storage.

The foregoing figures indicate over 100 percent recovery; the ratio of measured weight removed to measured weight added is 1382.2 ÷ 1380.6 = 1.0012, or within 0.12% in this case. This small difference, indicating over 100 percent recovery, is so small as to easily be within measurement accuracy. Again, visual observations confirmed that the fuel assembly was virtually free of trapped shot.

Loose as-poured bulk density within the test fixture for Fill Test No. 2 was:

$$609.5 \text{ kg} \div (0.1346 \text{ m}^3 \times 1000) = 4.529 \text{ g/cc}$$

This value is about 1.9 percent below the loose as-poured test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-2). This value is 0.86 percent higher than the value for test No. 1. However, individual test values in Table 7.3-2 exhibit larger variations than this.

Vibrated bulk density within the test fixture for Fill Test No. 2 was:

$$626.2 \text{ kg} \div (0.1346 \text{ m}^3 \times 1000) = 4.653 \text{ g/cc}$$

This value is about 1.6 percent below the vibrated test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-3).

The loose and vibrated bulk densities computed from the loaded test fixture exhibit values over 3 percent lower than the small-sample testing. This phenomenon may well be attributable to what is termed "edge effects" due to the very large surface area-to-free volume ratio inherent in a fuel assembly. Edge effects are normally inconsequential, but in this case, the total surface area of all of the fuel tubes and other fuel assembly hardware plus the test fixture walls, compared to the free volume between those tubes plus the volume around the assembly, is a ratio far greater than for the 100 ml test container (in the range of 100 mm tall by 23 mm diameter). Edge effects result from larger interstitial spaces at the interface between the edge particles and the surface against which those edge particles rest; as a consequence, this would reduce bulk density within the test fixture (which is emplaced weight ÷ free volume) compared to material bulk density.

7.4.3 Fill Test No. 3

7.4.3.1 Instructions

Repeat the testing procedure described previously in Fill Test No. 1, using the larger shot size.

7.4.3.2 Observations and Results

A measured total of 1291.8 lb (586.0 kg) of large size shot was emplaced in the loose condition. As stated earlier in Section 7.4, the testing procedure was simplified to dispense with draining the shot after the loose fill, and again filling in like fashion for the vibrated test. Instead, the already loose-filled test fixture was utilized to progress directly into the vibrated test No. 4.

Loose as-poured bulk density within the test fixture for Fill Test No. 3 was:

$$586.0\ \text{kg} \div (0.1346\ \text{m}^3 \times 1000) = 4.353\ \text{g/cc}$$

This value is about 5.7 percent below the loose as-poured test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-2).

7.4.4 Fill Test No. 4

7.4.4.1 Instructions

Repeat the testing procedure described previously in Fill Test No. 2, using the larger shot size.

7.4.4.2 Observations and Results

A measured total of 1291.8 lb (586.0 kg) of large size shot was emplaced in the loose condition for test No. 3. The test fixture was then vibrated for a period of about 30 minutes, following which 38.4 lb (17.4 kg) of shot was added to bring the level back to the fill line, for a measured total of 1330.2 lb (603.4 kg) emplaced for the vibrated condition. A measured total of 1322.2 lb (599.7 kg) of shot was removed by gravity draining. Vibrating the empty test fixture drained another 1.2 lb (0.5 kg) which was segregated for later examination. Another 1.8 lb (0.8 kg) of residual shot was removed from the test fixture following the test during cleanout, before changing to the other fuel assembly and the smaller shot size. The final total measured quantity removed was 1325.2 lb (601.1 kg). Thus, the inferred weight of shot still trapped in the fuel assembly is 5.0 lb (2.3 kg). The segregated shot was returned to storage.

The foregoing figures indicate a high percentage recovery; the ratio of measured weight removed to measured weight added is 1325.2 ÷ 1330.2 = 0.9962, or within 0.38% in this case. Again, visual observations confirmed that the fuel assembly was virtually free of any consequential quantity of trapped shot, although it was evident that more isolated particles were caught within the tube guides for this larger shot size in comparison to the small shot size.

Vibrated bulk density within the test fixture for Fill Test No. 4 was:

$$603.4 \text{ kg} \div (0.1346 \text{ m}^3 \times 1000) = 4.483 \text{ g/cc}$$

This value is about 4.9 percent below the vibrated test results obtained for the large sized shot based on the small-sample bulk density testing (see Table 7.3-3).

7.4.5 Fill Test No. 5

7.4.5.1 Instructions

Remove the 15x15 Mark-B assembly and replace it with the 17x17 Mark-BW assembly. Repeat the testing procedure described previously in Fill Test No. 1, using the smaller shot size.

7.4.5.2 Observations and Results

A measured total of 1380.6 lb (626.2 kg) of small size shot was emplaced in the loose condition. As stated earlier in Section 7.4, the testing procedure was simplified to dispense with draining the shot after the loose fill, and again filling in like fashion for the vibrated test. Instead, the already loose-filled test fixture was utilized to progress directly into the vibrated test No. 6.

Loose as-poured bulk density within the test fixture for Fill Test No. 5 was:

$$626.2 \text{ kg} \div (0.1380 \text{ m}^3 \times 1000) = 4.538 \text{ g/cc}$$

This value is about 1.7 percent below the loose as-poured test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-2).

7.4.6 Fill Test No. 6

7.4.6.1 Instructions

Repeat the testing procedure described previously in Fill Test No. 2, using the smaller shot size.

7.4.6.2 Observations and Results

A measured total of 1380.6 lb (626.2 kg) of small size shot was emplaced in the loose condition for test No. 5. The test fixture was then vibrated for a period of about 30 minutes, following which 9.0 lb (4.1 kg) of shot was added to bring the level back to the fill line, for a measured total of 1389.6 lb (630.3 kg) emplaced for the vibrated condition. A measured total of 1389.8 lb (630.4 kg) of shot was removed by gravity draining. Vibrating the empty test fixture drained another 2.0 lb (0.9 kg) which was segregated for later examination. Based on the results and discussions of tests Nos. 1 and 2, it may be assumed that approximately another 1.0 lb (0.5 kg) of residual shot was removed from the test fixture following the test during cleanout before changing to the larger shot size (the actual amount was not weighed, but was judged to be no more than a pound). The final total quantity removed was 1392.8 lb (631.8 kg). Thus, the inferred weight of shot still trapped in the fuel assembly is negative 3.2 lb (1.5 kg).

The foregoing figures indicate over 100 percent recovery; the ratio of measured weight removed to measured weight added is 1392.8 ÷ 1389.6 = 1.0023, or within 0.23% in this case. This small difference, indicating over 100 percent recovery, is so small as to easily be within measurement accuracy. Again, visual observations confirmed that the fuel assembly was virtually free of trapped shot.

Vibrated bulk density within the test fixture for Fill Test No. 6 was:

$$630.3 \text{ kg} \div (0.1380 \text{ m}^3 \times 1000) = 4.568 \text{ g/cc}$$

This value is about 3.4 percent below the vibrated test results obtained for the small sized shot based on the small-sample bulk density testing (see Table 7.3-3).

7.4.7 Fill Test No. 7

7.4.7.1 Instructions

Repeat the testing procedure described previously in Fill Test No. 1, using the larger shot size.

7.4.7.2 Observations and Results

A measured total of 1337.8 lb (606.8 kg) of large size shot was emplaced in the loose condition. As stated earlier in Section 7.4, the testing procedure was simplified to dispense with draining the shot after the loose fill, and again filling in like fashion for the vibrated test. Instead, the already loose-filled test fixture was utilized to progress directly into the vibrated test No. 8.

Loose as-poured bulk density within the test fixture for Fill Test No. 7 was:

$$606.8 \text{ kg} \div (0.1380 \text{ m}^3 \times 1000) = 4.397 \text{ g/cc}$$

This value is about 4.7 percent below the loose as-poured test results obtained for the large sized shot based on the small-sample bulk density testing (see Table 7.3-2).

7.4.8 Fill Test No. 8

7.4.8.1 Instructions

Repeat the testing procedure described previously in Fill Test No. 2, using the larger shot size.

7.4.8.2 Observations and Results

A measured total of 1337.8 lb (606.8 kg) of large size shot was emplaced in the loose condition for test No. 7. The test fixture was then vibrated for a period of about 30 minutes, following which 13.4 lb (6.1 kg) of shot was added to bring the level back to the fill line, for a measured total of 1351.2 lb (612.9 kg) emplaced for the vibrated condition. A measured total of 1344.8 lb (610.0 kg) of shot was removed by gravity draining. Vibrating the empty test fixture drained another 4.2 lb (1.9 kg) which was segregated for later examination. Based on the results and discussions of tests Nos. 1 and 2, it may be assumed that approximately another 1.0 lb (0.5 kg) of residual shot was removed from the test fixture following the test during final cleanout. The final total quantity removed was 1350.0 lb (612.4 kg). Thus, the inferred weight of shot still trapped in the fuel assembly is 1.2 lb (0.5 kg). The segregated shot was returned to storage.

The foregoing figures indicate a high percentage recovery; the ratio of measured weight removed to measured weight added is 1350.0 ÷ 1351.2 = 0.9991, or within 0.09% in this case. Again, visual observations confirmed that the fuel assembly was virtually free of any consequential quantity of trapped shot, although it was evident that more isolated particles were caught within the tube guides for this larger shot size in comparison to the small shot size.

When the Mark-BW fuel assembly was finally removed from the test fixture, unlike the Mark-B fuel assembly, it was observed that the vanes on the Mark-BW spacer grids still retained a small amount of this larger sized shot, which had not been dislodged during the test fixture vibration following gravity draining. This small amount of trapped shot was not captured for measurement; however, test personnel estimated the total to be perhaps 1-2 pounds, which would be in the range of the inferred quantity of non-recovered shot.

Vibrated bulk density within the test fixture for Fill Test No. 8 was:

$$612.9 \text{ kg} \div (0.1380 \text{ m}^3 \times 1000) = 4.441 \text{ g/cc}$$

This value is about 5.8 percent below the vibrated test results obtained for the large sized shot based on the small-sample bulk density testing (see Table 7.3-3).

7.4.9 Angle of Repose Test

7.4.9.1 Instructions

The surface of a bulk material may be inclined to some angle from horizontal, above which the material surface will become unstable; this is termed the angle of repose. Knowledge of this parameter for as-poured loose steel shot samples could be of interest when studying or predicting free space filling during loose filler placement testing.

Determination of the angle of repose shall be performed at ambient temperature, for each size of shot being used in the filler placement testing. The suggested apparatus would consist of a square or rectangular container that may be tilted about one edge. The bulk material should be leveled within the container, although not vibrated to cause particle reorientation. The container would then be tilted slowly and smoothly, and the angle at which surface slump begins noted as the angle of repose. The test should be repeated a number of times (>3). If the test results are quite consistent, then an average figure may be reported; if the results indicate that initiation of slump is variable over a range, that observation and the noted range of angle should be reported instead.

Determination of in-place angle of repose is also desired; that is, the maximum angle of repose that would occur within the basket cell with a fuel assembly in place. The presumption is that the presence of the closely-spaced tubes would result in a larger value for angle of repose than for the free surface test condition. The test setup would utilize the transparent fill test fixture, and may be conducted as an adjunct to the fill tests.

Conceptually, this testing would require that the shot be introduced uniformly along just one side of the fuel assembly, between the edge of the assembly and the test cell wall. Newly added shot would cascade through the array of tubes to the far side, and would presumably result in a somewhat planar inclined surface that could be measured and photographed from the exterior of the transparent test fixture.

Execution of this testing could be performed as follows:

1) Allow enough shot to drain from the test fixture that the level falls to about the top of the first spacer grid below the top end spacer grid; or alternatively, interrupt the filling operation.

2) Introduce additional shot along just one side of the test fixture. If found necessary, temporarily install a dam (e.g., a flat piece of material) so as to obtain a nearly planar inclinded surface for the poured shot.

3) Pour in additional shot so that the resulting inclined surface generally falls between the two adjacent spacer grids (to provide a clear view of the surface). Observe the characteristics of the inclined surface established by the shot cascading through the array of tubes to the far side. Record observations and measurements, including photographs.

4) Resume filling of the test fixture.

5) In the event that any of the test series No. 1, 3, 5, or 7 should happen to be repeated, the in-place angle of repose testing need not also be repeated.

7.4.9.2 Observations and Results

Angle of Repose Tests

Angle of repose testing was first conducted using a second transparent polycarbonate test fixture (having the same cross-section as the full-sized basket cell test fixture, only shorter) without the fuel assembly inside. The bottom of the test fixture was filled with shot and the shot surface was leveled. The fixture was then tilted until the mass of shot began to move, and the angle of the test fixture was measured, corresponding to the shot angle at initial movement. A total of 4 tests were performed for each shot size. Results of the testing varied somewhat; the averages and standard deviations of the test results are noted below:

Shot Size	Initial Slump Angle	Standard Deviation
S230	30.9°	3.9%
S330	29.6°	8.2%

Angle of repose testing was also performed using a small clear container (2.7 in. × 1.7 in., 69 mm × 43 mm). In addition to determination of the initial angle at which slump occurred (the maximum stable angle of repose), it was desired to also determine the final stable angle of repose at the conclusion of slump. This smaller angle, the angle at which stability was reestablished, should really be nearer the angle occurring after shot is poured into a pile, or the angle of the residual shot on the test fixture bottom plate after gravity draining.

The testing was performed under carefully controlled conditions, and repeated a total of

8 times for each shot size. This testing produced the following results, which were quite repeatable, as indicated by the standard deviation values:

Shot Size	Initial Slump Angle	Standard Deviation	Final Slump Angle	Standard Deviation
S230	34.6°	2.0%	28.7°	1.8%
S330	36.4°	2.5%	28.9°	2.1%

Initial slump angle (maximum angle of repose) is lower for the testing conducted with the short test fixture, a larger fixture than the later small-scale testing. Given that the initial slump angle is a metastable threshold, the larger-scale fixture has a larger surface area and thus more sites from which the slump may be initiated. Also, initial slump is quite sensitive to how carefully the surface is leveled; this was controlled quite carefully for the later small-scale testing.

The angle of repose testing has demonstrated that the initial slump angle can vary somewhat, depending on test setup (i.e., the values obtained for the small-scale testing are in the range of 3-7 degrees higher than the larger-scale testing). The angle of repose information which will probably prove to be most useful for future waste package filler studies is the final slump angle; that value being about 28-29 degrees for either size of shot.

In-Place Angle of Repose Tests

The first in-place angle of repose tests were conducted utilizing a short model; a fuel assembly segment consisting of two spacer grids supporting a full array of short dummy fuel tubes and guide tubes, accurately represening the Mark-B design for a single span (see picture page A9). The two spacer grid model was then placed within a second transparent test fixture having the same cross-section as the full-sized basket cell test fixture, only shorter. This model was small enough to be handled manually (e.g., move the assembly in the test fixture, tilt the test fixture, etc.) which allowed for closer observation and detailed inspection of the characteristics of the shot filling. The test fixture was placed on the floor and the partial fuel assembly was inserted. The fuel assembly was positioned with contact to one side of the test fixture. This represents the worst case scenario for actual loading, since the actual fuel assemblies may be distorted and will not be centered in the basket.

The first test was run using the larger of the two shot sizes (S330). The shot was poured along one side of the fixture and flowed downhill through the fuel assembly, the surface inclined from right to left. A total of five pours were used to fill the model to a level completely covering the lower spacer grid, so that the angle of repose would be measured in the free span between the two spacer grids (see picture page A6). For comparison purposes, the angle was also measured below the lower spacer grid during the filling process (following the earlier pours) to determine if the proximity of the spacer grid had any observable effect. The first measurement was taken after the second pour, and the angle was measured as 33.75 degrees from horizontal. The second measurement taken following the third pour was also 33.75 degrees. The third measurement was taken following the fourth pour, for that part of the inclined surface between the two spacer grid locations, and was 35 degrees. From this testing, it may be concluded that in-place angle of repose would be ~34 degrees for the larger S330 shot within a Mark-B fuel assembly. Following the last pour, the fixture was tapped repeatedly with a rubber coated T-handle hex driver to observe how the shot settled following agitation. The S330 shot did settle significantly, and the final measured angle was 26.5 degrees.

The filling was performed on only one side of the fixture with minimal bundle penetration while pouring (~3 rows). There were noticeable voids on the lower spacer grid on the side which contacted the test fixture. The S330 shot did not leave any noticeable voids other than the ones observed at the contact surface. The shot flowed well between the fuel rods and around the spacer grid. It was observed that each pour left an line of demarcation that was attributed to the "dust" on the surface of the shot. It was also observed that the polycarbonate fixture was statically charged because the irregular steel particle debris (fines) adhered to the inner surface. It was considered interesting that the debris adhering to the sides of the fixture was exclusively the scale-like particles, and not well defined shot. During the draining process the S330 shot remained in the tab regions of the lower spacer grid and in the corners of the spacer grid.

The second test was conducted using the smaller S230 shot, following the cleaning of the model, and used the same method of filling. The first measured angle was 32.25 degrees and the second angle was measured as 33 degrees. From this testing, it may be concluded that in-place angle of repose would be ~32.5 degrees for the smaller S230 shot within a Mark-B fuel assembly. Following external agitation with the T-handle hex driver, the angle was measured as 30.75 degrees.

There was a more pronounced void area where the lower spacer grid contacted the test fixture than was experienced with the larger shot. The smaller shot did flow through the vertical slots in the spacer grid with no noticeable internal voids. There was less residual shot material remaining in the model following the initial drain, compared to the larger shot, as was expected.

The Mark-BW fuel assembly was tested for the in-place angle of repose using the full-sized test fixture and dummy fuel assembly. The test was conducted during the filling operation (fill test No. 5) using S230 shot. The filling operation was stopped when the test fixture had been filled just past the second grid from the top. The shot was slowly poured down one side, following which the angle of repose was then measured. The operation was then repeated during the S330 shot fill test No 7. The following tabulation summarizes results for both the Mark-B testing and the Mark-BW testing:

Shot Size	Mark-B Angle	Mark-BW Angle
S230	32.5±°	35°
S330	34±°	39.75°
Rod spacing	3.50 mm	3.10 mm

The Mark-BW figure with the S330 shot appears to be somewhat above the other in-place figures; which suggests that the larger shot (nominally ~1 mm diameter) is more sensitive to the closer spacing between tubes for the Mark-BW fuel assembly.

Summary of Angle of Repose Testing

A considerable amount of test information was gathered regarding shot angle of repose. The bulk free surface is metastable for angle of repose in the range of ~35 degrees. Following surface slump, the resulting stable angle of repose is in the range of ~29 degrees. It is believed that the lower stable figure will be more useful during any future design work, rather than the higher metastable figure. Observed in-place angles of repose tend to be higher than the free surface angle of repose (the stable ~29 degrees value), with in-place values ranging from approximately 4 degrees to 10 degrees higher.

7.4.10 Thermal Conductivity Test

7.4.10.1 Instructions

The thermal conductivity testing may be conducted in parallel with the test fixture filler placement testing using low-carbon bainite cast steel shot. Samples from each batch of the two different shot sizes shall be tested to determine bulk thermal conductivity. The testing shall be conducted for a range of preconditioned bulk temperatures, from ambient up to the range of approximately 350°C. Running two samples for each of the tests and assuming nominally six preconditioned bulk temperatures would result in a total of two sample setups, which times six temperatures for each sample, equals a grand total of 12 test runs.

The actual thermal conductivity test used must be approved by Waste Package Engineering Development prior to conducting the test.

7.4.10.2 Observations and Results

The thermal conductivity testing was performed by Holometrix of Bedford, MA. The *Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique*, (ASTM E 1225-87) (Ref. 20) was used to determine the thermal conductivity over a range of temperatures from 50°C to 350°C. Althouth the testing was performed in accordance with the above ASTM procedure by a nationally accredited lab, and despite Holometrix being qualified for the same test under Sandia/CRWMS QA program for thermal conductivity testing on ESF borehole samples, the absence of M&O recognized approval of the Holometrix QA program and the fact that the Holometix report did not meet ASTM Requirements requires that the data be identified as unqualified.*

The test procedure was approved by Waste Package Engineering Development. The results are shown in the following table and are to be considered unqualified data:

SAMPLE	TEMPERATURE °C	THERMAL CONDUCTIVITY* (W/m-K)
S230 Steel Shot	50	0.379
	109	0.430
	170	0.469
	231	0.504
	291	0.567
	351	0.658
S330 Steel Shot	50	0.325
	109	0.371
	170	0.414
	230	0.441
	290	0.507
	350	0.591

The original calculations regarding the thermal acceptability of filler were run assuming that the thermal conductivity of steel shot would be between 1 and 4 W/m-K. The figures recorded above indicate that the shot bulk conductivity is on the order of two orders of magnitude less than carbon steel. As a consequence, the thermal analyses will need to be reevaluated based on the actual data in the above table. Due to the unexpectedly low values obtained from the first series of testing with the loose shot, Waste Package Engineering Development made the decision not to test the vibrated shot condition. The near-pure iron shot testing was cancelled for the same reasons as the vibrated shot testing. These tests may be undertaken at a later date should the updated thermal conductivity calculations still show use of filler material to be thermally acceptable.

8. CONCLUSIONS

The results reported herein describe results of a most successful test program. Test objectives were fully met; placement of the selected steel shot filler material resulted in all cases in excess of 94 percent fill of available free space around/within the simulated nuclear fuel assembly resting within the test fixture, versus the stated minimum acceptable fill of 85 percent. Additionally, selected physical properties of the steel shot filler material were obtained, including bulk density, material density, bulk material angle of repose, and bulk material thermal conductivity (refer to Section 7.4.10.2 for thermal conductivity data qualification) over a temperature range of 50°C to 350°C.

The filling and draining tests performed have demonstrated that placement of small diameter shot may be readily accomplished, utilizing material with reasonably high density and having a relatively smooth hard surface. Based on the demonstrated test results, fill percentage within the fuel basket cells may be expected to exceed 96.5 percent if the smaller Size S230 shot is used, and to exceed 94 percent if the larger Size S330 shot is used. Either of these figures considerably exceeds the minimum required 85 percent figure; however, the minimum figure applies to the basket as a whole rather than just the cells of the fuel assemblies. Nonetheless, the minimum figure should be easily attainable, given appropriate access to other free spaces existing within a waste package fuel basket.

The procedure needed for addition of filler material is the same as presented in Ref. 23, *Analysis of MPC Access Requirements for Addition of Filler Materials*. The procedure requires access to essentially all free spaces within a loaded waste package. The design and operational requirements appropriate for small-diameter, near-spherical shot type of filler material include:

1. Design of the SNF basket and other internal structures shall not preclude attainment of a stipulated minimum percentage free volume fill, with the waste package oriented vertically, based on loose as-poured filler bulk density.

2. The SNF basket and other internal structure shall be designed to provide access to essentially all free spaces; that includes free spaces within any flux trap basket designs. Accessibility to any space shall be as nearly as practical at the top of the free space, with the waste package oriented vertically.

3. Inherent in item 2 above is the requirement that the filler material "flow stream" would be directed over the entire open top-end cross-sectional area of the SNF basket and internal structure, whereupon the filler material is intended to flow down into all open free spaces.

The filler material is intended to flow around and throughout each and every SNF assembly resting within the basket.

4. Achievement of the minimum fill would be by means of placement of a premeasured mass of filler material, the quantity appropriate to the particular type of SNF therein. This may be accomplished easily by utilizing preweighed hoppers on a crane, or by a movable chute to cover the entire top of the waste package. Recovery from possible off-normal filling (e.g., not achieving the minimum fill) is an MGDS responsibility that does not impact waste package design.

The stated percentages of free space filling is really a comparison of the amount of material actually emplaced compared to an ideally predicted value. This may be expressed most simply by comparing fill test density (emplaced mass ÷ free volume) as a percentage of the bulk material density. The success of the filler placement testing is summarized in Table 8-1. The column entitled "Fill Test Percent Fill" presents the testing results obtained for loose as-poured filler placement into the test fixture, which contained either of two dimensionally accurate replications of actual fuel assemblies, using two different sizes of graded steel shot, as compared to the ideally predicted values. The final column is the value: 100% minus the actual fill percent.

Table 8-1. Summary of Results for Loose As-Poured Shot Placement Testing

Small Shot, Size S230					Large Shot, Size S330				
Fill Test Number	Fill Test Density,g/cc	Shot Avg. Density,g/cc	Fill Test Percent Fill	Fill Test % Free Space	Fill Test Number	Fill Test Density,g/cc	Shot Avg. Density,g/cc	Fill Test Percent Fill	Fill Test % Free Space
1	4.490	4.617	97.25	2.75	3	4.353	4.615	94.32	5.68
2	4.529	4.617	98.09	1.91	7	4.397	4.615	95.28	4.72
5	4.538	4.617	98.29	1.71					
		average	97.88				average	94.80	
		std. dev.	0.55				std. dev.	0.67	
		std. dev. %	0.6				std. dev. %	0.7	

Results for each shot size are presented separately, as the results appear to be separate populations, even though the populations are quite small for statistical analysis. That is, the larger shot appears to fall further from the ideal than does the smaller shot, the larger shot having approximately double the amount of unfilled free spaces (including edge effects) as does the smaller shot. This result is not altogether surprising, as the smaller shot should result in less unfilled free space (and might be expected to be less susceptible to possible edge effects). Although seldom the case, should all other things be equal, these results would recommend that the smaller shot size be utilized, in the event that the program should decide to use filler material in waste packages. The tests show that the Society of Automotive Engineers (SAE) specifications were sufficient for procuring shot for the waste package fill.

9. REFERENCES

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2. *Waste Package Implementation Plan*, YMP/92-11Q, REV 1, Yucca Mountain Site Characterization Project.

3. QAP-3-5 *Development of Technical Documents*, REV 06, CRWMS M&O.

4. *Spent Nuclear Fuel Waste Package Filler Testing Technical Guidelines Document*, DI#: BBA000000-01717-2500-00003 REV 03, CRWMS M&O.

5. *Initial Review/Analysis of Thermal and Neutronic Characteristics of Potential MPC/WP Filler Materials*, DI#: BBA000000-01717-5705-00001 REV 00, CRWMS M&O.

6. *21 PWR Assembly MPC Waste Package Criticality Analysis*, DI#: BBABB0000-01717-0200-00004 REV 00, CRWMS M&O.

7. *Mined Geologic Disposal System Requirements Document*, DOE/RW-404P, DI#: B00000000-00811-1708-00002 REV 02, U.S. Department of Energy (DOE) Office Of Civilian Radioactive Waste Management (OCRWM).

8. *Engineered Barrier Design Requirements Document*, YMP/CM-0024, REV 0, ICN 1, Yucca Mountain Site Characterization Project.

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16. *SAE Cast Shot and Grit Size Specifications for Peening and Cleaning*, Society of Automotive Engineers Specification J444, Revised May 1993.

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18. *CRC Handbook of Chemistry and Physics*, 61st Edition, CRC Press, Inc., 1980-1981.

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20. *Standard Test Method for Thermal Conductivity of Solids by Means of the Guarded-Comparative-Longitudinal Heat Flow Technique*, American Society for Testing and Materials, ASTM Designation: E 1225-87 (Reapproved 1993).

21. *Advanced Engineering Mathematics*, Seventh Edition, E. Kreyszig, John Wiley & Sons, Inc., 1993 (referenced in Appendix A).

22. *Mechanical Measurements*, Third Edition, T. G. Beckwith, et.al., Addison-Wesley Publishing Company, 1982 (referenced in Appendix A).

23. *Analysis of MPC Access Requirements for Addition of Filler Materials*, DI#: BB0000000-01717-0200-00010 REV 01, CRWMS M&O.

24. *QAP-2-3 Control of Activities*, REV 02, CRWMS M&O.

25. *NLP-2-0 Determination of Importance Evaluations*, REV 02, CRWMS M&O.

APPENDIX A

Metaltec
Steel
Abrasive Co.

41155 Joy Rd., Carlton, Michigan 48187
(313) 459-7900 Fax # (313) 459-7907

PO#37113
RL#

Quality Control Certification

CUSTOMER: FRAMATONE COGEMA FUELS DATE APPROVED: February 01, 1996

SHOT SIZE: S-330 CUSTOMER SPECIFICATIONS: SAE

WEIGHT: 2,000 LBS.

MICRO STRUCTURE: UPPER AND LOWER CASE BAINITE

DENISTY AND APPERANCE: 7.2 g/cc , IRREGULAR

ROCKWELL "C" HARDNESS(1,000 g VICKERS INDENTER):44.8AVG. 10 READINGS

SAE SCREENING: SEE ATTACHED

% IRREGULAR VOIDS, HOLLOWS: ≤ 5 %

CHEMISTRY: C: 0.08 - 0.15 , Mn: 1.00 - 1.55 , Si: 0.125 - 0.245 , P: ≤ 0.05 , S: ≤ 0.05

LAB APPROVAL: [signature]

SHIPPMENT DATE: 2/1/96

METALTEC STEEL ABRASIVE COMPANY — LABORATORY TEST REPORT

DATE: 2/1/96

LAB No.

COMPANY: FRAMATOME Cogema Fuels
ADDRESS:
CITY: STATE: ZIP:

SAMPLE No. 1 S-330
SAMPLE No. 2
SALESMAN

SCREEN ANALYSIS			S-330			
ASTM-E11			SAMPLE No. 1		SAMPLE No. 2	
MESH	OPEN	SPECIFIC	RETAINED	ACCUM.	RETAINED	ACCUM.
5	.1570					
6	.1350					
7	.1110					
8	.0937					
10	.0787					
12	.0661					
14	.0555	all Pass	0.0	0.0		
16	.0469	5% max	0.2	0.2		
18	.0394		37.6	37.8		
20	.0331	85% min	58.9	96.7		
25	.0278	96% min	2.8	99.5		
30	.0234	PAN	0.5	100.0		
35	.0197					
40	.0165					
45	.0139					
50	.0117					
80	.0070					
120	.0049					
PAN						

CHEMICAL ANALYSIS

ELEMENT	SAMPLE No. 1	SAMPLE No. 2
CARBON		
MANGANESE		
SILICON		

COMMENTS:

DURABILITY TESTING — TAKE OUT SCREEN

100% LIFE TEST: 500 PASSES PER TEST RUN

	SAMPLE No. 1			SAMPLE No. 2		
ACCUM. PASSES	% REMAIN	% LOSS	ACCUM LOSS%	% REMAIN	% LOSS	ACCUM LOSS%
500						
1000						
1500						
2000						
2500						
3000						
3500						
4000						
4500						
5000						
	PASSES : 100.0			PASSES : 100.0		

THE LIFE OF SAMPLE No. 1 IS % OF SAMPLE No. 2

ARC HEIGHT TESTING (ATTACHED)

SAMPLE No. 1 (adx) : inches

SAMPLE No. 2 (adx) : inches

HARDNESS TESTING: ROCKWELL "C" SCALE

SAMPLE No. 1	SAMPLE No. 2
AVERAGE :	AVERAGE :
RANGE :	RANGE :

LABORATORY TECHNICIAN: DH

REVIEWED BY:

SUBMITTED TO:

DATE:

Metaltec Steel Abrasive Co.

41155 Joy Rd., Canton, Michigan 48187
(313) 459-7900 Fax # (313) 459-7907

PO#37113
RL#

Quality Control Certification

CUSTOMER: FRAMATONE COGEMA FUELS DATE APPROVED: February 01, 1996

SHOT SIZE: S-230 CUSTOMER SPECIFICATIONS: SAE

WEIGHT: 2,000 LBS.

MICRO STRUCTURE: UPPER AND LOWER CASE BAINITE

DENISTY AND APPERANCE: 7.2 g/cc, IRREGULAR

ROCKWELL "C" HARDNESS(1,000 g VICKERS INDENTER):44.8AVG. 10 READINGS

SAE SCREENING: SEE ATTACHED

% IRREGULAR VOIDS, HOLLOWS: ≤ 5 %

CHEMISTRY: C: 0.08 - 0.15, Mn: 1.00 - 1.55, Si: 0.125 - 0.245, P: ≤ 0.05, S: ≤ 0.05

LAB APPROVAL: Derek Hawn

SHIPPMENT DATE: 2/1/96

METALTEC STEEL ABRASIVE COMPANY — LABORATORY TEST REPORT

DATE: 2/1/96

LAB No.

COMPANY: FRAMATOME Cogema Fuels
ADRESS:
CITY: STATE: ZIP:

SAMPLE No. 1 S-230
SAMPLE No. 2
SALESMAN

SCREEN ANALYSIS S-230

ASTM-E11			SAMPLE No. 1		SAMPLE No. 2	
MESH	OPEN	SPECIFIC	RETAINED	ACCUM.	RETAINED	ACCUM.
5	.1570					
6	.1350					
7	.1110					
8	.0937					
10	.0787					
12	.0661					
14	.0555					
16	.0469					
18	.0394	All Pass	0.0	0.0		
20	.0331	10% max	5.9	6.0		
25	.0278		88.1	94.1		
30	.0234	85% min	5.4	99.6		
35	.0197	97% min	0.4	99.9		
40	.0165	PAN	0.1	100.0		
45	.0139					
50	.0117					
80	.0070					
120	.0049					
PAN						

CHEMICAL ANALYSIS

ELEMENT	SAMPLE No. 1	SAMPLE No. 2
CARBON		
MANGANESE		
SILICON		

COMMENTS:

DURABILITY TESTING TAKE OUT SCREEN

100x LIFE TEST: 500 PASSES PER TEST RUN

	SAMPLE No. 1			SAMPLE No. 2		
ACCUM. PASSES	% REMAIN	% LOSS	ACCUM LOSS%	% REMAIN	% LOSS	ACCUM LOSS%
500						
1000						
1500						
2000						
2500						
3000						
3500						
4000						
4500						
5000						
	PASSES : 100.0			PASSES : 100.0		

THE LIFE OF SAMPLE No. 1 IS % OF SAMPLE No. 2

ARC HEIGHT TESTING (ATTACHED)

SAMPLE No. 1 (max) : inches

SAMPLE No. 2 (max) : inches

HARDNESS TESTING: ROCKWELL "C" SCALE

SAMPLE No. 1	SAMPLE No. 2
AVERAGE :	AVERAGE :
RANGE :	RANGE :

LABORATORY TECHNICIAN: DH

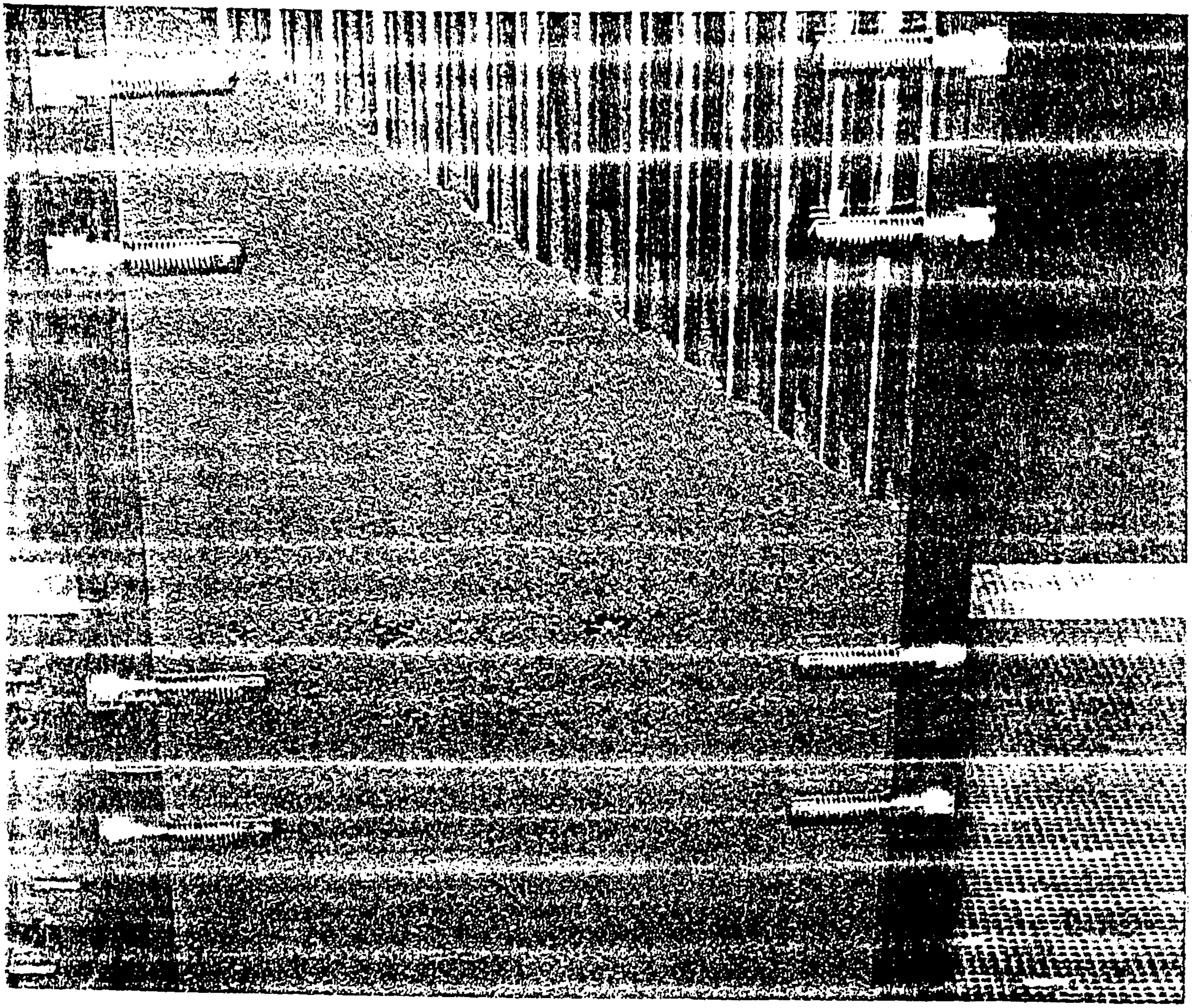
REVIEWED BY:

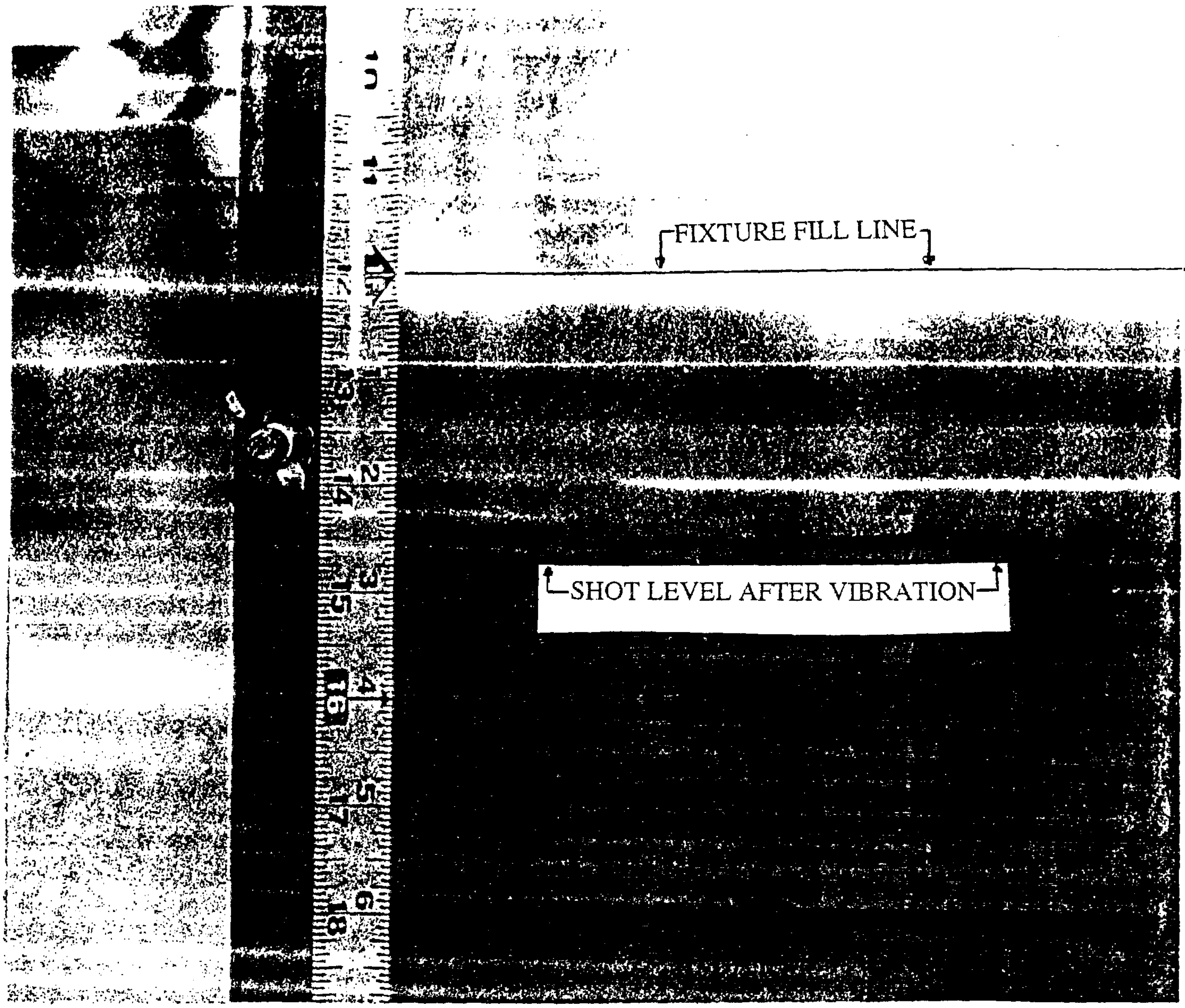
SUBMITTED TO:

DATE:

MT006

BBA000000-01717-2500-00008 REV 01 A5 07/29/96

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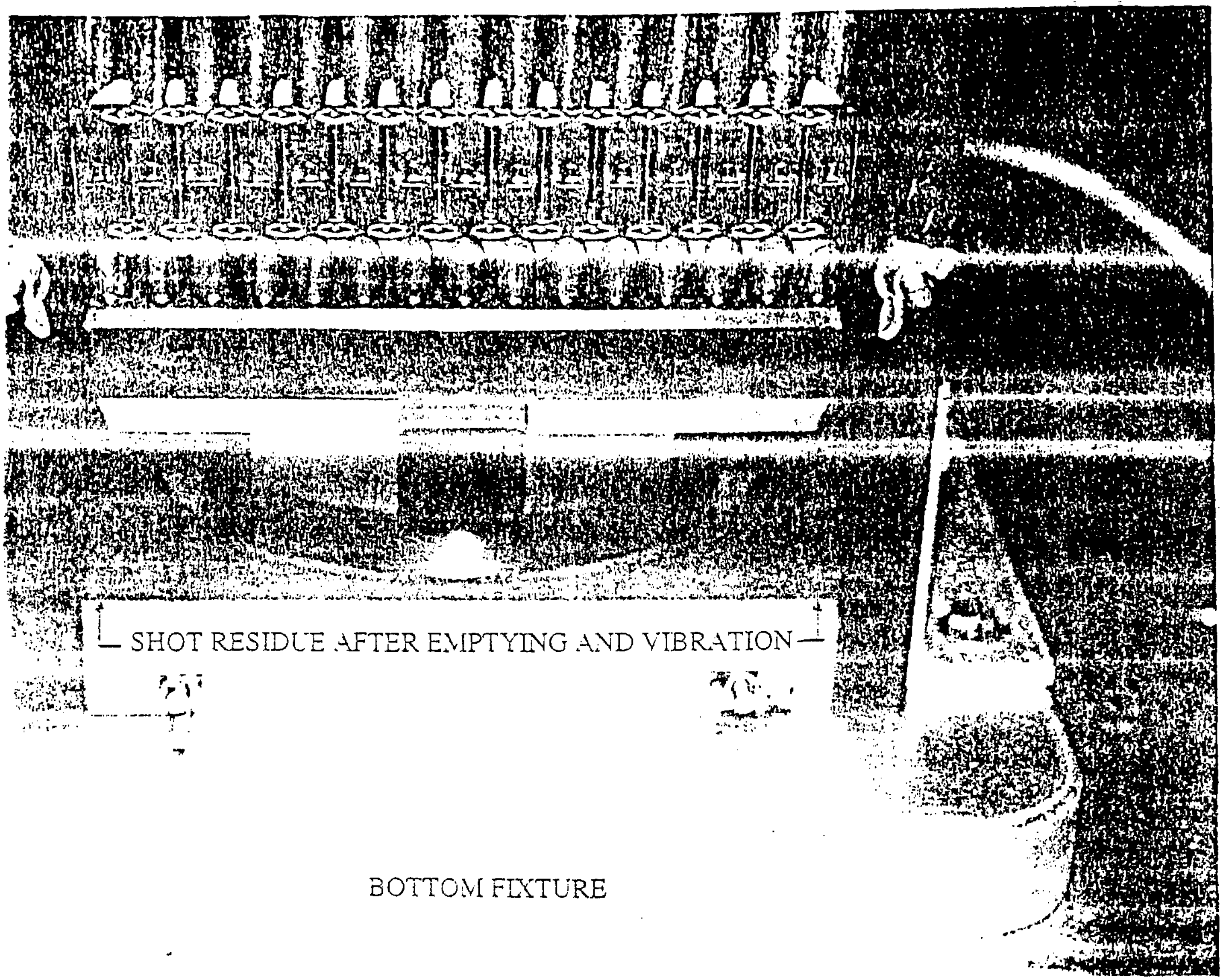
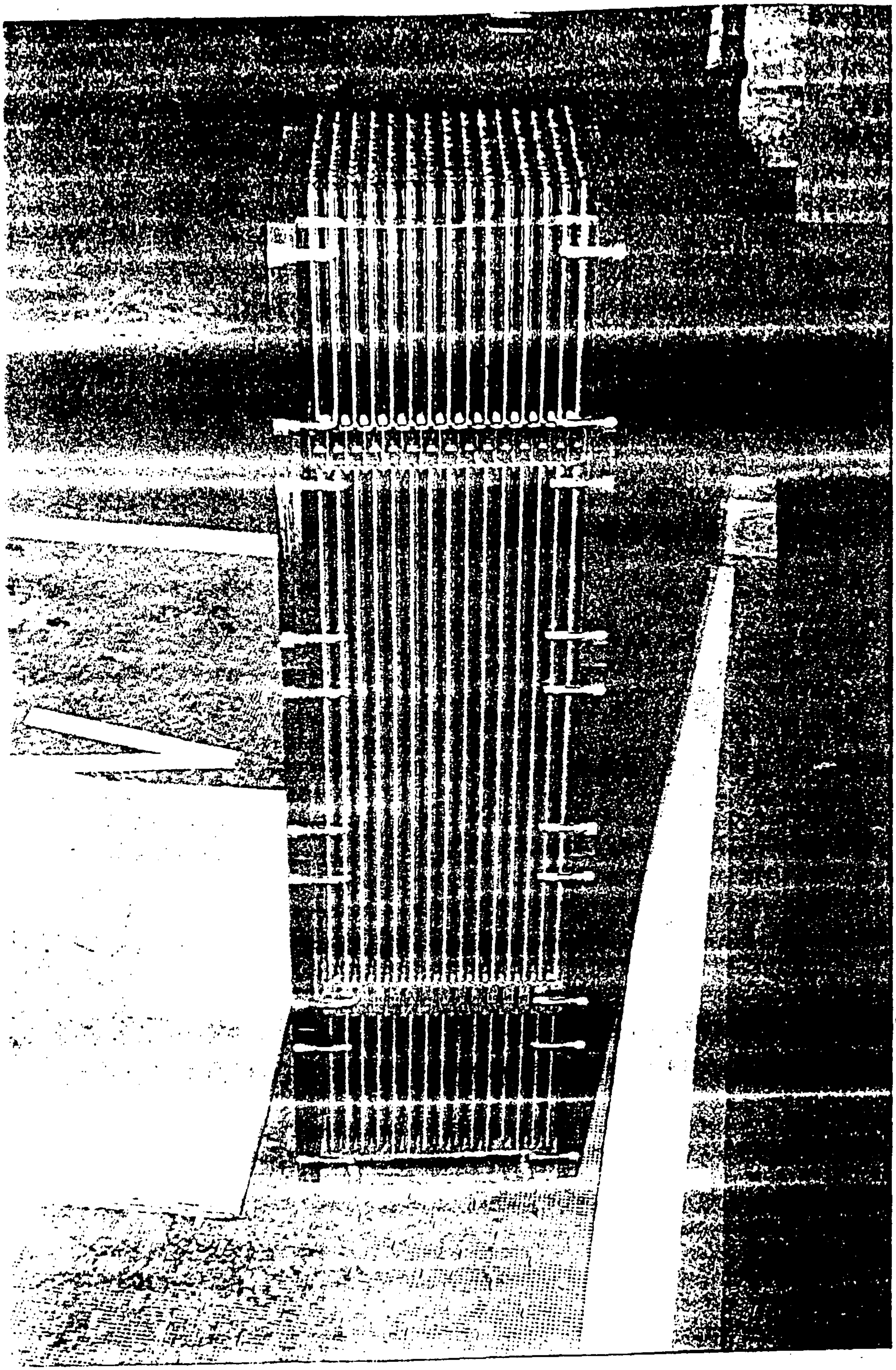
SHOT LEVEL AFTER VIBRATION



BOTTOM FIXTURE

SMALL FIXTURE AND TWO GRID BUNDLE



Test Measurement Accuracy

Two different scales were used during the testing at FCF Lynchburg to measure weight; one being a small laboratory platform scale used to weigh the 100 ml graduated container plus contents for determination of bulk densities, and the other being a scale upon which each bucket of shot could be suspended.

Digital Platform Scale

Type: NCI Model 8250 (scale used for testing) with Remote Model 3222 (not used)
Identification Number: Model 8250 S/N SR91920348, Remote Model 3222 S/N SR63920198
Date of last calibration: 1/2/96
Date of next calibration: 4/22/96
Post-test performance calibration check: No (calibrated 4/22/96)
Range of scale: 0 to 2.2 kg; 0 to 22 kg remote
Range of weights actually measured: 0 to 0.65 kg
Graduation: 0.0005 kg (0.5 g)
Measurement accuracy: Model 8250, zero error observed for all points between 20 g and 1 kg, both calibration dates

Suspended Digital Crane Scale

Type: Samson Model SC-500, Digital Crane Scale
Serial Number: QC-2058
Date of last calibration: 2/26/96
Date of next calibration: (annual)
Post-test performance calibration check: No
Range of scale: 0 to 500 lb
Range of weights measured during testing: 0 to 115 lb
Graduation: 0.2 lb
Measurement accuracy: see Table A-1
(Tester used is Weidemann Baldwin Emery Load I INDICATOR (QC-519) which was calibrated to 1% accuracy traceable to National Bureau of Standards)

Estimation of weight measurement accuracy for the crane scale involves both measurement bias and measurement uncertainty for each weight measurement taken, and then the combination of the bias and uncertainty for the number of incremental weights (number of buckets of shot) making up the total weight added or removed from the test fixture for any given fill test. References 21 and 22 were used to provide guidance on the treatment of test measurements and inaccuracy.

First, the tester used to calibrate the crane scale is stated as being within 1% accuracy; consequently, the total weight of filler added or removed could be inaccurate by ±1%, or ~ ±14 lb, even if the scale were assumed to be perfectly accurate.

Addition of filler was performed in each test with $\leq$31 weighed buckets of ~40-90 lb of shot each; removal of filler was performed in each test with $\leq$16 weighed buckets of ~100 lb of shot each. The crane scale graduation is 0.2 lb. The scale calibration registered 0.4 lb high at 100 lb, thus the scale bias at 100 lb is 0.4±0.1 lb high, a figure which should be subtracted from readings in the 100 lb range. No other calibration readings are available between 0 and 100 lb load. Lacking calibration for the ~40-90 lb range, it was first assumed that the 0.4±0.1 lb bias at 100 lb also exists for the ~40-90 lb range (i.e., a constant bias of 0.4±0.1 lb from 0 to 100 lb, a rather severe assumption considering the bias error was zero at 0 lb).

Fill Test No. 2 will be used as an example to examine for crane scale bias, and to test the assumption stated in the previous paragraph. The total number of buckets for filling was 31 (including vibration fill), average weight ~45 lb. Total number of bucket for draining was 16, average weight ~86 lb. Utilizing the 0.4±0.1 lb bias for all measurements, the total weight to fill would be adjusted downward by 12.4±3.1 lb for a new total of 1368.2±3.1 lb, and the total weight removed would be adjusted downward by 6.4±1.6 lb to 1372.8±1.6 lb. These adjusted results indicate more weight was removed than was originally added (~4.6 lb plus unrecovered residual of 3.0 lb for a total of ~7.6 lb), which is clearly not correct. Thus, it must be concluded that the assumption of the 0.4±0.1 lb bias for ~40-90 lb range could not have been a valid assumption.

The alternative and more likely assumption is that the crane scale bias is proportional to weight, between 0 to 100 lb, and would result in equivalent and canceling bias adjustments to the totals for filler added and removed; both totals would be adjusted downward by 0.4±0.1%, or 5.52±1.38 lb. That is, the cumulative bias for filler addition should be approximately equal to the cumulative bias upon filler removal.

To summarize, the cumulative weight uncertainty as a consequence of the crane scale being calibrated to a tester with 1% accuracy results in a weight uncertainty of ~ ±14 lb. The cumulative affect of the crane scale bias has been deduced to necessitate a downward adjustment of measured values by ~ -5.5 lb (note: the test results were not adjusted, the as-measured results have been used throughout this report).

Fill tests resulted in differences between filler added and filler removed (including residual) follows:

Fill Test No. 1	+0.6 lb
Fill Test No. 2	-1.6 lb
Fill Test Nos. 3 & 4	+5.0 lb
Fill Test Nos. 5 & 6	-3.2 lb
Fill Test Nos. 7 & 8	+1.2 lb
Average	+0.3 lb
Standard Deviation	3.1 lb

Table A-1. Crane Scale Calibration Report Test Results

Tester Reading	Scale Reading	Error
0	0	0
100	100.4	+0.4
150	149.4	-0.6
200	199.8	-0.2
300	298.4	-1.6
400	396.6	-3.4
500	496.4	-3.6

Standard deviation = 0.5%