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Projected Source Terms for Potential Sabotage Events Related to Spent Fuel Shipments

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ABSTRACT

Two major studies, one sponsored by the U.S. Department of Energy and the other by the U.S. Nuclear Regulatory Commission, were conducted in the late 1970s and early 1980s to provide information and source terms for an optimally successful act of sabotage on spent fuel casks typical of those available for use. This report applies the results of those studies and additional analysis to derive potential source terms for certain classes of sabotage events on spent fuel casks and spent fuel typical of those which could be shipped in the early decades of the 21st century. In addition to updating the cask and spent fuel characteristics used in the analysis, two release mechanisms not included in the earlier works were identified and evaluated. As would be expected, inclusion of these additional release mechanisms resulted in a somewhat higher total release from the postulated sabotage events. Although health effects from estimated releases were addressed in the earlier study conducted for U.S. Department of Energy, they have not been addressed in this report. The results from this report may be used to estimate health effects.

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Discussions with William Schwinkendorf, INEEL liaison with Sandia's Geoscience and Environment Center, were instrumental in developing an awareness of pressurized rod plenum gas blowdown and the need to consider this effect in our estimates. This turned out to have a major impact on the results.

We are indebted to Steve Maheras, SAIC, Dublin, OH who was our project manager for this work. Throughout the course of writing this report, Steve provided positive support in smoothing out procedural issues and also provided sage counsel and data relating to the technical aspects of the task. In his role as single point of contact with DOE-RW, DOE-LV, the Yucca Mountain Project, Bettis Nuclear Laboratory, Jason Associates, and other supporting contractors, he made this effort much simpler than it might have been.

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AMAD	activity mean aerodynamic diameter
BCL	Battelle Columbus Laboratories
BWR	boiling water reactor
DOE	U.S. Department of Energy
HEDD	high energy density device
INEEL	Idaho National Engineering and Environmental Laboratory
NRC	U.S. Nuclear Regulatory Commission
OD	outside diameter
PWR	pressurized water reactor
SFR	spent fuel to surrogate fuel aerosol ratio
SNL	Sandia National Laboratories
STP	standard temperature and pressure

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EXECUTIVE SUMMARY

This report was prepared to develop a source term[1] for estimating the radiological consequences of potential sabotage events during transport of spent nuclear fuel in the early decades of the 21st century.

Sabotage/terrorist acts are defined as deliberate, unlawful actions intended to cause an undesirable consequence. Because sabotage/terrorism is a deliberate act, no defensible probability can be assigned to the likelihood of such an action because the probability cannot be inferred from historical information or statistical analysis. However, the magnitudes of potential source terms (amounts of material released to the environment) can be quantitatively assessed. This report provides results of optimally successful attacks with a type of device thought to produce significant damage. It omits many details concerning sabotage device selection and methods of attack in order to avoid giving potential saboteurs a "blueprint" for action and to avoid classification issues.

Background - The primary source for estimates of material released by sabotage attacks employing high energy density devices (HEDDs) is the work from Sandia National Laboratories (SNL) in the early 1980s by Sandoval et al. (1983). The impetus for SNL's work was the "Urban Study" (DuCharme et al., 1978), which considered the potential effects of a successful sabotage act in the heart of a major urban area. The Sandoval report and related Sandia studies were reviewed and evaluated for the present report. Other work reviewed includes work by the U.S. Nuclear Regulatory Commission, Battelle Columbus Laboratories (BCL), and the Idaho National Engineering and Environmental Laboratory (INEEL). The SNL and BCL work agreed quite well and suggested that the fraction of the fuel affected by the HEDD and released from the cask to the environment is about 5E-04 (0.0005). Some companion work by INEEL suggested that 5 to 6 times as much respirable[2] material was produced from spent fuel compared to the

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[1] Source term: The amount of radioactive material released to the environment as a result of an event. (Usually stated as a fraction of the total material at risk or normalized by some other convenient quantity.)

[2] Respirable material is made up of aerosol particles that can be taken into the pulmonary region of the lung during the breathing process. In general, particles that have the same settling velocity as a spherical particle with a density of 1 g/cm^3 (this is the definition of aerodynamic diameter.) with diameters smaller than 10 μm are considered respirable. Aerosols are suspensions of fine particles that will remain airborne for times in excess of a few minutes whose size distribution is generally characterized by its AMAD (activity mean aerodynamic diameter).

surrogate material used by Sandoval et al., (1983). When Sandoval et al., (1983) extrapolated their release fraction and the spent fuel to surrogate fuel aerosol ratio (SFR) to a spent fuel shipment typical of that period, the respirable release fraction relative to the entire cask contents was estimated to be in the range 2E-05 to 4E-05.

Issues - The main issues addressed in this study relate to the fact that prior studies are somewhat dated; that is:

- Spent fuel casks likely to be used in the future are not the same design as those considered in earlier work. The number of spent fuel assemblies they contain is larger, and their wall construction is different, e.g., use of depleted uranium for shielding rather than lead, less use of fins for heat rejection, and somewhat reduced need for shielding.
- The potential attack devices available may include some that are thought to be more penetrating or that have different delivery mechanisms than those used in past experiments.

In addition, there is a need to look at the details of the work done in the past to ensure that it is applicable to the current situation. Two items are particularly in need of study:

- An additional mechanism for material dispersal was determined to exist that was not included in earlier analyses. The early experiments utilized unpressurized sections of spent fuel rods and spent fuel simulants that were not fully representative of intact spent fuel in casks, which are pressurized. Not including the effect of this gas release can impact source term estimates. Since this effect was not part of the earlier work, some additional analysis was required.
- The basis of the SFR in the range of 5 to 6 was reevaluated to ensure it was appropriate.

Analysis Process – Computer simulations of attacks on new cask designs with two distinct HEDDs were performed with SCAP, a SNL computer code (Robinson, 1985). The devices simulated were HEDD1, which is the same device as that used in the Sandoval full-scale test, and HEDD2, a newer device designed for optimal armor penetration and capable of remote, rocket-propelled delivery. As part of this study, SCAP was benchmarked against the Sandoval full-scale test and another HEDD1 test and found to reproduce the penetration depth closely but to underestimate the diameter of the affected area. By using an estimate of depth of penetration from SCAP and an affected area corrected by reference to the Sandoval tests, it was possible to estimate the damaged volume in modern design casks. These designs encompassed a truck cask holding 4 pressurized water reactor spent nuclear fuel assemblies and a rail cask holding 26 assemblies subjected to the action of the HEDD1 and HEDD2 devices.

Data from the Sandoval report were analyzed and recast into a format in which the observed respirable aerosol fraction was related to the UO_2 mass in the "swept" volume (defined by the observed depth and diameter of missing material). This value was found to be 7.7E-04 for the full-scale test, which is most relevant to the situation of interest here.

Because pressurized water reactor and boiling water reactor spent fuel rods are pressurized and the rods used in the earlier tests were not, it was postulated that some additional aerosol generated in the cask by the HEDD would be swept out by the released gas from each failed fuel rod. Thus, the respirable release fraction obtained by Sandoval would have to be increased by some amount to account for this "blowdown" effect. Without definitive data from any of the earlier experiments, a model of the process had to be developed to estimate the amount of aerosol within the cask and the amount released from the cask by blowdown.

The value of the ratio (SCF) of respirable spent fuel aerosol produced by an HEDD to that produced in the UO_2 surrogate material was assumed by Sandoval et al. (1983) to be approximately 5.6 based on wet sieve data developed by INEEL in a coordinated part of the original project. Based on examination of the BCL and INEEL data, consultation with aerosol experts, and reference to standard test methods, the ratio is more likely to be about 3 (as suggested by relevant BCL and INEEL data), therefore, a value of 3 is used in this report and still is thought to be conservative.

Results - The SCAP predictions were that:

- The HEDDs would only penetrate one wall of the cask (as in the Sandoval full-scale test)
- The depth of penetration and the number of fuel rods affected were found to be as shown in the table below.

	Truck		Rail	
	HEDD1	**HEDD2**	**HEDD1**	**HEDD2**
Depth of Penetration [in fractions of an assembly (about 9 in. square)]	2	2	2.4	1.7
Number of Affected Rods	272	136	294	90

By combining results from the SCAP code with experimental correlations from earlier work (modified as described herein) and characteristics of spent fuel likely to be shipped in the near future, estimates of the respirable release fractions for various components of the release source term were calculated. Results for respirable release fractions (relative to entire cask contents) are as shown in the table below. The first line of the table indicates the result if only the directly ejected respirable material were included (i.e., unmodified extrapolation from the Sandoval results).

	Truck		Rail	
Release Fractions	**HEDD1**	**HEDD2**	**HEDD1**	**HEDD2**
Ejected Respirable Matrix Fraction [a]	*8.0E-6*	*1.8E-6*	*1.1E-6*	*1.5E-7*
Total Respirable Matrix Fraction	1.2E-4	1.8E-5	3.1E-6	2.3E-7
Respirable Crud Fraction[3]	7.5E-5	9.1E-6	1.3E-6	4.7E-8
Respirable Volatile Fraction	1.0E-3	1.4E-4	1.7E-5	7.2E-7
Noble Gas Fraction	2.0E-2	6.2E-3	4.1E-4	3.9E-5

a. Extrapolated from Sandoval results.

[3] Crud, originally written CRUD for Chalk River Unidentified Deposits, consists of deposited metal-bearing compounds on the outer surface of fuel rods.

Sources of uncertainty and considerations leading to less-than-perfect execution or reduced consequences of the modeled attacks are discussed. They include factors such as obliquity (angle of device relative to cask wall at moment of detonation), stand-off distance, meteorological factors, and population density.

Observations - There are several important observations to be drawn from the results presented in this report:

- The first is that although HEDD1 and HEDD2 will penetrate a single wall of a spent nuclear fuel cask, neither HEDD1 nor HEDD2 fully penetrate all the way through a spent nuclear fuel cask.
- The second observation is that HEDD1 would cause more damage to both the truck and rail casks than HEDD2.
- The third observation is that an additional mechanism of release was identified that was not accounted for in previous tests of analyses. This additional mechanism was due to the expulsion of aerosol from the interior space of the cask as a result of venting the high-pressure gases from the plenum of disrupted fuel rods.
- The fourth observation is that the largest release fractions were observed for HEDD1 and the truck cask principally as a result of the diameter of the penetration and the smaller internal volume that accentuates the blowdown effect.
- The fifth important observation is that the releases due to the direct ejection of material by HEDD1 obtained in this analysis are consistent with the results obtained by Sandoval et al. (1983). When the contributions from blowdown and diffusion are included, the source terms change from a range of 2.4E-5 to 3.4E-5 (Sandoval et al., 1983) to a range of 3.1E-6 to 1.2E-4 in this report. This is about 0.0003% to 0.01% of the total cask contents.
- The sixth important observation is that the consequence source terms obtained in this study are comparable to those used for consequence estimates in risk assessments related to spent fuel transport.

1. INTRODUCTION

This report has been prepared to develop a source term for estimating the radiological consequences of potential sabotage events during transport of spent nuclear fuel made in the early decades of the 21st century. The safety of spent nuclear fuel shipments is of paramount concern to the U.S. Department of Energy (DOE) and other stakeholders. Understanding the potential impacts from accidents and other events during transport is important to ensuring such shipments do not pose significant risks to those along transport routes. Concern has been expressed regarding the vulnerability of shipments of spent nuclear fuel or high level radioactive waste to sabotage/terrorist acts and the potential consequences of such acts. This report reviews the work done in this subject area in the past and extrapolates the results to the particular transportation situations associated with current and future spent nuclear fuel shipments.

This report also addresses issues relating to applicability of past studies of sabotage resistance of spent fuel casks transported by truck or rail mode that have been raised by members of the public and other stakeholders. The key issues are:

- Influence of design of casks used in past studies carried out by Sandia National Laboratories (SNL) to the casks intended for use in transportation of spent fuel in the early decades of the 21st century
- Potential availability of a larger array of destructive devices, which may pose a greater threat than those assessed in the earlier studies.

Sabotage/terrorist acts are defined as deliberate, unlawful actions intended to cause an undesirable consequence. The undesirable consequence is generally intended to damage, discredit, or intimidate the saboteur's target. Incidents and accidents are initiated by random events and are expected to occur in transportation with low but probabilistically predictable frequencies. Sabotage is not the result of a random event and cannot be analyzed with traditional probabilistic-based risk analysis. Risk is usually defined as the product of the probability, expressed as a likelihood or frequency of occurrence, and the consequence of an event (usually, but not necessarily, an undesirable consequence) summed over all potential events.

For a sabotage event, human volition is involved, randomness is absent, and a defensible probability cannot be assigned to the likelihood of a sabotage attempt. Without a probability term, sabotage risk cannot be quantitatively assessed. However, analysis can address the likelihood of success of an attempt. The inventory (amount of material available for release) and the potential release magnitude of various hypothetical sabotage scenarios can also be quantitatively evaluated, thereby, permitting an assessment of potential events and their consequences. This report includes such assessments where appropriate.

Details concerning device selection and methods of attack are omitted throughout this report. Inclusion of such details would result in this document being classified, which would defeat its stated purpose of responding to public concerns raised regarding potential sabotage consequences.

1.1 PREVIOUS STUDIES

In the late 1970s and early 1980s, SNL and the Idaho National Engineering and Environmental Laboratory (INEEL) performed analyses and a coordinated set of experiments to assess sabotage threats for spent fuel casks for the DOE. Battelle Columbus Laboratories (BCL) carried out similar analyses and experiments for the U.S. Nuclear Regulatory Commission (NRC) in the same time frame. BCL carried out tests on simulated scaled cask configurations with short lengths of surrogate fuel as well as actual spent fuel rods as targets for a high energy density device (HEDD) (Schmidt et al., 1981; Schmidt et al., 1982). In 1981 and 1982, SNL conducted a series of sub-scale and full-scale tests of spent fuel casks. INEEL carried out sub-scale evaluations of HEDDs on actual irradiated and unirradiated fuel segments to develop a scale factor to relate spent fuel behavior to that of the surrogate spent fuel used in the Sandia experiments. These projects provided actual experimental data that is the basis for the analyses presented to demonstrate the potential consequences of a sabotage event on radioactive material shipments and on spent nuclear fuel shipments in particular.

The impetus for the SNL and BCL work was the original and revision of the "Urban Study" (DuCharme et al., 1978; Finley et al., 1980), which considered the potential consequences of a successful sabotage act in a major urban area. The analysis contained in the original Urban Study was based on a conservative set of analytical assumptions utilizing upper limits for the various parameters involved in the consequence calculation. The results presented predicted tens of early fatalities and hundreds to thousands of latent cancer fatalities from an optimally effective attack scenario in a location with a very high population density such as the Borough of Manhattan in New York City. In response to the analysis in the Urban Study, the NRC conducted a rulemaking to require armed escort of spent fuel shipments if they were to pass through urban areas. A second outcome was interest by the NRC and DOE in delineating the actual extent of the threat through further analytical and experimental work at BCL and SNL. The revision of the Urban Study recognized the conservative nature of the assumed source term in the first report and repeated the impact estimates with a more realistic smaller release. The source term in the revised analysis was also thought to be quite conservative (Sandoval et al., 1983).

The SNL tests provided empirical data regarding the degree of resistance of casks to a malevolent attack and the potential magnitude of radiological consequences of a successful attack in a densely populated urban area as treated in the Urban Study. A report (Sandoval et al., 1983) was published to supplement the Urban Study, and features that were notably different from those of high-severity accidents were analyzed in depth. Crud, non-respirable particulate, and noble gas components of the material released from the cask were not explicitly evaluated in the Sandia tests because these components were considered in the analyses of high-severity accidents in the Urban Study. The main difference between the Urban Study accidents and the sabotage scenario was that the sabotage scenario involved explosion-driven expulsion of fuel particulates from the cask. The main impact of this manner of release was increasing the respirable component available for dispersal beyond the immediate vicinity of the incident. The impact of the non-respirable component deposited on the ground near the incident site was comparable to the impact of a high-severity accident. However, the incremental crud contribution to the inhalation dose calculation was not included in Sandoval et al. (1983).

1.2 OVERVIEW OF PRESENT REPORT

Previous reports neglected releases from crud and fuel depressurization. The goal of this report was to estimate release source terms based on the identification of five possible categories of material (Figure 1) that might be expelled from the cask:

- Crud
- Volatiles in the fuel-clad gap
- Noble gases in the fuel-clad gap
- Preexisting fuel-matrix particulates in the fuel-clad gap
- Particulates created by direct action of the HEDD detonation.

Further, three means of releasing these materials, as shown schematically in Figure 1, were considered:

- Expulsion by direct action of the HEDD (seconds)
- Expulsion by blowdown of plenum gases (minutes)
- Diffusive flow and coupled deposition and condensation of aerosols (hours).

The magnitudes of the five potential material source term categories can be estimated from previous studies with actual spent fuel segments. The contribution of expulsion by the first mechanism (direct action of the HEDD) can be extrapolated from the Sandia full-scale and sub-scale tests. Potential contributions from blowdown and diffusive processes were not considered in previous studies and were estimated by analysis based on data from extrapolation from other published studies.

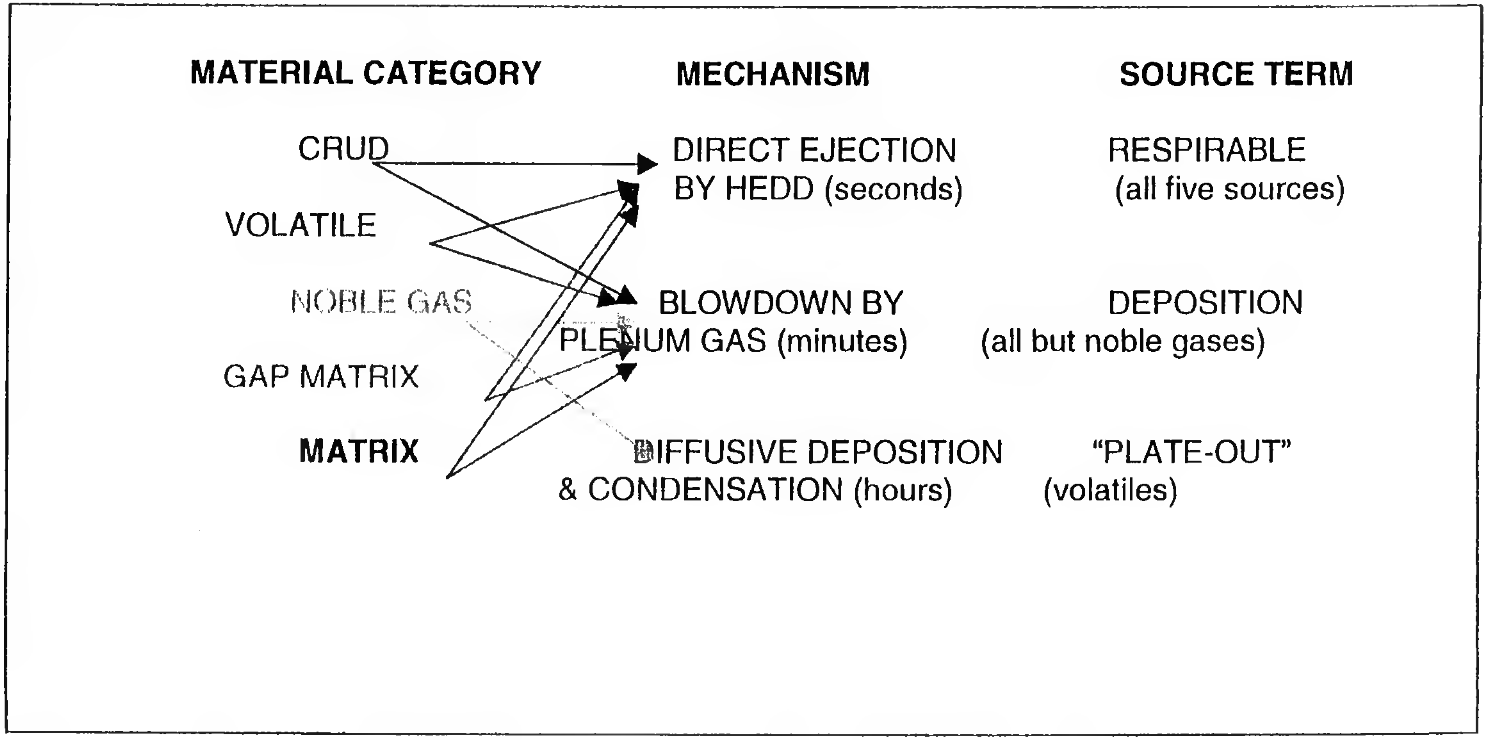
Some fraction of all five types of material can be expected to be in respirable form (Figure 1). For the noble gases, this fraction is 100%. For the remaining categories, some fraction would be expelled in larger, non-respirable sizes that would be deposited nearby. In the case of volatiles, some fraction of potentially respirable size aerosol also would "plate out" on nearby surfaces. Both of these phenomena would create a somewhat diffuse, but still highly localized, static source with the damaged cask more or less at its center, that would not result in the exposure of persons beyond the immediate vicinity. Only respirable aerosols/gases are capable of being transported downwind and inhaled by persons located at large distances from the attack site.[4] Respirable aerosols/gases, therefore, represent the only material form generated by an HEDD attack that could potentially result in large population doses. Thus, it is important to identify all mechanisms that could contribute to the creation, release, and dispersion of respirable aerosols/gases. The previously unstudied blowdown and diffusive processes are examined in this report, and their impact on respirable aerosol and gas release estimates is assessed.

[4] There is a technical distinction between "inhalable" particles, which can be several tens of microns in aerodynamic diameter and which do not penetrate beyond the nasopharyngeal region, and "respirable" particles which are smaller (10 microns or less) and may be inhaled into the deep lung. "Inhalable" particles can be trapped in mucus and expectorated or swallowed. In the latter case a relatively minor ingestion dose may result. However, since settling velocity is directly proportional to the square of the diameter, large inhalable particles travel relatively short distances downwind. This study focuses on respirable particles that may be transported many kilometers away from an accident site.

Chapter 2 is a critical review of the studies identified in Section 1.1. Questions regarding device availability and selection for this analysis are described in Chapter 3. Any effort to assess the consequences of a terrorist act directed against spent fuel casks must consider the cask's physical characteristics, which render them resistant to malevolent attacks. The characteristics of expected cask designs are discussed in Chapter 4 along with other related factors that affect the source term (e.g., transportation-mode-dependent differences in cask capacity and the range of spent fuel types that may be transported).

The potential consequences of completely successful performance of the HEDDs are calculated as part of this study. The resulting radioactive source terms and the methods used to develop them are described in Chapter 5. Factors potentially affecting successful execution action are also discussed in Chapter 5. These factors present uncertainties associated with critical variables. Observations and conclusions are given in Chapter 6.

Figure 1. Schematic of Material Types and Release Mechanisms



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2. BACKGROUND

Early work that preceded the full-scale test at SNL, the Sandia tests themselves and critical evaluations of the tests are discussed in this section.

2.1 EARLY WORK

In 1977, Hodge and Campbell published a study sponsored by the NRC, Division of Safeguards, entitled *Calculations of Radiological Consequences from Sabotage of Shipping Casks for Spent Fuel and High-Level Waste* (Hodge and Campbell, 1977). The authors judged "massive rupture" of a spent fuel cask to be "incredible" and postulated a small penetration that could result in the release of a maximum of 1% of the total fuel solids and 100% of the gases (e.g., krypton-85). The effect of selectively raising the release fraction of specific volatile isotopes (radiocesium and radiotellurium) to 1.0 was also examined. The radionuclide inventory was for short-cooled (150 days out of reactor) spent fuel. The maximum release (in which 100% of volatiles was assumed released) yielded an estimate of 2 early fatalities and 40 to 260 latent cancer fatalities in an area with a population density of 10,000 persons/mi^2. In the alternative scenario, the release fractions of all isotopes were set to 1% except for noble gases, which remained at 100%. For this scenario, an estimate of zero early fatalities and 40 latent cancer fatalities was obtained.

Approximately 5 years later, Schmidt et al. (1982) described experiments and analyses carried out at BCL. A total of 10 tests were performed in which an HEDD was fired to optimally impact a mock up of a spent fuel cask loaded with segments of *actual* pressurized water reactor (PWR) spent fuel rods. As part of the test shakedown, tests using depleted uranium pellets as a surrogate for spent fuel were carried out. The respirable fraction estimated on the basis of the actual spent fuel tests was 1.91E-05.[5] Schmidt et al. (1982) also estimated scaling factors and predicted that for a full-scale test of the same type (optimally placed HEDD charge on a truck cask carrying one 15 x 15 spent fuel pin assembly), the total airborne release would be approximately 9 g of material. Based on a comparable full-scale test performed by SNL (see Section 2.2), the total aerosol release was approximately 3 g, and the comparable respirable fraction was approximately 0.64E-5.[6]

2.2 SANDIA TESTS

A series of sub-scale and full-scale tests carried out at SNL between 1980 and 1981 and published in Sandoval et al. (1983) are discussed in this section. The discussion highlights some additional analysis of the data that has been done for this report. Information extracted from the report and calculations using the data to apply to this analysis are contained in Appendix A. Table A-1 provides the data contained in following sections in tabular form for easier understanding.

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[5] Schmidt et al. (1982, p. 73) calculated conservatively from sub-scale experiment data. The product of the highest calculated value of 5E-04g/L/row of pins, a chamber size of 230 L, and a mass-density scaling factor of 5.2 for a 15 x 15 assembly gives a total airborne release of 8.97 g. When 8.97 g is divided by the uranium oxide mass of a PWR assembly (4.7E+05 g), the result, 1.91E-05 g, is the resulting release fraction.

[6] The 3-g release figure is grams of UO_2,which, when divided by 4.7E+5 g, gives 0.64E-5. The published release fraction of 1.46E-05 was based on a mass of 201 kg of UO_2.

The main thrust of the experiments was to determine what fraction of the cask contents could be turned into an aerosol, the *only* form in which material could be dispersed away from the immediate vicinity of a sabotage attack. No attempt was made at the time to investigate forms of material that remained in the immediate vicinity of the penetrated cask. Large particles and debris that did remain in the immediate vicinity would contribute to a radiation field around the cask and be modeled the same way as the loss-of-shielding scenario in a typical accident analysis.

2.2.1 Surrogate Fuel

Surrogate fuel assemblies made up of depleted uranium oxide (DUO_2) were used in the tests. The fuel elements consisted of pellets 9.33 mm (0.367 in.) in diameter and 15.2 mm (0.598 in.) long placed in Zircaloy tubes that were 1.08 cm in outside diameter (OD) with 0.6 mm wall thickness. Each pellet occupied a volume of approximately 1 cm^3 and had a mass of approximately 10 g.

For the quarter-scale test, the pellets were placed in elements (pins) 90 cm long. The pin pitch (distance from pin center to pin center in the assembly) was approximately 1.4 cm. A 5 x 5-fuel assembly was constructed with hardware of the type normally used in actual fuel assemblies. The assembly contained a total of 15.3 kg of DUO_2 pellets. The cask body was constructed in nominal quarter scale, but the fuel pins were full scale. Because of the difficulty and cost in making quarter-scale surrogate fuel pins, the number of fuel pins in the array, rather than the size of the fuel pins and pellets, was reduced in this test. The diameter of the fuel pins and the DUO_2 pellets were the same as those used in the full-scale test.

For the full-scale test, the pellets were placed in elements (pins) 1.2 m. The pin pitch (distance from pin center to pin center in the assembly) for the square array was approximately 1.4 cm. A 15 x 15-fuel assembly was constructed with hardware of the type normally used in actual fuel assemblies. The assembly contained a total of 201 kg of DUO_2 pellets. The rods in the assembly were not pressurized as is typical of reactor fuel.

2.2.2 Cask and Scale-Model Construction

Each nominal quarter-scale model cask consisted of steel-lead-steel cylindrical walls with a thin steel-walled water jacket on the exterior and a steel bolt-on closure. Relevant features of the full-scale cask were reproduced at scale. Inessential details of actual casks, such as lifting trunnions, were not reproduced. The walls of the cask body were approximately 4.65 cm (1.83 in.) thick and constructed of steel-lead-steel with approximate dimensions 0.9/3.7/0.5 cm (0.35/1.46/0.2 in.), respectively.

The cask used in the full-scale test was a GE-100 truck cask, manufactured by General Electric. The cask body was of steel-lead-steel construction. It weighed 25.45 tonnes and had a milled-steel bolt-on closure. The inner cavity was 38.1 cm (15 in.) in diameter, 356 cm (140 in.) long, and was capable of holding one PWR fuel assembly. The cask wall consisted of a

- Steel outer shell 2.54 cm (1 in.) thick
- Lead 21.27 cm thick (8.38 in.) thick
- Steel inner shell 1.9 cm (0.75 in.) thick.

2.2.3 Tests Performed

Prior to carrying out either quarter- or full-scale tests, five preliminary tests were conducted on simulated wall sections, thick steel targets, and bare simulated fuel. In each case, a nearly quarter-scale commercially available HEDD was used. The purpose of the preliminary tests was to confirm that the 4.5 x 7-ft test chamber for the sub-scale tests and all associated apparatus were functioning properly.

Two quarter-scale tests were performed: one dry and one wet. In the dry test, the cask cavity and the water jacket contained no water. In the wet test, the cask cavity and the water jacket were filled with water. Only the results of the dry test are discussed in this report because the dispersal was greatest in the absence of water in the quarter-scale test and no wet full-scale test was performed. Moreover, wet shipments (i.e., shipments with water in the cask cavity) are no longer carried out in the United States.

A series of impactors, filters, and collector plates were used to collect samples of particulates generated during the tests. Post-test activities included collection of debris deposits from the test chamber and analysis of particulate samples.

The full-scale test, like the quarter-scale tests, was performed in a containment chamber. The chamber was larger than the one used for the sub-scale tests (3.1 m [10.2 ft] inside diameter and 6.1 m [20 ft] long with 2.22 cm [0.875 in.] thick steel walls). It was equipped with an array of sampling devices intended to provide a time history of the aerosols produced in the first few minutes post-detonation.

2.2.4 Results

Quarter-Scale Tests

As a result of the HEDD detonation, both cask walls were penetrated. The entry hole was 1.27 cm (~0.5 in.) in diameter, and the penetration depth was equal to the full diameter of the model (27.9 cm or 11 in.). The average diameter of the hole created in the fuel assembly by the detonation was approximately 2 cm (somewhat larger than the entry hole diameter). Approximately 20% of the fuel pins experienced at least some mass loss. If *total swept mass* is defined as the fuel mass directly acted on by the detonation, then it can be estimated from known fuel mass and the dimension data given above to be 0.170 kg. The average missing length of pin was 2.1 cm (0.83 in.).

Approximately 99% of the total uranium (15.2 kg) remained in the fuel pins in the cask model, and 1.17% (0.18 kg) of the uranium mass was released from the pins. Of that amount, approximately 68% (0.123 kg) remained in the cask. The other 32% (0.0565 kg) of the material released from the pins was expelled from the cask into the test chamber. Approximately 0.0478 kg of the expelled material was deposited on various surfaces in the chamber, including the external cask surface and the chamber walls.

Considerably less material (0.00078 kg) was suspended in the chamber (outside the cask) in aerosol form. Particle concentrations extrapolated to zero time were used to estimate this measurement for both the quarter- and the full-scale test. A total (100%) of the aerosol was found to be respirable in size. A small fraction (approximately 4.4E-03) of the total mass released from the pins was released as respirable aerosol. Of the total UO_2 mass in the cask, less than 5E-05 was released as respirable aerosol.

The remaining approximately 0.00792 kg of the material was not accounted for directly in the post-test data. This mass is approximately 5.2E-4 of the total material in the cask or about 5% of the material released from the pins. The mass of this "lost material" was obtained by subtracting the mass of recovered macroscopic materials from the total fuel mass. The lost material may be the result of accumulated measurement errors in one number when subtracted from another of almost the same size. Alternately, it could be microscopic material that was produced by the action of the HEDD that was deposited on surfaces within the cask and chamber but not recovered as part of the macroscopic collection and accounting process.

Full-Scale Test

As a result of the detonation of the HEDD there was not full penetration the cask; thus, there was no exit hole. The entry hole was 15.2 cm (~6 in.) in diameter, and the depth of penetration into the cask cavity was 42 cm (16.5 in.). Approximately one-half the fuel rods experienced some mass loss. These results can be expressed in terms of a *total swept mass* and a *total swept volume*, which are defined as the total mass of fuel and fuel cavity volume, respectively, *directly* acted upon (or removed from the pins) by the detonation of the postulated HEDD. The total swept mass was 3.8 kg. A hole (based on maximum missing fuel pin length) approximately 7.6 cm (3 in.) in diameter was created in the fuel bundle with an "affected" length of pin of about 27 cm (~11 in.).[7]

Greater than 97% of the total uranium remained in the cask inside the fuel-pin cladding, and 2.72% (5.46 kg) of the uranium mass was released from the pins. Of that amount, 53% (2.91 kg) remained in the cask. The remaining 47% (2.55 kg) of the material released from the pins was expelled from the cask into the test chamber. Approximately one-half kilogram (0.540 kg) of the expelled material was deposited on various surfaces in the chamber, including the external cask surface and the chamber walls. Approximately 3 grams (0.00293 kg) was found to be suspended in the chamber in aerosol form. All (100%) of the suspended aerosol was respirable in size (i.e., activity mean aerodynamic diameter [AMAD] less than 10 μm).

[7] The term "affected length" refers to the length of a fuel pin extending from the detonation site that, while not destroyed and removed (i.e., not part of the swept mass), was bent, distorted, or otherwise affected by the force of the detonation.

The remaining (approximately 2 kg) were not accounted for directly in the post-test data, but could not have been present in the measured respirable aerosol without detection. This mass is approximately 1.0E-2 of the total material in the cask and about 52% of the material released from the pins. The mass of this "lost material" was obtained by subtracting the mass of recovered macroscopic materials from the total fuel mass. Thus, it may be the result of accumulated measurement errors in one number when subtracted from another of almost the same size. Alternately, it could be microscopic material that was produced by the action of the HEDD, which was deposited on surfaces interior to the cask and chamber but not recovered as part of the macroscopic collection and accounting process.

The fraction (5.4E-04) of the mass released from the pins (as measured) that was released as respirable aerosol, was approximately an order of magnitude *smaller* than in the quarter-scale test (4.4E-3). The fact that the fuel pins in the quarter-scale test were full scale, but reduced in number, should make little difference in the results because the device had to penetrate a thickness of fuel in the cask cavity somewhat greater than a quarter-scale fuel assembly would have presented. Since the test still resulted in penetration of the far side of the quarter-scale cask, there can be no doubt that a closer fuel scaling would have yielded the same results.

Here, as elsewhere in this report, fractional releases are reported to be consistent with sophisticated consequence analysis codes that require input in terms of (a) the total amount of material available for release and (b) the fraction of material released in various forms and scenarios. Fractional releases are the best basis for comparison of the action of the two HEDDs. For direct comparison of effects not related to cask capacity, releases are also presented in terms of release (kg) per inventory (kg) of one spent fuel assembly (i.e., as release fractions).

Correlation Tests by INEEL

Part of the testing sponsored by DOE was a set of experiments coordinated by Sandia and performed at INEEL (Alvarez et al., 1982). The experiments were intended to develop a correlation between the respirable aerosol produced when actual spent fuel (same 6.5-year-old fuel used by BCL) and the surrogate pellets used by Sandia were subjected to the conditions of HEDD disruption in the same test configuration.[8]

For these tests, only a single set of direct aerosol measurements was obtained that permitted comparison of spent fuel with DUO_2 surrogate fuel for the size range of interest in the tests conducted. The data obtained from these tests required a number of significant assumptions but suggested a spent fuel to surrogate fuel aerosol ratio (SFR) of approximately 0.53 (Sandoval et al., 1983). The SFR relates only to the respirable aerosol formed by the action of the HEDD (i.e., the ratio of spent fuel respirable to surrogate respirable material in an essentially identical test). Researchers at the INEEL (Alvarez et al., 1982) obtained a value for SFR of 5.6 from wet-sieve data (using non-polar solvents). They used a non-standard curve-fitting technique to extrapolate the ratio to particle diameters in the respirable range. However, the results from wet-

[8] Use of 6.5-year-old spent fuel in the BCL tests provides a good link to future spent fuel shipments even though the casks in service in the early 1980s were certified to ship short-cooled (150-day-old) fuel. In the current application, the age of the spent fuel approaches that of fuel likely to be shipped in the future (e.g., at least 10 years old), and the minimum age would be 5 years old. Thus, the spent fuel used in the tests is representative of actual spent fuel that would be shipped in the future.

sieving, which is used primarily for separating particles by size in soil samples and industrial powders such as magnesium oxide, becomes increasingly inaccurate for small particle sizes. Sandoval et al. (1983) used the SFR of 5.6 to estimate releases and radiological consequences; however, Sandoval et al. (1983) recognized that using an SFR of 5.6 was probably a significant overestimate.

2.2.5 Discussion

The quarter-scale and full-scale test results showed two important differences. First, there was full penetration in the quarter-scale tests but not in the full-scale test. Second, while there was an attempt to scale the HEDDs to get similar results in the two tests, it was not possible to obtain an exactly scaled HEDD. The quarter-scale cask walls were as close to quarter-scale as nominal dimension construction materials permitted. The fuel pins, although not quarter-scale, were positioned so as to present the same fuel mass to the penetration path of the HEDD as a scaled fuel assembly would have done. Thus, the HEDD scaling deviation was primarily responsible for the differences in outcomes of the two tests. A commercially available HEDD was used, which was more penetrating than planned and gave an experimental result different from the full-scale test.

A difference in behavior is evident depending on the existence of an exit hole. In the event of full penetration, which produces an exit hole, a flow that carries material directly out of the cask may have been induced. As a result, the "aerosol fraction" for the quarter-scale test as would be used in the RADTRAN computer code (i.e., the fraction of material released that is in aerosol form, see Madsen et al., 1983) was approximately 4E-03. This was approximately one order of magnitude greater than the same value estimated by Sandoval et al. (1983) for the full-scale test (5E-04). Because the fraction of material released in all forms is approximately the same for the two tests, this implies that, all other factors being equal, the total effect of a full penetration event may be to increase aerosol release by approximately10 times the aerosol release fraction from partial (i.e., one-hole) penetration.

The Battelle researchers predicted that 9 g of material would become respirable aerosol in the full-scale test; the measured value was approximately 3 g. Agreement within a factor of 2 or 3 between data from independent lines of inquiry from two separate laboratories using non-identical HEDDs and non-identical test setups indicates that the basic mechanisms for producing and releasing aerosols are well accounted for by the experimental analysis methods used. Thus, there is increased confidence in the prediction that the release of material from such an explosive attack would be a relatively small fraction of the material at risk. The relatively good agreement between the Battelle and Sandia tests, given the differences in test setup and instrumentation, also underscores the accuracy of Battelle's and Sandia's explosive-charge scaling methods.

2.2.6 Additional Analysis

The suite of previous experiments provides the basis to extrapolate to the specific situation of potential shipments to a future spent fuel storage or disposal facility. However, some additional analysis is required to make the extension as well determined as possible. Three specific areas require additional analysis:

- Scaling to hole volume
- Respirable aerosol quantity created by the HEDD action
- Ratios of spent fuel respirable aerosol to surrogate respirable production (values of SFR).

Scaling to Hole Volume

An alternate method of analyzing the test results in the Sandoval report was used in this report because it enables evaluation of the magnitude of the potential source term in other situations based on calculated hole volumes. The Sandoval report provides data for hole size in the fuel elements penetrated by the HEDD in the full-scale and quarter-scale events. The effective release fraction from the swept volume of the hole in the fuel assembly is deducible from the hole size. The numerator of this release fraction is the respirable mass estimate provided in the report (MR), and the denominator is the swept volume of pellets in pins disrupted by the HEDD. The swept volume was estimated from the missing length of fuel pin by assuming that this length was equal to the diameter of a round hole through the assembly. The amount of fuel assumed to be affected longitudinally in the pin at the center of the hole was assumed to be the number of pellets (NP) in the missing length rounded up to the next whole pellet. The affected number of pins laterally (NL) was assumed to be the number of pins within the hole diameter rounded up to the next integer. Thus the mass of fuel swept (MS) used in calculating the swept-mass respirable release fraction, MR/MS, from the Sandoval data is estimated to be

$$MS = (\pi/4) \times NP \times NL \times NR \times PL \times PD$$

where:

NP = (L/L_p) rounded to next integer pellet
L = missing length of pin or hole diameter (m)
L_p = length of pellet (m)
NL = (L/PP) rounded to next integer pin (m^2)
PP = pin pitch (pins/unit distance, measured from pin-center to pin-center) (m^{-1})
NR = number of rows of pins along the disruption path/PP
MS = swept mass (UO_2 in hole produced by HEDD action) (kg)
PL = (NR/PP) = depth of penetration of pin disruption
PD = pellet density (kg/m^3)
MR = mass of respirable aerosol as measured in the Sandoval experiments (kg)

The parameter, MR/MS, has a value of 5.0E-03 for the quarter-scale test and 7.6E-04 for the full-scale test. These values are close to those given above (4.4E-03 and 5.4E-04) for the measured respirable mass fraction that was based on the experimentally determined (by weighing) mass of pellets removed from the pins as a result of the HEDD's damage. It implies that scaling to a geometrically defined estimate of swept mass produced by a calculated estimate of hole volume, as is used in this analysis, is a reasonably consistent alternate method for describing HEDD damage and aerosol production.

Respirable Aerosol Production

The only mechanisms for ejecting pulverized surrogate fuel from the cask that was tested in the SNL experiments was spallation from the rods by the HEDD and/or airborne transport through the opening in the cask driven by whatever cask pressurization was generated by HEDD action. This ejection process would occur within seconds of the HEDD detonation. It seems clear that, in addition to the aerosol released from the cask, there was a significant amount of surrogate fuel aerosol created within the cask by the HEDD that remained inside and was ultimately deposited on the inner surfaces of the cask. Some or all of the unaccounted material in the Sandoval tests could make up part of this material. This aerosol material could represent an additional external source term if there was a mechanism to create a flow of gas out of the cask following the action of the HEDD.

Such a mechanism exists for actual commercial spent fuel because each fuel rod is pressurized during manufacture,[9] and the pressure increases as a result of fission gas generation and elevated temperature during and after power production. The disruption of the fuel rods by the HEDD action allows this gas to escape from the broken rods and produce a gas flow from the cask that will carry gas-borne aerosolized material into the environment. The average amount of gas released by each rod amounts to 745 cm^3 at standard temperature and pressure (STP) (Balfour et al., 1985). The gas is liberated over a time period measured in several 10s of seconds because the flow path from the plenum at the end of the rods is through narrow and tortuous crack networks in the fuel pellets remaining in the fuel rod (Sprung et al., 1998).

Because the surrogate fuel used in the Sandoval test (and all the other tests cited, with both spent and surrogate fuel) was unpressurized, there are no data from which to estimate the importance of this additional source term. In addition, there also was no direct measurement of the actual quantity of respirable aerosol within the cask that would comprise this potential source term component. As a result, some additional analysis is required to link the existing surrogate and real fuel data to the situation with pressurized fuels. Estimates can be made to define the order of magnitude of the total respirable material created and the effect of pressurization based on information in the literature.

A primary information source for a means to estimate the amount of respirable material generated during the HEDD event is work done at Argonne National Laboratory in the 1980s (Jardine et al., 1982). Jardine developed experimental data on the amount and size distribution of particulate material produced by calibrated hammer impacts on brittle materials. His work developed a linear relationship between energy density in the material from the impact and the mass of particulate material with geometric diameter smaller than 10 μm over 2 orders of magnitude in energy. Materials considered by Jardine were Pyrex, various Synroc formulations, waste form glasses, and concrete. All materials were sufficiently refractory to assure that melting and vaporization were not a factor in the tests. While these materials are not UO_2, many of the materials were a pressed ceramic form resembling surrogate fuel pellets used by Sandoval et al. (1983) and were subjected to impacts on their diameter as was essentially the configuration in the Sandoval tests. Jardine's data are shown in Figure 2 and tabulated in Table A-4 with relevant detail.

Limited data from other sources (also shown in Figure 2) indicate that uranium oxide pellets follow the same general relationship. Two data points for UO_2 at the lower end of the energy range were obtained from a report on work by Mechem (MacDougall et al., 1987). Data for UO_2 and spent fuel from the INEEL experiments (Alvarez et al., 1982) are plotted at the upper end of

[9] Both PWR and boiling water reactor (BWR) fuels receive initial prepressurization, but the pressure level in PWR rods is greater.

the range. These tend to confirm the relationship found by Jardine at the higher energy densities typical of the full-scale experiments by Sandoval et al. (1983)

The upper line on Figure 2 shows the linear relationship suggested by the data for the mass in particles less than 10 μm geometric size. However, of interest to this study is the quantity of particles that are of respirable size. For uranium oxide particles with a density of 10.5 g/cm^3, this corresponds to a geometric size of about 3 μm. Using the parameters for the log-probability fits to each data set determined by Jardine, the mass fraction of particles smaller than 3 μm were determined for each data set. A line drawn through those values yields the lower line on Figure 2. This curve is used to estimate the amount of respirable material produced by impacts on DUO_2 surrogate fuel pellets over a range of impact energy density.

Also shown in the upper right of Figure 2 is the range of impact energies expected from HEDD1. These were obtained by taking the estimated HEDD kinetic energy and dividing by the estimated swept volume of the disrupted fuel. The highest energy represents no attenuation of the HEDD energy by penetrating the wall. Since the HEDD action penetrated about equal amounts of mass per unit area passing through the wall and passing through the fuel, the residual energy deposited in the fuel is likely to be one-half to one-third of the initial energy density. This is shown by the low end of the range indicated on the plot. The projected intersection of the respirable mass curve and the lower limit energy density suggests that a reasonable value for respirable UO_2 aerosol production as a result of HEDD action is about 5%.

Since there was no direct measurement of the aerosol created in the cask in the Sandoval full-scale experiment, there is no direct confirmation of the 5% respirable value. However, as shown in the following argument, the value is plausible. As a result of the action of HEDD1 in the Sandoval full-scale experiment, about 190 g of respirable aerosol would have been created in the cask volume. A relatively small fraction of that was ejected and measured (3 g) by Sandoval et al. (1983). Since the aerosol measured was released very shortly after the action of the HEDD, the volume from which the particles came probably did not encompass the entire cask void volume but a more limited volume in the vicinity of the pin damage. If the initial mixing volume within the cask was about 200 swept fuel volumes (200 hole volumes), then a gas release of 6 L would yield the 3-g release measured in the Sandoval experiment. The volume of material moved by the HEDD's action, together with entrained air and overpressure generated by the HEDD could easily account for an outflow of 6 L of gas carrying the aerosol to the samplers.

Spent Fuel to Surrogate Fuel Aerosol Ratio

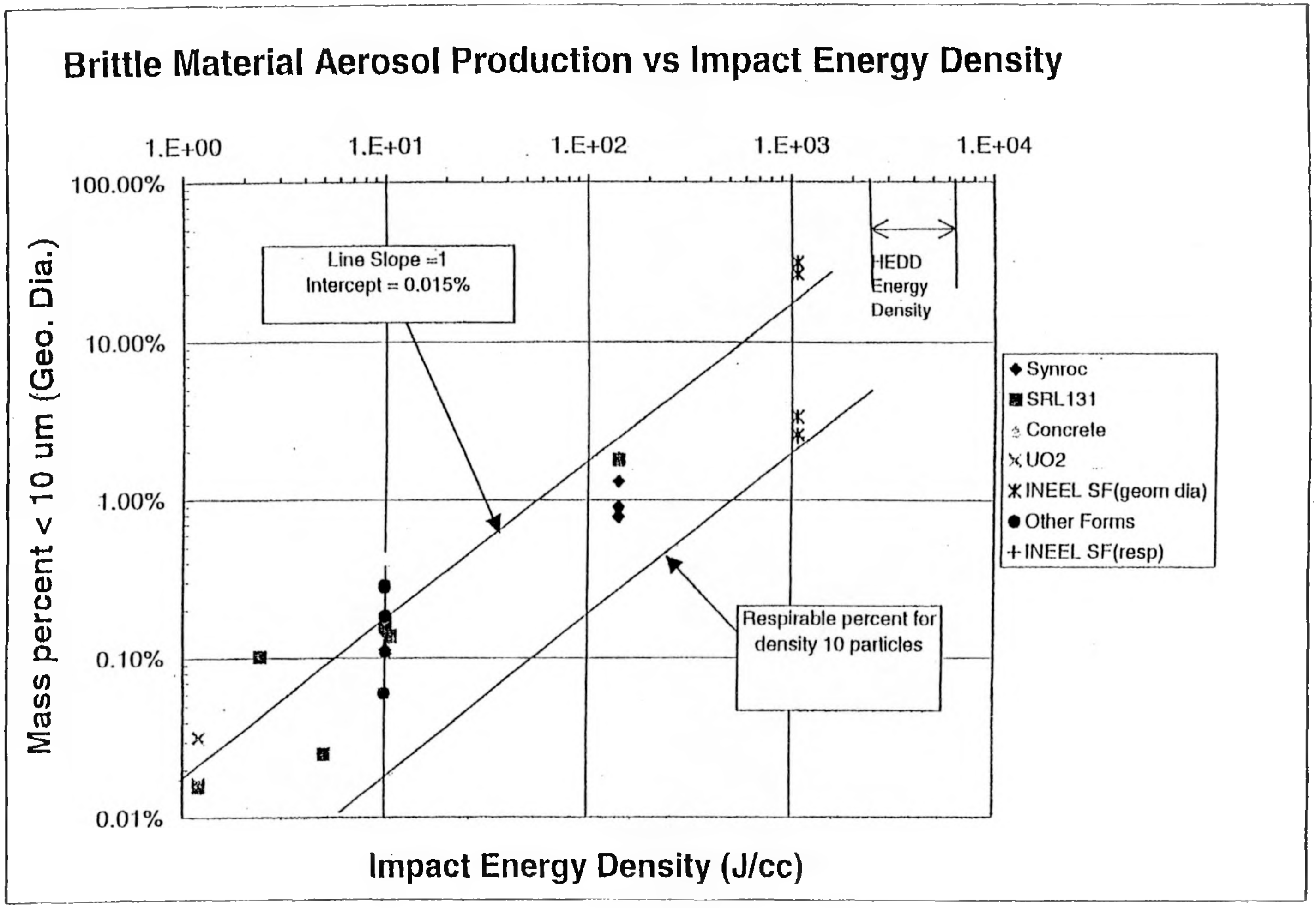
A key parameter for the analysis is the relative behavior of actual spent fuel when subjected to HEDD action compared to that measured for surrogate fuel. Several values for SFR were derived or quoted by Sandoval et al. (1983) from the work at INEEL and BCL, which included values of 0.53, 5.6, 0.71, 0.42, and 3. The INEEL experiment, which yielded an SFR of 5.6, was not repeated. Although none of the values has been confirmed by a repeated test, the high ratio value is not consistent with the other reported values. The SFR values smaller than 3 are, however, subject to considerable question relating to assumptions made in their estimation. Moreover, a value for SFR less than 1 for a material that starts out in a fractured condition compared to an intact UO_2 pellet seems implausible.

An independent analysis of BCL data for one surrogate pellet test and four spent fuel tests in the same configuration gave values for SFR of 2.8, 2.5, 3.0 and 12 (see Table A-3). The BCL spent fuel and surrogate tests that were most comparable (HS2 and CS8) gave a value of 2.5. Additional weight to a value between 2 and 3 is provided by the single spent fuel data point (2.4%) from INEEL plotted in Figure 2 at 1000 J/cm^3. This data point is consistent with an SFR of 2 when compared with the prediction implied by the respirable curve derived for UO_2 in the Sandoval experiments.

In this analysis, a value of 3 for the SFR was used, based on:

- The analysis of the BCL data, which suggest most SFR values between 2.5 and 3
- The implausibility of an SFR smaller than 1
- Use of the single INEEL spent fuel data point for europium as a tracer for matrix material that suggests a factor of approximately 2.54
- The fact that the INEEL data point is about a factor of two above the relationship developed from the Jardine data (though it is within the likely confidence range for the Jardine data).
- The limitations in the wet-sieve method and nonstandard curve-fitting technique used to obtain the INEEL value of 5.6.

Figure 2. Less Than 10 μm and Respirable Aerosol Produced by Impact



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3. SELECTION OF HEDDS

The possible sabotage scenarios that are candidates for consideration in this document are limited only by the inventiveness of the human mind. As a result, no specific scenario is proposed in this report. As was the case for the Sandoval work, it is assumed that an attempt at sabotage is made using a typical HEDD that might be available to a person wishing to carry out an attack.

The terrorists are assumed to have the knowledge necessary to select an appropriate device. One of the HEDDs considered here is the device that was used in the earlier Sandia full-scale test. A second HEDD was selected from *Infantry Support Weapons, Mortars, Missiles and Machine Guns* (Hogg, 1995) for the purposes of comparison, based on its purported greater penetration capability. However, it should be noted that unlike tanks and other typical targets of armor-piercing weapons, nuclear waste casks contain no explosive or combustible materials that could be touched off by the HEDD penetration, so little secondary damage is expected. In other words, only penetration and swept volume of spent fuel disrupted determine the magnitude of the damage that can be inflicted by an attack on a cask, not penetration depth *per se*. Another factor in device selection was the desire to include at least one device that could be delivered from a remote location by a launcher/guidance system typical of the weapons designed for infantry support that are man-portable (as defined by the U.S. Army). HEDD2 falls into this category and, thus, satisfies this condition; however, devices of this type are somewhat more available than their accompanying launch/guidance system. The table below indicates and compares some of the features of the HEDDs considered.

Features Considered	Device	
	HEDD1	**HEDD2**
Availability	Yes	Yes
Portability	Less portable than HEDD2	More portable than HEDD1
Penetration in Steel	Less penetration in steel than HEDD2	More penetration in steel than HEDD1
Swept Volume	Larger swept volume than HEDD2	Smaller swept volume than HEDD1
Remote Delivery	No	Yes

It should be noted that lesser explosive charges, even if designed for metal penetration, simply would not create as large a swept volume, and hence, swept mass, as the HEDD used in the Sandoval test. Therefore, the test results can be used directly to estimate the maximum impact of this type of attack.

4. SOURCE TERM CONSIDERATIONS

Source term as it defined in this report as the product of the cask inventory and the release fraction (f_{rel}) for a given scenario. In other words, it is the quantity of radioactive materials that might be released from the cask as a result of a postulated attack scenario. The source term escaping from the cask is in three parts: the noble gases, the respirable aerosols, and the materials expelled from the cask that remain in its immediate vicinity. Each of these source term components is designated by its principal radionuclide where possible.

The source term is defined by the characteristics of the cask and its likely load of fuel as well as by the characteristics of the HEDD that is of interest. In the following sections, the characteristics of the casks, the fuel, and the projected results of the HEDD actions are discussed. These are then combined to provide the specifications of the source term.

4.1 SPENT FUEL CASKS

Two cask designs (one truck, one rail) considered representative of those being proposed for use in transporting spent fuel in the early decades of the 21st century were selected for analysis of likely penetration by an HEDD. While it is not known what specific casks will be used for all shipments, the cask designs considered here are typical of those that would be used to transport spent nuclear fuel of the burnup and age likely to be shipped in the early decades of the 21st century.

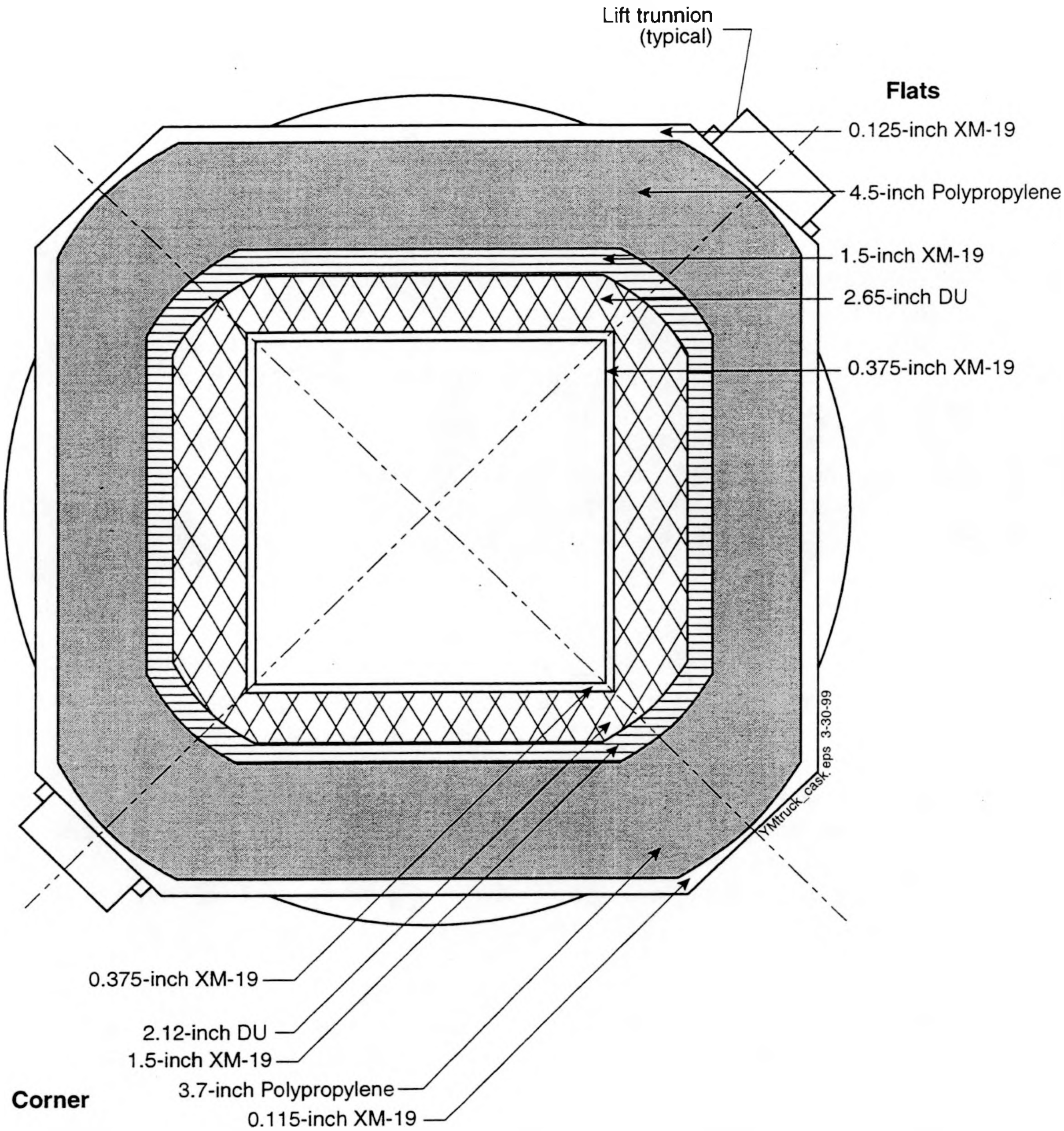
Both casks use depleted uranium as a gamma shielding material. Lead might also be used, but the difference is unlikely to have an impact on the results of this analysis. Although lead is not a high strength material like depleted uranium, HEDD penetration should be about the same because it is the areal density (units of g/cm^2) that governs penetration and shielding effectiveness.

One of these casks has a solid neutron shield and the other a water jacket neutron shield. For the purposes of this analysis, it was assumed that the neutron shield is a solid in both cases. This assumption should yield the maximum source term. The Sandia quarter-scale experiments (Sandoval et al., 1983) included a water jacketed configuration whose source term was significantly lower. This was postulated to result from scavenging of aerosol particles by water droplets and mists.

4.1.1 Truck Cask

The truck cask is capable of carrying four PWR assemblies. The cask body consists of about 7 cm (2.5 in.) of depleted uranium within outer and inner layers of stainless steel and surrounded by a polypropylene neutron shield. The cask weighs approximately 25 tons. A cross section view is shown in Figure 3.

Figure 3. Cross Sectional Drawing of a Typical Truck Cask (General Atomics 1993)



Legend
XM-19 - alloy steel
DU - depleted uranium metal

4.1.2 Rail Cask

The rail cask design is capable of carrying 26 PWR fuel assemblies. The cask body consists of about 1.3 cm (0.5 in.) of lead and about 5.6 cm (2.2 in.) of depleted uranium within outer and inner layers of stainless steel surrounded by a water-jacket type neutron shield. The cask weighs approximately 125 tons. A cross section view is shown in Figure 4.

4.2 SPENT FUEL CHARACTERISTICS

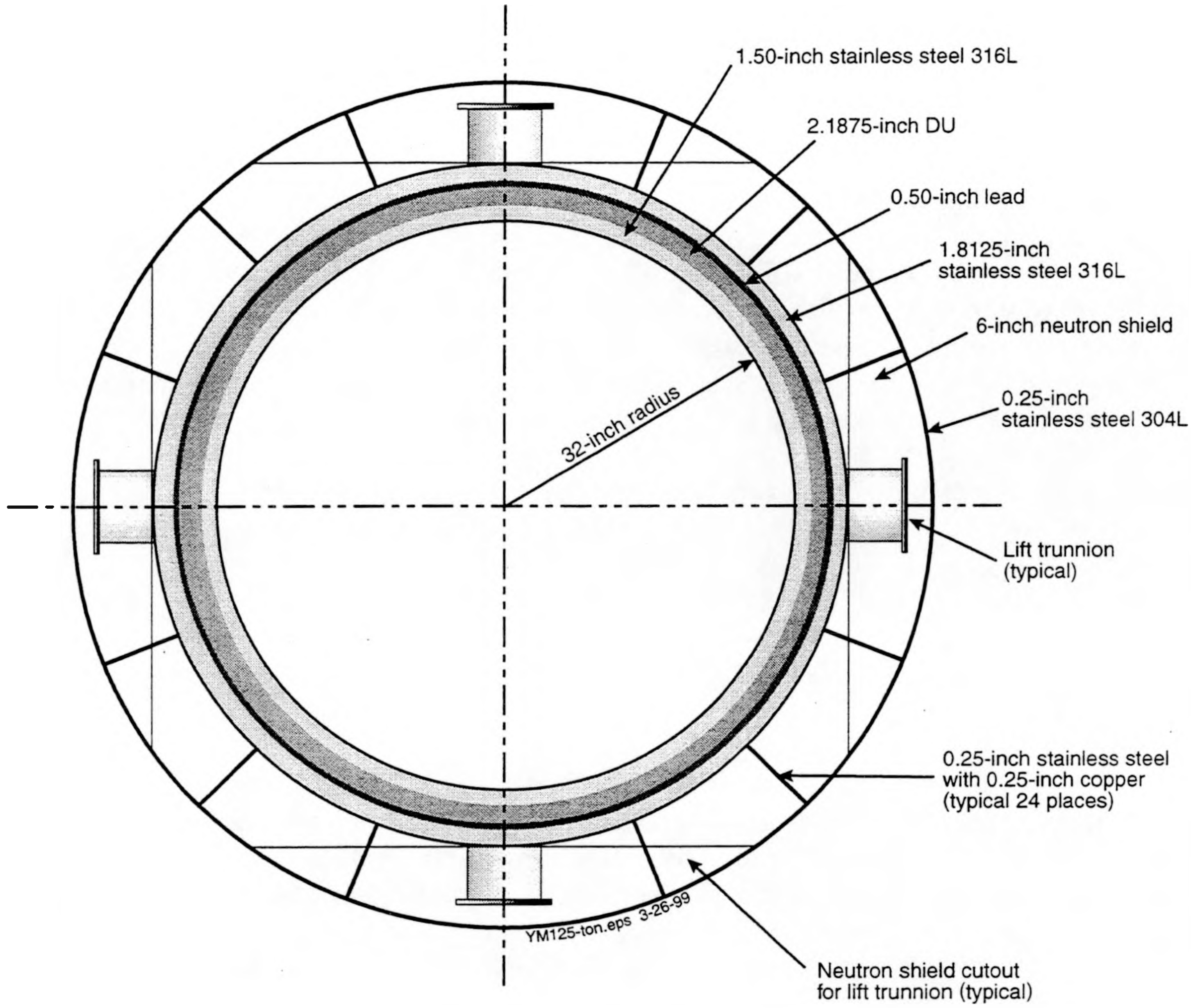
Each of the typical casks described above is capable of carrying various types of PWR and BWR spent fuel assemblies. For simplicity of analysis and maximum parallelism to the work described in the Sandoval report, the PWR-carrying configuration was used because:

- This is a common type of fuel assembly (about 2/3 of all spent fuel)
- The initial pressurization of PWR fuel is higher than BWR fuel, leading to greater gas release
- The radioisotope inventory of a PWR assembly is generally higher on a MTU normalized basis than the radioisotope inventory of a BWR assembly.

While PWR fuel assemblies do vary somewhat, the common 17 x 17 pin configuration was judged most appropriate for this analysis. Each fuel pin is approximately 0.95 cm (0.374 in.) OD and 406 cm (13.3 ft) long. Each assembly could have 289 fuel pins, but in typical configurations there will be approximately 35 control rods and burnable poison rods included in the assembly. For the purposes of the HEDD penetration analysis, it will be assumed that all the rods are fuel bearing. However, the total source term will reflect the actual nuclide load in the spent fuel assembly (see Tang and Saling, 1990).

The spent fuel was assumed to have a burnup of between 40,000 and 74,000 MWD/MTU and to have been out of the reactor a minimum of 5 to 25 years. These characteristics embrace the likely range of burnup and age considered for transport in the early decades of the 21st century. The exact values used for burnup and decay in the calculation are not important because the results are expressed as fractional releases related to the content of a cask or to a single assembly. The spent fuel specimens used by INEEL and BCL were of a similar age (6.5 years) and somewhat lower burnup (28,000 MWD/MTU). In addition, it is assumed that none of the rods have experienced a failure that would release the internal pressure resulting from initial pressurization and subsequent buildup of fission gases. The initial pressure in the rods is approximately 30 atmospheres when new and as much as 40 atmospheres at temperatures typical of dry transport of large quantities of relatively young fuel (derived from Balfour et al., 1985). For this analysis, it is assumed that the individual rod pressurization is such that about 745 cm^3 of gas at STP would be released from a failed rod.

Figure 4. Cross Sectional Drawing of a Typical Rail Cask (TRW Environmental Safety Systems, Inc. 1995)



Legend
DU - depleted uranium metal

On the outside of the fuel rods there may be an accumulation of activated corrosion products referred to as crud. Typically, this is a tightly adherent scale that is dislodged with some difficulty. For this calculation, it will be assumed rod segments directly impacted by the HEDD will release their entire crud load. It will also be assumed that the "affected" lengths of the disrupted rods in the vicinity of the disrupted area will release crud as defined by parameters in the literature (Mishima and Olson, 1990), where the material was spalled off fuel rods by mechanical impact forces.

4.3 ESTIMATES OF HEDD EFFECTS

For the purposes of this analysis, two basic HEDD types were considered. The first, herein referred to as HEDD1, is the same as used by Sandoval et al. (1983) in the experiments in the early 1980s. This is a common HEDD that was designed for relatively imprecise applications in which the maximum volume of the cavity produced by the HEDD action was desired. Its weight and size are near the limit for man-transported and deployed devices (as defined by the U.S. Army). The second HEDD has been fairly carefully engineered for maximum penetration depth. It is of somewhat smaller mass than HEDD1 and would normally be deployed in an anti-tank weapon.
Estimates of the penetration of the two spent fuel casks were accomplished using the SCAP computer code.

SCAP is an interactive modeling code developed and validated at SNL (Robinson, 1985; Vigil, 1988). SCAP is able to accommodate features, such as miniaturized components and specialized materials, and a wide variety of HEDD design concepts for weapons, other military uses, and civilian applications.

SCAP is designed for flexibility in device configuration, choice of competing modeling techniques, and implementation of new models for various aspects of penetration phenomena. The code contains models for material acceleration, penetrator formation, dynamics, and stability as well as target effects. Different models are available for some portions of the code and may be chosen via a menu format. Few *a priori* assumptions are built into the code with the intent that the program structure allows the modeling of HEDDs of nonstandard design.

Robinson (1985) provides background information on SCAP including phenomenology, rationale for its design, initialization and zoning formats for the code, depiction of the material dynamics, and a short comparison of code results with experimental data.

SCAP is written in FORTRAN 77 and is currently run on PC systems using Version 5.0 of Microsoft FORTRAN. The code produces both hardcopy output listings and plotted output. Plotting portions of the code allow creation of a movie of material dynamics. The code is most convenient to run on dual alphanumeric and graphics terminals.

Input for the code was extracted from the information provided above and derived from consideration of the most likely geometry for the deployment of the HEDD or the geometry that yields the maximum swept volume. Table 1 provides some of the relevant input and output information. For calibration purposes, SCAP was used to predict the Sandoval full-scale experiment and one other experiment not documented in the open literature. In each case, the code modeled penetration depth well but tended to underestimate hole diameter. Underestimation is believed to be a result of some secondary effects, such as the dispersive layered nature of the targets, the relatively unfocused nature of HEDD1, and the near one-dimensional nature of the flow dynamic of the code. The ratio of the actual to the SCAP-predicted diameter of the cavity in the fuel for the Sandoval full-scale test (the ratio is 2.0) was used in the following calculations to estimate what the cavity diameter would be in a real event.

An effective entry-hole diameter (D_{eff}) was calculated from the SCAP code results using the ratio described above. The estimate of penetration depth was adjusted upward by one rod-pitch increment to account for damage beyond the calculated depth caused by "plowing" of rod fragments (i.e., by secondary collisions of shrapnel-like fragments of fuel broken off and accelerated by direct action of the HEDD). The hole shape was modeled as a truncated cone, to conform to the SCAP code results, which clearly show a hole narrowing with increasing depth. The D_{eff} is the diameter of the base of a truncated right circular cone with h equal to adjusted penetration depth. The D_{eff} for the HEDD1 truck cask scenario is 9.02 cm (see Table 2), slightly larger than the maximum disrupted rod length of 7.6 cm in the Sandia full-scale test.

Some of the particles are ejected immediately after the detonation and some fraction of the remainder is swept out by the rod plenum gas blowdown, which is primarily a function of cask free volume, number of rods penetrated, and rod plenum pressure. The effect of depressurization of the disrupted fuel pins was not reproduced in the Sandoval test because the surrogate fuel pins were unpressurized as were those used at BCL and INEEL. This has two effects on these calculations. First, releases of gap volatiles and gap fines away from the rod break are inhibited. Volatiles are elements, such as ruthenium, that become relatively mobile at high temperatures, and migrate to cooler parts of the fuel rod (next to the cladding). "Gap fines" are particles with relatively small AMAD's that generally can be thought of as aerosolizable and which are in the gap between the pellets and the clad as a result of comminution processes. Second, respirable aerosol in the cask that was generated as a result of the HEDD action can be swept out through the entry hole to enhance the source term over that observed by Sandoval et al. (1983) or Schmidt et al. (1982).

This contribution to the source term from fuel outside of the swept volume resulting from rod depressurization was estimated. Recent work in Sprung et al. (1998) and Soffer et al. (1995) indicate that more fuel fines may be released from the immediate vicinity of a rupture in the case of spent fuel as compared to fresh fuel. However, the "physical and dimensional changes cause the fuel-cladding gap in aged irradiated fuel to be converted into a network of cracks and voids" (Sprung et al., 1998). Because gas flows following depressurization must pass through this internal network, there will be resistance to travel of fuel fines entrained in the gas flow as well as the gas flow itself. This flow resistance was estimated by Sprung et al. (1998) to be approximately 430 times greater than that of fresh fuel. This effect decreases the calculated releases of radiocesium and other gap volatiles and gases by approximately an order of magnitude compared to those used in prior analyses of burst-rupture and similar severe accident scenarios (cited in Sprung et al., 1998). Therefore, only gap fines in the volume directly impacted by the HEDD would be expected to be released. This is a small amount compared to the fines created by the action of the HEDD.

Table 1. Input Information for HEDD Calculation Results

	Truck Cask [a]	Notes	**Rail Cask** [b]	Notes
Neutron Shield	11.748 cm (4.625 in.)	0.318 cm XM-19 SS [c] and 11.43 cm polypropylene	15.875 cm (6.25 in.)	0.635 cm 304L SS and 15.24 cm water
Layer 1	3.810 cm (1.500 in.)	XM-19 SS	4.604 cm (1.813 in.)	316L SS
Layer 2	6.730 cm (2.650 in.)	Depleted uranium	1.270 cm (0.500 in.)	Lead
Layer 3	0.952 cm (0.375 in.)	XM-19 SS	5.556 cm (2.188 in.)	Depleted uranium
Layer 4	1.524 cm (0.600 in.)	XM-19 SS (basket walls)	3.810 cm (1.500 in.)	316L SS
Layer 5	Not applicable		1.588 cm (0.625 in.)	304L SS (basket walls)
Total Wall Thickness	23.240 cm		32.703 cm	Plus a 20-cm air gap on attack path
Assembly Fuel Area Mass Density	4.743 g/cm^3	Spent nuclear fuel, Zircaloy-4, air	5.10 g/cm^3	Spent nuclear fuel, Zircaloy-4, air
HEDD Line of Action	Diagonal		Horizontal	
Assemblies in Line	2		5	

a. Source: General Atomics (1993).

b. Source: TRW Environmental Safety Systems, Inc. (1995).

SS = stainless steel.

The simultaneous initiation of depressurization in 85 or more fuel rods, depending on the scenario, could contribute to turbulence and net entrainment and outflow of these respirable particles from the cask cavity and is captured in Tables 2 and 3. This contribution to the source term was estimated from the calculated expansion and flow from the cask cavity to the external environment of gases in the fuel-clad gap, expressed as a volume blowdown factor. This factor added an increment of fuel mass to the total respirable release, which is reflected in the results shown in Tables 2 and 3.

4.4 SOURCE TERM RESULTS

The following sections describe the calculation of respirable aerosol terms for each of the five material types: crud, noble gases, volatiles, fuel matrix fines in the fuel-clad gap, and fuel matrix. Most of the details of these calculations are also contained in the worksheets in Appendix A.

4.4.1 Crud

As noted in Section 4.2, crud is a corrosion product. It consists of radiocobalt and other metallic activation products; it is deposited on fuel-rod cladding while an assembly is in the reactor and during pool storage. Crud deposition is influenced by pool chemistry and varies somewhat from reactor to reactor. Some fraction of the crud would be released in aerosol form from affected fuel rods.

There are two regions of a fuel rod that must be considered. The first is the *missing length* (also called the *directly impacted length*), which is the length directly acted upon by the HEDD. Typical values for missing rod length are shown in Appendix A, Table A-2; they vary from a maximum of 9 cm (3.5 in.) for HEDD1 with a truck cask to a minimum of 3.3 cm (1.3 in.) for HEDD2 with a rail cask. The entire crud complement of a missing fuel-rod segment is considered to be released in particulate form, and 5% of that material is estimated to be in respirable aerosol form. This value is based on the results of Jardine et al. (1982) and with the assumption that the crud is deposited as a brittle layer on the rod outer surface (Mishima and Olson, 1990). A fraction of this aerosol is ejected from the cask and the rest remains in the cask cavity until deposited or carried outside by the plenum gas blowdown process. The ejected fraction is derived from the Sandia full-scale test and varies from 2.3E-07 to 4.6E-09, depending on device and cask combination.

The second region is the *affected or disturbed segment*, which consists of the fuel rod lengths immediately adjacent to the directly impacted segments. These segments are modeled as having been impacted by the force of the detonation to a sufficient degree that some fraction of the crud is spalled off the surface of the fuel rod. The length of the typical affected segment is obtained by multiplying the missing length by 3.62. This is an empirically determined ratio of affected/missing lengths derived from the Sandia full-scale experiment data. The calculated length varies from a little over 32 cm (about 13 in.) for HEDD1 with a truck cask to 12 cm (4.7 in.) for HEDD2 with a rail cask.

From Mishima and Olson (1990), which looked at crud spalling as a result of various mechanical forces, it was possible to derive values of 4.1E-04 for the fraction of crud in the affected length that is spalled and 5.4E-04 for the fraction of spalled crud that is respirable. This respirable aerosol is modeled as being released into the cask cavity. Mishima and Olson also developed new data on the crud inventory (in terms of radiocobalt deposition) of typical fuel rods. Their value of 3.11E-03 Ci of cobalt per rod is used in this report.

Aerosols released into the cask cavity will experience some depletion from deposition of material onto cask surfaces. Based on the calculations contained in Sprung et al. (1998) and using the ratio of noble gas to particle releases for large cask leaks it was estimated that 40% of the respirable particulates are depleted in this manner. Some fraction of the remaining respirable aerosol will be swept out of the cask by the blowdown effect. The blowdown factor (fraction of cask volume that is released) varies from 0.38 to 0.014, depending on the cask and HEDD combination.

4.4.2 Gap Fines

As noted in Section 4.2, the fuel-clad gap in spent fuel is no longer a simple annular space but is rather a network of voids and fuel fines. All of the fines in the missing fuel rod lengths are modeled as described for crud. Some fraction of the fines in adjacent affected segments is modeled as being expelled to the cask cavity following fuel disruption by the HEDD. This fraction varies from 7.2E-07 for HEDD1 with a truck cask down to 1.3E-08 for HEDD2 with a rail cask. Some fraction of the aerosol fines are expelled from the cask into the environment by the cask blowdown factor, as described for crud.

4.4.3 Noble Gases

Noble gases, mainly krypton-85, are fission products that form in spent fuel. Being chemically non-reactive, noble gases accumulate in spent fuel rods, contributing to the increase in rod pressurization noted in Section 4.2. They remain in the gaseous state at nearly all temperatures encountered during reactor operation and spent-fuel storage and transportation. Much of the krypton-85 and other noble gases remain trapped in the fuel matrix, but it is estimated (Sprung et al., 1998) that about 20% is available for immediate release if fuel-rod integrity is compromised. The noble gas inventory, given in Appendix A, Table A-2, ranges from 5010 Ci for a truck cask of typical fuel to 32,600 Ci for a rail cask. The total release is the sum of the amount released virtually instantaneously, which was contained in the missing fuel segments, and the amount that is released over the next few 10s of minutes by blowdown of the disrupted rods. Between 90 and 294 rods, depending on HEDD and cask type, are modeled as being affected by action of an HEDD. This corresponds to a total release of between 85.8 and 290 Ci. All values used in this calculation are given in Appendix A, Table A-2.

4.4.4 Volatiles

Volatiles, mainly the radiocesiums, are chemically reactive fission products that become mobile at moderate temperatures (< 400 C). Radiocesium dominates this group from a health physics point of view because the decay of both common radioisotopes (cesium-134 and cesium-137) produces fairly high energy gamma radiation. The volatile elements formed within the fuel matrix during active fission tend to migrate into the fuel-clad gap during storage. The inventory of this "gap cesium" has been estimated at 126 Ci for the truck cask and 819 Ci for the rail cask. The creation of respirable aerosols of radiocesium in the gap is complicated by the aforementioned reactivity of the element and its strong tendency to condense on the nearest available surface. The initial release of particulates from disrupted fuel rods into the cask cavity, thus, must be discounted by factors that account for deposition mechanisms. All of the radiocesium is assumed to be in respirable form when released. Some of it is directly ejected from the cask by the action of the HEDD, and the remainder is released into the cask cavity. According to Sprung et al. (1998), about 40% of this material deposits on surfaces within the cask. Some of the remaining aerosol is subsequently forced from the cask by the blowdown effect described in Section 4.2. The values given in Tables 2 through 5 for volatile (cesium) aerosol release are the sums of the amounts calculated as being released in aerosol form by each of the various mechanisms described.

4.4.5 Matrix

The majority of all the UO_2 and all the fission products in spent fuel remains in the ceramic fuel pellets and is referred to as the fuel matrix. This material is relatively refractory (i.e., not easily disrupted when confined in its cladding); however, spent fuel is granular unlike the surrogate fuel used in the Sandia tests. This difference is accounted for by the SFR (see Section 2.2). The SFR used in this report is 3; its derivation is discussed in Section 2.2.6. The primary release of matrix material in respirable form is calculated from the amount of fuel in the missing fuel rod segments that is ejected from the cask and multiplying this value by the fraction of the fuel in the missing fuel rod segments that is released in respirable form (from the Sandia full-scale test) and the SFR. In addition to material directly ejected from the cask by the action of the HEDD, material is also released into the cask cavity, where a fraction of it (40%) deposits on surfaces within the cask. A fraction of the remaining aerosol is modeled as being forced out of the cask cavity by the blowdown effect. The values given in Tables 2 through 5 for matrix aerosol release are the sums of the amounts calculated as being released from the cask in aerosol form by each of the mechanisms described.

Table 2. Results for HEDD1 Releases as Fraction of Total Inventory

	Truck Cask	Notes/Range [a]	**Rail Cask**	Notes/Range
Assemblies penetrated	2	89 cm	2.4	107 cm
Number of rods disrupted	272		294	
Volume blowdown factor	0.38		0.046	
Average rod missing length	9.0 cm		7.7 cm	
Average assembly swept mass Maximum assembly mass swept mass	7.3 kg 9.6 kg	Spent nuclear fuel, Zircaloy-4, air	6.7 kg 8.7 kg	Spent nuclear fuel, Zircaloy-4, air
Average respirable release Maximum respirable release (ejected by HEDD)	1.7E-2 kg 2.2E-2 kg		1.5E-2 kg 2.0E-2 kg	
Average estimated respirable mass created inside cask by HEDD Maximum estimated respirable mass created inside cask by HEDD	1.1 kg 1.4 kg		0.98 kg 1.3 kg	
Average respirable aerosol release fraction Maximum respirable aerosol release fraction	1.2E-4 1.6E-4	4.7E-5 to 3.0E-4 5.4E-5 to 3.9E-4	3.1E-6 4.0E-6	1.1E-6 to 8.5E-6 1.3E-6 to 1.0E-5
Crud release fraction	7.5E-5	3.1E-5 to 1.4E-4	1.3E-6	4.5E-7 to 3.0E-6
Noble gas release fraction	2.0E-2	1.2E-2 to 2.6E-2	4.1E-4	2.3E-4 to 6.7E-4
Total volatile aerosol fraction [b]	1.0E-3	4.2E-4 to 2.0E-3	1.7E-5	6.2E-6 to 4.0E-5

a. Range obtained using @ RISK code (Palisades Corp). Input and output values are contained in Appendix A, Table A-4.
b. Highest value given in Wilmot et al. (1983) for gap volatiles (radiocesium) was 2.95E-03.

Table 3. Results for HEDD2 Releases as Fraction of Total Inventory

	Truck Cask	Notes/Range[a]	**Rail Cask**	Notes/Range
Assemblies penetrated	2	88 cm	1.7	95 cm
Number of rods disrupted	136		90	
Volume blowdown factor	0.23		0.014	
Average rod missing length	4.1 cm		3.3 cm	
Average assembly swept mass Maximum assembly swept mass	1.7 kg 2.2 kg	Spent nuclear fuel, Zircaloy-4, air	0.87 kg 1.1 kg	Spent nuclear fuel, Zircaloy-4, air
Average respirable release Maximum respirable release (Ejected by HEDD)	3.8E-03 kg 5.0E-03 kg		2.0E-3 kg 2.6E-3 kg	
Average estimated respirable mass created inside cask by HEDD Maximum estimated respirable mass created inside cask by HEDD	2.5E-1 kg 3.2E-1 kg		1.3E-1 kg 1.7E-1 kg	
Average respirable aerosol release fraction Maximum respirable aerosol release fraction	1.8E-5 2.4E-5	4.9E-6 to 3.6E-5 6.1E-6 to 4.6E-5	2.3E-7 3.0E-7	1.1E-7 to 7.3E-7 1.2E-7 to 8.2E-7
Crud release fraction	9.1E-6	3.0E-6 to 1.4E-5	4.7E-8	2.3E-8 to 1.5E-7
Noble gas release fraction	6.2E-3	3.3E-3 to 7.0E-3	3.9E-5	3.1E-5 to 8.6E-5
Total volatile aerosol fraction[b]	1.4E-4	4.6E-5 to 2.2E-4	7.2E-7	3.5E-7 to 2.3E-6

a. Range obtained using @ RISK code (Palisades Corp). Input and output values are contained in Appendix A, Table A-4.

b. Highest value given in Wilmot et al. (1983) for gap volatiles (radiocesium) was 2.95E-03.

Table 4. Results for HEDD1 as Releases per Assembly [a]

	Truck Cask	Rail Cask
Average respirable aerosol release fraction Maximum respirable aerosol release fraction	5.0E-4 6.5E-4	8.0E-5 1.1E-4
Crud release fraction	3.0E-4	3.3E-5
Noble gas release fraction	8.1E-2	1.1E-2
Total volatile aerosol fraction	4.1E-3	4.5E-4
a. Total amount released (kg) per kg of spent fuel in one assembly.		

Table 5. Results for HEDD2 as Releases per Assembly [a]

	Truck Cask	Rail Cask
Average respirable aerosol release fraction Maximum respirable aerosol release fraction	7.2E-5 9.4E-5	5.9E-6 7.8E-6
Crud release fraction	3.7E-5	1.2E-6
Noble gas release fraction	2.5E-2	1.0E-3
Total volatile aerosol fraction	5.7E-4	1.9E-5
a. Total amount released (kg) per kg of spent fuel in one assembly.		

5. ANALYSIS OF CASK PERFORMANCE AND RELATED FACTORS

5.1 ANALYSIS OF RESULTS

5.1.1 Fuel Disruption

The total respirable fuel matrix release is dominated by the blowdown of the aerosol presumed to have been produced within the cask by the action of the HEDD. Blowdown transports, but does not itself, produce aerosols. There are two independent blowdown mechanisms: depressurization of damaged fuel rods and depressurization of the cask. Sandoval et al. (1983) did not observe this source because of the unpressurized nature of the surrogate fuel used in the experiment. The exact magnitude of this source is not known, but reasoned estimates have been made in order to provide as complete a picture of sabotage impacts as possible. Another factor included here is the scaling to spent fuel from the surrogate used by Sandoval et al. (1983). In this report, a ratio of 3 is used (i.e., 3 kg of spent fuel aerosol is predicted for each kilogram of surrogate aerosol production). Thus, three modifying factors affect the results reported herein compared to Sandoval et al. (1983):

- A source of fuel matrix aerosol in the cask (not measured in, nor the goal of, the Sandoval experiments)
- Fuel aerosol sources extrapolated from surrogate data to spent fuel by a factor of 3 (could not be directly measured in the Sandoval tests)
- Emanation of aerosols from within the cask as a result of release of fuel rod plenum gases after disruption of the rod by the HEDD (could not be directly observed by Sandoval et al., 1983).

HEDD1

The results of the analysis for the truck cask design indicate larger releases than in the Sandia full-scale test as a result of fines entrainment following depressurization. The predicted average respirable release (shown in Tables 2 and 3) of 1.7E-02 kg is approximately 6 times the value for the Sandia test of 2.93E-03 kg. In the scenario analyzed here, the HEDD penetrated 2 fuel assemblies rather than 1, and the SFR of 3 accounts for the factor of 6 increase in prompt respirable release.

The total respirable aerosol fraction from the truck cask subjected to HEDD1 was 1.2E-4, which can be compared to the value from the Sandoval report of 1.5E-5. The order of magnitude increase for this analysis is a result of the factors noted above (i.e., 1.5E-5 x 6 • 1E-4).

In the rail cask calculations, the average amount released as respirable material is estimated at 1.5E-02 kg. These values agree within about a factor of 2 with the predicted value of 7.1E-03 kg obtained by multiplying the 1-assembly Sandia test value (2.93E-03 kg) by the number of assemblies penetrated (2.4) and, thus, are reasonably consistent. The average fraction released as respirable aerosol (3.1E-06) is considerably lower, of course, because the total mass of fuel in the rail cask is much higher.

HEDD2
The aerosol production values for this device are not as large as those for HEDD1. The truck cask analysis indicates that HEDD2, like HEDD1, would penetrate 2 assemblies (the maximum number of assemblies that could be penetrated for the optimal line of attack) but would not penetrate the back wall of the cask. While HEDD2 was designed to be highly efficient in penetrating power for the high explosive it contains, the damage diameter it produces is approximately one-half that of HEDD1; therefore, the affected volume is smaller. As a result, a smaller average prompt respirable release of 3.8E-03 kg and a correspondingly smaller total respirable release fraction of 1.8E-5 is predicted.

The rail cask data indicate that penetration would be somewhat reduced to 1.7 assemblies, versus 2.4 for HEDD1, with smaller affected volume. The average prompt respirable release is calculated to be 2.0E-03 kg, or approximately one-tenth of the HEDD1 release. This is reflected in the reduced total respirable release fraction of 2.3E-7.

5.1.2 Other Fuel Components

Spent fuel contains fission products that are noble gases (e.g., krypton-85) or volatiles (e.g., cesium-137) that might be released from the fuel-clad gap and driven out of the ceramic fuel matrix by the HEDD attack. While the noble gases are easily mobilized, cesium would require temperatures in excess of 750 C to be released in vapor form. Sandoval et al. (1983) found evidence of temperatures in that range during the full scale tests. In addition, PWR fuel may have crud deposits on the outer surfaces of the fuel rods. These deposits contain cobalt-60, a high-energy gamma emitter that is an activation product. The amount of gaseous and volatile fission products released in a HEDD attack can be estimated by determining the amount present in the swept fuel volume. Experiments with actual spent fuel rod segments carried out at Battelle (Lorenz et al., 1979) indicated that even when fuel rod failure is caused by heating to burst rupture, the rapid depressurization that follows releases only material in the immediate vicinity of the failure point and that additional gases and volatiles are not released from more distal regions of the fuel rods. Recent work by Sprung et al. (1998) provided an explanation for and a mathematical model of this phenomenon. One should also note that a larger fraction of the volatiles would be expected to condense on the nearest available cold surface. Because a HEDD attack, unlike an accident involving prolonged prior heating from a fire, would present an abundance of cold surfaces in the immediate vicinity of the release point, it can be expected that very little of this material would be available for downwind dispersion. However, no attempt has been made to quantify this plate out effect.

The crud release calculation is based on Mishima's estimate of 0.9 Ci of crud per assembly (Mishima and Olson, 1990). In addition, they report that under significant mechanical forces, only 7.5E-7 of crud spalled off fuel rods being processed, of which 2.2E-7 became airborne (and presumably, respirable). For the HEDD1 scenarios, all crud in the disrupted lengths of 9.02 cm and 7.70 cm, respectively, was assumed to be released as particulate matter with 5% being respirable. In the affected areas, 7.5E-7 was assumed to be released with 30% respirable. This gives an equivalent release fractions to the environment of 7.5E-5 and 1.3E-06 for truck and rail casks, respectively. Because effective diameters for HEDD2 scenarios are approximately one-half of the diameter values for HEDD1, releases of crud also decrease (see Tables 2 and 3).

5.2 UNCERTAINTIES ASSOCIATED WITH ANALYSIS

5.2.1 Factors Affecting Performance of HEDD

The analyses performed at SNL assumed flawless execution. There are a number of physical factors that may act to prevent complete success. These factors apply most particularly to scenarios in which an HEDD is delivered by means of a rocket attack on a cask-carrying truck or railcar. As noted earlier, while the rockets themselves may be purchasable on some weapons black markets, the ancillary launch and guidance equipment is less likely to be available.

Obliquity

Any explosive device that focuses HE Energy requires zero obliquity (perpendicular strike) for optimum performance (penetration). Terrorists in physical control of a shipment would have little difficulty ensuring this condition is satisfied. Attacks from a distance, i.e., by means of a rocket-propelled projectile, however, are not certain to satisfy this condition. Should an attack be attempted with a homemade launcher, for example, the chances of success are greatly diminished. In the absence of an active guidance system, the angle of impact is difficult to control. The impact angle could be somewhat oblique (depending on weapon speed). Even under the assumption that the guidance equipment could be obtained along with the rocket itself, other factors influence the probability of success, and they are discussed in the next paragraphs.

Among these other factors is operator training. Adequate training implies previous actual firing of the same or a similar device as many times as would occur in an armed forces training school on the use of such devices. The amount of training required varies and is more extensive the more sophisticated the weapon (actual training times for particular weapons cannot be identified in this document.). Such training is generally only obtainable while serving in the armed forces, and a conservative point estimate of the likelihood of adequate training is represented by the fraction of the adult population who are armed forces veterans (approximately 10%).[10] This conditional probability modifies any estimate that might be made of the likelihood of an armed forces veteran becoming a terrorist.

Range-related inaccuracy is another potential problem in a "shoot from a distance" situation. These weapons were not meant to be used at very close range. It is impossible to adequately track and lock on to a moving target less than a few hundred meters away (exact distances cannot be disclosed). Because this factor could result in a total miss, it is worthy of consideration. This factor cannot be considered as entirely independent of the training factor because one aspect of training is learning the effective range of a device. Nevertheless, errors in distance measurement or estimation, terrain-related constraints, and so forth could influence actual firing distance.

Shape of the target surface is yet another factor. Achieving 0° obliquity on a rounded surface is difficult. The shape of the cask becomes important when considering this factor. A broadside

[10] Based on current estimates of a total veteran population of approximately 26,000,000 (from Veteran Affairs website http://www.va.gov/OCA/403drt~1.doc) and a total U.S. population of approximately 271,000,000 (from the Census Bureau website's PopClock for Oct 13, 1998, http://www.census.gov/main/www/popclock.html).

attack would result in impact on a relatively low-curvature surface for the rail cask and angled or more rounded surface for the truck cask. In either case, it could be assumed that any degree of obliquity from +90° to -90° is achievable but with relatively large angles more likely for the truck cask. The U.S. Army has quantitatively correlated degree of penetration with obliquity for many devices.

To summarize, factors affecting achievement of zero obliquity are:

- Use of home-made launcher
- Inadequate operator training (assumes possession of proper launcher/guidance equipment)
- Inaccuracy due to operation outside the range recommended for the device (any launcher)
- Impact of projectile with a rounded cask surface (any launcher).

Stand-Off Distance

Many devices perform sub-optimally if the proper standoff distance (distance between target surface and the HEDD) is not achieved. Intervening features, such as antipersonnel barriers and impact limiters, could defeat an attack by causing the device to detonate at a sub-optimal distance from the cask surface. The "active armor" in modern military tanks takes advantage of this fact. Detonation at sub-optimal standoff distances could result in either a lesser breach or no breach of the cask containment barrier. The primary consequence of inadequate penetration would be to reduce the magnitude of the source term.

5.2.2 Meteorological Factors

Four meteorological factors are considered when potential dispersal of any material that is toxic by inhalation is assessed. These factors are

- Atmospheric stability
- Wind speed
- Wind direction
- Precipitation.

Atmospheric stability indicates the degree of mixing and dilution that occurs as a "puff" of some respirable material moves downwind. Dilution tends to occur rapidly except in highly stable, low wind speed conditions, which are relatively uncommon. The greater and more rapid the dilution, the lower the health effects expected in potentially exposed persons located downwind of the release point. The occurrence of precipitation during or immediately following a release event results in what is often called rain out or wash out, which cause airborne aerosol to drop precipitously and be deposited on the ground instead. This results in a localized pocket of ground contamination, from which persons can be rapidly evacuated, and a large decrease in inhalation dose.

5.2.3 Surrounding Population

Persons in the Plume Footprint during Downwind Dispersal

In the event of a successful attack, some of the disrupted fuel will be released as aerosols. As noted previously, the respirable aerosol fraction was estimated from actual experimental data by Sandoval et al. (1983) and found to be about 0.5% of the total released material or 1.46E-05 of the total cask inventory. The calculated values for the two new cask designs are comparable.

Population subgroups potentially affected by dispersal consist of those persons who might be in the plume footprint. They are:

- Residential population
- Worker population (e.g., drivers, escorts)
- On-link population (e.g., commuters)
- Nonresident population (e.g., shoppers).

The presence of these groups is location-specific and time dependent. The sizes and distributions of these populations directly affect the potential magnitude of population dose resulting from aerosol release. For any given location, wind direction and the other meteorological factors discussed previously, also influence potential dose magnitude. The Sandoval report considered a highly urban population (approximately 10,000 persons/mi^2 uniformly distributed) as an upper bound.

Persons in the Immediate Vicinity

In the event of a successful attack, some of the disrupted fuel that is not dispersed as aerosol will fall onto nearby surfaces as particulates and fragments. The majority of the fuel in the cask will remain in the cask, and the penetration in the cask wall could create a localized loss of shielding. In the event of precipitation (rain or snow), a fraction of the aerosol released to the atmosphere could be rained out within fairly short radial distances of the event site. These phenomena could combine to generate a localized radiation field of high intensity. It is possible that some members of the public would be unavoidably exposed, especially in a standoff attack situations in which there is little or no time to carry out precautionary evacuation. In most cases, terrorists seeking to assume physical control of a shipment will have been sufficiently overt that most of the population remaining in the immediate vicinity would have been able to withdraw from the area.

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6. OBSERVATIONS AND CONCLUSIONS

There are several important observations to be drawn from the results presented in Chapter 5.

- The first is that although HEDD1 and HEDD2 are shown to penetrate a single wall of a spent nuclear fuel cask, neither HEDD1 nor HEDD2 fully penetrate both walls and intervening spent fuel of the cask types considered here. The fact that HEDD1 and HEDD2 will penetrate a single wall of a spent nuclear fuel cask should not be viewed as unusual because spent nuclear fuel casks are not designed to resist attack by HEDDs, such as HEDD1 or HEDD2, and many armored vehicles would also be penetrated by HEDD1 or HEDD2.

- The second important observation is that HEDD1 would cause more damage to both the truck and rail casks than HEDD2. For the truck cask, both HEDD1 and HEDD2 penetrate 2 spent fuel assemblies. However, the average diameter of the penetration created by HEDD1 in the spent fuel assemblies is over twice as large as the average diameter in the spent fuel assemblies created by HEDD2. For the rail cask, HEDD1 penetrates about 2.4 spent fuel assemblies, while HEDD2 penetrates about 1.7 spent fuel assemblies even though the HEDD2 has greater penetration depth in steel. The layered nature of the cask's construction vitiates HEDD2 more readily compared to HEDD1, probably as a result of its smaller diameter. As with the truck cask, the average diameter of the penetration created by HEDD1 in the spent fuel assemblies is over twice as large as the average diameter in the spent fuel assemblies created by HEDD2. In addition, the volume of damaged spent fuel created by HEDD1 in the truck cask is larger than the volume of damaged spent fuel created by HEDD1 in the rail cask, even though HEDD1 penetrates slightly further into spent fuel assemblies contained in the rail cask. These results confirm the choice of HEDD1 made in Sandoval et al. (1983) and also confirm that HEDD1 is expected to cause more damage than other HEDDs similar to HEDD2.

- The third important observation is that an additional mechanism of release was identified that was not accounted for in previous tests or analyses. This additional mechanism was due to the expulsion of aerosol from the interior space of the cask as a result of venting the high-pressure gases from the plenum of disrupted fuel rods. This mechanism is commonly known as blowdown. During blowdown, this high-pressure gas escapes from the cask, also transporting the aerosol from the cask. Methods and data that are likely to overestimate the amount of material released during blowdown were used to estimate the magnitude of this additional release mechanism.

- The fourth important observation is that the largest release fractions were observed for HEDD1 and the truck cask (see Tables 2 and 3). The reasons for this were:
  1. the average diameter of the penetration created by HEDD1 in the spent fuel assemblies is over twice as large as the average diameter of the penetration in the spent fuel assemblies created by HEDD2 for either the truck or rail casks,
  2. the volume of damaged spent fuel created by HEDD1 in the truck cask is larger than the volume of damaged spent fuel created by HEDD1 in the rail cask,
  3. the truck cask has a smaller internal volume than the rail cask, which increases the releases due to blowdown, and

4. the number of spent fuel assemblies penetrated by either HEDD1 or HEDD2 is a larger fraction of the total number of spent fuel assemblies contained in the truck cask than contained in the rail cask.

- The fifth important observation is that the releases due to the direct ejection of material by HEDD1 obtained in this analysis are in reasonable agreement with the results obtained by Sandoval et al. (1983). For example, Sandoval et al. (1983) predicted a release of about 3 g of respirable aerosol from a truck cask carrying a single spent fuel assembly. If two spent fuel assemblies were penetrated, a release of about 6 g would be predicted. Using an SFR of 3, Sandoval et al. (1983) would predict a release of about 18 g of respirable irradiated spent nuclear fuel. This analysis predicted a release of about 20 g of respirable irradiated spent nuclear fuel from the direct ejection of material by HEDD1, which is in reasonable agreement with the value of 18 g that would be predicted by Sandoval et al. (1983).

  When the contribution from blowdown is included, the source terms ranged from 3.1E-6 to 1.2E-4. This is about 0.0003% to 0.01% of the total cask contents. Blowdown accounts for about 50% of the total source term from the rail cask and over 90% of the total source term from the truck cask. A conservative method was used to estimate the likely contribution of blowdown to the source term. Although it is possible to develop a more precise estimate, it is expected that the current analysis would bound those results.

- The sixth important observation is that the release fractions developed in this report are similar to those used to develop consequence estimates for accidents in prior transportation risk assessments. For the purpose of comparison with comparable levels of accident-caused damage, respirable aerosol release fractions for high severity accidents taken from spent fuel accident risk analyses performed in the past two decades were obtained and compared as shown in Table 6.

  The earliest study cited in Table 6, the "Cost-Risk Study," describes a six-category accident severity classification scheme for spent fuel casks that has been used in a number of past DOE environmental analyses (e.g., DOE, 1986). The more recent "Modal Study" describes a 20-category classification scheme that is currently being used in DOE environmental analyses. Table 6 gives maximum values for the most severe accident(s) for all physical-chemical groups considered in the "Modal Study".

  As Table 6 indicates, the accident-related release fractions (except for matrix materials) are greater than the release fractions for HEDD2 and HEDD1, but, in general, the release fractions are comparable to the Modal Study values. The matrix release fraction values for accidents are generally lower because accident-driven matrix oxidation is less efficient at releasing matrix material than the action of HEDDs. Thus, the sabotage results derived in this report do not represent an extraordinary change in the release fraction compared to those for accidents.

Table 6. Comparison of Sabotage and Accident Release Fractions

Cask Type / Physical-Chemical Group	HEDD1 Attack	HEDD2 Attack	"Modal Study" Most Severe Accident [a]	"Cost-Risk Study" Most Severe Accident [b]
Truck Cask				
Co-60 (crud)	7.5E-05	9.1E-6	Not Reported	6.0E-04
Radiocesium	1.0E-03	1.4E-4	2.0E-03	2.8E-04
Noble Gas	2.0E-02	6.2E-3	6.3E-01	1.1E-01
Matrix	1.2E-04	1.8E-5	2.0E-05	2.5E-09
Rail Cask				
Co-60 (crud)	1.3E-06	4.7E-8	Not Reported	6.0E-04
Radiocesium	1.7E-05	7.2E-7	2.0E-03	2.8E-04
Noble Gas	4.0E-04	3.9E-5	6.3E-01	1.1E-01
Matrix	3.1E-06	2.3E-7	2.0E-05	2.5E-09

a. Fischer et al. (1987).
b. Neuhauser et al. (1984).

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APPENDICES

Appendix A

Table A-1: Selected Results from the Sandoval Report (SAND82-2365) with Additional Analysis

Table A-2: HEDD Calculation Worksheet

Table A-3: Analysis of Data from BCL Tests (NUREG CR-2472/BMI2095 & NUREG CR-2472/BMI2089)

Table A-4: Data for Aerosol Production from Brittle Materials Subjected to High Intensity Impacts

Table A-5a: Simulation Variables for YMPre29r.xls Input and Output Tables from @RISK Analysis for Range of Results

Table A-5.b: Output Cell Statistics for @RISK Calculation

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Table A-1: Selected Results from the Sandoval Report (SAND82-2365) with Additional Analysis

Common Elements:		diameter =	9.33E+00 *mm	3.67E-01 *in
		length	1.52E+01 *mm	5.98E-01 *in
	surrogate fuel	volume	1.04E+00 cc	
		density	1.04E+01 g/cc (95 % of theor.)	
		mass	1.08E+01 gm/pellet	

Parameter	1 / 4 Scale Dry Test - Pre-test		Full Scale - Pre Test	
fuel pins matrix is	5	5 x 5	1.50E+01	15 x 15
pin length	9.00E+02 *mm		1.20E+03 *mm	
pin pitch in assembly	1.36E+01 mm (approx. scaled from photo)		1.36E+01 mm (approx. scaled from photo)	
estimated pin o.d.	1.08E+01 mm		1.08E+01 mm	
1.53E+01 *Kg DUO2	1.42E+03 pellets		2.01E+02 *Kg DUO2	1.86E+04 pellets
1.89E+01 Kg total mass	8.63E+02 pellet length/pin		2.58E+02 Kg total mass	
3.55E+00 *Kg Zr-4	6.49E+00 g/cc		5.70E+01 *Kg Zr-4	
5.70E-01 mm tube wall	3.50E+00 kg Zr-4 (mass check)			

Parameter	1/4 Scale Dry Test - Post-test				Full Scale Post-Test			
	UO2 Mass		fraction		UO2 Mass		Mass Fraction	
Mass Remaining in pins in cask =	1.52E+01	*kg	9.88E-01		1.96E+02	*kg	9.73E-01	
Released from pins =	1.80E-01	*kg	1.17E-02		5.46E+00	*kg	2.72E-02	
In cask - not in pins =	1.23E-01	*kg	8.01E-03		2.91E+00	*kg	1.45E-02	
Released from cask (in chamber) =	5.65E-02	*kg	3.68E-03		2.55E+00	*kg	1.27E-02	
Deposited on chamber/cask surfaces =	4.78E-02	*kg	3.11E-03		5.40E-01	*kg	2.69E-03	
Airborne in chamber =	7.80E-04	*kg	5.08E-05		2.93E-03	*kg	1.46E-05	
Respirable in chamber =	7.80E-04	*kg	5.08E-05		2.93E-03	*kg	1.46E-05	
Unaccounted loss =	7.92E-03	*kg	5.16E-04		2.01E+00	*kg	9.98E-03	
Total UO2 Mass =	1.53E+01	*kg	1.00E+00		2.01E+02	*kg	1.00E+00	
Fuel Rods with some mass loss =	1.00E+01	*	(~20%)		1.11E+02	*	(~50%)	
Maximum affected length of pin	ns				2.75E+02	*mm		
Maximum missing length of pin	ns				7.60E+01	*mm		
Affected length to missing length ratio					3.62E+00			
Average missing length of pin =	2.10E+01	*mm			ns			
Average diameter of hole in array	1.98E+01	*mm			ns			
Est. swept UO2 mass in hole in fuel pins =	1.70E-01	Kg			3.82E+00	Kg		
Unaccounted Loss / Swept Mass			4.66E-02				5.25E-01	
Aerosolized fraction of mass within hole =	4.59E-03				7.67E-04			
Aerosolized fract of mass released from pins =	4.35E-03	*		Surrogate	5.37E-04	*		This is resp fraction outside the cask
Released from pins / est. swept mass =	1.06E+00				1.43E+00			
Released from cask/estimated swept mass =	3.33E-01				6.67E-01			This is non resp. outside the cask
Estimated total UO2 resp.mass produced (Kg) =					1.91E-01		5%	This is respirable inside and outside the cask with 5% respirable fraction based on Jardine et al
Correction for Spent Fuel/Surrogate fuel =				Spent Fuel	3.00E+00	*		Choices were: 0.42(BCL), 0.53(INEEL), 0.71(BCL), 3(BCL), 5.6(INEEL)
Rf of ejected SF mass within swept mass =					2.30E-03			
Estimated total SF resp.mass produced (Kg) =					5.73E-01			The latter value (5.6) was not chosen because method used to obtain it was probably not valid.
Est'd total SF aerosol mass/swept mass =					1.50E-01			The smaller values (< 1) were not used because they lack conservatism
penetration depth in cask	(FULL)	27.9* cm			(PARTIAL)	42* cm		
Entry hole diameter	1.27E+01	*mm			1.52E+02	*mm		
Lead layer hole diameter	5.00E+01	*mm.			ns			
exit hole ?	yes				none			

*denotes data gathered from Sandoval Report

Conclusion: There may be a difference in behavior depending on whether the penetration is complete or not. Full penetration by the HED, which produces another escape hole and apparently induces a flow that carries material directly out of the cask, has a release fraction that is 1 / 2 to 1 order of magnitude greater depending on how the reference mass for the release ratio is calculated.

Table A-2: HEDD Calculation Worksheet

	HEDD1		HEDD2								
	Truck Cask	Rail Cask	Truck Cask	Rail Cask	Fuel Data per Rod	Fuel Data per Assembly	value	Source			
										Rod Data (m)	
Number of Assemblies	4.00E+00	2.60E+01	4.00E+00	2.60E+01		2.89E+02	1.70E+01	rw184r1/p2A-30		0.0125984	pitch
Number of Rods	1.16E+03	7.61E+03	1.16E+03	7.51E+03		2.64E+02		ornlm10-213		0.0094996	diameter
Number of Fuel Rods	1.02E+03	6.60E+03	1.16E+03	7.61E+03		6.58E+02		App A pA-14			
Assembly Mass (kg)	2.63E+03	1.71E+04	2.63E+03	1.71E+04							
Assembly Cross Section Area (m^2)						7.72E-01	3.60E+00	meters active length rw184r1/p2A-30		3.86E+00	length
Rod Spacing/Rod Diameter						1.33E+00		Length in Inches rw184r1/p2A-30			
Rod Diameter (m)					9.50E-03		Dia	rw184r1/p2A-30			
Rod Longitudinal Cross Section Area (m^2)					3.47E-02		Proj Area	rw184r1/p2A-30			
Noble Gas Inventory (Ci)	5.01E+03	3.26E+04	5.01E+03	3.26E+04	4.93E+00	1.25E+03	8.26E+03	Curies - App A pA-9 Bounding PWR	0.2	Fraction of noble gases that are freed:Sprung	
Crud Inventory (Ci of Co 60)	3.60E+00	2.34E+01	3.60E+00	2.34E+01	3.11E-03	9.00E-01	8.00E-01	curies per assembly (Mishima)			
Fuel Pellet Inventory (kg)	2.11E+03	1.37E+04	2.11E+03	1.37E+04		5.26E+02	4.64E+02	kg Uranium/ass'y rw184r1/p2A-30		237.85	Mean At.Mass
Gap Fines Aerosol Inventory (Kg)	6.32E-02	4.11E-01	6.32E-02	4.11E-01	8.22E-05	1.58E-02	3.00E-05	Fuel Matrix Gap Fines fraction by Lorenz		7.E+00	Cs enrichment in fines
Matrix Cs Inventory	6.00E+05	3.90E+06	6.00E+05	3.90E+06	5.91E+02	1.50E+05	1.50E+05	Ci of Cs / ass'y bounding			
Matrix Te Inventory	1.38E+02	8.97E+02	1.38E+02	8.97E+02	1.36E-01	3.45E+01	3.45E+01	Ci of Te / ass'y estimated		2.30E-04	scaled to Cs from Sprung
Gap Cs Inventory	1.26E+02	8.19E+02	1.26E+02	8.19E+02							
Gap Te Inventory	2.90E-02	1.88E-01	2.90E-02	1.88E-01							
Average UO2 Mass Areal Density per Assembly (Kg/M^2)						6.82E+02		Random shot through an assembly			
Max. UO2 Mass Areal Density per Assembly (Kg/m^2)						8.91E+02		Shooting down the center of a row of rods			
Assembly Depth Available	2.00E+00	5.00E+00	2.00E+00	5.00E+00							
Assemblies Penetrated	2.00E+00	2.42E+00	2.00E+00	1.73E+00		From shaded areas below					
Average Diameter of Missing Section (m)	9.02E-02	7.70E-02	4.08E-02	3.32E-02		From shaded areas below					
Affected length of rod (m)	3.26E-01	2.78E-01	1.48E-01	1.20E-01		3.62E+00		Ratio of affected to missing length from Sandoval			
No. Rods Affected	2.72E+02	2.94E+02	1.36E+02	9.00E+01				Estimated From Hole Size; Is Consistent With Sandoval Experiment - About Half the Rods Affected			
Max. Fuel Pellet Mass Disrupted (kg)	9.60E+00	8.69E+00	2.17E+00	1.14E+00							
Average Fuel Pellet Mass Disrupted (kg)	7.34E+00	6.65E+00	1.66E+00	8.74E-01							

Table A-2: HEDD Calculation Worksheet (con't)

Row	B	C	D	E	F	H	J	K	N
33	Noble Gas Released to cavity	2.68E+02	2.90E+02	1.34E+02	6.87E+01				
34	Noble Gas Fraction Released to cavity	5.35E-02	8.90E-03	2.68E-02	2.73E-03	(Includes spall fraction from affected section and all Crud from missing			
35	Crud Release to cavity (Ci)	3.49E-04	2.20E-02	4.73E-03	2.66E-03			4.11E-04 Average crud fraction spalled from disturbed section per Mishima (only from rod length "affected")	
36	Respirable Crud Released to Cask Cavity (Ci)	1.19E-03	1.10E-03	2.36E-04	1.27E-04			6.37E-04 Spalled Crud Respirable fraction per Mishima	
37	Respirable Crud Fraction Released to cavity	3.30E-04	4.68E-05	6.56E-05	5.43E-06			5.00E-02 Fraction of brittle crud in missing length that is respirable	
38	Gap Fuel Matrix Aerosol Released to cavity (Kg)	1.61E-03	1.39E-03	3.41E-04	1.84E-04			Gap aerosol relesed from length "affected"	
39	Gap Matrix Aerosol Fraction Released to cavity (cf total fuel mass)	7.17E-07	1.02E-07	1.62E-07	1.34E-08				
40	Gap Cs Released to Cavity (Ci)	3.01E+00	2.78E+00	5.98E-01	3.22E-01			Release is assumed proportional to affected rod length and gap deposit.	
41	Cs released from disrupted pellets	2.73E+03	2.47E+03	6.18E+02	3.25E+02				
42	Fraction of total Cs released to cavity	4.56E-03	6.35E-04	1.03E-03	8.35E-05				
43	Gap Te released to cavity (ci)	8.93E-04	6.39E-04	1.38E-04	7.40E-05			Release is assumed proportional to affected rod length and gap deposit	
44	Te released from disrupted pellets	6.29E-01	5.69E-01	1.42E-01	7.48E-02				
45	Fraction of total Te released to cavity	4.56E-03	6.36E-04	1.03E-03	8.35E-05				
47	Max. Respirable Fuel Matrix Material Ejected from Cask (kg)	2.21E-02	2.00E-02	4.99E-03	2.63E-03				
48	Avg. Respirable Material Ejected from cask (kg)	1.69E-02	1.53E-02	3.82E-03	2.01E-03		2.30E-03	Sandoval.xls full scale data corrected by SF/Surrogate fuel ratio of	3.00E+00
49	Max. Respirable Material left in cask from HEDD action (kg)	1.42E+00	1.28E+00	3.20E-01	1.69E-01		1.60E-01	SF resp frac: Sandoval.xls full scale data RI corrected by SF/Surrogate fuel ratio	
50	Avg Respirable Material in cask from HEDD action (kg)	1.08E+00	9.81E-01	2.45E-01	1.29E-01				
51	Max. RI in cask from HEDD action (kg)	6.73E-04	9.37E-05	1.52E-04	1.23E-05				
52	Avg. RI in cask from HEDD action (kg)	5.16E-04	7.17E-05	1.16E-04	9.43E-06				
53	Max. Respirable Fuel Matrix Fraction Ejected from Cask	1.05E-05	1.46E-06	2.37E-06	1.92E-07				
54	Avg. Respirable Fuel Matrix Fraction Ejected from Cask	8.02E-06	1.12E-06	1.81E-06	1.47E-07				
55	Max. Fuel Mass Released to surroundings (not resp.) (kg)	6.40E+00	5.79E+00	1.46E+00	7.62E-01		6.67E-01	sandoval.xls	
56	Avg. Fuel Mass Released to surroundings (not resp.) (kg)	4.90E+00	4.43E+00	1.11E+00	5.83E-01				Cask Dimensions

Table A-2: HEDD Calculation Worksheet (con't)

Row	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
58																
59											Internal Vol	Length truck	Dia truck	Length rail	Dia rail	Vol internals
60	Cask Internal Volume (m^3)	8.52E-01	1.02E+01	8.52E-01	1.02E+01						4.90E-01	4.01E+00	4.61E-01	4.91E+00	1.83E+00	1.02E+00
61	Cask Int'l Vol (less Ass'ys and structural in (M^3)	4.90E-01	6.70E+00	4.90E-01	6.70E+00		2.74E-04	9.49E-02	Pin/Assembly volumes		SARP calcs					Est from Drawings
62	Plenum Volume Released (m^3)	2.95E-01	3.19E-01	1.48E-01	9.78E-02		7.45E-04	volume at STP (m^3) per Balfour et al	1.25E+02	Cask Internal Temp (C) <----Truck Rail---->	1.25E+02		HEDD1		HEDD2	
63	Volume Blowdown Factor	3.76E-01	4.55E-02	2.32E-01	1.44E-02								Truck	Rail	Truck	Rail
64	Total Max Resp Fraction Fuel Matrix Released to Environment	1.63E-04	4.02E-06	2.35E-06	2.98E-07	Not including Volatiles	This does not include Cs and Te		6.00E-01	Fraction of aerosol in cask escaping to outside without deposition Obtained from Sprung Figure 10-6 @ 310 mm^2 leak area =0.5/0.8			6.50E-04	1.05E-04	9.41E-05	7.78E-06
65	Total Avg. Resp Fraction Fuel Matrix Released to Environment	1.24E-04	3.08E-06	1.80E-05	2.28E-07		This does not include Cs and Te		6.00E-01				4.98E-04	8.00E-05	7.20E-05	5.93E-06
66	Total Respirable Fraction Co as Crud Released to Environment	7.45E-05	1.20E-06	9.11E-06	4.68E-08				6.00E-01				2.98E-04	3.32E-05	3.85E-05	1.22E-06
67	Total Fraction Cs as Released to Environment	1.03E-03	1.73E-05	1.43E-04	7.20E-07	Incl. Entire Volatile Cont.			6.00E-01				4.12E-03	4.60E-04	6.73E-04	1.87E-05
68	Total Fraction Te Released to Environment	1.03E-03	1.73E-05	1.43E-04	7.20E-07				6.00E-01				4.12E-03	4.50E-04	5.73E-04	1.87E-05
69	Total Fraction Noble Gases Released to Environment	2.01E-02	4.05E-04	6.20E-03	3.92E-05				1.00E+00				8.00E-02	1.05E-02	2.48E-02	1.02E-03
70	Max.Fuel mass Fraction Ejected (not resp.)	3.04E-03	4.23E-04	6.87E-04	5.57E-05	Incl. Volatile & Matrix							1.22E-02	1.10E-02	2.75E-03	1.45E-03
71	Avg.Fuel mass Fraction Ejected (not resp.)	2.33E-03	3.24E-04	8.26E-04	4.26E-05								9.31E-03	8.42E-03	2.10E-03	1.11E-03
72	Crud Fraction Ejected by HEDD (not resp)	2.26E-07	3.04E-07	8.91E-07	4.83E-09								9.01E-07	7.90E-08	2.78E-08	1.20E-07
73	new file as of 2/18/99															
74																
75																

Normalized relative to the number of assemblies in the cask in question

Normalize by the content of a single test fuel assembly

Table A-2.a: SCAP Calculations

									Truck Assembly Dimension =			12.598425	inches	
M. Vigil results in Inches										Rail Assembly Dimension =		9.3	inches (incl. basket)	
	hed	penetration	Dic	Dif		Dmin	Dff	Daf	Lf	Vf	direction	Na		
truck	1	35	3.7	2.56		1.77	0.85	1.71E+00	24.80	56.9	diagonal	1.97	2	
truck	2	34.6	4.1	1.03		0.89	0.55	7.90E-01	24.80	12.2	diagonal	1.97	2	
rail	1	42.1	9.8	1.91		0.41	1.08	1.50E+00	21.60	37.9	flat	2.31	2.31	
rail	2	37.4	5.9	0.75		0.14	0.55	6.50E-01	15.00	4.96	flat	1.61	1.61	

Manny's results in inches CORRECTED BY REL BASED ON FIGURE PRESENTED														
	hed	penetration	Dic	Dif			Dff	Daf	Lf*	Vf	direction	Na	N affected	
truck	1	35	3.7	2.56		1.77	0.85	1.71E+00	24.80	56.90	diagonal	1.97	2.00	max ass'ys
truck	2	34.6	4.1	1.03		0.89	0.55	7.90E-01	24.80	12.20	diagonal	1.97	2.00	max ass'ys
rail	1	42.1	9.8	1.91		0.41	1.08	1.50E+00	22.00	37.90	flat	2.37	2.42	as in col L but one row of
rail	2	37.4	5.9	0.75		0.14	0.55	6.50E-01	15.60	4.96	flat	1.67	1.73	pins added to depth

	Results in meters											
	hed	penetration	Dic	Dif		Dmin	Dff	Daf	Lf	Vf	Vf con. hole)	D effective
truck	1	8.89E-01	9.40E-02	6.50E-02		4.50E-02	2.16E-02	4.34E-02	6.30E-01	9.32E-04	1.01E-03	4.51E-02
truck	2	8.79E-01	1.04E-01	2.62E-02		2.26E-02	1.40E-02	2.01E-02	6.30E-01	2.00E-04	2.06E-04	2.04E-02
rail	1	1.07E+00	2.49E-01	4.85E-02		1.04E-02	2.74E-02	3.81E-02	5.59E-01	6.21E-04	6.49E-04	3.85E-02
rail	2	9.50E-01	1.50E-01	1.91E-02		3.56E-03	1.40E-02	1.66E-02	3.94E-01	8.13E-06	8.49E-06	1.66E-02

	Result with Diameter mutiplier =			2.00E+00	(from A-2.b)		based on ratio of hedd1 actual to calculated hole diameter in Sandoval expt					
	hed	penetration	Dic	Dif		Dmin	Dff	Daf	Lf	Vf	Vf con. hole)	D effective
truck	1			1.30E-01			4.32E-02		1.26E+00		8.06E-03	9.02E-02
truck	2			5.24E-02			2.80E-02		1.26E+00		1.65E-03	4.08E-02
rail	1			9.71E-02			5.49E-02		1.12E+00		5.20E-03	7.70E-02
rail	2			3.81E-02			2.80E-02		7.88E-01		6.81E-04	3.32E-02

Highlighted cells used in Table A-1 and related calculations

Lf was calculated from depth of penetration values (in cm) read off the plots provided by M. Vigil

Lf was rounded up 1 additional rod pitch increment (0.5 in) in N50 to N53 to acount for damage beyond calculated depth

HED - HIGH ENERGY DEVICE
P - TOTAL TRANSPORT PLUS FUEL PENETRATION
Dic - INITIAL, ENTRANCE HOLE DIAMETER IN TRANSPORT CASK
Dif - ENTRANCE HOLE DIAMETER IN FUEL
Dmin - MINIMUM HOLE DIAMETER IN TRANSPORT CASK
Dff - FINAL HOLE DIAMETER AT MAXIMUM PENETRATION IN FUEL
Daf - AVERAGE HOLE DIAMETER IN FUEL
Lf - DEPTH OF FUEL PENETRATED
Vf - APPROXIMATE VOLUME OF FUEL PENETRATED
Na - NUMBER OF FUEL ASSEMBLIES PENETRATED
SOopt - OPTIMUM STANDOFF
D eff - EFFECTIVE DIAMETER OF HOLE IN FUEL CONSISTENT WITH VOLUME AND DEPTH
N affected - NUMBER OF ASSEMBLIES DAMAGED = Na + ONE ADDITIONAL ROW OF PINS

TABLE A-2.b HED # 1 SCAP CODE PREDICTED VERSUS MEASURED HOLE DIAMETER DATA
(information from M. Vigil (9/22/98)

Data Source			Di	De		Da	
	PWR ARRAY	Fuel Composite Density (g/cc)	Initial SCAP Fuel Hole Diameter (in)	Exit SCAP FuelHole Diameter (in)		Average SCAP FuelHole Diameter	
SCAP CODE	15 X 15	7.10E+00	1.60E+00	1.22E+00		1.41E+00	
SAND82-2365	15 X 15	7.10E+00	3.00E+00	NA		3.00E+00	Max Fuel Rod Missing Length
Dr - Diameter Ratio			1.88E+00	2.00E+00	(to Tbl. A-2.a)	2.13E+00 Avg Ratio	(EXP./SCAP)

NA - NOT AVAILABLE
Dr - EXPERIMENTALLY (EXP.) MEASURED VALUE DIVIDED BY THE SCAP CODE PREDICTED VALUE.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Table A-3: Analysis of Data from BCL Tests (NUREG CR-2472/BMI2095 & NUREG CR-2472/BMI2089)												
2													
3		<-------------BMI 2095 Source------------------>								Sample Chamber Volume =		230 liters	
4		<--Table 5.1-->		<-----------Table 5-3----------->									
5	Test Event	M dis (g)	M rel (g)	Time (Min)	SR (l/m)	Cass 1 (ug)	SR (l/m)	Cass 2 (ug)	Aerosol Conc. (g/ltr) (h + f)/(g + e) / Del t	Airborne Mass (g) (value at left/K3)	(Aerosol Mass) / (Mass Disrupted) (value at left/col B)	SFR (value at left/K43)	
6	HS1	115.1	32.6	0.5	10	0	10	0	0.00				
7				1	10	19.8	10	301	32.08				
8				2	10	938.3	10	798.2	86.83				
9				5	10	612.1	10	120.2	12.21				
10				10	10	9.1	10	169.4	1.79				
11								Total	132.90	3.06E-02	2.66E-04	2.8	
12													
13													
14	HS2	81.3	16.9	0.5	10	9.4	10	2.4	1.18				
15				1	10	3.6	10	477.5	48.11				
16				2	10	506	10	0.3	25.32				
17				5	10	441.3	10	6.5	7.46				
18				10	10	16.8	10	2.8	0.20				
19								Total	82.26	1.89E-02	2.33E-04	2.5	
20													
21													
22	HS7	117.8	35.1	0.5	12.9	351.1	14.1	435.2	58.24				
23				1	13.6	172.9	14.1		12.48				
24				2	14	388.7	14.3	1214	56.63				
25				5	13.5	496.5	13.9	723.3	14.84				
26				10	13.5	239.9	13.7	176.7	3.06				
27								Total	145.26	3.34E-02	2.84E-04	3.0	
28													
29													
30	HS8	131	37.7	0.5	13	2905	14.1	759	270.41				
31				1	13	2674	14.1	916	264.94				
32				2	14	6	15.7	677	23.00				
33				5	13.5	4988	13.8		60.90				
34				10	13.5	2739	13.7	89	20.79				
35								Total	640.04	1.47E-01	1.12E-03	12.0	
36													
37	BMI 2089												
38	CS8	82.3	14.4	0.5					18.00	(read from Fig 7-5, BMI2089			
39				1					7.00				
40				2					4.50				
41				5					2.50				
42				10					1.50				
43								Total	33.50	7.71E-03	9.36E-05		
44													
45													

Table A-4: Data for Aerosol Production from Brittle Materials Subjected to High Intensity Impacts

									Particle Size Distribution Parameters						
		Speciman Characteristics				Impact Data			Mass Median		eom. Std. Dev		Mass < 10um geom		Est. Resp.
Material	Source	iamete	Length	Mass	Density	Dir.*	Energy in	E density	Dia. (mm)	+ / -	Sig g	+ / -	Percent	+ / -	Percent
SRL131 (1)	Table 6 / Jar	25.5	27.0	39.70	2.88	dia	146.00	10.59	2.6	0.4	6.4	0.2	0.1370%	0.02	0.14%
SRL131 (2)		25.4	29.1	40.70	2.76	dia	148.00	10.04	2.6	0.2	6.6	0.4	0.1606%	0.05	0.16%
Hi Si		28.1	28.9	47.20	2.63	dia	178.00	9.93	3.7	0.7	8.5	0.3	0.2862%	0.03	0.29%
Alkoxide		25.7	25.4	33.20	2.52	dia	131.00	9.94	2.2	0.6	7	0.3	0.2788%	0.05	0.28%
PNL76-68		25.4	25.2	37.70	2.95	dia	128.00	10.02	2.3	0.3	6.5	0.3	0.1835%	0.04	0.18%
Pyrex		25	25.8	28.00	2.21	dia	127.00	10.03	1.4	0.2	6	0.2	0.2908%	0.03	0.29%
Synroc B		26.8	25.9	60.50	4.14	dia	146.00	9.99	4.2	0.8	7.6	0.3	0.1450%	0.02	0.14%
Synroc D		25.4	27.3	53.50	3.87	dia	138.00	9.98	4.7	0.7	8.1	0.3	0.1634%	0.02	0.16%
Synroc C1		20.7	20.4	29.90	4.36	dia	69.00	10.05	6.4	2.4	8.2	0.5	0.1067%	0.03	0.11%
Synroc C2		20.7	19.9	28.40	4.24	dia	67.00	10.00	10	3	9.6	0.9	0.1129%	0.03	0.11%
Tailored		26.8	18.2	40.80	3.97	dia	102.00	9.94	13.7	2.1	9.3	0.3	0.0600%	0.01	0.06%
Fuetap		25.4	25.5	23.00	1.78	dia	131.00	10.14	2.3	0.3	7.9	0.2	0.4256%	0.04	0.43%
Uranium 1	Fig5-4 / Mac	13.7	13.6	21.26	10.60	dia	25.51	1.20	18	2	9	0.3	0.0323%	0.04	0.03%
Uranium 2	Fig 5-5 / Mac	13.7	13.6	21.26	10.60	dia	25.51	1.20	20	2	8.3	0.3	0.0164%	0.04	0.02%
Pyrex	Table 9 / Jar	12.65	13.3	3.72	2.22	dia	236.00	141.00	0.18	0.02	4.7	1	3.0902%	0.2	3.09%
SRL131		12.78	12.7	4.465	2.74	dia	230	141	0.32	0.08	5.2	0.2	1.7770%	0.3	1.78%
Synroc B		12.78	14.0	7.42	4.14	dia	253.00	141.00	0.59	0.05	5.4	0.1	0.7805%	0.1	0.78%
Synroc D		12.84	13.1	6.69	3.93	dia	240.00	141.00	0.52	0.03	5.9	0.1	1.3003%	0.1	1.30%
SRL131 (1)	Table 7 / Jar	25	25.0	34.62	2.82	dia	122.77	10.00	2.7	0.6	6.8	0.4	0.1747%	0.05	0.17%
SRL131 (1)		25	25.0	34.62	2.82	dia	61.38	5.00	5.4	1.7	6.1	0.4	0.0251%	0.018	0.03%
SRL131 (1)		25	25.0	34.62	2.82	dia	29.46	2.40	5	1.7	7.5	0.5	0.1020%	0.008	0.10%
SRL131 (1)		25	25.0	34.62	2.82	dia	14.73	1.20	9.5	2.5	6.7	0.4	0.0156%	0.004	0.02%
Pyrex		25	25.0	27.13	2.21	dia	122.77	10.00	1.7	0.5	6.3	0.4	0.2633%	0.04	0.26%
Pyrex		25	25.0	27.13	2.21	dia	61.38	5.00	3.4	0.7	6.7	0.4	0.1090%	0.02	0.11%
Pyrex		25	25.0	27.13	2.21	dia	29.46	2.40	6.9	1.4	7.3	0.5	0.0504%	0.007	0.05%
Pyrex		25	25.0	27.13	2.21	dia	14.73	1.20	11	3	8.7	0.5	0.0604%	0.01	0.06%
Synroc1 (Aus)	Table 8 / Jar	12.5	12.5	6.45	4.20	ax	216.38	141.00	0.41	0.14	4.8	0.2	0.8956%	0.24	0.90%
Synroc2 (Aus)		12.5	12.5	6.45	4.20	ax	216.38	141.00	0.65	0.22	7.3	0.4	1.7868%	0.4	1.79%
Synroc3 (Aus)		12.5	12.5	6.45	4.20	ax	216.38	141.00	0.66	0.48	7.4	0.9	1.8162%	0.8	1.82%
SF-1 (max)	Fig 7-9 / Alv	9.3	15.2	10.41	10.08	dia	1100.00	1065.13	0.045	NA	11	NA	26.5248%	NA	26.52%
SF-1 (min)		9.3	15.2	10.41	10.08	dia	1100.00	1065.13	0.021	NA	1.5	NA	3.3637%	NA	3.36%
SF-2 (max)		9.3	15.2	10.41	10.08	dia	1100.00	1065.13	0.032	NA	11	NA	31.3813%	NA	31.38%
SF-2 (min)		9.3	15.2	10.41	10.08	dia	1100.00	1065.13	0.022	NA	1.5	NA	2.5913%	NA	2.59%
SF-3 resp	Fig 7-27 / Alv	9.3	15.2	10.41	10.08	dia	1100.00	1065.13	NA	NA	NA	NA		NA	2.54%

Mac = MacDougall H. R. et al, "Site Characterization Plan Conceptual Design Report: Appendix F", SAND84-2641, Sandia National Laboratories, Sept. 1987.
Jar = Jardine, L. J. et al, "Final Rep't of Experimental Lab Scale Brittle Fracture Studies of Glasses and Ceramics", ANL 82-29, Argonne Nat'l Laboratory, Oct. 1982.
Alv = Alvarez, J. L. et al "Waste Forms Response Project: Correlation Testing", EGG-PR-5590, Idaho National Engineering Laboratory, Sept. 1982
* Direction of Impact; dia = diametral; ax = axial

Output Variables:

Cell	Name	Current
C64	Total Max Resp. Fraction Fuel Matrix Released to Environmen	0.00016257
D64	Total Max Resp. Fraction Fuel Matrix Released to Environmen	4.01836E-06
E64	Total Max Resp. Fraction Fuel Matrix Released to Environmen	2.35287E-05
F64	Total Max Resp. Fraction Fuel Matrix Released to Environmen	2.98E-07
C65	Total Avg. Resp. Fraction Fuel Matrix Released to Environme	0.000126913
D65	Total Avg. Resp. Fraction Fuel Matrix Released to Environme	3.41844E-06
E65	Total Avg. Resp. Fraction Fuel Matrix Released to Environme	1.85677E-05
F65	Total Avg. Resp. Fraction Fuel Matrix Released to Environme	2.73E-07
C66	Total Respirable Fraction Co as Crud Released to Environmen	7.45254E-05
D66	Total Respirable Fraction Co as Crud Released to Environmen	1.27774E-06
E66	Total Respirable Fraction Co as Crud Released to Environmen	9.11304E-06
F66	Total Respirable Fraction Co as Crud Released to Environmen	4.68E-08
C67	Total Fraction Cs as Released to Environment / Truck Cask	0.001029511
D67	Total Fraction Cs as Released to Environment / Rail Cask	1.73214E-05
E67	Total Fraction Cs as Released to Environment / Truck Cask	0.000143217
F67	Total Fraction Cs as Released to Environment / Rail Cask	7.20E-07
C68	Total Fraction Te Released to Environment / Truck Cask	0.001029511
D68	Total Fraction Te Released to Environment / Rail Cask	1.73214E-05
E68	Total Fraction Te Released to Environment / Truck Cask	0.000143217
F68	Total Fraction Te Released to Environment / Rail Cask	7.20E-07
C69	Total Fraction Noble Gases Released to Environment / Truck	0.020139408
D69	Total Fraction Noble Gases Released to Environment / Rail	0.000404798
E69	Total Fraction Noble Gases Released to Environment / Truck	0.006201065
F69	Total Fraction Noble Gases Released to Environment / Rail	3.91697E-05
C70	Max.Fuel mass Fraction Ejected (not resp.) / Truck Cask	0.003040777
D70	Max.Fuel mass Fraction,Ejected (not resp.) / Rail Cask	0.000423254
E70	Max.Fuel mass Fraction Ejected (not resp.) / Truck Cask	0.000687002
F70	Max.Fuel mass Fraction Ejected (not resp.) / Rail Cask	5.56418E-05
C71	Avg.Fuel mass Fraction Ejected (not resp.) / Truck Cask	0.00232709
D71	Avg.Fuel mass Fraction Ejected (not resp.) / Rail Cask	0.000323914
E71	Avg.Fuel mass Fraction Ejected (not resp.) / Truck Cask	0.000525759
F71	Avg.Fuel mass Fraction Ejected (not resp.) / Rail Cask	4.25824E-05
C72	Crud Fraction Ejected by HEDD (not resp) / Truck Cask	2.25E-07
D72	Crud Fraction Ejected by HEDD (not resp) / Rail Cask	3.04E-07
E72	Crud Fraction Ejected by HEDD (not resp) / Truck Cask	6.91E-07
F72	Crud Fraction Ejected by HEDD (not resp) / Rail Cask	4.63E-09

Table A-5a (con't): Simulation Variables for YMPre29r.xls

Input Variables:

Cell	Name	Current	Worksheet	Distribution Formula in Cell
! K42	ns / Full Scale Post-Test	Uniform(0.9,1.1)	[YMPre29r.xls]Sandoval	'=RiskUniform(0.9,1.1)*275
! K43	ns / Full Scale Post-Test	Uniform(0.9,1.1)	[YMPre29r.xls]Sandoval	'=RiskUniform(0.9,1.1)*76
! K49	Aerosolized fraction of mass within hole = / ns	Uniform(0.9,1.1)	[YMPre29r.xls]Sandoval	'=RiskUniform(0.9,1.1)*K36/K47
! K53	Released from cask/estimated swept mass = / ns	Uniform(0.9,1.1)	[YMPre29r.xls]Sandoval	'=RiskUniform(0.9,1.1)*K34/K47
! K57	Spent Fuel / ns	Uniform(2,4)	[YMPre29r.xls]Sandoval	'=RiskUniform(2,4)
! K60	Est'd total SF aerosol mass/swept mass= / ns	Uniform(0.9,1.1)	[YMPre29r.xls]Sandoval	'=RiskUniform(0.9,1.1)*K59/K47
! O35	Average crud fraction spalled from disturbed section per Mis	Uniform(0.8,1.2)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.8,1.2)*0.00041
! O36	Spalled Crud Respirable fraction per Mishima / Spalled Crud	Uniform(0.8,1.2)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.8,1.2)*0.00000022
! O37	Fraction of brittle crud in missing length that is respirabl	Uniform(0.8,1.2)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.8,1.2)*0.00000075
! H62	Plenum Volume Released (m^3) / (includes spall fraction from	Normal(0.000745,0.000018)	[YMPre29r.xls]YMPinput	'=RiskNormal(0.000745,0.000018)
! J62	Pin plenum volume at STP (m^3) per Balfour et al / Pin/Assem	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*125
! J64	This does not include Cs and Te / Pin/Assembly volumes	Uniform(0.4,0.8)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.4,0.8)
! F88	truck / Dif	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*F82
! I88	truck / Dff	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*I82
! K88	truck / Lf*	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*K82+0.5
! F89	truck / Dif	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*F83
! I89	truck / Dff	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*I83
! K89	truck / Lf*	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*K83+0.5
! F90	rail / Dif	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*F84
! I90	rail / Dff	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*I84
! K90	rail / Lf*	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*K84+0.5
! F91	rail / Dif	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*F85
! I91	rail / Dff	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*I85
! K91	rail / Lf*	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*K85+0.5
! F138	NA	Uniform(0.9,1.1)	[YMPre29r.xls]YMPinput	'=RiskUniform(0.9,1.1)*(E137/2+H137/2)

Table A-5.b.1: Output Cell Statistics for @RISK Calculation

@RISK Simula Run on 2/2 Simulations Iterations = 5000

Row	B	C	D	E	F	G	H	I	J
6	Name	Total Max Resp. Fraction Fuel Matrix Released to Environment / Truck Cask	Total Max Resp. Fraction Fuel Matrix Released to Environment / Rail Cask	Total Max Resp. Fraction Fuel Matrix Released to Environment / Truck Cask	Total Max Resp. Fraction Fuel Matrix Released to Environment / Rail Cask	Total Avg. Resp. Fraction Fuel Matrix Released to Environment / Truck Cask	Total Avg. Resp. Fraction Fuel Matrix Released to Environment / Rail Cask	Total Avg. Resp. Fraction Fuel Matrix Released to Environment / Truck Cask	Total Avg. Resp. Fraction Fuel Matrix Released to Environment / Rail Cask
7	Description	Output	Output	Output	Output	Output	Output	Output	Output
8	Cell	C64	D64	E64	F64	C65	D65	E65	F65
9	Minimum =	5.42E-05	1.3E-06	6.09E-06	1.24E-07	4.27E-05	1.11E-06	4.9E-06	1.13E-07
10	Maximum =	0.000388	1.04E-05	4.55E-05	8.2E-07	0.000301	8.54E-06	3.57E-05	7.28E-07
11	Mean =	0.000151	3.58E-06	2.17E-05	2.84E-07	0.000118	3.03E-06	1.71E-05	2.59E-07
12	Std Dev. =	5.11E-05	1.17E-06	7.38E-06	7.73E-08	3.96E-05	9.65E-07	5.75E-06	6.93E-08
13	Variance =	2.62E-09	1.36E-12	5.45E-11	5.97E-15	1.57E-09	9.31E-13	3.3E-11	4.8E-15
14	Skewness =	0.778656	0.784392	0.327032	1.0094	0.774158	0.756447	0.317339	0.932432
15	Kurtosis =	3.639569	3.808802	2.664059	5.502284	3.631056	3.715355	2.655214	5.109901
16	Errors Calc'd =	0	0	0	0	0	0	0	0
17	Mode =	0.000137	3.34E-06	1.54E-05	2.44E-07	0.000125	2.7E-06	1.92E-05	2.71E-07
18	5% Perc =	8.16E-05	1.97E-06	1.03E-05	1.79E-07	6.39E-05	1.69E-06	8.18E-06	1.63E-07
19	10% Perc =	9.15E-05	2.23E-06	1.22E-05	1.94E-07	7.16E-05	1.9E-06	9.74E-06	1.77E-07
20	15% Perc =	9.95E-05	2.41E-06	1.38E-05	2.06E-07	7.81E-05	2.06E-06	1.09E-05	1.88E-07
21	20% Perc =	0.000106	2.57E-06	1.5E-05	2.16E-07	8.3E-05	2.2E-06	1.19E-05	1.97E-07
22	25% Perc =	0.000113	2.71E-06	1.62E-05	2.27E-07	8.81E-05	2.32E-06	1.28E-05	2.06E-07
23	30% Perc =	0.000119	2.86E-06	1.74E-05	2.37E-07	9.31E-05	2.43E-06	1.37E-05	2.16E-07
24	35% Perc =	0.000125	2.99E-06	1.84E-05	2.47E-07	9.79E-05	2.54E-06	1.45E-05	2.25E-07
25	40% Perc =	0.000132	3.15E-06	1.93E-05	2.57E-07	0.000103	2.67E-06	1.52E-05	2.34E-07
26	45% Perc =	0.000137	3.27E-06	2.02E-05	2.66E-07	0.000107	2.78E-06	1.6E-05	2.43E-07
27	50% Perc =	0.000143	3.41E-06	2.12E-05	2.77E-07	0.000112	2.9E-06	1.68E-05	2.52E-07
28	55% Perc =	0.00015	3.56E-06	2.22E-05	2.87E-07	0.000117	3.02E-06	1.75E-05	2.61E-07
29	60% Perc =	0.000156	3.72E-06	2.33E-05	2.97E-07	0.000122	3.15E-06	1.83E-05	2.71E-07
30	65% Perc =	0.000164	3.89E-06	2.43E-05	3.09E-07	0.000127	3.3E-06	1.91E-05	2.81E-07
31	70% Perc =	0.000173	4.08E-06	2.53E-05	3.19E-07	0.000135	3.45E-06	1.99E-05	2.91E-07
32	75% Perc =	0.000181	4.28E-06	2.66E-05	3.3E-07	0.000141	3.61E-06	2.09E-05	3E-07
33	80% Perc =	0.000191	4.52E-06	2.79E-05	3.44E-07	0.000149	3.82E-06	2.19E-05	3.13E-07
34	85% Perc =	0.000205	4.82E-06	2.96E-05	3.6E-07	0.00016	4.05E-06	2.33E-05	3.27E-07
35	90% Perc =	0.000222	5.19E-06	3.19E-05	3.82E-07	0.000172	4.35E-06	2.5E-05	3.47E-07
36	95% Perc =	0.000246	5.74E-06	3.47E-05	4.15E-07	0.000191	4.8E-06	2.72E-05	3.74E-07

	B	K	L	M	N	O	P	Q	R
1	Table A-5.b.1:	Table A-5.b.2							
2									
3									
4	@RISK Simula								
5									
6	Name	Total Respirable Fraction Co as Crud Released to Environment / Truck Cask	Total Respirable Fraction Co as Crud Released to Environment / Rail Cask	Total Respirable Fraction Co as Crud Released to Environment / Truck Cask	Total Respirable Fraction Co as Crud Released to Environment / Rail Cask	Total Fraction Cs as Released to Environment / Truck Cask	Total Fraction Cs as Released to Environment / Rail Cask	Total Fraction Cs as Released to Environment / Truck Cask	Total Fraction Cs as Released to Environment / Rail Cask
7	Description	Output	Output	Output	Output	Output	Output	Output	Output
8	Cell	C66	D66	E66	F66	C67	D67	E67	F67
9	Minimum =	3.13E-05	4.54E-07	2.95E-06	2.34E-08	0.000424	6.16E-06	4.63E-05	3.49E-07
10	Maximum =	0.000143	2.98E-06	1.42E-05	1.51E-07	0.00197	4.03E-05	0.000223	2.28E-06
11	Mean =	7.02E-05	1.17E-06	8.54E-06	4.91E-08	0.00096	1.58E-05	0.000133	7.46E-07
12	Std Dev. =	1.98E-05	3.71E-07	2.44E-06	1.39E-08	0.000271	5E-06	3.8E-05	2.11E-07
13	Variance =	3.91E-10	1.37E-13	5.95E-12	1.92E-16	7.32E-08	2.5E-11	1.44E-09	4.44E-14
14	Skewness =	0.594022	0.607291	-0.17992	1.721614	0.597427	0.609023	-0.17606	1.708983
15	Kurtosis =	3.128804	3.197555	2.223318	9.95381	3.137662	3.199543	2.223769	9.832681
16	Errors Calc'd =	0	0	0	0	0	0	0	0
17	Mode =	4.76E-05	1.56E-06	8.29E-06	5.1E-08	0.000764	1.2E-05	0.000169	7.81E-07
18	5% Perc =	4.09E-05	6.48E-07	4.17E-06	3.11E-08	0.000563	8.72E-06	6.49E-05	4.74E-07
19	10% Perc =	4.57E-05	7.22E-07	5.08E-06	3.39E-08	0.000628	9.75E-06	7.93E-05	5.15E-07
20	15% Perc =	4.99E-05	7.84E-07	5.89E-06	3.6E-08	0.000683	1.05E-05	9.16E-05	5.46E-07
21	20% Perc =	5.32E-05	8.39E-07	6.32E-06	3.76E-08	0.000728	1.13E-05	9.82E-05	5.72E-07
22	25% Perc =	5.57E-05	8.94E-07	6.71E-06	3.92E-08	0.000762	1.2E-05	0.000104	5.97E-07
23	30% Perc =	5.8E-05	9.41E-07	7.1E-06	4.09E-08	0.000793	1.27E-05	0.00011	6.22E-07
24	35% Perc =	6.04E-05	9.88E-07	7.49E-06	4.26E-08	0.000826	1.33E-05	0.000116	6.47E-07
25	40% Perc =	6.29E-05	1.03E-06	7.93E-06	4.43E-08	0.00086	1.4E-05	0.000123	6.72E-07
26	45% Perc =	6.53E-05	1.08E-06	8.28E-06	4.59E-08	0.000893	1.45E-05	0.000129	6.97E-07
27	50% Perc =	6.76E-05	1.12E-06	8.66E-06	4.76E-08	0.000925	1.52E-05	0.000135	7.23E-07
28	55% Perc =	7.01E-05	1.17E-06	9.01E-06	4.92E-08	0.000958	1.57E-05	0.00014	7.45E-07
29	60% Perc =	7.27E-05	1.23E-06	9.39E-06	5.09E-08	0.000994	1.65E-05	0.000146	7.72E-07
30	65% Perc =	7.55E-05	1.28E-06	9.75E-06	5.26E-08	0.001033	1.73E-05	0.000152	7.99E-07
31	70% Perc =	7.93E-05	1.34E-06	1.01E-05	5.44E-08	0.001081	1.81E-05	0.000158	8.28E-07
32	75% Perc =	8.37E-05	1.42E-06	1.05E-05	5.66E-08	0.001144	1.91E-05	0.000163	8.59E-07
33	80% Perc =	8.81E-05	1.49E-06	1.09E-05	5.85E-08	0.001205	2.01E-05	0.000169	8.91E-07
34	85% Perc =	9.25E-05	1.58E-06	1.12E-05	6.12E-08	0.001262	2.13E-05	0.000175	9.31E-07
35	90% Perc =	9.7E-05	1.69E-06	1.17E-05	6.47E-08	0.001331	2.29E-05	0.000182	9.83E-07
36	95% Perc =	0.000104	1.84E-06	1.23E-05	7.03E-08	0.001417	2.48E-05	0.000191	1.07E-06
37									
38									
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40									

	B	S	T	U	V	W	X	Y	Z
1	Table A-5.b.1:	Table A-5.b.3							
2									
3									
4	@RISK Simula								
5									
6	Name	Total Fraction Te Released to Environment / Truck Cask	Total Fraction Te Released to Environment / Rail Cask	Total Fraction Te Released to Environment / Truck Cask	Total Fraction Te Released to Environment / Rail Cask	Total Fraction Noble Gases Released to Environment / Truck Cask	Total Fraction Noble Gases Released to Environment / Rail Cask	Total Fraction Noble Gases Released to Environment / Truck Cask	Total Fraction Noble Gases Released to Environment / Rail Cask
7	Description	Output	Output	Output	Output	Output	Output	Output	Output
8	Cell	C68	D68	E68	F68	C69	D69	E69	F69
9	Minimum =	0.000424	6.16E-06	4.63E-05	3.49E-07	0.011647	0.000233	0.003327	3.08E-05
10	Maximum =	0.00197	4.03E-05	0.000223	2.28E-06	0.026362	0.000665	0.007016	8.62E-05
11	Mean =	0.00096	1.58E-05	0.000133	7.46E-07	0.018806	0.000368	0.005761	4.09E-05
12	Std Dev. =	0.000271	5E-06	3.8E-05	2.11E-07	0.002506	7.02E-05	0.00096	6.57E-06
13	Variance =	7.32E-08	2.5E-11	1.44E-09	4.44E-14	6.28E-06	4.92E-09	9.21E-07	4.32E-11
14	Skewness =	0.597427	0.609023	-0.17606	1.708983	0.319474	0.336588	-1.60888	2.768406
15	Kurtosis =	3.137662	3.199543	2.223769	9.832681	2.695728	2.682657	3.843343	16.086
16	Errors Calc'd =	0	0	0	0	0	0	0	0
17	Mode =	0.000764	1.2E-05	0.000169	7.81E-07	0.01638	0.000351	0.006062	3.4E-05
18	5% Perc =	0.000563	8.72E-06	6.49E-05	4.74E-07	0.015664	0.000261	0.003631	3.36E-05
19	10% Perc =	0.000628	9.75E-06	7.93E-05	5.15E-07	0.015882	0.000275	0.003724	3.44E-05
20	15% Perc =	0.000683	1.05E-05	9.16E-05	5.46E-07	0.016028	0.000287	0.003834	3.51E-05
21	20% Perc =	0.000728	1.13E-05	9.82E-05	5.72E-07	0.016169	0.0003	0.005803	3.59E-05
22	25% Perc =	0.000762	1.2E-05	0.000104	5.97E-07	0.01629	0.000312	0.005933	3.66E-05
23	30% Perc =	0.000793	1.27E-05	0.00011	6.22E-07	0.016444	0.000324	0.006004	3.73E-05
24	35% Perc =	0.000826	1.33E-05	0.000116	6.47E-07	0.016626	0.000336	0.006049	3.81E-05
25	40% Perc =	0.00086	1.4E-05	0.000123	6.72E-07	0.018179	0.000345	0.006081	3.88E-05
26	45% Perc =	0.000893	1.45E-05	0.000129	6.97E-07	0.019347	0.000353	0.006117	3.95E-05
27	50% Perc =	0.000925	1.52E-05	0.000135	7.23E-07	0.019671	0.000361	0.006145	4.02E-05
28	55% Perc =	0.000958	1.57E-05	0.00014	7.45E-07	0.019824	0.00037	0.006174	4.09E-05
29	60% Perc =	0.000994	1.65E-05	0.000146	7.72E-07	0.019961	0.000382	0.006201	4.17E-05
30	65% Perc =	0.001033	1.73E-05	0.000152	7.99E-07	0.020083	0.000394	0.006225	4.25E-05
31	70% Perc =	0.001081	1.81E-05	0.000158	8.28E-07	0.020189	0.000408	0.006254	4.31E-05
32	75% Perc =	0.001144	1.91E-05	0.000163	8.59E-07	0.020312	0.000421	0.006285	4.39E-05
33	80% Perc =	0.001205	2.01E-05	0.000169	8.91E-07	0.02045	0.000435	0.00632	4.47E-05
34	85% Perc =	0.001262	2.13E-05	0.000175	9.31E-07	0.020629	0.000448	0.006359	4.57E-05
35	90% Perc =	0.001331	2.29E-05	0.000182	9.83E-07	0.020995	0.000463	0.006406	4.67E-05
36	95% Perc =	0.001417	2.48E-05	0.000191	1.07E-06	0.023976	0.00048	0.006489	4.83E-05
37									
38									
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40									

	B	AA	AB	AC	AD	AE	AF	AG	AH
1	Table A-5.b.1:	Table A-5.b.4							
2									
3									
4	@RISK Simula								
5									
6	Name	Max.Fuel mass Fraction Ejected (not resp.) / Truck Cask	Max.Fuel mass Fraction Ejected (not resp.) / Rail Cask	Max.Fuel mass Fraction Ejected (not resp.) / Truck Cask	Max.Fuel mass Fraction Ejected (not resp.) / Rail Cask	Avg.Fuel mass Fraction Ejected (not resp.) / Truck Cask	Avg.Fuel mass Fraction Ejected (not resp.) / Rail Cask	Avg.Fuel mass Fraction Ejected (not resp.) / Truck Cask	Avg.Fuel mass Fraction Ejected (not resp.) / Rail Cask
7	Description	Output	Output	Output	Output	Output	Output	Output	Output
8	Cell	C70	D70	E70	F70	C71	D71	E71	F71
9	Minimum =	0.001238	0.000193	0.000268	2.96E-05	0.000947	0.000148	0.000205	2.27E-05
10	Maximum =	0.004358	0.000648	0.000883	9.92E-05	0.003335	0.000496	0.000675	7.6E-05
11	Mean =	0.002605	0.00036	0.000587	5.05E-05	0.001993	0.000276	0.000449	3.86E-05
12	Std Dev. =	0.000527	7.4E-05	0.000118	8.97E-06	0.000403	5.67E-05	9.03E-05	6.87E-06
13	Variance =	2.78E-07	5.48E-09	1.39E-08	8.05E-11	1.63E-07	3.21E-09	8.16E-09	4.72E-11
14	Skewness =	0.358556	0.329608	-0.23855	0.78654	0.358556	0.329608	-0.23855	0.78654
15	Kurtosis =	2.848829	2.660915	2.378777	5.00346	2.848829	2.660915	2.378777	5.00346
16	Errors Calc'd =	0	0	0	0	0	0	0	0
17	Mode =	0.002051	0.000382	0.000499	5.52E-05	0.00157	0.000274	0.000497	4.23E-05
18	5% Perc =	0.001797	0.000248	0.000376	3.73E-05	0.001376	0.00019	0.000287	2.85E-05
19	10% Perc =	0.001935	0.000268	0.000425	3.95E-05	0.001481	0.000205	0.000325	3.03E-05
20	15% Perc =	0.002046	0.000281	0.000454	4.14E-05	0.001566	0.000215	0.000347	3.17E-05
21	20% Perc =	0.00215	0.000295	0.00048	4.28E-05	0.001645	0.000226	0.000367	3.27E-05
22	25% Perc =	0.002229	0.000306	0.000501	4.4E-05	0.001706	0.000234	0.000383	3.37E-05
23	30% Perc =	0.002304	0.000317	0.000521	4.54E-05	0.001763	0.000242	0.000398	3.47E-05
24	35% Perc =	0.002367	0.000326	0.000541	4.64E-05	0.001811	0.00025	0.000414	3.55E-05
25	40% Perc =	0.002435	0.000335	0.000562	4.76E-05	0.001863	0.000256	0.00043	3.64E-05
26	45% Perc =	0.002496	0.000343	0.000579	4.88E-05	0.00191	0.000263	0.000443	3.74E-05
27	50% Perc =	0.002554	0.000353	0.000597	5E-05	0.001955	0.00027	0.000457	3.82E-05
28	55% Perc =	0.002627	0.000362	0.000614	5.11E-05	0.00201	0.000277	0.00047	3.91E-05
29	60% Perc =	0.002695	0.000374	0.00063	5.23E-05	0.002062	0.000286	0.000482	4E-05
30	65% Perc =	0.002772	0.000386	0.000647	5.35E-05	0.002121	0.000296	0.000495	4.1E-05
31	70% Perc =	0.002872	0.000399	0.000662	5.49E-05	0.002198	0.000306	0.000507	4.2E-05
32	75% Perc =	0.002974	0.000414	0.000678	5.61E-05	0.002276	0.000317	0.000519	4.29E-05
33	80% Perc =	0.003072	0.000428	0.000697	5.75E-05	0.002351	0.000328	0.000533	4.4E-05
34	85% Perc =	0.00318	0.000444	0.000715	5.9E-05	0.002434	0.00034	0.000547	4.52E-05
35	90% Perc =	0.003313	0.000463	0.000734	6.14E-05	0.002535	0.000354	0.000562	4.7E-05
36	95% Perc =	0.0035	0.000488	0.000764	6.48E-05	0.002678	0.000373	0.000585	4.96E-05
37									
38									
39									
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	B	AI	AJ	AK	AL
1	Table A-5.b.1:	Table A-5.b.5			
2					
3					
4	@RISK Simula				
5					
6	Name	Crud Fraction Ejected by HEDD (not resp) / Truck Cask	Crud Fraction Ejected by HEDD (not resp) / Rail Cask	Crud Fraction Ejected by HEDD (not resp) / Truck Cask	Crud Fraction Ejected by HEDD (not resp) / Rail Cask
7	Description	Output	Output	Output	Output
8	Cell	C72	D72	E72	F72
9	Minimum =	4.42E-08	9.57E-08	1.69E-07	1.96E-09
10	Maximum =	4.91E-07	6.65E-07	1.04E-06	1.37E-08
11	Mean =	1.87E-07	2.53E-07	5.8E-07	4.35E-09
12	Std Dev. =	7.54E-08	8.57E-08	1.74E-07	1.29E-09
13	Variance =	5.69E-15	7.35E-15	3.04E-14	1.66E-18
14	Skewness =	0.969326	0.660814	-0.43309	2.477484
15	Kurtosis =	4.140499	3.354604	2.582466	14.01868
16	Errors Calc'd =	0	0	0	0
17	Mode =	1.13E-07	1.4E-07	6.47E-07	4.42E-09
18	5% Perc =	9.3E-08	1.37E-07	2.54E-07	2.85E-09
19	10% Perc =	1.02E-07	1.51E-07	2.89E-07	3.08E-09
20	15% Perc =	1.1E-07	1.62E-07	3.24E-07	3.26E-09
21	20% Perc =	1.17E-07	1.72E-07	4.52E-07	3.41E-09
22	25% Perc =	1.24E-07	1.82E-07	4.92E-07	3.54E-09
23	30% Perc =	1.32E-07	1.92E-07	5.21E-07	3.68E-09
24	35% Perc =	1.41E-07	2.03E-07	5.46E-07	3.81E-09
25	40% Perc =	1.51E-07	2.16E-07	5.66E-07	3.93E-09
26	45% Perc =	1.7E-07	2.29E-07	5.86E-07	4.04E-09
27	50% Perc =	1.83E-07	2.42E-07	6.04E-07	4.18E-09
28	55% Perc =	1.94E-07	2.57E-07	6.23E-07	4.3E-09
29	60% Perc =	2.03E-07	2.71E-07	6.42E-07	4.42E-09
30	65% Perc =	2.12E-07	2.84E-07	6.59E-07	4.56E-09
31	70% Perc =	2.21E-07	2.98E-07	6.79E-07	4.71E-09
32	75% Perc =	2.3E-07	3.12E-07	6.99E-07	4.87E-09
33	80% Perc =	2.41E-07	3.27E-07	7.25E-07	5.06E-09
34	85% Perc =	2.53E-07	3.45E-07	7.51E-07	5.29E-09
35	90% Perc =	2.73E-07	3.65E-07	7.83E-07	5.62E-09
36	95% Perc =	3.31E-07	4E-07	8.28E-07	6.1E-09
37					
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