SYRACUSE UNIVERSITY
BUILDING ENERGY AND ENVIRONMENTAL SYSTEMS LABORATORY (BEESL)
263 Link Hall, Syracuse University, Syracuse, NY 13244-1240; <http://BEESL.Syr.Edu>

SYRACUSE UNIVERSITY TEST REPORT ON UPTAKE FACTOR RESULTING FROM A DROPPED STORAGE CONTAINER PHASE II

FINAL REPORT

By
Zhi Gao, PhD, Research Associate
Jianshun (Jensen) S. Zhang, PhD, Principal Investigator*

(*Tel. 315-443-1366; Fax 315-443-9099; Email: jszhang@syr.edu)

January 2012

Prepared For
US DOE/B&W Y-12

DISCLAIMER

This work of authorship and those incorporated herein were prepared by Contractor as accounts of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, use made, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency or Contractor thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency or Contractor thereof.

EXECUTIVE SUMMARY

Under certain circumstances, powder from an accidentally dropped container can become airborne and inhaled by people nearby such as those who are moving the containers. The inhaled fine particles can deposit on respiratory tracts and lungs, causing asthma, lung cancer, and other acute respiratory illnesses and chronic symptoms. The objective of this study was to develop a standard procedure to measure the airborne concentrations of different size particles within the vicinity of a dropped container where a significant portion of the contained powder is ejected.

Tungsten oxide (WO_3) was selected in this study to represent relatively heavy powders (7.16 g/cm^3 specific gravity for WO_3). A typical can with the outer dimensions of 4.25" diameter and 4.875" tall was used as the container. The powder was dropped in two different configurations: 1) contained within a can covered by a lid that has a 0.25" diameter hole, and 2) contained within a can without a lid. The packing volume of the powder was 51.4 in^3 (842.7 cm^3) and the target mass was 1936 g. The tests were carried out in a full-scale stainless steel environmental chamber with an interior volume of 852 ft^3 (24.1 m^3). The chamber system includes an internal recirculation loop with a rectangular air diffuser and 10 variable frequency drive fans to provide a typical room air recirculation flow pattern. Two air filters were installed in the chamber air supply duct and return duct to achieve the required low background particle concentration. The initial chamber air conditions were set at 70°F ($\pm 5^\circ\text{F}$) and 50% ($\pm 10\%$) RH. A supporting frame and releasing device were designed and built to trigger consistently the dropping of the can. The particle sampling inlet was placed 5 ft above the floor and 6 inches laterally away from the can's falling path. Concentrations of particles between $0.5 \mu\text{m}$ and $20 \mu\text{m}$ were recorded in units of mass and number of particles per unit volume. The data acquisition rate was once every 2 seconds during the first 2 hours.

A test procedure was developed and verified. A total of thirty two drop tests were performed, eight in Phase I and twenty four in Phase II, covering variations in dropping height (8 ft or 4 ft from the floor), room air movement (0.25-0.30 m/s or 0.10-0.15 m/s near the ceiling), landing scenario (on a flat plate or a block), and lid condition ($\frac{1}{4}$ " lid hole or no lid). There were ten tests with flat plate and $\frac{1}{4}$ " lid hole, ten tests with flat plate no lid and twelve tests with block no lid. Major findings are summarized below:

- The amount of spilled powder varied from 0.01 g to 1061.15 g. The corresponding percentage of the spilled powder ranged from below 0.01% to 54.81%. Specifically, the spilled powder was within 0.12 ~ 4.42 g (0.01 ~ 0.23%) with 8 ft drop height, 0.01 ~ 0.07 g ($<0.01\%$) with 4 ft drop height for flat plate with $\frac{1}{4}$ " lid hole; within 0.43 ~ 190.44 g (0.02 ~ 9.84%) with 8 ft drop height, 1.08 ~ 2.05 g (0.06 ~ 0.11%) with 4 ft drop height for plate with no lid and 74.23 ~ 631.01 g (3.83 ~ 32.65%) with 8 ft drop height, 320.03 ~ 1061.15 g (16.53 ~ 54.81%) with 4 ft drop height for block with no lid.
- The peak value of particle number concentration after the dropping of the can occurred at approximately $0.9 \mu\text{m}$ particle size per measured data of individual channels. The

peak value of particle mass concentration occurred in the range of 4.3 - 10 μm particle size per grouped data calculated from the measured data.

- ❑ After the dropping of the can, the total airborne mass concentrations ranged from 0.02 to 1.85 mg/m^3 , while the total airborne number concentrations ranged from 2.4 to 383.5 $\#/\text{cm}^3$. In general, tests with lid had smaller concentrations than tests without lid.
- ❑ The uptake factor and associated inhalation exposure can be readily assessed by the test method developed. But it is challenging to use the method to check the mass balance since the ratio of airborne mass to non-recovered mass was very small, ranging from 0.1% to 7.4%.
- ❑ Assuming a breathing rate of 1.2 m^3/h , the calculated cumulative uptake mass within first 10 minutes after the dropping of the can for each test was within the range of 0.002 mg to 0.2 mg, while the uptake factor during the first 10 minutes was calculated to be between 1.13×10^{-9} and 1.03×10^{-7} in reference to the amount loaded; or between 6.44×10^{-8} and 3.55×10^{-4} in reference to the amount spilled. In general, larger amount of powder ejection results in a larger uptake factor.

The experimental results of this study provides previously unavailable data for estimating the exposure and associated risk to building occupants in the case of an accidental dropping of heavy powder containers. For materials used at the Y-12 National Security Complex like uranium oxide with an A_2 of 3,000 grams an acceptable release or spill of $A_2 \times 10^{-3}$ (3 grams) generates a 5 rem CEDE inhalation uptake dose limit of 3×10^{-3} grams per IAEA Safety Guide TS-G-1.1-2008 and DOE M 441.1-1, 2008. Based on the linear average correlation between the amount of respirable oxide spilled and the inhalation dose for a 10 minute accident event using the test results in this study, reaching the same of 3×10^{-3} grams dose limit would require an estimate respirable oxide spill of 21,350 grams based upon the average linear equation in Figure 20 instead of the 3 grams from DOE M 441.1-1, 2008. This means the DOE M 441.1-1 is 7,116 (21,350/3) times safer.

It should be noted that the present study covers a limited number of accidental dropping scenarios under one typical type of room air distribution environment. It is recommended that a more comprehensive study be conducted to develop and validate a computational fluid dynamics model that can be used to evaluate a wider range of accidental spill scenarios. The mechanism of particle ejection due to accidental dropping and its correlation to the airborne concentration and associated exposure also need to be further studied to devise effective means to reduce the amount of spill and exposure level.

TABLE OF CONTENTS

1. INTRODUCTION AND OBJECTIVES	7
2. TEST FACILITIES	8
2.1 Full-scale Stainless Steel Environmental Chamber	8
2.2 Selection of Surrogate Material	8
2.3 Container Size and Filling Conditions	11
2.4 Dropping Mechanism	11
2.5 Instrumentation for Sampling and Analysis	12
3. EXPERIMENTAL AND DATA ANALYSIS METHODS	12
3.1 Test Method and Procedure	12
3.2 Experimental Design.....	13
3.3 Data Analysis Method.....	15
4. EXPERIMENTAL RESULTS AND DISCUSSIONS	16
4.1 Test Conditions	16
4.2 Amount of Ejected Materials.....	17
4.3 Airborne Mass and Number Concentrations.....	22
4.4 Uptake Factor	28
4.5 Parametric Analysis.....	30
4.6 Observation of Material Ejection Behavior.....	32
5. CONCLUSIONS AND RECOMMENDATIONS	33
6. ACKNOWLEDGEMENTS.....	34
7. REFERENCES.....	35
APPENDIX 1: TEST PROCEDURE.....	36
APPENDIX 2: TEST EQUIPMENT	38
APPENDIX 3: RELATED DOCUMENTS	39
A3-1 Aerodynamic Diameter and Stokes Correction.....	39
A3-2 Certificate of Calibration of APS 3321 (TSI Inc.).....	41
A3-3 Physical Size Distribution Analysis of Tungsten Oxide (LOT # Q1844) by Powder Technology Inc.	43
A3-4 In-House Calibration of Veloci-Calc 8347 Air Velocity Meter (TSI Inc.).....	44
A3-5 Certificate of Calibration of Veloci-Calc 9565-9 and Probe 964 (TSI Inc.)	45
APPENDIX 4: TEST RESULTS	47
Test 01 HHFQ1	47
Test 02 HHFQ2	51
Test 03 HHFQ3	55
Test 04 HHFQ4	59
Test 05 HLFQ1.....	63
Test 06 HLFQ2.....	67
Test 07 LHFQ1.....	71
Test 08 LHFQ2.....	75
Test 09 LLFQ1	79
Test 10 LLFQ2	83

Test 11 HHFN1	87
Test 12 HHFN2	91
Test 13 HHFN3	95
Test 14 HHFN4	99
Test 15 HLFN1	103
Test 16 HLFN2	107
Test 17 LHFN1	111
Test 18 LHFN2	115
Test 19 LLFN1	119
Test 20 LLFN2	123
Test 21 HHBN1	127
Test 22 HHBN2	131
Test 23 HHBN3	135
Test 24 HLBN1	139
Test 25 HLBN2	143
Test 26 HLBN3	147
Test 27 LHBN1	151
Test 28 LHBN2	155
Test 29 LHBN3	159
Test 30 LLBN1	163
Test 31 LLBN2	167
Test 32 LLBN3	171

1. INTRODUCTION AND OBJECTIVES

Under certain circumstances, powder from an accidentally dropped container can become airborne and inhaled by people nearby such as those who are moving the containers. One of the objectives of this study is to develop a standard procedure to measure the airborne concentrations of different size particles within the vicinity of a dropped container when a significant portion of the contained powder is ejected. While the ultimate goal of this study is to determine a realistic uptake factor that may replace the 10^{-3} estimate published in IAEA Safety Guide TS-G-1.1 and DOE M 441.1-1 for materials in use at the Y-12 National Security Complex. Phase I of the testing represents the first step in providing measured data and improved understanding of the particle ejection and distribution in support of the potential replacement of the estimate. The parametric study of Phase II consists of tests using the same surrogate powder in Phase I under expanded test configurations. In order to obtain repeatable and reliable test results, the same standardized test method and procedure were used in Phase II as those in Phase I, including environmental test conditions, container size and filling conditions, sampling method and location.

Specific objectives of the study are:

- 1) Measure the actual breathing zone airborne particle concentrations of a surrogate powder resulting from a dropped storage container (4.25" diameter and 4.87" tall) by using a full-scale environmental chamber under the specified standard test conditions ($70^{\circ}\text{F} \pm 5^{\circ}\text{F}$, $50\% \pm 10\%$ RH and sampling height of 5 ft);
- 2) Experimentally determine the uptake factor. Vary important testing parameters to determine similar correlations with respect to changes of drop height and air speed in the environmental chamber that simulates ventilated spaces;
- 3) Generate drop tests that release respirable oxide spill as much as possible to further establish the correlations between the uptake factor and the amount of particles spilled from the container for a wider range of spilled amount conditions;
- 4) Improve the understanding of the particle ejection behavior by using high speed video imaging technique.

2. TEST FACILITIES

2.1 Full-scale Stainless Steel Environmental Chamber

A full-scale stainless steel environmental chamber was used in the test. The chamber (Figure 1) has dimensions of 12 ft × 7.1 ft × 10 ft high (3.66 m × 2.16 m × 3.05 m high) and an interior volume of 852 ft³ (24.1 m³). Detailed description of this chamber facility and its performance including air-tightness, cleanness, air mixing, environmental control accuracy can be found in Herrmann et al. (2003). For this study, the original chamber system was modified to include an internal recirculation loop with a rectangular air diffuser and 10 variable frequency drive fans to provide a typical room air recirculation flow pattern and the range of air velocity approximately 12" from the ceiling of the room (0.25 - 0.3 m/s). The slot was adjusted to be 1.5" wide and fan frequency was adjusted to be 40 Hz for 0.25 - 0.30 m/s and 25 Hz for 0.10 - 0.15 m/s. Two air filters (24"×12"×2.75") were installed in the chamber air supply duct and return duct to achieve the required low background particle concentration. The chamber's air-tightness was verified by tracer gas test to be around 0.02 ACH. The chamber air conditions were set at 70°F (± 5°F), 50% (± 10%) RH.

a. Exterior

b. Interior

Figure 1. The modified ultra-clean full-scale climate chamber

2.2 Selection of Surrogate Material

The most important factor of inhalation hazard is the material's aerodynamic diameter particle size distribution. A typical Y-12 National Security Complex oxide aerodynamic diameter distribution can be found in Hoover et al.'s study (1998). The U₃O₈ enriched uranium bulk density of the loose powder measured by Hoover et al. was approximately 2 g/cm³. Particle density is approximately 8 g/cm³. Chemical analysis at the Y-12 Plant Laboratory showed that the sample is 0.846 uranium by mass. The total weight of the

surrogate material in the can is also important since it affects the impacting energy and hence the ejection of the particles.

In this study, the surrogate was selected from commercially available products. The candidate surrogate materials included titanium oxide, tungsten oxide and Arizona dust (ultrafine, fine, medium and coarse). Tungsten oxide (CAS #: 1314-35-8) was chosen because it approximately matches the aerodynamic diameter particle size distribution of U_3O_8 , and has similar particle density. The material properties are shown in Table 1.

Table 1. Material properties of tungsten oxide

Formula	Specific gravity	Melting point	OSHA /PEL ^[1]	ACGIH /TLV ^[2]	HMIS ^[3] ratings	Appearance
WO ₃	7.16 g/cm ³	1473°C	5 mg/m ³	10 mg/m ³	Health: 2	Dark green, heavy powder, no odor. When heated, it turns dark orange

Note:

[1] Occupational Safety & Health Administration / Permissible Exposure Limits.

[2] American Conference of Governmental Industrial Hygienists / Threshold Limit Value, represented as time-weighted-average (TWA) inhalation exposure for up to 10 hours in a 40 hour working week.

[3] Hazardous Materials Identification System.

Figure 2. Size distribution of tested tungsten oxide

The physical and aerodynamic size distributions of tested tungsten oxide are shown in Figure 2. The aerodynamic size distributions of uranium oxide and tested tungsten oxide are compared in Table 2.

Table 2. Comparison of aerodynamic size distributions of uranium oxide and tested tungsten oxide

Aerodynamic diameter (μm)	Fraction of the total mass		Fraction of mass < 50 μm		Fraction of mass < 20 μm		Fraction of mass < 10 μm	
	U_3O_8	WO_3	U_3O_8	WO_3	U_3O_8	WO_3	U_3O_8	WO_3
$d > 50$	0.64	0.48	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
$20 < d < 50$	0.22	0.27	0.61	0.52	N.A.	N.A.	N.A.	N.A.
$10 < d < 20$	0.12	0.09	0.33	0.18	0.91	0.38	N.A.	N.A.
$4.3 < d < 10$	0.0051	0.0476	0.014	0.091	0.039	0.19	0.44	0.30
$2.9 < d < 4.3$	0.0043	0.0112	0.012	0.021	0.033	0.045	0.37	0.07
$2.0 < d < 2.9$	0.0018	0.0116	0.005	0.022	0.014	0.046	0.16	0.07
$1.2 < d < 2.0$	0.0002	0.0243	0.0006	0.047	0.0015	0.097	0.02	0.16
$d < 1.2$	<0.0001	0.0616	0.0003	0.118	0.0008	0.25	<0.01	0.39

Figure 3. Mass ratio of tungsten oxide to uranium oxide at different aerodynamic sizes

Figure 3 shows the mass ratio of tungsten oxide to uranium oxide at different particle sizes. It can be seen that WO_3 and U_3O_8 have comparable amounts of large particles (larger than 10 μm). However, this batch of WO_3 has more small particles than U_3O_8 . When particle size is between 1.2 μm and 2 μm , or smaller than 1.2 μm , the mass ratio of $\text{WO}_3 / \text{U}_3\text{O}_8$ is as big as about 120 and 620, respectively. Since particles must be airborne to become an inhalation hazard, using WO_3 as the testing material can be seen as the worst case scenario of the real condition of U_3O_8 , and hence a conservative approach for inhalation exposure control.

2.3 Container Size and Filling Conditions

The container (House of Cans 1817) is 4.25" diameter and 4.875" tall from outside. When minus the thickness of top rim (0.125") and bottom rim (0.125"), the can is 4.625" tall. The powder was filled to a level 1" below the top rim of the can. So the final packing height was 3.625" and the packing volume was 51.425 in³ (842.7 cm³). Loose packing was adopted, and the packing density was determined by averaging the results from three packing density tests (Table 3). The target mass of powder was 1936 g, calculated as the product of the packing volume times the packing density. Figure 4 shows the loose packed powder in the container.

Table 3. Determination of loose pack density

#	Loose pack volume (cm ³)	Mass of powder (g)	Loose pack density (g/cm ³)	
1	33	75.55	2.289	2.297
2	43	97.26	2.262	
3	48	112.36	2.341

Figure 4. The container with loose packed powder

2.4 Dropping Mechanism

A supporting frame and releasing device (Figure 5) were made to trigger the dropping of the can to the impacting surface. The impacting surface was a 0.5" thick square steel plate (29"×29"), weighing 54 kg (119 lb). The releasing device was a solenoid that pulled the rod supporting the bottom of the can in the cylinder.

Figure 5. The supporting frame and releasing device

2.5 Instrumentation for Sampling and Analysis

APS 3321 (TSI Inc.) aerosol particle sizer was used for measurement of the concentration of particles ranging from 0.5 to 20 μm in diameter. Temperature and RH in the chamber were monitored by IAQ-Calc 8762 (TSI Inc.) in Phase I or Veloci-Calc 9565-P (TSI Inc.) with Probe 964 in Phase II. A photoacoustic gas monitor (INNOVA 1312) was used for real-time measurement of the concentration of tracer gas (SF_6) to determine the actual clean air change rate from the decay curve of SF_6 . The detection limit, accuracy and precision of the quantities measured with the sampling and analysis instruments described above are as follows (Table 4):

Table 4. Data quality indicator table

Parameter or Instrument	Detection Limit or Range	Accuracy ($\pm\text{STD}$)	Precision ($\pm\text{STD}$)
APS 3321	0.001 particles/ cm^3	<5% coincidence at 0.5 μm ; <10% coincidence at 10 μm (at 1000 particles/ cm^3)	$\pm 10\%$ of reading plus variation from counting statistics
Air Change Rate	/	$\pm 5.0\%$	$\pm 3.0\%$
Temperature	0 - 60°C	$\pm 1.0^\circ\text{C}$	$\pm 0.5^\circ\text{C}$
Relative Humidity	5% - 95%	$\pm 5.0\%$	$\pm 3.0\%$

3. EXPERIMENTAL AND DATA ANALYSIS METHODS

3.1 Test Method and Procedure

Figure 6 shows the conceptual schematic of the test procedure of this project. It consists of four test periods. In the beginning, the chamber is flushed with clean air at 14 air

changes per hour (ACH) for more than 10 hours. Three-quarter hour before the dropping of the can, the test performer enters the chamber with proper protective wear, sets up the equipment (light, camera and other equipment) and leaves the chamber. One-quarter hour before the dropping of the can, The HVAC system is shut down and the valves at the supply and return duct are closed. Ten small fans in the diffuser box are turned on and the chamber is operated at full-recirculation mode. At time zero, the solenoid valve of the releasing device is triggered from outside of the chamber to drop the can. Detailed step-by-step procedure is described in Appendix 1.

Figure 6. Conceptual schematic of test procedure

The particle sizer APS 3321 is placed on a stainless steel stand, which is about 3 ft above the floor and in the middle of the chamber. Silicone tubing is used for particle sampling because it reduces the build-up of static charge and minimizes particle loss to the tubing wall. The particle sampling inlet is placed 5 ft above the floor and 6 inches laterally away from the can's falling path. Concentrations of particles between 0.5 μm and 20 μm were recorded in units of mass and number of particles per unit volume. The data acquisition rate was once every 2 seconds during the first 2 hours.

3.2 Experimental Design

Two different configurations of the can lid were tested: (1) with a lid that has a 0.25" hole at the center of the lid (Figure 7), and (2) without a lid. The other varying parameters included:

- **Impacting surface** To release respirable oxide spill as much as possible to bolster the large release correlations, we used a can with no lid dropped on a 6" $\times$ 4" $\times$ 3" steel block (Figure 8) placed on the steel flat plate so the can could tumble upon impact.
- **Drop height** In Phase II testing, the releasing device was modified in order that the can could also be dropped at a height of 4 feet besides 8 feet (Figure 9).

- **Air Speed** By adjusting the slot width and the frequency of the 10 variable frequency drive fans in the recirculation fan bank, the maximum air velocity due to room air recirculation was around 0.25 – 0.30 m/s near the top of the room in Phase I. In Phase II, we lowered the frequency of the fans to have an air speed of 0.10 – 0.15 m/s (Figure 10).

Figure 7. The container covered by a lid with a hole

Figure 8. Impacting block

a. Drop height of 8 ft

b. Drop height of 4 ft

Figure 9. The release device with different drop heights

Figure 10. The electrical device to change the frequency of variable speed fans

A total of 32 tests were conducted, 8 in Phase I and 24 in Phase II (Table 5). The chamber was cleaned between each test. Prior to each dropping test, the air would be conditioned and filtered to achieve the required test condition.

Table 5. Test cases

Drop Height (ft)	Air Speed (m/s)	Number of Tests Flat Plate (0.25" lid hole)	Number of Tests Flat Plate (no lid)	Number of Tests Block (no lid)
8	0.25-0.30	HHFQ ^[1] 4 (1-4) ^[2]	HHFN 4 (11-14) ^[2]	HHBN 3 (21-23)
8	0.10-0.15	HLFQ 2 (5-6)	HLFN 2 (15-16)	HLBN 3 (24-26)
4	0.25-0.30	LHFQ 2 (7-8)	LHFN 2 (17-18)	LHBN 3 (27-29)
4	0.10-0.15	LLFQ 2 (9-10)	LLFN 2 (19-20)	LLBN 3 (30-32)
Total test cases		10	10	12

Notes:

[1] The naming method: “HHFQ” to represent “High drop”, “High air speed”, “Flat plate” and “Quarter inch hole”; while “LLBN” to represent “Low drop”, “Low air speed”, “Block” and “No lid”.

[2] Tests 1 through 4 and Tests 11 through 14 were performed in Phase I.

3.3 Data Analysis Method

The uptake factor can be defined as

$$\text{spilled uptake factor}_N = \frac{\text{breathing rate} \times \sum_i^N [(t_i - t_{i-1}) \times \text{airborne concentration}_i]}{\text{spilled mass}} \quad (1)$$

or

$$\text{loaded uptake factor}_N = \frac{\text{breathing rate} \times \sum_i^N [(t_i - t_{i-1}) \times \text{airborne concentration}_i]}{\text{loaded mass}} \quad (2)$$

at the Nth data point. The spilled mass is the difference between the initial and final mass of the can. The breathing rate estimate of 1.2 m³/h and a 10-min time interval were used in this study.

Note that Equation (1) defines the uptake factor in reference to the spilled/ejected mass at impacting as in the current standard. Equation (2) defines the uptake factor in reference to the loaded mass - i.e., the initial mass in the can before dropping, which can be controlled precisely, and hence is a more stable reference parameter. Results from both definitions are presented in the following sections.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Detailed results for each test are presented in Appendix 4. In this section, we summarize and discuss the major findings that are of particular interest to the objectives of this study.

4.1 Test Conditions

Chamber air temperature and relative humidity during the test are shown in Figure A*-a (“*” denotes test number) in Appendix 4. In general, we can see that when switching from flushing mode to recirculation mode, temperature begins to increase slightly due to heat from the fans and measurement devices, and relative humidity begins to drop slightly due to the increase in temperature. The ranges of test conditions of the tests (10-min duration after the dropping of the can) are: 1) temperature: 68.0 ~ 75.5°F; and 2) RH: 44.3 ~ 58.7 %. The test conditions after the dropping of the can are summarized in Table 6.

Table 6. Summary of test conditions after can dropping

Test No.	10-min duration after can dropping		1- hr duration after can dropping	
	Temperature (°F)	RH (%)	Temperature (°F)	RH (%)
01 HHFQ1	73.2±0.3	49.6±0.4	74.8±1.1	47.1±1.6
02 HHFQ2	73.1±0.2	44.3±0.4	74.7±1.1	42.0±1.5
03 HHFQ3	73.2±0.2	47.8±0.4	74.9±1.1	45.4±1.6
04 HHFQ4 ^[1]	81.5±0.3	47.2±0.3	82.8±0.9	45.4±1.2
05 HLFQ1	74.9±0.2	48.3±0.3	76.0±0.7	46.7±1.1
06 HLFQ2	74.5±0.2	52.1±0.3	75.2±0.4	51.1±0.5
07 LHFQ1	74.7±0.3	42.9±0.4	74.3±0.3	43.7±0.4
08 LHFQ2	74.2±0.4	57.3±0.1	75.3±0.5	56.9±0.3
09 LLFQ1	73.3±0.3	44.4±0.4	73.9±0.3	43.5±0.4
10 LLFQ2	73.1±0.3	44.7±0.5	73.7±0.3	44.0±0.4
11 HHFN1 ^[2]	/	/	/	/
12 HHFN2	68.0±0.5	55.6±0.8	69.8±1.7	51.8±2.5
13 HHFN3	73.8±0.3	47.1±0.3	75.4±1.1	44.7±1.6
14 HHFN4	68.1±0.2	58.7±0.3	71.3±2.3	53.6±3.7
15 HLFN1	73.6±0.3	45.6±0.3	74.7±0.5	44.3±0.6
16 HLFN2	74.4±0.4	43.9±0.5	75.1±0.4	43.1±0.4
17 LHFN1	74.4±0.3	44.0±0.4	74.1±0.2	44.5±0.4
18 LHFN2	74.6±0.3	42.8±0.3	74.3±0.2	43.3±0.3
19 LLFN1	72.2±0.3	44.6±0.4	73.0±0.4	43.6±0.5
20 LLFN2	72.7±0.3	44.6±0.4	73.4±0.4	43.6±0.5

21 HHBN1 ^[2]	/	/	/	/
22 HHBN2	75.5±0.3	44.5±0.4	75.3±0.3	44.9±0.3
23 HHBN3	73.2±0.3	46.8±0.4	72.9±0.2	47.3±0.3
24 HLBN1	75.2±0.3	55.2±0.5	76.0±0.4	53.8±0.7
25 HLBN2	73.1±0.3	48.7±0.4	73.6±0.3	48.1±0.4
26 HLBN3	72.9±0.3	46.7±0.4	73.4±0.3	46.0±0.4
27 LHBN1	74.1±0.3	44.9±0.4	73.8±0.2	45.2±0.3
28 LHBN2 ^[2]	/	/	/	/
29 LHBN3	72.0±0.3	46.2±0.4	71.8±0.2	46.3±0.2
30 LLBN1	73.8±0.3	46.6±0.4	74.4±0.4	45.8±0.5
31 LLBN2	72.5±0.3	46.3±0.5	73.2±0.4	45.3±0.5
32 LLBN3	72.2±0.3	47.4±0.4	72.6±0.3	46.7±0.4

Notes:

[1] Test conditions of Test 04 are significantly different from those of others, in which temperature is about 7 °F higher due to a problem in the initial temperature control. However, such temperature difference is not expected to significantly change the particle ejection, distribution in the room and the intake factor in the present study.

[2] The accurate readings of Test 11, 21 and 28 are not available. However, the test conditions were within the range of temperature 68.0 ~ 75.0°F and RH 44.0 ~ 60.0 % through test observation.

4.2 Amount of Ejected Materials

Figure 11 shows the position of the container after dropping for each test. It should be noted that when dropped from 4 ft height on the flat plate, the can stayed upright and there was almost no horizontal movement for all test cases. The ranges of the spilled amounts and percentages are:

- **Flat plate with ¼” lid hole** 0.12 ~ 4.42 g (0.01 ~ 0.23%) with 8 ft drop height; 0.01 ~ 0.07 g (<0.01%) with 4 ft drop height.
- **Flat plate with no lid** 0.43 ~ 190.44 g (0.02 ~ 9.84%) with 8 ft drop height; 1.08 ~ 2.05 g (0.06 ~ 0.11%) with 4 ft drop height.
- **Block with no lid** 74.23 ~ 631.01 g (3.83 ~ 32.65%) with 8 ft drop height; 320.03 ~ 1061.15 g (16.53 ~ 54.81%) with 4 ft drop height.

Test 01 HHFQ1
(0.23 g, 0.01%)

Test 02 HHFQ2
(0.49 g, 0.03%)

Test 03 HHFQ3
(4.42 g, 0.23%)

Test 04 HHFQ4
(0.12 g, 0.01%)

Test 05 HLFQ1
(1.93 g, 0.10%)

Test 06 HLFQ2
(0.13 g, 0.01%)

Test 07 LHFQ1
(0.02 g, <0.01%)

Test 08 LHFQ2
(0.07 g, <0.01%)

Test 09 LLFQ1
(0.02 g, <0.01%)

Test 10 LLFQ2
(0.01 g, <0.01%)

a. Flat plate with 0.25" lid hole

Test 11 HHFN1
(131.56 g, 6.80%)

Test 12 HHFN2
(0.43 g, 0.02%)

Test 13 HHFN3
(116.82 g, 6.03%)

Test 14 HHFN4
(25.98 g, 1.34%)

Test 15 HLFN1
(171.18 g, 8.84%)

Test 16 HLFN2
(190.44 g, 9.84%)

Test 17 LHFN1
(1.39 g, 0.07%)

Test 18 LHFN2
(1.34 g, 0.07%)

Test 19 LLFN1
(1.08 g, 0.06%)

Test 20 LLFN2
(2.05 g, 0.11%)

b. Flat plate with no lid

Test 21 HHBN1
(74.23 g, 3.83%)

Test 22 HHBN2
(130.77 g, 6.75%)

Test 23 HHBN3
(373.92 g, 19.31%)

Test 24 HLBN 1
(449.16 g, 23.20%)

Test 25 HLBN2
(316.51 g, 16.35%)

Test 26 HLBN3
(631.01g, 32.65%)

Test 27 LHBN1
(894.94 g, 46.23%)

Test 28 LHBN2
(1061.15g, 54.81%)

Test 29 LHBN3
(718.33 g, 37.10%)

Test 30 LLBN1
(320.03 g, 16.53%)

Test 31 LLBN2
(643.15 g, 33.22%)

Test 32 LLBN3
(634.32 g, 32.76%)

c. Block with no lid

Figure 11. The position of the container after dropping

Note: Spilled amount (g) and percentage (%) in the brackets.

Table 7a. Mass (g) measurement before can dropping

Test #	1	2	3	4 (=1+2+3)	5	6 (=4+5)
	Can Body	Can Lid	Clips	Can	Powder	Total Weight
01 HHFQ1	101.00	23.22	1.90	126.12	1936.00	2062.12
02 HHFQ2	100.19	23.33	1.90	125.42	1936.00	2061.42
03 HHFQ3	100.52	23.10	1.90	125.52	1936.00	2061.52
04 HHFQ4	100.76	23.47	1.90	126.13	1936.00	2062.13
05 HLFQ1	100.92	23.24	1.90	126.06	1936.00	2062.06
06 HLFQ2	101.24	23.24	1.90	126.38	1936.00	2062.38
07 LHFQ1	100.66	23.24	1.90	125.80	1936.00	2061.80
08 LHFQ2	101.12	23.24	1.90	126.26	1936.00	2062.26
09 LLFQ1	101.16	23.21	1.90	126.27	1936.00	2062.27
10 LLFQ2	100.92	23.21	1.90	126.03	1936.00	2062.03
11 HHFN1	100.89	/	/	100.89	1937.76	2038.65
12 HHFN2	100.83	/	/	100.83	1936.00	2036.83
13 HHFN3	100.13	/	/	100.13	1936.00	2036.13
14 HHFN4	100.07	/	/	100.07	1936.00	2036.07
15 HLFN1	101.16	/	/	101.16	1936.00	2037.16
16 HLFN2	101.22	/	/	101.22	1936.00	2037.22
17 LHFN1	100.22	/	/	100.22	1936.00	2036.22
18 LHFN2	100.88	/	/	100.88	1936.00	2036.88
19 LLFN1	100.91	/	/	100.91	1936.00	2036.91
20 LLFN2	101.40	/	/	101.40	1936.00	2037.40
21 HHBN1	101.25	/	/	101.25	1936.00	2037.25
22 HHBN2	101.23	/	/	101.23	1936.00	2037.23
23 HHBN3	100.93	/	/	100.93	1936.00	2036.93
24 HLBN1	100.59	/	/	100.59	1936.00	2036.59
25 HLBN2	101.08	/	/	101.08	1936.00	2037.08
26 HLBN3	101.13	/	/	101.13	1936.00	2037.13
27 LHBN1	101.14	/	/	101.14	1936.00	2037.14
28 LHBN2	101.33	/	/	101.33	1936.00	2037.33
29 LHBN3	101.54	/	/	101.54	1936.00	2037.54
30 LLBN1	101.57	/	/	101.57	1936.00	2037.57
31 LLBN2	101.29	/	/	101.29	1936.00	2037.29
32 LLBN3	100.83	/	/	100.83	1936.00	2036.83

Table 7b. Mass (g) measurement after can dropping

Test #	7	8 (=7-4)	9 (=6-7 or =5-8)	10	11 (=9-10)
	Can with Inside Powder	Inside Powder	Spilled Powder	Outside Powder	Non-recovered Powder ^[1]
01 HHFQ1	2061.89	1935.77	0.23	0.02	0.21
02 HHFQ2	2060.93	1935.51	0.49	0.28	0.21
03 HHFQ3	2057.10	1931.58	4.42	4.29	0.13
04 HHFQ4	2062.01	1935.88	0.12	0.01	0.11
05 HLFQ1	2060.13	1934.07	1.93	1.71	0.22
06 HLFQ2	2062.25	1935.87	0.13	0.00	0.13
07 LHFQ1	2061.78	1935.98	0.02	0.00	0.02
08 LHFQ2	2062.19	1935.93	0.07	0.00	0.07
09 LLFQ1	2062.25	1935.98	0.02	0.00	0.02
10 LLFQ2	2062.02	1935.99	0.01	0.00	0.01
11 HHFN1	1907.09	1806.20	131.56	130.88	0.68
12 HHFN2	2036.40	1935.57	0.43	0.07	0.36
13 HHFN3	1918.13	1818.00	116.82	118.00	1.18
14 HHFN4	2010.09	1910.02	25.98	25.79	0.19
15 HLFN1	1865.98	1764.82	171.18	158.66	12.52 ^[2]
16 HLFN2	1846.78	1745.56	190.44	189.28	1.16
17 LHFN1	2034.83	1934.61	1.39	1.20	0.19
18 LHFN2	2035.54	1934.66	1.34	1.09	0.25
19 LLFN1	2035.83	1934.92	1.08	0.77	0.31
20 LLFN2	2035.35	1933.95	2.05	1.82	0.23
21 HHBN1	1963.02	1861.77	74.23	69.6	4.63 ^[2]
22 HHBN2	1906.46	1805.23	130.77	129.92	0.85
23 HHBN3	1663.01	1562.08	373.92	371.19	2.73 ^[2]
24 HLBN1	1587.43	1486.84	449.16	438.09	11.07 ^[2]
25 HLBN2	1720.57	1619.49	316.51	315.28	1.23
26 HLBN3	1405.12	1303.99	632.01	629.31	2.70 ^[2]
27 LHBN1	1142.20	1041.06	894.94	879.03	15.91 ^[2]
28 LHBN2	976.18	874.85	1061.15	1056.04	5.11 ^[2]
29 LHBN3	1319.21	1217.67	718.33	696.82	21.51 ^[2]
30 LLBN1	1717.54	1615.97	320.03	317.69	2.34 ^[2]
31 LLBN2	1394.14	1292.85	643.15	640.62	2.53 ^[2]
32 LLBN3	1402.51	1301.68	634.32	631.57	2.75 ^[2]

Notes:

[1] The calculation of the non-recovered mass is based on the mass of spilled powder and the recovered mass of powder visibly on the floor.

[2] Very big uncertainty due to the difficulty to recover the powder inside the joints on the floor.

Table 7a and Table 7b show the mass measurement before and after the dropping of the can. The spilled powder varies from 0.01 g to 1061.15 g and the non-recovered powder varies from 0.01 g to 21.51 g. Figure 12 shows the corresponding percentage of powder spilled, ranging from less than 0.01% to 54.81%.

Figure 12. Percentage of powder spilled for each test

4.3 Airborne Mass and Number Concentrations

Particle mass and number concentrations before and after the dropping of the can for each test are shown in Figure A*-b and Figure A*-c in Appendix 4 ("*" denotes test number). The size distributions (mass and number) for channel data are also shown in Figure A*-d and Figure A*-f. The size distributions (mass and number) for grouped data ($< 1.2 \mu\text{m}$, $1.2 - 2 \mu\text{m}$, $2 - 2.9 \mu\text{m}$, $2.9 - 4.3 \mu\text{m}$, $4.3 - 10 \mu\text{m}$ and $10 - 20 \mu\text{m}$) are shown in Figure A*-e and Figure A*-g. We can see that for channel data, the peak value of number concentration after the dropping of the can appears at approximately $0.9 \mu\text{m}$. Smaller particles always have bigger number concentrations than large particles despite their significantly smaller mass fraction. For grouped data, the group of $4.3 - 10 \mu\text{m}$ usually has the maximum mass concentration value after the dropping of the can.

Figure 13 and Figure 14 show the total airborne mass and number concentration versus the elapsed time for each test. We can see that after the dropping of the can, it takes less

than 1 or 2 minutes for the system to get a stable particle concentration reading in the dynamic process. Then the particle concentration begins to drop due to natural deposition.

a. Flat plate with 0.25" lid hole

b. Flat plate with no lid

c. Block with no lid

Figure 13. Total airborne mass concentration versus the elapsed time for each test

a. Flat plate with quarter inch hole on the lid

b. Flat plate with no lid

c. Block with no lid

Figure 14. Total airborne number concentration versus the elapsed time for each test

Figure 15. Total airborne mass concentration

Figure 16. Total airborne number concentration

Notes:

- [1] “ $C_{\max}$ ” is the first peak value per mass concentration with a 10 seconds averaged value.
“ $C_{n_{\max}}$ ” is the number concentration at the time mass concentration “ $C_{\max}$ ” occurred.
[2] “After 10 min” denotes the 10 seconds averaged value centered at 10 minutes after “ $C_{\max}$ ”.

Figure 15 and Figure 16 show the comparison of airborne total mass and number concentration. It should be noted that because the definition of “ $C_{\max}$ ” is based on mass concentration, the number concentration of “ $C_{n_{\max}}$ ” may not necessarily be the maximum value. We can also notice that “ $C_{\max}$ ” has relatively big variance due to the unsteadiness of the system.

From Figure 15 and Figure 16 we can also find that after the dropping of the can, the ranges of total airborne mass concentration and number concentration are

- **Flat plate with 1/4” lid hole** 0.03 ~ 0.08 mg/m³ and 2.4 ~ 46.0 #/cm³ with 8 ft drop height; 0.02 ~ 0.06 mg/m³ and 10.5 ~ 30.3 #/cm³ with 4 ft drop height.
- **Flat plate with no lid** 0.06 ~ 0.50 mg/m³ and 35.6 ~ 122.8 #/cm³ with 8 ft drop height; 0.05 ~ 0.11 mg/m³ and 40.1 ~ 96.1 #/cm³ with 4 ft drop height.
- **Block with no lid** 0.20 ~ 0.92 mg/m³ and 67.5 ~ 225.2 #/cm³ with 8 ft drop height; 0.65 ~ 1.85 mg/m³ and 166.8 ~ 383.5 #/cm³ with 4 ft drop height.

In general, tests with lid have smaller concentrations compared with tests without lid as expected.

Figure 17. Ratio of airborne mass to loaded mass, spilled mass and non-recovered mass

From the total airborne mass concentration, we can calculate the airborne particle mass. Figure 17 shows the ratio of airborne mass to loaded mass, spilled mass and non-

recovered mass. The ratio of airborne mass to non-recovered mass was very small, ranging from 0.1% to 7.4%. This means that it is challenging to use this method to check the mass balance.

4.4 Uptake Factor

Figure 18. Cumulative uptake mass

Figure 18 shows the calculated cumulative uptake mass within first 10 minutes after the dropping of the can for each test. The ranges are

- **Flat plate with 1/4" lid hole** $2.19 \times 10^{-3} \sim 8.59 \times 10^{-3}$ mg with 8 ft drop height; $2.72 \times 10^{-3} \sim 8.32 \times 10^{-3}$ mg with 4 ft drop height.
- **Flat plate with no lid** $1.09 \times 10^{-2} \sim 4.69 \times 10^{-2}$ mg with 8 ft drop height; $7.00 \times 10^{-3} \sim 1.74 \times 10^{-2}$ mg with 4 ft drop height.
- **Block with no lid** $2.04 \times 10^{-2} \sim 1.14 \times 10^{-1}$ mg with 8 ft drop height; $6.22 \times 10^{-2} \sim 2.00 \times 10^{-1}$ mg with 4 ft drop height.

Figure 19. Uptake factor

By using Equations (1) and (2), we can calculate the particle uptake factor. The results are shown in Figure 19. The ranges of the uptake factors are

- **Flat plate with 1/4" lid hole** $1.13 \times 10^{-9} \sim 4.44 \times 10^{-9}$ for loaded uptake factor and $4.96 \times 10^{-7} \sim 5.82 \times 10^{-5}$ for spilled uptake factor with 8 ft drop height; $1.41 \times 10^{-9} \sim 4.30 \times 10^{-9}$ for loaded uptake factor and $1.19 \times 10^{-4} \sim 3.55 \times 10^{-4}$ for spilled uptake factor with 4 ft drop height.
- **Flat plate with no lid** $5.62 \times 10^{-9} \sim 2.42 \times 10^{-8}$ for loaded uptake factor and $9.31 \times 10^{-8} \sim 2.53 \times 10^{-5}$ for spilled uptake factor with 8 ft drop height; $3.61 \times 10^{-9} \sim 9.01 \times 10^{-9}$ for loaded uptake factor and $5.03 \times 10^{-6} \sim 1.44 \times 10^{-5}$ for spilled uptake factor with 4 ft drop height.
- **Block with no lid** $1.05 \times 10^{-8} \sim 5.90 \times 10^{-8}$ for loaded uptake factor and $6.44 \times 10^{-8} \sim 9.19 \times 10^{-7}$ for spilled uptake factor with 8 ft drop height; $3.21 \times 10^{-8} \sim 1.03 \times 10^{-7}$ for loaded uptake factor and $8.66 \times 10^{-8} \sim 3.90 \times 10^{-7}$ for spilled uptake factor with 4 ft drop height.

We can see that tests with no lid have higher loaded uptake factors but lower spilled uptake factors compared with tests with lid. Figure 19 shows that the spilled uptake factor is largest when the spills are the smallest. As the spill size increases in mass the spilled uptake factor is reduced. A larger percentage of the spilled mass ends up staying on the floor and not in the air. The tabulated data on cumulative uptake mass and uptake factor for each test are shown in Table 8.

Table 8. Tabulated data on cumulative uptake mass and uptake factor for each test

Test #	Cumulative uptake amount (mg)	Loaded uptake factor	Spilled uptake factor
01 HHFQ1	8.59×10^{-3}	4.44×10^{-9}	3.74×10^{-5}

02 HHFQ2	7.36×10^{-3}	3.80×10^{-9}	1.50×10^{-5}
03 HHFQ3	2.19×10^{-3}	1.13×10^{-9}	4.96×10^{-7}
04 HHFQ4	6.99×10^{-3}	3.61×10^{-9}	5.82×10^{-5}
05 HLFQ1	4.11×10^{-3}	2.12×10^{-9}	2.13×10^{-6}
06 HLFQ2	3.33×10^{-3}	1.72×10^{-9}	2.56×10^{-5}
07 LHFQ1	2.72×10^{-3}	1.41×10^{-9}	1.36×10^{-4}
08 LHFQ2	8.32×10^{-3}	4.30×10^{-9}	1.19×10^{-4}
09 LLFQ1	4.45×10^{-3}	2.30×10^{-9}	2.23×10^{-4}
10 LLFQ2	3.55×10^{-3}	1.83×10^{-9}	3.55×10^{-4}
11 HHFN1	1.62×10^{-2}	8.38×10^{-9}	1.23×10^{-7}
12 HHFN2	1.09×10^{-2}	5.62×10^{-9}	2.53×10^{-5}
13 HHFN3	3.20×10^{-2}	1.65×10^{-8}	2.74×10^{-7}
14 HHFN4	1.31×10^{-2}	6.76×10^{-9}	5.04×10^{-7}
15 HLFN1	4.69×10^{-2}	2.42×10^{-8}	2.74×10^{-7}
16 HLFN2	1.77×10^{-2}	9.16×10^{-9}	9.31×10^{-8}
17 LHFN1	7.00×10^{-3}	3.61×10^{-9}	5.03×10^{-6}
18 LHFN2	1.13×10^{-2}	5.86×10^{-9}	8.47×10^{-6}
19 LLFN1	1.55×10^{-2}	8.01×10^{-9}	1.44×10^{-5}
20 LLFN2	1.74×10^{-2}	9.01×10^{-9}	8.50×10^{-6}
21 HHBN1	6.82×10^{-2}	3.52×10^{-8}	9.19×10^{-7}
22 HHBN2	3.01×10^{-2}	1.56×10^{-8}	2.30×10^{-7}
23 HHBN3	7.19×10^{-2}	3.71×10^{-8}	1.92×10^{-7}
24 HLBN1	1.14×10^{-1}	5.90×10^{-8}	2.54×10^{-7}
25 HLBN2	2.04×10^{-2}	1.05×10^{-8}	6.44×10^{-8}
26 HLBN3	4.49×10^{-2}	2.32×10^{-8}	7.10×10^{-8}
27 LHBN1	2.00×10^{-1}	1.03×10^{-7}	2.23×10^{-7}
28 LHBN2	1.35×10^{-1}	7.00×10^{-8}	1.28×10^{-7}
29 LHBN3	6.22×10^{-2}	3.21×10^{-8}	8.66×10^{-8}
30 LLBN1	1.25×10^{-1}	6.45×10^{-8}	3.90×10^{-7}
31 LLBN2	1.34×10^{-1}	6.94×10^{-8}	2.09×10^{-7}
32 LLBN3	7.66×10^{-2}	3.95×10^{-8}	1.21×10^{-7}

4.5 Parametric Analysis

The testing parameters influencing the released powder and oxide uptake can be summarized as

- **Impacting surface** Using the steel block as the first impacting object can release more respirable oxide spill and generate higher airborne particle concentration. Compared with the cases without the block, the loaded uptake factors are larger, while the spilled uptake factors are very close, or even smaller.
- **Drop height** When dropped from 4 ft height on the flat plate, the can stayed upright and there was almost no horizontal movement for all test cases. The oxide uptake is higher for high drop with flat plate no lid, but lower for high drop with block no lid. For the cases of flat plate and ¼" hole on the lid, the oxide uptake is very close between high drop and low drop. We can also notice that the spilled uptake factors are higher for low drop with flat plate and ¼" hole on the lid.
- **Air Speed** Air speed does not have pronounced effect on the oxide uptake.
- **Lid** Tests with no lid have higher loaded uptake factors but lower spilled uptake factors compared with tests with ¼" lid hole.

Figure 20. Correlation between the amount of respirable oxide spill and the inhalation dose

Plotted in Figure 20 is the average linear correlation between the amount of respirable oxide spill and the inhalation dose for a 10 minute accident event using 32 test results from Phase I and Phase II. Uranium oxide with an A_2 value of 3,000 grams generates a 5 rem inhalation uptake dose of 3×10^{-3} grams ($A_2 \times 10^{-6}$). IAEA Safety Guide TS-G-1.1 and DOE M 441.1-1 manual assumes a spill uptake factor of 1×10^{-3} for all spill sizes creating a DOE M 441.1-1 manual maximum uranium spill release of 3 grams. Based upon the test data correlation between the amount of respirable oxide spill and the inhalation dose for a 10 minute accident event using the test results in this study, reaching the same dose limit would require an estimate respirable oxide spill of 21,350 grams based upon an average linear curve. In general, larger amount of powder ejection spills results in a smaller spill uptake factor and a larger total mass uptake.

4.6 Observation of Material Ejection Behavior

In order to improve the understanding of the phenomenon of particle ejection from the can due to impacting on the surface, a video camera was used for this application. The particle cloud was illuminated by a light-sheet generated by an incandescent flight sheet (part of a bubble flow visualization system, without generating bubbles in this application). For all the tests, the duration of the visibly particle cloud was within 3 seconds to 10 seconds.

T = 0 s

T = 0 s

Test = 1 s

Test = 0.25 s

Test = 2 s

T = 0.5 s

T = 3 s

T = 0.75 s

T = 5 s

T = 8 s

Figure 21a Test 28 LHB2

T = 1 s

T = 5 s

Figure 21b Test 17 LHF1

Figure 21. The observation of material ejection behavior

Figure 21 shows the impacting process in Test 28 LHB2 and Test 17 LHF1. It should be noted that Test 20 has the maximal ejected powder (1061.15g, 54.81%). While the spilled powder in Test 17 is only 1.39 g (0.07%). The qualitative and quantitative analyses of the material ejection process need further investigation.

5. CONCLUSIONS AND RECOMMENDATIONS

A test procedure has been developed and used to measure the airborne concentrations of different size particles within the vicinity of a dropped container where a significant portion of the contained powder is ejected. The following conclusions may be drawn:

- ❑ A total of thirty two drop tests were performed, eight in Phase I and twenty four in Phase II, covering variations in dropping height (8 ft or 4 ft from the floor), room air movement (0.25-0.30 m/s or 0.10-0.15 m/s near the ceiling), landing scenario (on a flat plate or a block), and lid condition ($\frac{1}{4}$ " lid hole or no lid). There were ten tests with flat plate and $\frac{1}{4}$ " lid hole, ten tests with flat plate no lid and twelve tests with block no lid.
- ❑ The amount of spilled powder varied from 0.01 g to 1061.15 g. The corresponding percentage of the spilled powder ranged from below 0.01% to 54.81%. Specifically, the spilled powder was within 0.12 ~ 4.42 g (0.01 ~ 0.23%) with 8 ft drop height, 0.01 ~ 0.07 g (<0.01%) with 4 ft drop height for flat plate with $\frac{1}{4}$ " lid hole; within 0.43 ~ 190.44 g (0.02 ~ 9.84%) with 8 ft drop height, 1.08 ~ 2.05 g (0.06 ~ 0.11%) with 4 ft drop height for plate with no lid and 74.23

~ 631.01 g (3.83 ~ 32.65%) with 8 ft drop height, 320.03 ~ 1061.15 g (16.53 ~ 54.81%) with 4 ft drop height for block with no lid.

- ❑ The peak value of particle number concentration after the dropping of the can occurred at approximately 0.9 μm particle size per measured data of individual channels. The peak value of particle mass concentration occurred in the range of 4.3 - 10 μm particle size per grouped data calculated from the measured data.
- ❑ After the dropping of the can, the total airborne mass concentrations ranged from 0.02 to 1.85 mg/m^3 , while the total airborne number concentrations ranged from 2.4 to 383.5 $\text{\#}/\text{cm}^3$. In general, tests with lid had smaller concentrations than tests without lid.
- ❑ The uptake factor and associated inhalation exposure can be readily assessed by the test method developed. But it is challenging to use the method to check the mass balance since the ratio of airborne mass to non-recovered mass was very small, ranging from 0.1% to 7.4%.
- ❑ The calculated cumulative uptake mass within first 10 minutes after the dropping of the can for each test was within the range of 0.002 mg to 0.2 mg. Assuming a breathing rate of 1.2 m^3/h , the uptake factor during the first 10 minutes was calculated to be between 1.13×10^{-9} and 1.03×10^{-7} in reference to the amount loaded; or between 6.44×10^{-8} and 3.55×10^{-4} in reference to the amount spilled.
- ❑ Uranium oxide with an A_2 of 3,000 grams generates a 5 rem inhalation uptake dose of 3×10^{-3} grams ($A_2 \times 10^{-6}$) for materials at Y-12 National Security Complex. In the current IAEA Safety Guide TS-G-1.1 and DOE M 441.1-1 manual a spill uptake factor of 1×10^{-3} is assumed for all spill sizes creating a DOE M 441.1-1 manual maximum uranium spill release of 3 grams. Based upon the test data correlation between the amount of respirable oxide spill and the inhalation dose for a 10 minute accident event using the test results in this study, reaching the same dose limit would require an estimate respirable oxide spill of 21,350 grams based upon an average linear curve. In general, larger amount of powder ejection spills results in a smaller spill uptake factor and a larger total mass uptake.

It should be noted that the present study covers a limited number of accidental dropping scenarios under one typical type of room air distribution environment. It is recommended that a more comprehensive study be conducted to develop and validate a computational fluid dynamics model that can be used to evaluate a wider range of accidental spill scenarios. The mechanism of particle ejection due to accidental dropping and its correlation to the airborne concentration and associated exposure also need to be further studied to devise effective means to reduce the amount of spill and exposure level.

6. ACKNOWLEDGEMENTS

The authors appreciate the fruitful discussions with and insightful advises from Y-12 researchers including Mohamed Alsharif, Jerry Byington, Sanford Bloom, Douglas

Clark, Walter Irwin North, and Donna Bennett. They would also like to thank Mr. Jim Smith, Ms. Robbin Mocarski, Shewangizaw Semahegn and Denis Pradhan of BEESL for their help in setting up the test facility and purchasing the test materials. The use of NYSTAR Funded Research Facility and Instruments for conducting experiments in this study is also gratefully acknowledged.

7. REFERENCES

1. Hoover M.D., Newton G.J., Guilmette R.A., Howard R.J., Ortiz R.N., Thomas J.M., Trotter S.M. and Ansoborlo E. Characterization of Enriched Uranium Dioxide Particles from a Uranium Handling Facility. *Radiation Protection Dosimetry*, 1998. 79 (1-4), pp57-62.
2. International Atomic Energy Agency (IAEA). *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards Series No. TS-G-1.1 (Rev. 1), IAEA, Vienna (2008). International Atomic Energy Agency (IAEA)
3. US Department of Energy (DOE). Office of Nuclear Safety and Environment. *Nuclear Material Packaging Manual*. DOE M441.1-1. 2008.
4. US Department of Transportation (DOT). Pipeline and Hazardous Materials Safety Administration. *Shippers--General Requirements for Shipments and Packagings*. 49 CFR 173.435. 2008.
5. Herrmann TJ, Zhang JS, Zhang Z, Smith J, Gao X, Li H, Chen W, Wang S. Performance Test Results for an Innovative Large Coupled Indoor/Outdoor Environmental Simulator (C-I/O-ES). *ASHRAE Transaction*, 2003. 109 (2), pp503-516.

APPENDIX 1: TEST PROCEDURE

1. Container Preparation

- Prepare 4 can lids with a 0.25" diameter hole in the center.
- Check the weight of each empty can and lid by balance.
- Pack 8 cans with tungsten oxide. The powder should be loosely filled to a level approximately 1" below the top rim of the can.
- Check the weight of each full can by balance. The weight differences of all 8 cans should be within 1% and recorded to 0.01 g.
- Label each can with a unique test name.

2. Chamber Preparation

- Close the valves at the air supply duct and return duct.
- Turn on 10 small fans in the chamber.
- Use velocity meter to check the air velocity near the top of the room (6 ~ 12" from the ceiling) to be 0.25 to 0.3 m/s. Adjust the fan speed as needed by using the variable frequency drive (VFD).
- Inject tracer gas into the chamber from the sampling port and monitor its concentration by gas monitor. Calculate the air-tightness. The value should be below 0.02 ACH.

3. Chamber Cleaning

- Use vacuum cleaner to clean floor surfaces.
- Use paper towel or clean cloth (with isopropyl alcohol 70% solution and distilled water) to clean all surfaces, including fan blades and interior surfaces of the diffuser box.

4. Equipment Setup and Background Sampling

- Keep the valves at the air supply duct and return duct open.
- Use Andover system to pre-condition the chamber at $70^{\circ}\text{F} \pm 5^{\circ}\text{F}$ in temperature and $50\% \pm 10\%$ RH in relative humidity.
- Enter the chamber with shoe covers and mask. Put the can into the chamber and hold it with the magnetic device at 8 ft above the impacting surface.
- Set up particle sizer APS 3321 with 2 s as the sampling time.
- Set up IAQ-Calc 8762 (or Veloci-Calc 9569P) meter for measurements of temperature and relative humidity with 20 s as the sampling time.
- Set up the video camera and lighting system. Close the chamber.
- Run the system to achieve the required low background particle concentration (clean room class 3.5).

5. Recirculation Mode

- Shut down Andover system.
- Close the valves at the air supply duct and return duct.
- Turn on 10 small fans in the chamber from outside. Record the time.
- Let the system run 15 minutes.

6. Can Dropping

- Trigger the dropping of the can by using the magnetic solenoid valve from outside of the chamber. Record the time.
- Monitor particle concentrations at least 30 minutes or wait the concentrations to go back to the background.

7. Test Wrap-up

- Take pictures of the system, especially the can and the powder.
- Check the weight of the can.
- Download the data of particle sizer APS 3321. Turn off particle sizer.
- Download the data of temperature and RH from Andover system and IAQ-Calc 8762 (or Veloci-Calc 9569P).
- Download the video file.
- Analyze the data.

8. Repeat the Test

- Repeat the procedure 3-7 for 4 tests without a lid.
- Repeat the procedure 3-7 for 4 tests with a tight lid with a 0.25" diameter hole in the center.

APPENDIX 2: TEST EQUIPMENT

- (1) Aerodynamic Particle Sizer Spectrometer – Model 3321 (TSI Inc.)
 - Particle size range: 0.5 to 20 μm aerodynamic sizing, 0.37 to 20 μm optical detection (PSL equivalent)
 - Aerodynamic size resolution: 0.02 μm at 1.0 μm ; 0.03 μm at 10 μm
 - Display resolution: 32 channels per decade of particle size (logarithmic), 52 channels total; 1,024 bins of raw time-of-flight data (4 nsec per bin) in uncorrelated mode
 - Particle type: airborne solids and nonvolatile liquids
 - Maximum recommended particle concentration: 1000 particles/ cm^3 at 0.5 μm with <5% coincidence; 1000 particles/ cm^3 at 10 μm with <10% coincidence; usable data up to 10,000 particles/ cm^3
 - Minimum particle concentration: 0.001 particles/ cm^3
 - Concentration range : $\pm 10\%$ of reading plus variation from counting statistics
 - Maximum processing rate for aerodynamic sizing: > 200,000 particles/sec
 - Sampling time: programmable and repeatable from 1 sec to 18 hr per sample; sampling schedules selected by user
 - Flow rates: aerosol sample: 1.0 ± 0.1 lpm; sheath air: 4.0 ± 0.1 lpm; total flow rate: 5.0 ± 0.2 lpm
- (2) Weighing balance GF-2000 (A&D Company, Limited). Max: 2100 g, Min: 0.5 g, e = 0.1 g, d = 0.01 g
- (3) IAQ-Calc 8762 Meter (TSI Inc.) for measurement of temperature and RH
- (4) Veloci-Calc 9569P with Probe 964 (TSI Inc.)
- (5) 1312 Photoacoustic Multi-gas Monitor (INNOVA Air Tech Instruments) for continuously monitoring tracer gas concentration
- (6) SAI (Sage Action Inc.) Arc Lamp Optical Shroud OS 300-3 and Perkinelmer Arc Lamp Power Supply PS 300-13
- (7) GE 7 day indoor plug-in digital heavy duty timer with 2 grounded outlets - Model 15079
- (8) DC 500 heavy duty 2 gallon cordless/corded wet/dry vacuum (DeWALT)
- (9) Tracer gas cylinder

APPENDIX 3: RELATED DOCUMENTS

A3-1 Aerodynamic Diameter and Stokes Correction

Note: The following paragraph is adapted from the manual of APS 3321 (TSI Inc.)

Surface area, volume and mass calculations are based on geometric diameter of particles (D_p) while the APS measures the aerodynamic diameter of particles (D_a)

The relationship between D_a and D_p is

$$D_p = D_a \sqrt{\frac{\rho}{\rho_0}} \quad (A1)$$

Where ρ_0 is the unit density (1 g/cm³)

According to this relationship, for a fixed aerodynamic size distribution measured by the APS, the total mass m decreases to $m/\sqrt{N}$ when particle density ρ increases to $N \cdot \rho$.

$$\frac{m_1}{m_2} = \frac{\frac{1}{6} \pi \rho_1 D_{p1}^3}{\frac{1}{6} \pi \rho_2 D_{p2}^3} = \frac{\frac{1}{6} \pi \rho_1 \left(D_a \sqrt{\frac{\rho_0}{\rho_1}} \right)^3}{\frac{1}{6} \pi \rho_2 \left(D_a \sqrt{\frac{\rho_0}{\rho_2}} \right)^3} = \frac{\frac{1}{6} \pi N \rho_2 \left(D_a \sqrt{\frac{\rho_0}{N \rho_2}} \right)^3}{\frac{1}{6} \pi \rho_2 \left(D_a \sqrt{\frac{\rho_0}{\rho_2}} \right)^3} = \frac{1}{\sqrt{N}} \quad (A2)$$

Stokes correction should be applied while sampling particles with density below 0.9 g/cm³ or above 1.1 g/cm³.

The APS spectrometers are calibrated using Polystyrene Latex (PSL) spheres of density close to 1.05 g/cm³. In addition, the APS does not measure the aerodynamic size of particles in still air (the classical definition of aerodynamic size) but in a flow velocity of approximately 150 m/s. This means that the particle Reynolds numbers are outside the stokes regime ($R > 0.5$). For particle densities other than unity, the particles will be incorrectly sized smaller for densities below unity and sized larger for densities above unity. The magnitude of this difference increases for larger particle sizes. For example, a particle of density 0.8 can be underestimated by as much as 5% and a particle of density 2 can be overestimated by as much as 10%.

If the density of the particles is known, the non-stokes error can be corrected using equations from the paper by Hwachi Wang and Walter John (1987), "Particle density correction for the aerodynamic particle sizer", Aerosol science and Technology 6(2): 191-198.

$$D_{a2} = D_{a1} \left[\frac{6 + R_2^{2/3}}{6 + R_1^{2/3}} \right]^{1/2} \quad (A3)$$

D_{a2} : corrected aerodynamic diameter (μm)

D_{a1} : uncorrected aerodynamic diameter (μm)

A3-2 Certificate of Calibration of APS 3321 (TSI Inc.)

Particle Instrument Division
Mailing Address: P.O. Box 64394 St. Paul, MN 55164 USA
Shipping Address: 500 Cardigan Road Shoreview, MN 55126 USA
Phone: 1-800-677-2708 or (651)490-2833 FAX: (651)490-3860

Certificate of Calibration TSI model 3321

Date of Calibration: May 25, 2010
Serial Number: 1290

	Geometric Diameter (μm)	Accumulator Median Bin	Particle Density (g/ml)
Particle #1	.350	205.2	1.05
Particle #2	.400	206.6	1.05
Particle #3	.519	212.6	1.05
Particle #4	.707	224.1	1.05
Particle #5	.993	244.5	1.05
Particle #6	1.998	309.7	1.05
Particle #7	4.98	477.7	1.05
Particle #8	7.02	577.3	1.05
Particle #9	10.00	691.9	1.05
Particle #10	15.02	860.8	1.05
Particle #11	20.00	1015.3	1.05

TSI Incorporated does hereby certify that all materials, components, and workmanship used in the manufacture of this equipment are in strict accordance with the applicable specifications agreed upon by TSI and the customer and with all published specifications. All performance and acceptance tests were successfully conducted according to required specifications. TSI Incorporated certifies that the instruments used to calibrate this instrument are traceable to the National Institute of Standards and Technology (NIST), where applicable, and internal TSI calibration standards where NIST standards do not exist.

Calibrated by: Larry Bennett

A3-2 Certificate of Calibration of APS 3321 (TSI Inc.) Continued

TSI.

Particle Instrument Division
Mailing Address: P.O. Box 64394 St. Paul, MN 55164 USA
Shipping Address: 500 Cardigan Road Shoreview, MN 55126 USA
Phone: 1-800-677-2708 or (651)490-2833 FAX: (651)490-3860

Certificate of Calibration

TSI model 3321

Date of Calibration: June 09, 2011
Serial Number: 1290

	Geometric Diameter (μm)	Accumulator Median Bin	Particle Density (g/ml)
Particle #1	.350	204.2	1.05
Particle #2	.400	207.9	1.05
Particle #3	.498	210.7	1.05
Particle #4	.707	221.8	1.05
Particle #5	.993	241.7	1.05
Particle #6	1.998	303.3	1.05
Particle #7	5.003	477.5	1.05
Particle #8	7.028	576.0	1.05
Particle #9	10.00	690.0	1.05
Particle #10	15.02	872.0	1.05
Particle #11	20.00	1015.0	1.05

TSI Incorporated does hereby certify that all materials, components, and workmanship used in the manufacture of this equipment are in strict accordance with the applicable specifications agreed upon by TSI and the customer and with all published specifications. All performance and acceptance tests were successfully conducted according to required specifications. TSI Incorporated certifies that the instruments used to calibrate this instrument are traceable to the National Institute of Standards and Technology (NIST), where applicable, and internal TSI calibration standards where NIST standards do not exist.

Calibrated by: C. Kramlinger

A3-3 Physical Size Distribution Analysis of Tungsten Oxide (LOT # Q1844) by Powder Technology Inc.

A3-4 In-House Calibration of Veloci-Calc 8347 Air Velocity Meter (TSI Inc.)

Note:

Calibration made on June 11, 2010

Calibration equipment:

1) Wind tunnel for calibration and dynamic tests (Sensor)

Software: Automatic wind tunnel TunCal Ver 4.0

2) DP-Calc 8705 (TSI Inc.)

A3-5 Certificate of Calibration of Veloci-Calc 9565-P and Probe 964 (TSI Inc.)

CERTIFICATE OF CALIBRATION AND TESTING

TSI Incorporated, 500 Cardigan Road, Shoreview, MN 55126 USA
Tel: 1-800-874-2811 1-651-490-2811 Fax: 1-651-490-3824 http://www.tsi.com

ENVIRONMENT CONDITION				MODEL		9565-P	
TEMPERATURE		67.5 (19.7)		°F (°C)			
RELATIVE HUMIDITY		62		%RH			
BAROMETRIC PRESSURE		28.82 (976.0)		inHg (hPa)			
☒ AS LEFT ☐ AS FOUND				☒ IN TOLERANCE ☐ OUT OF TOLERANCE			

- CALIBRATION VERIFICATION RESULTS -

THERMO COUPLE						SYSTEM PRESSURE01-01			Unit: °F (°C)
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE		
1	69.2 (20.7)	69.2 (20.7)	67.2~71.2 (19.6~21.8)						

DIFFERENTIAL PRESSURE						SYSTEM PRESSURE01-01			Unit: inH ₂ O (Pa)
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE		
1	-4.000 (-996.0)	-4.003 (-996.7)	-4.044~-3.956 (-1007.0~-985.0)	3	8.055 (2005.7)	8.056 (2005.9)	7.970~8.140 (1984.5~2026.9)		
2	2.191 (545.6)	2.189 (545.1)	2.165~2.217 (539.1~552.0)	4	14.145 (3522.1)	14.143 (3521.6)	14.000~14.290 (3486.0~3558.2)		

BAROMETRIC PRESSURE						SYSTEM PRESSURE01-01			Unit: inHg (hPa)
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE		
1	19.73 (668.1)	19.71 (667.5)	19.34~20.12 (654.9~681.3)	3	34.37 (1163.9)	34.37 (1163.9)	33.68~35.06 (1140.5~1187.3)		
2	28.94 (980.0)	28.94 (980.0)	28.36~29.52 (960.4~999.7)						

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the United States National Institute of Standards and Technology (NIST) or has been verified with respect to instrumentation whose accuracy is traceable to NIST, or is derived from accepted values of physical constants. TSI's calibration system is registered to ISO-9001:2008 and meets the requirements of ISO 10012:2003.

Measurement Variable	System ID	Last Cal.	Cal. Due	Measurement Variable	System ID	Last Cal.	Cal. Due
DC Voltage	E003299	06-23-10	12-23-11	DC Voltage	E003300	06-23-10	12-23-11
Temperature	E003170	12-09-10	12-09-11	Pressure	E003302	04-01-11	04-01-12
Pressure	E003303	04-07-11	10-07-11				

CHUNG LE

CALIBRATED

June 3, 2011

DATE

Doc. ID: CERT_GEN_WCC

© GCS 346

A3-5 Certificate of Calibration of Veloci-Calc 9565-9 and Probe 964 Continued

CERTIFICATE OF CALIBRATION AND TESTING

TSI Incorporated, 500 Cardigan Road, Shoreview, MN 55126 USA
Tel: 1-800-874-2811 1-651-490-2811 Fax: 1-651-490-3824 http://www.tsi.com

ENVIRONMENT CONDITION				MODEL		964	
TEMPERATURE	75.7 (24.3)	°F (°C)		SERIAL NUMBER		P11090067	
RELATIVE HUMIDITY	13	%RH					
BAROMETRIC PRESSURE	29.25 (990.5)	inHg (hPa)					

☒ AS LEFT
☐ AS FOUND

☒ IN TOLERANCE
☐ OUT OF TOLERANCE

- CALIBRATION VERIFICATION RESULTS -

TEMPERATURE VERIFICATION				SYSTEM T-100				Unit: °F (°C)
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE	
1	32.0 (0.0)	32.0 (0.0)	31.5-32.5 (-0.3-0.3)	2	140.0 (60.0)	140.0 (60.0)	139.5-140.5 (59.7-60.3)	

HUMIDITY VERIFICATION				SYSTEM H-100				Unit: %RH
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE	
1	10.0	10.5	7.8-12.2	4	70.0	69.7	67.8-72.2	
2	30.0	29.7	27.8-32.2	5	90.0	90.0	87.8-92.2	
3	50.0	49.6	47.8-52.2					

VELOCITY VERIFICATION				SYSTEM V-102				Unit: ft/min (m/s)
#	STANDARD	MEASURED	ALLOWABLE RANGE	#	STANDARD	MEASURED	ALLOWABLE RANGE	
1	0 (0.00)	0 (0.00)	-3-3 (-0.02-0.02)	7	648 (3.29)	649 (3.30)	629-668 (3.19-3.39)	
2	35 (0.18)	36 (0.18)	32-38 (0.16-0.19)	8	1003 (5.10)	1011 (5.14)	973-1033 (4.94-5.25)	
3	65 (0.33)	65 (0.33)	62-68 (0.32-0.35)	9	1483 (7.53)	1486 (7.55)	1439-1528 (7.31-7.76)	
4	100 (0.51)	100 (0.51)	97-103 (0.49-0.52)	10	2492 (12.66)	2510 (12.75)	2417-2566 (12.28-13.04)	
5	160 (0.81)	161 (0.82)	155-165 (0.79-0.84)	11	4504 (22.88)	4499 (22.85)	4369-4639 (22.20-23.57)	
6	330 (1.68)	330 (1.68)	320-340 (1.63-1.73)	12	7962 (40.45)	8040 (40.84)	7723-8201 (39.23-41.66)	

TSI does hereby certify that the above described instrument conforms to the original manufacturer's specification (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the United States National Institute of Standards and Technology (NIST) or has been verified with respect to instrumentation whose accuracy is traceable to NIST, or is derived from accepted values of physical constants. TSI's calibration system meets ISO-9001:2008 and meets the requirements of ISO 10012:2003.

Measurement Variable	System ID	Last Cal.	Cal. Due	Measurement Variable	System ID	Last Cal.	Cal. Due
Temperature	E003304	09-08-10	03-08-11	Temperature	E003305	09-08-10	03-08-11
Humidity	E003296	09-23-10	03-23-11	DC Voltage	E001662	08-11-10	02-11-12
Barometric Pressure	E001154	04-09-10	04-09-11	Temperature	E001594	02-03-11	08-03-11
Pressure	E001563	12-28-10	06-28-11	Pressure	E001264	12-07-10	06-07-11
Velocity	E003327	09-19-07	09-19-12

CALIBRATED

February 28, 2011

DATE

Doc ID: CERT_GEN_WCC

© GSES 346
 All Rights Reserved

APPENDIX 4: TEST RESULTS

Test 01 HHFQ1

Figure A1-a. Chamber conditions during Test HHFQ1

Figure A1-b. Particle mass concentration before and after the dropping of Test HHFQ1

Figure A1-c. Particle number concentration before and after the dropping of Test HHFQ1

Figure A1-d. Particle mass concentration versus particle size (channel data) of Test HHFQ1

Figure A1-e. Particle mass concentration versus particle size of Test HHFQ1

Figure A1-f. Particle number concentration versus particle size (channel data) of Test HHFQ1

Figure A1-g. Particle number concentration versus particle size of Test HHFQ1

Figure A1-h. Cumulative uptake amount of particle mass of Test HHFQ1

Test 02 HHFQ2

Figure A2-a. Chamber conditions during Test HHFQ2

Figure A2-b. Particle mass concentration before and after the dropping of Test HHFQ2

Figure A2-c. Particle number concentration before and after the dropping of Test HHFQ2

Figure A2-d. Particle mass concentration versus particle size (channel data) of Test HHFQ2

Figure A2-e. Particle mass concentration versus particle size of Test HHFQ2

Figure A2-f. Particle number concentration versus particle size (channel data) of Test HHFQ2

Figure A2-g. Particle number concentration versus particle size of Test HHFQ2

Figure A2-h. Cumulative uptake amount of particle mass of Test HHFQ2

Test 03 HHFQ3

Figure A3-a. Chamber conditions during Test HHFQ3

Figure A3-b. Particle mass concentration before and after the dropping of Test HHFQ3

Figure A3-c. Particle number concentration before and after the dropping of Test HHFQ3

Figure A3-d. Particle mass concentration versus particle size (channel data) of Test HHFQ3

Figure A3-e. Particle mass concentration versus particle size of Test HHFQ3

Figure A3-f. Particle number concentration versus particle size (channel data) of Test HHFQ3

Figure A3-g. Particle number concentration versus particle size of Test HHFQ3

Figure A3-h. Cumulative uptake amount of particle mass of Test HHFQ3

Test 04 HHFQ4

Figure A4-a. Chamber conditions during Test HHFQ4

Figure A4-b. Particle mass concentration before and after the dropping of Test HHFQ4

Figure A4-c. Particle number concentration before and after the dropping of Test HHFQ4

Figure A4-d. Particle mass concentration versus particle size (channel data) of Test HHFQ4

Figure A4-e. Particle mass concentration versus particle size of Test HHFQ4

Figure A4-f. Particle number concentration versus particle size (channel data) of Test HHFQ4

Figure A4-g. Particle number concentration versus particle size of Test HHFQ4

Figure A4-h. Cumulative uptake amount of particle mass of Test HHFQ4

Test 05 HLFQ1

Figure A5-a. Chamber conditions during Test HLFQ1

Figure A5-b. Particle mass concentration before and after the dropping of Test HLFQ1

Figure A5-c. Particle number concentration before and after the dropping of Test HLFQ1

Figure A5-d. Particle mass concentration versus particle size (channel data) of Test HLFQ1

Figure A5-e. Particle mass concentration versus particle size of Test HLFQ1

Figure A5-f. Particle number concentration versus particle size (channel data) of Test HLFQ1

Figure A5-g. Particle number concentration versus particle size of Test HLFQ1

Figure A5-h. Cumulative uptake amount of particle mass of Test HLFQ1

Test 06 HLFQ2

Figure A6-a. Chamber conditions during Test HLFQ2

Figure A6-b. Particle mass concentration before and after the dropping of Test HLFQ2

Figure A6-c. Particle number concentration before and after the dropping of Test HLFQ2

Figure A6-d. Particle mass concentration versus particle size (channel data) of Test HLFQ2

Figure A6-e. Particle mass concentration versus particle size of Test HLFQ2

Figure A6-f. Particle number concentration versus particle size (channel data) of Test HLFQ2

Figure A6-g. Particle number concentration versus particle size of Test HLFQ2

Figure A6-h. Cumulative uptake amount of particle mass of Test HLFQ2

Test 07 LHFQ1

Figure A7-a. Chamber conditions during Test LHFQ1

Figure A7-b. Particle mass concentration before and after the dropping of Test LHFQ1

Figure A7-c. Particle number concentration before and after the dropping of Test LHFQ1

Figure A7-d. Particle mass concentration versus particle size (channel data) of Test LHFQ1

Figure A7-e. Particle mass concentration versus particle size of Test LHFQ1

Figure A7-f. Particle number concentration versus particle size (channel data) of Test LHFQ1

Figure A7-g. Particle number concentration versus particle size of Test LHFQ1

Figure A7-h. Cumulative uptake amount of particle mass of Test LHFQ1

Test 08 LHFQ2

Figure A8-a. Chamber conditions during Test LHFQ2

Figure A8-b. Particle mass concentration before and after the dropping of Test LHFQ2

Figure A8-c. Particle number concentration before and after the dropping of Test LHFQ2

Figure A8-d. Particle mass concentration versus particle size (channel data) of Test LHFQ2

Figure A8-e. Particle mass concentration versus particle size of Test LHFQ2

Figure A8-f. Particle number concentration versus particle size (channel data) of Test LHFQ2

Figure A8-g. Particle number concentration versus particle size of Test LHFQ2

Figure A8-h. Cumulative uptake amount of particle mass of Test LHFQ2

Test 09 LLFQ1

Figure A9-a. Chamber conditions during Test LLFQ1

Figure A9-b. Particle mass concentration before and after the dropping of Test LLFQ1

Figure A9-c. Particle number concentration before and after the dropping of Test LLFQ1

Figure A9-d. Particle mass concentration versus particle size (channel data) of Test LLFQ1

Figure A9-e. Particle mass concentration versus particle size of Test LLFQ1

Figure A9-f. Particle number concentration versus particle size (channel data) of Test LLFQ1

Figure A9-g. Particle number concentration versus particle size of Test LLFQ1

Figure A9-h. Cumulative uptake amount of particle mass of Test LLFQ1

Test 10 LLFQ2

Figure A10-a. Chamber conditions during Test LLFQ2

Figure A10-b. Particle mass concentration before and after the dropping of Test LLFQ2

Figure A10-c. Particle number concentration before and after the dropping of Test LLFQ2

Figure A10-d. Particle mass concentration versus particle size (channel data) of Test LLFQ2

Figure A10-e. Particle mass concentration versus particle size of Test LLFQ2

Figure A10-f. Particle number concentration versus particle size (channel data) of Test LLFQ2

Figure A10-g. Particle number concentration versus particle size of Test LLFQ2

Figure A10-h. Cumulative uptake amount of particle mass of Test LLFQ2

Test 11 HHFN1

N/A

Figure A11-a. Chamber conditions during Test HHFN1

Figure A11-b. Particle mass concentration before and after the dropping of Test HHFN1

Figure A11-c. Particle number concentration before and after the dropping of Test HHFN1

Figure A11-d. Particle mass concentration versus particle size (channel data) of Test HHFN1

Figure A11-e. Particle mass concentration versus particle size of Test HHFN1

Figure A11-f. Particle number concentration versus particle size (channel data) of Test HHFN1

Figure A11-g. Particle number concentration versus particle size of Test HHFN1

Figure A11-h. Cumulative uptake amount of particle mass of Test HHFN1

Test 12 HHFN2

Figure A12-a. Chamber conditions during Test HHFN2

Figure A12-b. Particle mass concentration before and after the dropping of Test HHFN2

Figure A12-c. Particle number concentration before and after the dropping of Test HHFN2

Figure A12-d. Particle mass concentration versus particle size (channel data) of Test HHFN2

Figure A12-e. Particle mass concentration versus particle size of Test HHFN2

Figure A12-f. Particle number concentration versus particle size (channel data) of Test HHFN2

Figure A12-g. Particle number concentration versus particle size of Test HHFN2

Figure A12-h. Cumulative uptake amount of particle mass of Test HHFN2

Test 13 HHFN3

Figure A13-a. Chamber conditions during Test HHFN3

Figure A13-b. Particle mass concentration before and after the dropping of Test HHFN3

Figure A13-c. Particle number concentration before and after the dropping of Test HHFN3

Figure A13-d. Particle mass concentration versus particle size (channel data) of Test HHFN3

Figure A13-e. Particle mass concentration versus particle size of Test HHFN3

Figure A13-f. Particle number concentration versus particle size (channel data) of Test HHFN3

Figure A13-g. Particle number concentration versus particle size of Test HHFN3

Figure A13-h. Cumulative uptake amount of particle mass of Test HHFN3

Test 14 HHFN4

Figure A14-a. Chamber conditions during Test HHFN4

Figure A14-b. Particle mass concentration before and after the dropping of Test HHFN4

Figure A14-c. Particle number concentration before and after the dropping of Test HHFN4

Figure A14-d. Particle mass concentration versus particle size (channel data) of Test HHFN4

Figure A14-e. Particle mass concentration versus particle size of Test HHFN4

Figure A14-f. Particle number concentration versus particle size (channel data) of Test HHFN4

Figure A14-g. Particle number concentration versus particle size of Test HHFN4

Figure A14-h. Cumulative uptake amount of particle mass of Test HHFN4

Test 15 HLFN1

Figure A15-a. Chamber conditions during Test HLFN1

Figure A15-b. Particle mass concentration before and after the dropping of Test HLFN1

Figure A15-c. Particle number concentration before and after the dropping of Test HLFN1

Figure A15-d. Particle mass concentration versus particle size (channel data) of Test HLFN1

Figure A15-e. Particle mass concentration versus particle size of Test HLFN1

Figure A15-f. Particle number concentration versus particle size (channel data) of Test HLFN1

Figure A15-g. Particle number concentration versus particle size of Test HLFN1

Figure A15-h. Cumulative uptake amount of particle mass of Test HLFN1

Test 16 HLFN2

Figure A16-a. Chamber conditions during Test HLFN2

Figure A16-b. Particle mass concentration before and after the dropping of Test HLFN2

Figure A16-c. Particle number concentration before and after the dropping of Test HLFN2

Figure A16-d. Particle mass concentration versus particle size (channel data) of Test HLFN2

Figure A16-e. Particle mass concentration versus particle size of Test HLFN2

Figure A16-f. Particle number concentration versus particle size (channel data) of Test HLFN2

Figure A16-g. Particle number concentration versus particle size of Test HLFN2

Figure A16-h. Cumulative uptake amount of particle mass of Test HLFN2

Test 17 LHFN1

Figure A17-a. Chamber conditions during Test LHFN1

Figure A17-b. Particle mass concentration before and after the dropping of Test LHFN1

Figure A17-c. Particle number concentration before and after the dropping of Test LHFN1

Figure A17-d. Particle mass concentration versus particle size (channel data) of Test LHFN1

Figure A17-e. Particle mass concentration versus particle size of Test LHFN1

Figure A17-f. Particle number concentration versus particle size (channel data) of Test LHFN1

Figure A17-g. Particle number concentration versus particle size of Test LHFN1

Figure A17-h. Cumulative uptake amount of particle mass of Test LHFN1

Test 18 LHFN2

Figure A18-a. Chamber conditions during Test LHFN2

Figure A18-b. Particle mass concentration before and after the dropping of Test LHFN2

Figure A18-c. Particle number concentration before and after the dropping of Test LHFN2

Figure A18-d. Particle mass concentration versus particle size (channel data) of Test LHFN2

Figure A18-e. Particle mass concentration versus particle size of Test LHFN2

Figure A18-f. Particle number concentration versus particle size (channel data) of Test LHFN2

Figure A18-g. Particle number concentration versus particle size of Test LHFN2

Figure A18-h. Cumulative uptake amount of particle mass of Test LHFN2

Test 19 LLFN1

Figure A19-a. Chamber conditions during Test LLFN1

Figure A19-b. Particle mass concentration before and after the dropping of Test LLFN1

Figure A19-c. Particle number concentration before and after the dropping of Test LLFN1

Figure A19-d. Particle mass concentration versus particle size (channel data) of Test LLFN1

Figure A19-e. Particle mass concentration versus particle size of Test LLFN1

Figure A19-f. Particle number concentration versus particle size (channel data) of Test LLFN1

Figure A19-g. Particle number concentration versus particle size of Test LLFN1

Figure A19-h. Cumulative uptake amount of particle mass of Test LLFN1

Test 20 LLFN2

Figure A20-a. Chamber conditions during Test LLFN2

Figure A20-b. Particle mass concentration before and after the dropping of Test LLFN2

Figure A20-c. Particle number concentration before and after the dropping of Test LLFN2

Figure A20-d. Particle mass concentration versus particle size (channel data) of Test LLFN2

Figure A20-e. Particle mass concentration versus particle size of Test LLFN2

Figure A20-f. Particle number concentration versus particle size (channel data) of Test LLFN2

Figure A20-g. Particle number concentration versus particle size of Test LLFN2

Figure A20-h. Cumulative uptake amount of particle mass of Test LLFN2

Test 21 HHBN1

N/A

Figure A21-a. Chamber conditions during Test HHBN1

Figure A21-b. Particle mass concentration before and after the dropping of Test HHBN1

Figure A21-c. Particle number concentration before and after the dropping of Test HHBN1

Figure A21-d. Particle mass concentration versus particle size (channel data) of Test HHBN1

Figure A21-e. Particle mass concentration versus particle size of Test HHBN1

Figure A21-f. Particle number concentration versus particle size (channel data) of Test HHBN1

Figure A21-g. Particle number concentration versus particle size of Test HHBN1

Figure A21-h. Cumulative uptake amount of particle mass of Test HHBN1

Test 22 HHBN2

Figure A22-a. Chamber conditions during Test HHBN2

Figure A22-b. Particle mass concentration before and after the dropping of Test HHBN2

Figure A22-c. Particle number concentration before and after the dropping of Test HHBN2

Figure A22-d. Particle mass concentration versus particle size (channel data) of Test HHBN2

Figure A22-e. Particle mass concentration versus particle size of Test HHBN2

Figure A22-f. Particle number concentration versus particle size (channel data) of Test HHBN2

Figure A22-g. Particle number concentration versus particle size of Test HHBN2

Figure A22-h. Cumulative uptake amount of particle mass of Test HHBN2

Test 23 HHBN3

Figure A23-a. Chamber conditions during Test HHBN3

Figure A23-b. Particle mass concentration before and after the dropping of Test HHBN3

Figure A23-c. Particle number concentration before and after the dropping of Test HHBN3

Figure A23-d. Particle mass concentration versus particle size (channel data) of Test HHBN3

Figure A23-e. Particle mass concentration versus particle size of Test HHBN3

Figure A23-f. Particle number concentration versus particle size (channel data) of Test HHBN3

Figure A23-g. Particle number concentration versus particle size of Test HHBN3

Figure A23-h. Cumulative uptake amount of particle mass of Test HHBN3

Test 24 HLBN1

Figure A24-a. Chamber conditions during Test HLBN1

Figure A24-b. Particle mass concentration before and after the dropping of Test HLBN1

Figure A24-c. Particle number concentration before and after the dropping of Test HLBN1

Figure A24-d. Particle mass concentration versus particle size (channel data) of Test HLBN1

Figure A24-e. Particle mass concentration versus particle size of Test HLB1

Figure A24-f. Particle number concentration versus particle size (channel data) of Test HLB1

Figure A24-g. Particle number concentration versus particle size of Test HLB1

Figure A24-h. Cumulative uptake amount of particle mass of Test HLB1

Test 25 HLBN2

Figure A25-a. Chamber conditions during Test HLBN2

Figure A25-b. Particle mass concentration before and after the dropping of Test HLBN2

Figure A25-c. Particle number concentration before and after the dropping of Test HLBN2

Figure A25-d. Particle mass concentration versus particle size (channel data) of Test HLBN2

Figure A25-e. Particle mass concentration versus particle size of Test HLB2

Figure A25-f. Particle number concentration versus particle size (channel data) of Test HLB2

Figure A25-g. Particle number concentration versus particle size of Test HLB2

Figure A25-h. Cumulative uptake amount of particle mass of Test HLB2

Test 26 HLBN3

Figure A26-a. Chamber conditions during Test HLBN3

Figure A26-b. Particle mass concentration before and after the dropping of Test HLBN3

Figure A26-c. Particle number concentration before and after the dropping of Test HLBN3

Figure A26-d. Particle mass concentration versus particle size (channel data) of Test HLBN3

Figure A26-e. Particle mass concentration versus particle size of Test HLB3

Figure A26-f. Particle number concentration versus particle size (channel data) of Test HLB3

Figure A26-g. Particle number concentration versus particle size of Test HLB3

Figure A26-h. Cumulative uptake amount of particle mass of Test HLB3

Test 27 LHBN1

Figure A27-a. Chamber conditions during Test LHBN1

Figure A27-b. Particle mass concentration before and after the dropping of Test LHBN1

Figure A27-c. Particle number concentration before and after the dropping of Test LHBN1

Figure A27-d. Particle mass concentration versus particle size (channel data) of Test LHBN1

Figure A27-e. Particle mass concentration versus particle size of Test LHBN1

Figure A27-f. Particle number concentration versus particle size (channel data) of Test LHBN1

Figure A27-g. Particle number concentration versus particle size of Test LHBN1

Figure A27-h. Cumulative uptake amount of particle mass of Test LHBN1

Test 28 LHBN2

N/A

Figure A28-a. Chamber conditions during Test LHBN2

Figure A28-b. Particle mass concentration before and after the dropping of Test LHBN2

Figure A28-c. Particle number concentration before and after the dropping of Test LHBN2

Figure A28-d. Particle mass concentration versus particle size (channel data) of Test LHBN2

Figure A28-e. Particle mass concentration versus particle size of Test LHBN2

Figure A28-f. Particle number concentration versus particle size (channel data) of Test LHBN2

Figure A28-g. Particle number concentration versus particle size of Test LHBN2

Figure A28-h. Cumulative uptake amount of particle mass of Test LHBN2

Test 29 LHBN3

Figure A29-a. Chamber conditions during Test LHBN3

Figure A29-b. Particle mass concentration before and after the dropping of Test LHBN3

Figure A29-c. Particle number concentration before and after the dropping of Test LHBN3

Figure A29-d. Particle mass concentration versus particle size (channel data) of Test LHBN3

Figure A29-e. Particle mass concentration versus particle size of Test LHBN3

Figure A29-f. Particle number concentration versus particle size (channel data) of Test LHBN3

Figure A29-g. Particle number concentration versus particle size of Test LHBN3

Figure A29-h. Cumulative uptake amount of particle mass of Test LHBN3

Test 30 LLBN1

Figure A30-a. Chamber conditions during Test LLBN1

Figure A30-b. Particle mass concentration before and after the dropping of Test LLBN1

Figure A30-c. Particle number concentration before and after the dropping of Test LLBN1

Figure A30-d. Particle mass concentration versus particle size (channel data) of Test LLBN1

Figure A30-e. Particle mass concentration versus particle size of Test LLBN1

Figure A30-f. Particle number concentration versus particle size (channel data) of Test LLBN1

Figure A30-g. Particle number concentration versus particle size of Test LLBN1

Figure A30-h. Cumulative uptake amount of particle mass of Test LLBN1

Test 31 LLBN2

Figure A31-a. Chamber conditions during Test LLBN2

Figure A31-b. Particle mass concentration before and after the dropping of Test LLBN2

Figure A31-c. Particle number concentration before and after the dropping of Test LLBN2

Figure A31-d. Particle mass concentration versus particle size (channel data) of Test LLBN2

Figure A31-e. Particle mass concentration versus particle size of Test LLBN2

Figure A31-f. Particle number concentration versus particle size (channel data) of Test LLBN2

Figure A31-g. Particle number concentration versus particle size of Test LLBN2

Figure A31-h. Cumulative uptake amount of particle mass of Test LLBN2

Test 32 LLBN3

Figure A32-a. Chamber conditions during Test LLBN3

Figure A32-b. Particle mass concentration before and after the dropping of Test LLBN3

Figure A32-c. Particle number concentration before and after the dropping of Test LLBN3

Figure A32-d. Particle mass concentration versus particle size (channel data) of Test LLBN3

Figure A32-e. Particle mass concentration versus particle size of Test LLBN3

Figure A32-f. Particle number concentration versus particle size (channel data) of Test LLBN3

Figure A32-g. Particle number concentration versus particle size of Test LLBN3

Figure A32-h. Cumulative uptake amount of particle mass of Test LLBN3