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SPENT FUEL SABOTAGE TESTING: DEPLETED URANIUM OXIDE AEROSOL RESULTS

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ABSTRACT

We will summarize a multinational, multi-phase spent fuel sabotage test program that quantifies aerosol particles produced when the products of a high energy density device (HEDD) interact with and explosively particulate test rodlets that contain pellets of either surrogate materials or actual spent fuel. Testing has been underway for several years. This program provides source-term data that are relevant to plausible sabotage attack scenarios in relation to spent fuel transport and storage casks, and associated risk assessments. We present details and significant results from three Phase 3 tests performed using depleted uranium oxide pellets plus non-radioactive fission product dopants in surrogate spent fuel test rodlets. Measured aerosol results include: respirable fractions produced; amounts, nuclide content, and produced particle size distributions and morphology; measurements of volatile fission product species enhanced sorption – enrichment factors onto respirable particles; and, status on determination of the spent fuel ratio, SFR, needed for scaling studies. The DUO_2 aerosol particle results are compared directly with our similar, recent Phase 2 results from cerium oxide ceramic pellet and fission product dopant surrogate test rodlets. We also provide a status review on preparations for the final Phase 4 in this program, tests using individual short rodlets containing actual spent fuel from U.S. PWR reactors, with both high- and lower-burnup fuel. The source-term data, aerosol results, and program design have been tailored to support and guide follow-on computer modeling of aerosol dispersal hazards and radiological consequence assessments. Test results also provide a further validation of vulnerability studies associated with spent nuclear fuels, and a basis for evaluating appropriate levels of transportation physical protection and safeguards requirements. This spent fuel sabotage, aerosol test program was performed primarily at Sandia National Laboratories, with support provided by both the U.S. Department of Energy and the Nuclear Regulatory Commission. It has significant input from, and is strongly supported and coordinated by both the U.S. and international program participants in Germany and France, as part of the International Working Group for Sabotage Concerns of Transport and Storage Casks (WGSTSC).

INTRODUCTION

This report provides a detailed summary and update of significant results from an ongoing, multinational test program that is measuring aerosol particle data for a spent fuel sabotage scenario relevant to spent

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fuel transport and storage casks. The casks used for spent nuclear fuel transport are extremely resistant to releasing any significant fraction of their contents, even in very severe accident conditions. However, in some credible intentional sabotage scenarios, such as an attack employing a high energy density device (HEDD), i.e., explosive armor-piercing weapons, it is possible that a small percentage of aerosolized particles produced from disrupted fuel rod and pellet materials could be released as an inhalation source hazard. If released to the environment in a significant quantity, the spent fuel respirable particles have the potential to cause radiological consequences. Measurement of the actual amounts, nuclide content and size distribution of the particles produced from spent fuel and related surrogate materials is essential for predicting the significance of aerosol releases from the cask and their radiological inhalation impacts. These aerosol source-term data are the input for follow-on modeling studies to quantify respirable hazards, associated radiological risk assessments, vulnerability assessments, and potential cask physical protection design or safeguards modifications. The need for accurately quantifying this information has been strongly supported by program participants in the U.S., Germany, France, and others, as part of the International Working Group for Sabotage Concerns of Transport and Storage Casks. WGSTSC partners need, and are helping coordinate this research and subsequent modeling plus assessments, in order to develop potential preventative measures for plausible radiological sabotage events, if necessary.

The prime purpose of this document is to present details and significant aerosol particle results and recent interpretations from the Phase 3 portion of our test program using depleted uranium oxide pellets in surrogate spent fuel test rodlets, including added non-radioactive fission product dopants. The pellets are within a "simplified" single Zircaloy-4 cladding tube/target rodlet. The DUO_2 aerosol particle results are compared directly with our previous Phase 2 results from surrogate cerium oxide ceramic pellet and fission product dopant surrogate test rodlets. We provide summaries of previous test phase equipment, details, and available results, as documented in earlier reports [1-2]. We also include the current status for performance of Phase 4 actual spent fuel rodlet tests, required for the determination of the spent fuel ratio (SFR), and needed for modeling scaling studies.

Aerosol particle measurements performed in this program require sampling and quantification of the mass and physical characteristics of the aerosol particles produced from (spent fuel or surrogate rodlet) target-HEDD jet impact, with particle aerodynamic equivalent diameters (AED) up to 100 μm. For evaluations of aerosol and radiological consequences, there is a special emphasis on "respirable particles," commonly defined as 0 to ~ 10 μm AED in size. Data from the coarser aerosol particles in the ~ 10 to 100 μm AED range, termed the non-respirable "inhalable" fraction, are of interest primarily for radiological "ground-shine" (dispersion, soil contamination, potential ingestion) consequence estimates.

The major measured aerosol source term data needed, and results provided from our research include:
(1) The **Respirable Fraction (RF)** of particles *produced* is defined as: **RF =** the [mass of an element (i.e., U, Ce, Cs, Zr, etc.) in respirable particles] / [mass of that element in the rod swept volume (particulated)] by the HEDD. This RF, expressed as a percentage, is particularly relevant to the far-field (i.e., releases from a sabotage damaged spent fuel cask) airborne dispersion and consequence modeling studies. We also measured produced particle size distributions, elemental content, and morphology [2].
(2) The measurement of enhancement of volatile fission product nuclides like cesium preferentially sorbed onto specific, respirable particle size fractions in the sub-μm to μm size range. This enhanced sorption is expressed as an **Enrichment Factor (EF)**, and can be integrated over the respirable particle size range. The integrated Enrichment Factor is defined as:

IEF = RF(fission product element) / RF(uranium or cerium).

Differential EF values can also be measured as a function of individual particle size ranges and are observed to vary quite significantly as a function of size. Differential EF values are defined as:

EF = [fission product element fraction in a given size range] / [fission product element fraction in pellet].

(3) The **Spent Fuel Ratio (SFR)** for respirable particles is defined as:

SFR = [Spent Fuel respirable particle masses] / ["Surrogate" DUO_2 respirable particle masses].

The SFR determination is, essentially, the comparison of the respirable, aerosol particle data from irradiated, spent fuel (to be measured in Phase 4 of this test program) to the respirable, aerosol particle data from unirradiated, surrogate DUO_2 fuel, as measured from Phase 3 tests and presented herein. These

data are obtained in paired experiments using effectively the same apparatus, essentially identical test conditions, and using the same HEDD. The measured SFR values (not yet available) will provide a data bridge to previous, large-scale surrogate (DUO_2) aerosol-explosive cask tests [3-4] performed in both the U.S. and Germany, and to consequence assessments. The SFR values permit scaling to other geometries, from a simplified single short fuel rodlet, as tested here, to rod bundles in casks, by means of supporting modeling studies.

Sandia National Laboratories (SNL) Materials Transportation Testing and Analysis Department has the lead role for managing and performing this research program. Major support and expertise are provided by other SNL organizations including: Explosive Testing and Diagnostics, Aerosol Processes, and Radiation Sciences/Nuclear Facilities and Technologies. Overall sabotage and transportation program support is provided by both the U.S. Department of Energy (DOE RW, Office of Civilian Radioactive Waste Management, OCRWM) and the U.S. Nuclear Regulatory Commission (NRC, Office of Research). Argonne National Laboratory (ANL), Energy Technology Division, has provided the detailed characterization and fabrication work for all spent fuel test rodlets to be used in this program. German participants, the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) and the Fraunhofer Institute of Toxicology and Experimental Medicine (ITEM), are providing supporting aerosol testing, expertise, and data analyses. The Institut de Radioprotection et de Surete Nucleaire (IRSN), France, has provided the unirradiated depleted UO_2 (surrogate, DUO_2) fuel test rodlets for Phase 3 testing, plus supporting laboratory and modeling studies. Other organizations, the Japan Nuclear Energy Safety Organization (JNES) and Japan Atomic Energy Agency (JAEA), Japan, and the Office for Civil and Nuclear Security (OCNS), in the UK, have participated in a cooperative role.

EXPERIMENTAL DESIGN AND DETAILS

The overall surrogate and spent fuel sabotage explosive-aerosol measurement test program plan and design have been previously described in detail [1-2]. We shall focus herein primarily on details of the recent Phase 3 DUO_2 tests. The complete program [1-2] consists of four sequential test phases, paralleled by and followed by an extensive modelling effort. The major components for each test, specific to individual test phases, include: a single target test rodlet with internal ceramic pellets, plus support rods and hardware; a vertical, explosive-aerosol containment test chamber to withstand the explosive blast and contain all aerosol particles produced; the HEDD, a precision explosive device; aerosol particle samplers (particle impactors, sampling tubes, etc., described below); a HEDD-jet stop assembly; and, supporting test facilities needed to perform the tests and to analyze aerosol particulates.

Test Phase 1, performed in 2001-02, used glass targets as representative brittle materials and focused on performance quantifications of the HEDD devices, and refinement of the aerosol particle collection apparatus being used. The extensive test Phase 2 series, performed in 2002-04, used sintered ceramic pellets (~9 per test) of cerium oxide, CeO_2 (a non-radioactive, chemical and ceramic surrogate for UO_2 fuel pellets), contained within short, ~20 cm-long Zircaloy-4 cladding tube rodlets, representative of spent fuel rods. Pellet sizes (~7 mm-long x 9 mm-diameter) and cladding tubing were sized to match PWR fuel rods. Non-radioactive fission product dopants (for cesium, ruthenium, strontium, and europium) were incorporated into these test rodlets either external/adjacent to, or internal to the surrogate pellets. Successive tests in Phase 2 [1-2] allowed us to add and evaluate effects of multiple variables on target aerosolization response to HEDD jet impact, including: internal rodlet pressurization; different fission product dopant additions and form/distribution factors; several types of aerosol particle samplers; and, target rodlet materials (CeO_2 pellets of various lengths, plus doped surrogate high-level waste glass rodlets or pellets, contributed by our German test partners at GRS and Fraunhofer ITEM). All fission product dopant materials were within the swept volume and were totally aerosolized and possibly vaporized by the shock wave and thermal pulse from the action of the HEDD jet. We added a supplemental Phase 2+ series of non-radioactive tests in 2005, using fission product-doped CeO_2 pellets or doped surrogate German high-level waste glass pellets, to: (a) further evaluate the release and preferential sorption enhancement of cesium and other fission product dopants as a function of dopant distribution; and, (b) to evaluate the effects of explosive by-product carbon soot and chamber temperature rise from the HEDD detonation on the fission product measured RF and EF. We performed a final Phase

2+ test in 2007 using a CeO_2 pellet rodlet with multiple fission product disks, with all equipment enclosed in a 50 m^3 steel aerosol test chamber. The primary objectives of this test, 2/CSC, were to evaluate effects of lesser amounts of explosive soot (in an oxygen-rich vs. an oxygen-deficient environment) and lower test chamber temperatures on aerosol behaviour, in comparison to previous Phase 2 and 2+ tests. Respirable fraction (RF) and fission product enrichment factor (EF) results from the Phase 2 and 2+ tests [1-2] are summarized herein, for comparison with the Phase 3 DUO_2 results.

There are six Phase 3 tests that use slightly radioactive, unirradiated depleted uranium oxide pellets in Zircaloy cladding tube test rodlets. The Phase 3 target rodlets, shown in Figure 1, were fabricated by CERCA (a Framatome-ANP, AREVA subsidiary) in France for our French test partner, IRSN, for testing at SNL. Each test rod contains five 13.8 mm-long pellets of ~ 95% theoretical density DUO_2, with dished ends. Laser end-cap and seal welding were used to fabricate the rodlets. The test rodlet design, shown in Figure 2, was a collaborative effort by IRSN, SNL, and Argonne National Laboratory. The completed rodlets were He-leak tested, all welds were X-ray tested, and then the rodlets were shipped to SNL. These tests incorporate the variables of internal rodlet pressurization (1 or 40 bar of He within the rodlet end plenum regions, similar to PWR fuel rods at the end of their life), added non-radioactive fission product dopant disks (as illustrated in Figure 2, in three of the six rodlets), and an internal aerosol chamber atmosphere (either air or inert nitrogen). A post-test DUO_2 rodlet, with its center-region particulated, is shown in Figure 3. The Phase 3 tests use a vertical, self-containment (sealed), aerosol-explosive test chamber, shown in Figure 4, based on a similar, but less sophisticated, Phase 2 test chamber design [1-2]. This test chamber is approximately 0.6 m-diameter by 1.3 m-high, and is fabricated out of thick steel to contain the explosive blast (bottom chamber) and contain all aerosol particles produced (top chamber) for sampling. Three Phase 3 tests were completed to date, one in 2005 and two in 2006; the remaining three tests will be conducted when funding permits. These tests were performed at the SNL Explosive Components Facility within a secondary containment housing surrounding the test chamber, to prevent any radioactive particle release. Post-test, the aerosol apparatus systems shown at the top of Figure 4 were disassembled, and weights of all aerosol samples were obtained in an adjacent small plastic glove-box enclosure. The primary and secondary containment physical controls were accompanied by radiological protection surveys. Prior to the next test, the test apparatus was thoroughly cleaned and decontaminated.

These explosive-aerosol tests are primarily aerosol production and particle measurement/characterization experiments. We use 9-stage, multi-jet Marple cascade impactors (aerosol particle samplers) contained within four independent, replicate sampling assemblies per test, as shown in Figure 4, top. These impactors are designed to measure particle size distributions from about 0 to ~ 21 μm AED, plus an additional "pre-filter" stage for larger particles, ~21 to 35 μm AED. Aerosol sampling was conducted for a 10-second period following HEDD detonation. We also used separate, in-line, large-particle separators (LPS), jointly designed by SNL and Fraunhofer ITEM aerosol experts, for collecting the ~30-100 μm AED particles. Each Marple and LPS sampling assembly requires a vacuum bottle and a critical orifice to draw a calibrated, nominal 2 l/min flow rate through the samplers; a small HEPA filter is also used before the large vacuum bottle. The mass of all collected particles on the impactor stages are first determined by weight gain measurements, then chemically dissolved. Detailed chemical analyses of major elements and fission product species in the particles are necessary because much of the collected particle mass consists of fine carbon soot, a combustion by-product of the HEDD detonation; analyses were obtained using inductively coupled plasma-mass spectrometry, ICP/MS.

Eight planned Phase 4 tests will use radioactive, spent fuel pellets in their original irradiated Zircaloy-4 cladding from actual pressurized water reactor (PWR) spent fuel rods [2]. These spent fuel pellets are being fabricated into short test rodlets, with a rodlet end-fitting design similar to the Phase 3 DUO_2 rodlets. Four of the Phase 4 tests will use a high-burnup spent fuel (~72 GWd/MTU) originating from a U.S. pressurized water reactor (PWR). The other four tests will use a low-medium burnup (~38 GWd/MTU) spent fuel originating from a different PWR. Two different burnup fuels are being tested because

Fig. 1 Photograph of Phase 3 DUO_2 Test Rodlets

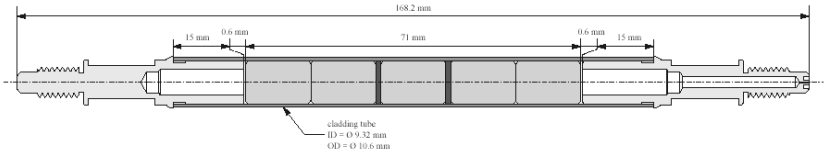

Fig. 2 Phase 3 DUO_2 Test Rodlet Schematic, with two central fission product dopant disks

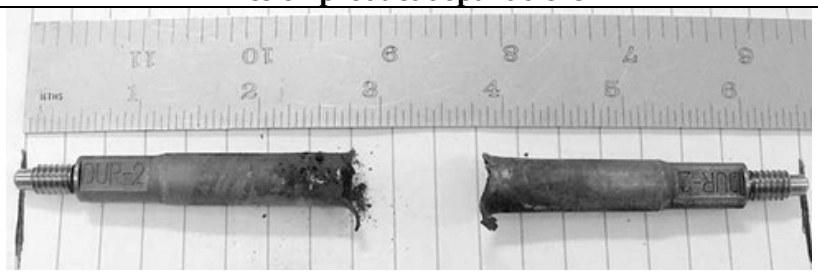

Fig. 3 Post-test Phase 3 DUO_2 Rodlet

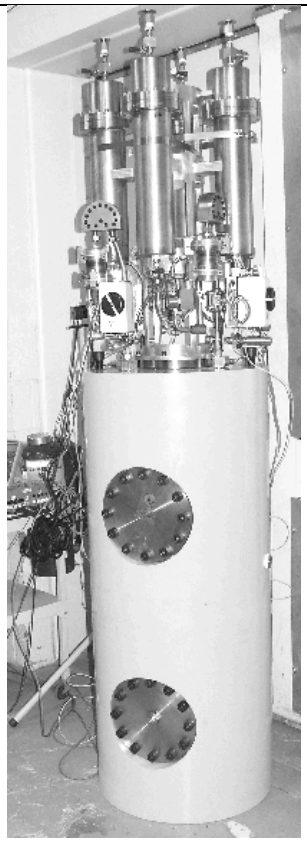

Fig. 4 Phase 3 Test Chamber and Aerosol Sampling System

it is postulated that each may yield a different respirable fraction of particles as a result of greater radiation damage in the higher-burnup fuel. All of the spent fuel has been characterized in detail and are being fabricated into test rodlets at Argonne National Laboratory, for SNL. The spent fuel characterizations include: visual exams, axial gamma scanning, cladding hydrogen content, optical metallography, and isotopic analyses, for following aerosol and radiological source term material behavior evaluations. The aerosol-explosive, vertical test chambers for Phase 4, spent fuel tests, are very similar to the Phase 3 vertical explosive-aerosol test chamber shown. Once the remotely inserted spent fuel test rodlet has been explosively disrupted by the HEDD jet, the post-test chamber will not be opened in order to prevent escape of highly radioactive particulates. The only particle sampling is via the four replicate, top-mounted aerosol impactor sampling assemblies. Aerosol particle gravimetric, radiological, and chemical analyses will be performed at both SNL and/or at ANL. Each Phase 4 test chamber will be used one time only, then shipped off-site for storage, before eventual permanent repository disposal. Two of the eight needed test chambers have been fabricated to date. The Phase 3 and Phase 4 tests will be performed under essentially identical test conditions, to permit direct comparisons of their resultant data.

The final measurement of the spent fuel ratio (SFR), calculated as a function of aerosol particle size ranges, will be obtained after the completion of Phase 4 tests. This spent fuel program has recently been authorized for conduct in the SNL Gamma Irradiation Facility (GIF), Test Cell 3, starting in 2008 or 2009, dependant on available program funding. The DOE Sandia Site Office (SSO; NNSA) has approved an updated version of the Documented Safety Analysis for the GIF which analyzes the explosive-aerosol tests with a bounding source term. The GIF Safety Evaluation Report identified no conditions of approval. Implementation of Technical Safety Requirements from the DSA into experiment specific procedures and supporting documentation is in process.

AEROSOL DATA AND RESULTS

During each observed Phase 2, 2+, and Phase 3 test, the HEDD jet "particulated" approximately a 24-32 mm length of the target rodlet (the swept volume), leaving the remaining end pellets (and rodlet ends) basically undamaged and wedged in the cladding tube. Instrument measured conditions within the vertical aerosol collection chamber include a temperature peak of up to ~900 K, dropping to ~400 K in 30 sec., and a peak pressure of ~3 bar, dropping rapidly [2]. This is due to the HEDD detonation heat input into a closed system; the temperature and pressure are related such that their ratio is constant. Peak temperatures and pressures measured were only ~ +6 K and 1.5 bar, respectively, within the external aerosol sampling lines on top. The sampling lines were isolated until 2 seconds after detonation; by that time, the pressure had declined. For the DUO_2 tests performed, negligible amounts of particulate contamination, at or below measurable levels, were released from the leak-tight test chamber during conduct and post-test sampling.

We have quantified the aerosol particle size distributions of all elemental species involved in the aerosol-explosive/sabotage process, including Ce or depleted U from the pellets, Cs, Ru, Sr, and Eu fission product species, Cu from the HEDD, and Zr from the Zircaloy cladding tube. From observations of the CeO_2 distributions in the ~ respirable size range, CeO_2 particles appear to peak broadly over the 3.5-9.8 µm AED range. The observed DUO_2 particle size distribution peaks quite strongly at about 3.5 µm AED, then decreases. Figure 5 shows the measured RF values for surrogate CeO_2 and DUO_2 pellet materials. The measured, average RF for CeO_2 was 0.65% ± 0.23% with a 99% confidence interval (CI), based on the most recent Marple impactor data (for tests 2/5E and later, considered our best quality and largest amount of interpretable data). Significant RF data scatter was observed in the older tests, possibly resulting from particle losses in the non-sealed aerosol collection chamber used. Similarly, using all measured data, including Marple plus older Respicon and Berner impactor data [1-2], the average RF for CeO_2 was 1.36% ± 0.50%. The measured DUO_2 RF value is 1.32% ± 0.32% based on data from the first three Phase 3 tests, also with a 99% CI. The measured RF for zirconium was 1.3% ± 0.3%. Fifteen tests with CeO_2 test rodlets, and one so far with DUO_2 test rodlets, have incorporated fission product dopants. The observed particle size distribution for cesium has a distinct peak at 0.5-3.5 µm AED. The measured cesium fission product dopant RF in all CeO_2 tests (test 2/4A and newer) was Cs RF = 24.9% ± 5.6% of dispersed mass. CeO_2 results for test 2/CSC in the 50 m^3 chamber are quite consistent with the most recent Phase 2 and 2+ results from the vertical test chamber tests. For the DUO_2 test, the Cs RF = 45% ± 16%, appreciably greater than in the CeO_2 tests.

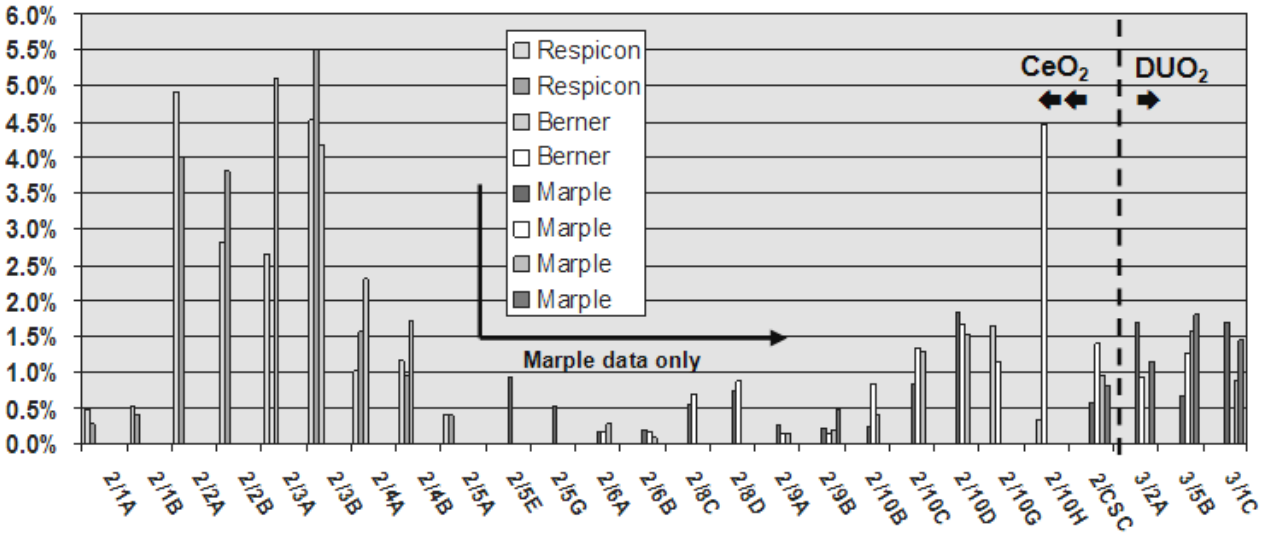

Figure 5. Measured Respirable Fraction (RF) Results for CeO_2 and DUO_2 Tests

The measured cesium fission product integrated enrichment factor (IEF) as shown in Figure 6 for the respirable size range of 0 to 10 µm AED, averaged 44 ± 17 for the CeO_2 tests and 36 ± 7 for the DUO_2

test, both with a 99% CI. We found a rather large standard deviation for Cs IEF values in the CeO_2 tests. Cs IEF values appear to be noticeably higher for the higher internal temperatures in sealed test chambers vs. semi-open test systems. As such, actual Cs IEF values may be appreciably lower than reported herein, dependent on test setup. A few tests in a Fraunhofer semi-open chamber and in the SNL 50 m^3 test chamber suggest that IEF data for Cs observed in the sealed test chamber with high explosion gas temperatures may overestimate the cesium IEF obtained with lower temperature conditions. However, temperatures within an actual spent fuel transport rail cask potentially breached by a HEDD jet can actually be at high temperatures more comparable to the sealed aerosol test chamber tests. Cs measured IEF and RF differences due to distribution of the Cs dopant within the test rodlet are not as obvious; these differences have not as yet been satisfactorily resolved. Differential cesium EF values were also measured as a function of particle size, as shown in Figure 7 for test 2/10C, for each size range of material collected in the Marple impactor and LPS. The cesium EF decreases from ~ 100 at ≤ 1 µm, to ~ 3 at 10 µm, then increases to ~ 10, again, before decreasing again at larger aerosol particle sizes. The second maximum needs further investigation as it has been observed in most, but not all tests. The cesium IEF data for the DUO_2 test are not as pronounced, having a flatter decrease with increasing size, and no appreciable second maxima. NOTE: Data bars for test 2/10CSC and "2/10CSC Ru" in Figure 6 originate from the same, singular test, but from different chemical analyses.

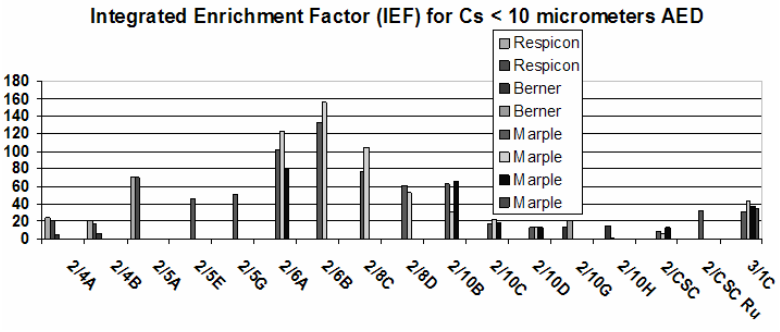

Figure 6. Enrichment Factor (IEF), Cesium fission product integrated over 0-10 µm respirable range

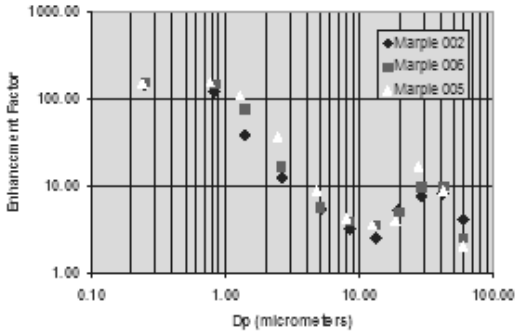

Figure 7. Cesium fission product Differential Enrichment Factor

DISCUSSION & SUMMARY

This test program has been performed primarily at SNL since 2001, to quantify and characterize aerosol particles produced in a plausible HEDD sabotage event on a spent fuel transport or storage cask. There has been cooperative design input, participation, and supplemental testing primarily from other U.S., German, and French partners, as part of the collaborative, International WGSTSC. This current "simplified single short-rodlet" testing portion of the overall program is designed to provide reliable, quantified source-term input data to parallel follow-on modeling efforts of near-field aerosol dispersion, computational fluid dynamics, and radiological consequence assessments. Several modeling studies have been initiated, to tie these WGSTSC test programs and results, both previous [2-5] and future, together.

Over the last two years, we have performed three Phase 3 tests using slightly radioactive, non-irradiated depleted uranium oxide pellet rodlets plus one surrogate CeO_2 test in a separate 50 m^3 test chamber. The Phase 3 DUO_2 tests are required to determine the spent fuel ratio, along with results from the still to-be-performed Phase 4 tests with actual spent fuel rodlets. Some progress has been made to initiate the Phase 4 tests at SNL and formal DOE SSO approval has been received to use the Sandia GIF facility for this explosive-aerosol testing. Several technical and administrative actions remain before this testing can continue. We have also analyzed and completed interpretation of a large body of aerosol data with the intent of reducing uncertainties. For instance, observed particle deposition in the sampling lines in the vertical test chamber, due presumably to thermophoretic, diffusiophoretic, and turbulence effects, can add some uncertainty or underestimation to measured RF values. However, consistent results from the test 2/CSC in the well-calibrated 50 m^3 test chamber suggest that explosively generated soot, plus higher internal temperatures and pressures in the vertical test chamber do not have a significant impact on the

source term data, probably by much less than a factor of two. The consistency of the measured RF and IEF values between the vertical chamber tests and the 50 m^3 chamber test strongly suggest that the line losses observed in the vertical chamber tests are likely to be from larger aerosol particles that most probably have some sort of inertial deposition mechanism such as turbulence or unsteady flow. Also, the measured high RF values for dopant fission product cesium (and other fission products [2]), and high observed IEF are a clear indication that a significant amount of the cesium is both mechanically particulated and thermally volatilized. That vapor then preferentially sorbs and is enriched onto adjacent respirable particles of particulated fuel or surrogate pellet materials, copper particles from the HEDD jet, soot particles, and other jet-impacted hardware or cask materials.

The measured respirable fraction (RF) values for surrogate CeO_2 and DUO_2 tests are quite similar, at 0.65% or 1.3%, respectively. Our measured RF values are for respirables *produced* within, not the realistically much smaller amount released [5] to the environment through a hole in a sabotage impacted cask. These surrogate CeO_2 and DUO_2 RF values are appreciably below, but not inconsistent with, the 5% RF value for spent fuel estimated in an earlier repository related transportation-sabotage analysis [5]. This suggests that the estimated respirable particle release predicted in that earlier analysis is likely to be appreciably conservative, i.e., the radiological consequences of a sabotage event on a spent fuel transport cask may not be as significant. Further results from the Phase 4 spent fuel tests plus future consequence assessment calculations are still needed to confirm this inference and to successfully complete this program. A separate, comprehensive SNL technical report including all measured data, findings, and conclusions to date is in preparation.

In conclusion, there are significant benefits for all governmental, regulatory, and test participant organizations involved for the successful conduct and completion of this test program and associated modeling, including: (1) Reliable, measured source term data are provided for supporting modeling analyses of release of respirable aerosol particles and atmospheric dispersion resulting from an intentional, plausible sabotage event. (2) The spent fuel ratio plus aerosol source term data and information from these tests and analyses allows extension or scaling to other types of transportation terrorist events via modeling. (3) A basis is provided for evaluating appropriate levels of physical protection and safeguard requirements for nuclear materials in use, transport, or storage. (4) Measured data help guide and validate technical bases for transport and storage regulations based on older, limited information [1-2, 5] and provide further validations of sabotage vulnerability studies. And, (5) This cooperative program leverages total program testing, modeling, capabilities, and benefits over all international U.S., German, French, and other WGSTSC participants, with significant, shared expense and policy benefits.

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