PERSPECTIVES ON SPENT FUEL CASK SABOTAGE

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ABSTRACT

Information relating to the magnitude of potential source terms for estimating the consequence of sabotage involving spent fuel casks in transit is provided. Included are a list of relevant publications, discussion of parameters that produce significant uncertainty in making release fraction estimates, as well as plans for experiments that could resolve some of the uncertainty in results obtained to date.

INTRODUCTION

There have been a number of experiments relating to sabotage of radioactive material transport containers (1-7). Most of the experiments deal with spent fuel casks because these shipments, if successfully sabotaged, have the potential to lead to significant radiological impacts from release of radioactive material to the environment. This potential is driven by the large amount of radioactive material (RAM) contained (frequently in the range of 2 to 20 MCi for commercial power reactor fuel). However, producing a release from a spent fuel cask is a formidable task owing to the robust design necessitated by spent fuel containment and shielding requirements. Projections of the potential releases and radiological impacts from spent fuel shipments have been performed a number of times (1, 4, 8-13).

Many of the works cited above were analyses or analytical extensions of measurements of surrogate spent fuel aerosols produced in experimental configurations that were

intended to model aspects of spent fuel shipments. Some experiments have been performed with actual spent fuel pellets as a target for an attack device, but the correlations with the larger number of companion experiments on surrogate materials are few in number and provide a wide spread of values for the relative aerosolization behavior of the two materials. The characteristic parameter used to extrapolate surrogate fuel behavior to that of real spent fuel is the ratio of spent fuel respirable aerosol mass to surrogate respirable aerosol mass (SFR). The SFR has a range of 0.7 to 12 between the lowest and highest estimates. An additional, but smaller, uncertainty results from an indication in some experiments with spent fuel (1-3) that there is an enrichment of volatile fission product in the respirable aerosol relative to that in larger particle diameters.

To provide an estimate of the source term used to calculate the radiological consequences from a successful sabotage attack, experimental data for spent fuel aerosol release as a result of attack by High Energy Density Devices (HEDD) is required. Lacking such a direct measurement three sets of data are frequently used. These are:

- respirable release fraction for experiments with an appropriate surrogate spent fuel,
- measurement of the SFR to relate the data in item 1 to real spent fuel, and
- measurements of any fractionation effects occurring.

While data indicated in item one have been obtained in a few configurations, there is less information on the second and less on the third. This imperfect understanding of the interaction phenomena when a (HEDD) is used to attack a spent fuel cask takes on a higher public profile as a result of public interest in the:

- petition by the State of Nevada (14) to the Nuclear Regulatory Commission (NRC) for revision of NRC's safeguards rules for spent fuel ,
- inclusion of a sabotage consequence estimate in the Department of Energy (DOE) Draft Environmental Impact Statement (DEIS) (13) for the Yucca Mountain Project (YMP),
- minimal treatment of sabotage in the PFS DEIS (15)

The sabotage estimate in the YMP DEIS used a spent fuel to surrogate aerosol generation ratio of 3, which is at the middle of the experimental values. It is believed that this is a conservative estimate for SFR, but the wide variation in potential values allows other assumptions to be made. Such a large spread in values for a parameter that has a direct influence on the predicted consequence of an optimally successful sabotage attack demands an experimental program to narrow the level of uncertainty. A proposal to pursue an experimental program in this area has been developed and is being considered for funding in the USA. Funding is already committed to a supporting experimental program in Germany.

Although significant work has been done in the USA and in Germany to assess sabotage impact on spent fuel casks and developing source terms for release of spent fuel

materials, some work remains to develop a complete understanding of potential sabotage consequences. The needed work is related to effectiveness of types of attack devices and to the behavior of actual spent fuel under the very energetic conditions that could occur in optimally successful HEDD attack scenarios. Work is underway to determine the effectiveness of various potential attack devices on typical cask designs. This effort looks at the spectrum of penetrator size and impact velocity to discern potential for penetrating a cask. If penetration is possible, the first order assumption is that the aerosolized fractions are the same as have been determined in prior works shown in the references (12,17). This would generally be a conservative assumption because the energy delivered per unit mass for experiments completed is very high. However, this is an area for additional study.

This paper provides an overview of the open literature relating to spent fuel sabotage phenomenology and results as well as more general work in the area of brittle material fracturing in high energy density environments. This latter area provides significant theoretical support in interpreting and extrapolating experimental results into areas where experiments with real spent fuel cannot be conducted. An experimental program described in a subsequent section has developed a modest amount of new information in this area and a more elaborate program has been proposed for summer and fall of 2001.

SOURCE TERM

The release of fine particles from a shipping cask after HEDD action is determined on the one hand by the initial source term, i.e. the "dust" generated inside the cask, and on the other hand by the transport term that characterizes the transport of airborne material from inside the cask to the outside environment. The transport term is essentially independent of the type of fuel pellets used and can be measured in experiments using realistic surrogate fuel elements in representative geometries(1, 6). The more critical parameter in estimation of the source term requires measurement of the amount and characteristics of the particles produced by the action of the HEDD. Obtaining the aerosol production parameters has been approached by measurement of aerosol from both surrogate and spent fuel in similar geometries. These data are expressed in the spent fuel ratio (SFR), which, when taken with the measured transport behavior of the surrogate material, allow determination of the corresponding spent fuel released mass and activity fractions vs. aerodynamic equivalent diameter (AED; see Addendum). Usually the SFR is sought for respirable particles (those with AED less than 10 micrometers in diameter) because inhalation of these particles in sufficient quantity can lead to health consequences and because they are small enough to be transported great distances from an attack site by the wind.

In reference 1 Sandoval suggested, based on his experiments at Sandia National Laboratories, that a respirable release fraction of 5.4E-4, of the mass of surrogate spent fuel disrupted by the action of an HEDD and released from the cask was appropriate for use in estimating the source term from a sabotage attack using a similar device on a spent fuel cask. The experiment involved a single simulated fuel assembly contained in a steel/lead/steel spent fuel cask. The simulated fuel was composed of UO_2 pellets in

Zircalloy tubes in a 15 x 15 configuration. The Sandia results were consistent with experiments conducted by NRC at about the same time by Schmidt et al (4,5) at Battelle Columbus Laboratory on surrogate and actual spent fuel pellets with a similar type HEDD.

Use of the surrogate respirable fraction data for estimating modern spent fuel sabotage source terms requires information on the amount of fuel likely to be disrupted by the action of the HEDD, the effect of the transport process within the cask that results in a release of material, as well as the SFR.

Sandoval estimated the respirable release fraction for his experiment through direct measurement of both the aerosol released from the cask and the mass of disrupted fuel. Alternately the release can be normalized with an estimate of the affected volume of fuel based on depth and diameter of the penetration in the affected fuel. Depth of penetration of the spent fuel cask by the HEDD yields the number of spent fuel assemblies affected. The missing length of fuel rods permits estimating the lateral dimensions of the cavity produced. Analytical estimates of disrupted depth and lateral geometry as obtained using computer codes (e.g., reference 16) also can be used for this process, as in reference 12.

A confirmation that the volume estimate process described above provides a reasonable approximation of the direct mass measurement was obtained from the Sandoval experiments. Using the disrupted depth and length of missing pins yielded an estimate of 7 E-4 for the respirable fraction (12).

The Sandia experiments (1) provided an estimate of the fractional release of respirable aerosol from the cask, but did not include the effect of gas released from each rod that is penetrated by the HEDD. This gas, which is released after the pressure pulse from the HEDD ejects material from the cask, can carry additional aerosol out to the surrounding environment. One process used in reference 12 to estimate this effect was to estimate the total respirable aerosol produced internal to the cask as a result of HEDD action and then estimate what portion of that mass might be released by voiding of the plenum gases. Estimates of the total respirable aerosol produced were based on an experimental relationship that suggests that, for brittle materials, the amount of mass created smaller than a given size is almost directly proportional to the specific energy input imparted to the material (see addendum). An upper limit estimate of 5% for the total respirable produced was developed for the specific HEDD's of interest in reference 11.

A second aerosol release fraction estimate for release from a realistic HEDD attack situation was obtained from the results of a recent experiment conducted in France and funded by GRS (6). The analysis was based on volume of disrupted fuel as was done for the Sandoval experiments. In the GRS experiments 9 surrogate fuel elements on a 3 x 3 array in a storage cask were subjected to 3 experiments involving penetration of a cask by an HEDD. Experiment 3 involved sub-atmospheric pressure in the cask prior to the experiment. All rods were pressurized, as they would be if they were spent fuel, unlike those in the Sandoval experiments. Experiment 1 resulted in penetration of three assemblies while experiment 2 penetrated only one fuel assembly. Since experiment 2

resulted in penetrating only 1 assembly (although with larger affected diameter), it is suspected that the HEDD used for experiment 2 was deficient in spite of being nominally the same as the others.

Careful measurements of the aerosol released from the cask after each HEDD was detonated provided a direct measurement of the respirable surrogate material released. Estimates of the disrupted mass of fuel (17) allowed calculation of the respirable release fraction for comparison with the Sandoval results. The estimates were 3.7 E-4, and 3.1 E-4, and 6 E-5 respectively. GRS Experiment 2 is most comparable to the Sandoval experiment since only one surrogate assembly was penetrated by the HEDD. Even with the effect of rod plenum gas release (about 7% of cask free volume) to increase the total released, the value is about a factor of two below that obtained by Sandoval. This may be a result of deficient energy input from the HEDD.

The results of GRS experiment 1 are somewhat higher but still a factor of two below the Sandoval result even with about an 11% plenum gas fraction to help transport material out of the cask. Since GRS experiments 1 and 2 released about the same mass of respirable aerosol, but differed in the number of assemblies penetrated (3 vs. 1), the authors of reference 6 postulated that all the mass released came from the first assembly penetrated and that the basket effectively screened material from the 2nd and 3rd assembly from being released. If that postulate were correct, the effective release fraction for GRS experiment 1 would be a factor of three higher (1.4 E-3) or about twice the Sandoval value and, thus, suggests a factor of two enhancement in release from plenum gas release.

To investigate the pressurization enhancement further, the method used in reference 12 to account for released plenum gas sweeping aerosol out of the cask was used with an 11% plenum gas volume. The result obtained was a factor of about 4 enhancement of the Sandoval result caused by depressurization. The calculation from reference 12 was based on an estimate of 5% respirable aerosol production in the cask resulting from the interaction of the HEDD with fuel. To obtain the factor of two enhancement suggested by GRS experiment 1 in the effective respirable fraction, would imply a respirable aerosol production rate of about 2%. Such a rate is well within the uncertainty of the 5% value derived in reference 12.

One experiment in the Sandoval test series was a ¼ scale test in which the HEDD penetrated the entire cask, that is, both walls and the single (but not scaled) surrogate spent fuel element. The respirable source term for that experiment was about a factor of 8 above the value discussed above for the full-scale test in which one wall and the surrogate element was penetrated. It is postulated that this resulted from aerosol materials being swept out of the cask by the induced flow through the cask from HEDD action. Neglecting the difference in scale and other features of the two experiments that were not fully similar, it appears that an HEDD that produces a through path may produce an order of magnitude larger respirable release fraction than one that produces only an entry path. Thus, if an HEDD were to penetrate both cask walls, multiple fuel assemblies, and their associated baskets one might expect a larger source term than from one wall penetration. However, the trapping effect seen in the GRS experiments would

likely mitigate the total release to that from the fuel assembly(s) closest to the exit hole. Of course, as cask capacity increases, the number of walls and fuel assemblies that must be penetrated vitiates the HEDD action and makes complete penetration (both cask walls) less likely.

The release fractions derived from UO_2 surrogate spent fuel experiments with HEDDs are summarized in Table I. Key information necessary to use these respirable release fractions is the estimate of surrogate fuel mass disrupted by the action of the HEDD. Also note that the volume of rod plenum gas released will have an impact on the total release. Where there is relatively little free volume in the cask compared to the volume of plenum gas, there will be a relatively large outflow of gas that may carry more of the aerosol released to the cask internal volume out to the environment.

Table I. Suggested Sabotage Respirable Release Fractions for UO_2 Surrogate Spent Fuel for Various Plenum Gas Volumes and Initial Respirable Aerosol Fraction Produced

	Base Value (gram/gram disrupted)	Base Value Multiplier for Respirable Release Fraction (for **2%** and **5%** In-Cask Respirable Fraction)			
Rod plenum gas volume as a percent of cask void volume (at STP)		5%	10%	20%	40%
One Wall Penetrated	**8 E-4**	**1.7**	**2.3**	**3.5**	**5.3**
Two Walls Penetrated	**5 E-3**	**&** *2.8*	**&** *4.5*	**&** *7.4*	**&** *12*

SPENT FUEL TO SURROGATE RATIO (SFR)

Relatively few experiments have been performed on actual spent fuel to determine its behavior compared to that of the usual DUO_2 surrogate materials (2, 3, 4). The small number of experiments combined with incomplete data from some experiments and non-similar experimental configuration has provided a less than perfect understanding of the relationship between the behaviors of the two materials. The existing data provide indications of the magnitude of the SFR, but there is not the kind of accuracy one might desire. Estimated values for the parameter range from 0.7 to 12, with several values (and the geometric mean of all values) at about 3. While use of a value for SFR of 3 is suggested here for consequence estimates, our understanding of this basic aspect of spent fuel sabotage consequence prediction parameter needs improvement.

It is clear that the source term of released radioactive aerosol particles and, hence, any estimate of radiological consequences based on the data, suffer from unsatisfactory knowledge of the correlation of aerosol mass release data between the surrogate material (un-irradiated depleted UO_2) and actual spent UO_2 fuel. Sandia National Laboratories, Lovelace Respiratory Research Institute, Fraunhofer Institute, and GRS have developed joint proposals to perform a series of experiments using real spent fuel and UO_2 surrogates in an attempt to narrow the range of values for SFR. In addition, there is insufficient knowledge of the importance of enhanced release of volatile elements

(termed fractionation). When fractionation occurs and the more volatile nuclides are found in the finest aerosol fractions (rather than equally dispersed) enrichment is said to have occurred. Enrichment was observed, but not well quantified, in both Battelle Columbus Laboratory and Idaho National Engineering and Environment Laboratory studies conducted in the early 1980s (2-4).

Thus, the goals of the proposed experimental program are designed to define two important features of the interaction of HEDDs with spent fuel:

- mass and physical characteristics of the particles produced – for AED up to 100 micrometers with special emphasis on the respirable fraction (<10 micrometer AED)
- enrichment of volatile nuclides like cesium and ruthenium in specific particle size fractions.

The information gained for spent fuel will be compared in paired experiments (using the same apparatus and with the same HEDD) to the data from UO_2 surrogate materials to get estimates of SFR. Use of DUO_2 as a surrogate will make effective use of information from prior experiments that have provided estimates of surrogate aerosols released from casks subjected to HEDD attacks.

Two sets of small-scale experiments have been described in the proposal. Both obtain measurements of the airborne radioactive particle release from spent fuel and from surrogate material following HEDD action on of fuel rod segments. The first set of experiments would use a small HEDD and a short segment of a fuel rod (a few fuel pellets in length) in a simple geometry. The HEDD's impact area would be a fraction of a pellet's diameter. Experiments would begin with DUO_2 pellets and then move to a few similar experiments with spent fuel pellets.

Experiments with spent fuel need to be performed in a shielded sealed glove box because of the high radiological hazard of spent fuel. Handling and analysis of samples will require similar precautions and perhaps remote manipulation. As a result even the most elementary experimental set-up and the sample analysis is planned to be as simple as possible to keep costs within reasonable bounds.

The second set of experiments proposed is larger scale and involves an array of pins and an HEDD design that is similar in size to those used in prior experimental programs. The HEDD impact area would be larger than a pellet diameter. This experiment will have value in delineating the effects of relative size of the HEDD to pellet dimensions.

The experimental setup for either experiment is shown schematically in Figure 1, which uses instrumentation similar to the existing aerosol sampling and classification system designed, calibrated and evaluated for non-radioactive experiments at the Fraunhofer Institute for Toxicology and Aerosol Research (ITA) in Hanover, Germany. The apparatus has been used successfully in a number of important aerosol measurement programs.

The first set of experiments would not be much more complicated than as indicated in Figure 1. Figure 2 provides a sketch of how the entire experimental station for the second set of experiments might appear. This apparatus combines:

- a vertical elutriator (sampling chamber) separating airborne (<100 micrometer AED) from non-airborne (>100 micrometer) particles,
- a centrifugal classifier for size analysis between 20 and 100 micrometer (three size ranges), and
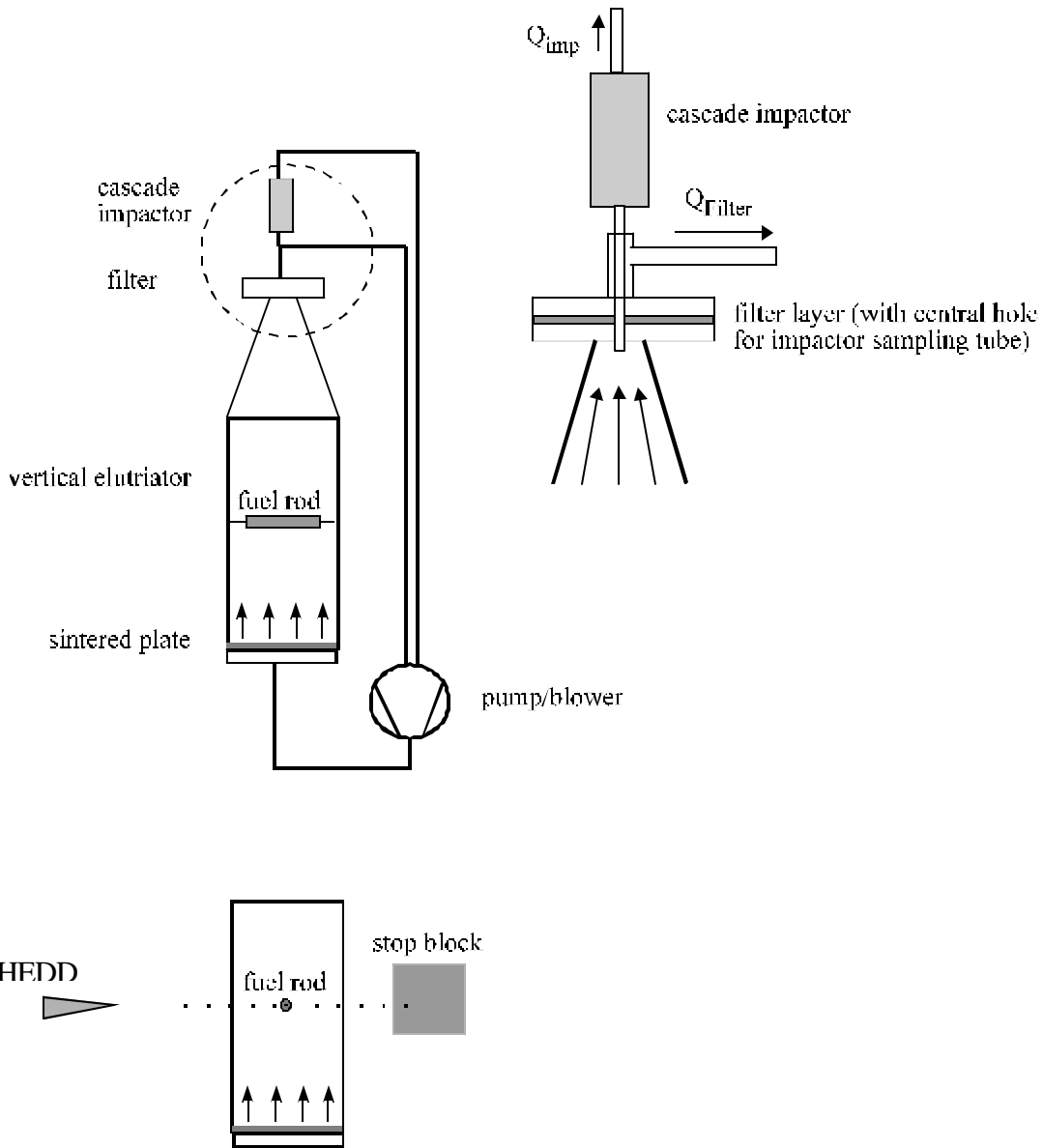- a conventional cascade impactor for size segregated sampling below 10 micrometer.

Fig. 1. Schematic of Experimental Concept

The fuel rod segments of either spent fuel or surrogate material would be positioned inside the sampling chamber such that the line of action of the HEDD is on a diameter of a fuel pin. In the upward directed air stream, released particles up to an aerodynamic diameter of 100 micrometers would be entrained and then collected on a filter with the exception of a side stream which is directed towards a fine (<10 micrometers) particle classifier (impactor) and then deposited according to particle size on the various stages of this instrument. The size of the chamber and the aerosol measuring equipment will be in accordance with the dimensions of the hot cell and the space required for positioning the HEDD.

It is expected that the line of action of the HEDD can be directed through an entrance hole into the interior of the sampling chamber and then onto the specimen. At the opposite side an outlet hole is drilled into the chamber. A stop block will prevent further damage by the HEDD. Part of the sampling chamber will be made of transparent material allowing a visual inspection of the destruction of the fuel rod. It will be necessary to operate the sampling chamber as a closed system in order to avoid any release of airborne material outside the chamber. The impactor would be constructed in such a way that it can be taken apart in pieces to be transported into a glove box for discharging and further handling of the aerosol material.
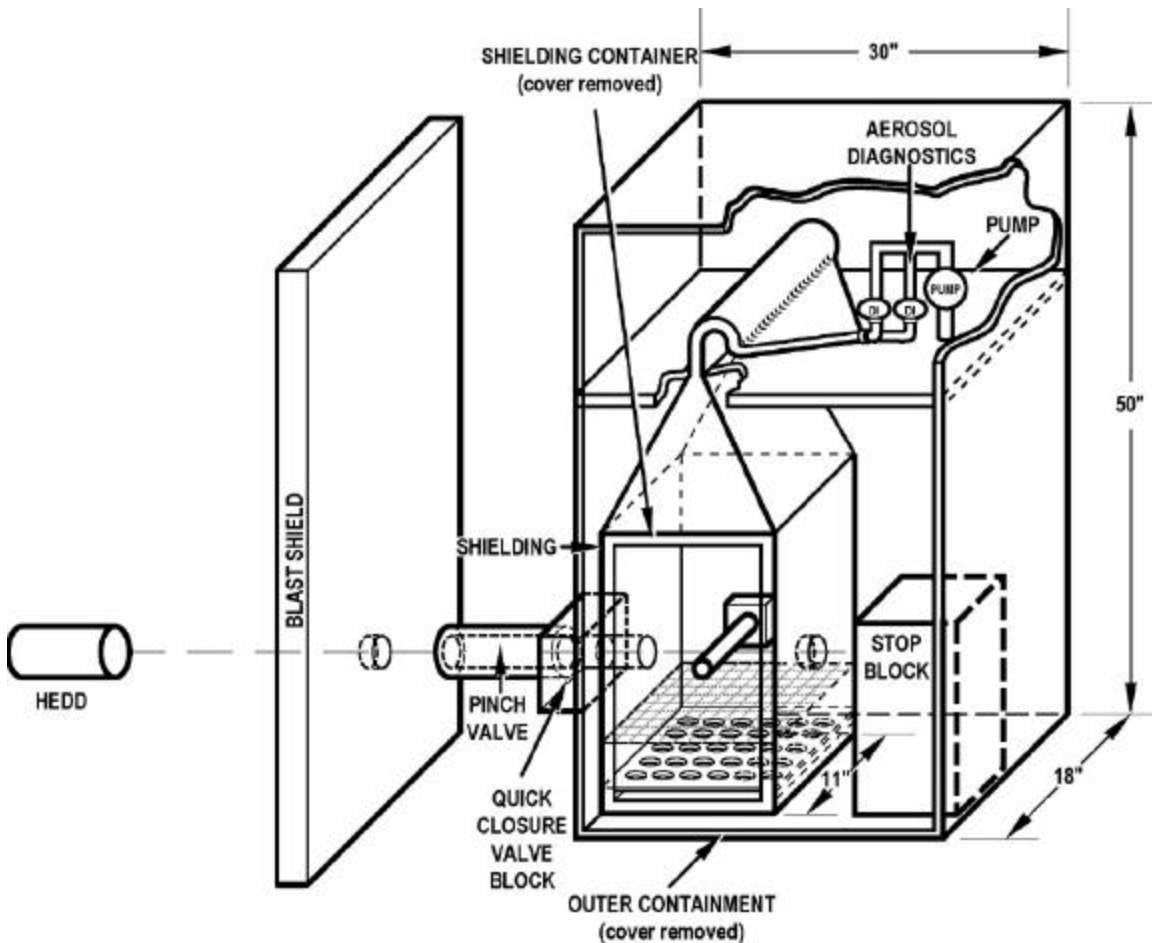
Fig. 2. Sketch of Possible Experimental Configuration

The final design of the experiments and analysis of its data will use information on the characteristics of aerosols produced from high-energy impacts of brittle materials. Experiments at the ITA addressed the formation of airborne particles after high-speed impact of brittle materials onto a hard surface and revealed a linear relationship between the released airborne mass fraction (all particles < 100 micrometer AED) of a test specimen and the specific energy input. This aspect of the behavior of brittle materials was discussed in a prior section of this paper.

It has been observed that the measured cumulative size distributions for brittle materials obey a nearly linear scaling law independent of the specimen material and geometry. As a result the cumulative size distribution can be universally represented as a linear function of the product of specific energy input times the aerodynamic particle diameter. These results could possibly allow simplifying the experimental set-up and the required aerosol and activity measurements. Thus using these scaling laws, a comparison of the airborne dust formation of spent fuel and depleted UO_2 specimens after a high energy impact could possibly be based on the comparison of the corresponding values of the released cumulative airborne masses up to a chosen diameter, e.g. of 100 micrometers.

Enhancement of volatile nuclides in the fine particle size fractions should be studied by additional measurement of the activity and mass size distribution in the size range below 10 micrometers AED. The measurement of mass and activity distributions in the range below 10 micrometers is well established by using impactors. The corresponding technique for classification of particles in the size range from 10 micrometers to 100 micrometers is more elaborate and therefore requires a more complicated set-up. It can probably be demonstrated by appropriate pretests with surrogate material that this is not needed if the scaling laws for brittle materials can be shown to hold for this situation.

CONCLUSION

There have been numerous views expressed with regard to the relative likelihood of sabotage attacks on our nation's nuclear material infrastructure and especially on transportation of spent fuel. Arguments of either side notwithstanding, estimating the impacts of an optimally successful sabotage attack on spent fuel casks and other containments for radioactive material have been under study since the early 80's. The results of those studies suggest that releases are not greatly different from what might occur in a severe transportation or facility accident. However, some uncertainty remains with regard to the behavior of real spent fuel in relation to the DUO_2 surrogates usually used. This paper provided guidance with regard to estimating the surrogate spent fuel source term as indicated by at least four experiments as well as indicating what the likely conversion factor (SFR) is between the spent fuel source term and the DUO_2 surrogate source term. The paper also provided an overview of the experiments that, if funded, might provide a better-defined value of SFR.

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ADDENDUM

Aerodynamic Equivalent Diameter (AED) is a measure of an aerosol particle's ability to negotiate changes in direction of the flow in which it is imbedded. Particles smaller than 10 micrometers AED are generally assumed to be respirable, i.e., can pass into the lung. The AED of a particle of arbitrary density material and size is the diameter of a particle with material density of 1gram/cc having the same gravitational fall rate in air. In general, the AED is the actual diameter times the square root of the ratio of the material's density to water.

Specific Energy Input is defined as the kinetic energy delivered to a material divided by the affected mass of the material. In the case of a specimen impacting onto a hard unyielding target this is the kinetic energy of the specimen divided by its mass. In the case of a projectile penetrating a material the specific energy input results from the energy loss of the projectile and the affected mass of the target material.