Release Fractions from Multi-Element Spent Fuel Casks Resulting from HEDD Attack

R. E. Luna, Ph.D., PE, Consultant
10025 Barrinson NE
Albuquerque, NM 87111
USA

ABSTRACT

This paper provides a simple model for estimating the release of respirable aerosols resulting from an attack on a spent fuel cask using a high energy density device (HEDD). Two primary experiments have provided data on potential releases from spent fuel casks under HEDD attack. Sandia National Laboratories (SNL) conducted the first in the early 1980s and the second was sponsored by Gessellshaft fur Anlagen- und Reaktorsicherheit (GRS) in Germany and conducted in France in 1994. Both used surrogate spent fuel assemblies in real casks. The SNL experiments used unpressurized fuel pin assemblies in a single element cask while the GRS tests used pressurized fuel pin assemblies in a 9-element cask. Data from the two test programs is reasonably consistent, given the differences in the experiments, but the use of the test data for prediction of releases resulting from HEDD attack requires a method for accounting for the effects of pin pressurization release and the ratio of pin plenum gas release to cask free volume (VR). To account for the effects of VR and to link the two data sources, a simple model has been developed that uses both the SNL data and the GRS data as well as recent test data on aerosols produced in experiments with single pellets subjected to HEDD effects conducted under the aegis of the International Consortium's Working Group on Sabotage of Transport and Storage Casks (WGSTSC).

INTRODUCTION

Two experimental programs have provided estimates of respirable aerosol release from spent fuel casks subjected to attack by an HEDD.

- The early 1980s experiments at Sandia National Laboratories [1] involving full-scale (SNL FS) and quarter scale (SNL ¼) casks containing a single surrogate PWR spent fuel assembly. The test assembly was composed of unpressurized pins containing depleted UO_2 pellets in Zircaloy cladding. In the SNL ¼ test both walls of the cask were penetrated by the HEDD, but in the SNL FS test one wall and the entire surrogate fuel assembly was penetrated. In each test the amount of respirable aerosol released from the cask to the surrounding volume was measured.

- The mid 1990s experiments conducted in France and supported by Gesellshaft fur Anlagen und Reaktorsicherheit (GRS) [2] used a shortened full scale cask (Castor IIe) containing 9 surrogate PWR spent fuel assemblies composed of pressurized pins containing depleted UO_2

pellets in a Zircaloy cladding. Particles smaller than 100 micrometers released from the cask were collected and reported as mass in several size fractions that included those that were respirable. Three tests were conducted; GRS 1 and GRS 2 had the initial cask internal pressure at local ambient, but the initial cask pressure for GRS 3 was at 0.8 of local ambient.

Results from the SNL and GRS tests were compared in an earlier paper [3] by the author. Table I provides a comparison of the data derived from the reports of the two experiments. On the surface the two sets of data of most interest (SNL FS and GRS 1) indicate similar amounts of respirable aerosol released from the cask. This is especially true if one takes the position (as suggested by the GRS report authors) that the released material only came from the first assembly penetrated (see shaded row in table). In their view, the aerosol from the second and third assembly was effectively trapped in the basket cavities behind the first.

Table I. Comparison of Results from SNL Quarter and Full-Scale Tests and GRS Tests

Parameter	SNL ¼	SNL FS	GRS 1	GRS 2	GRS 3
Surrogate Assemblies in Cask / No. in Path of HEDD Action	1/1	1/1	9/3	9/3	9/3
Surrogate Assemblies Penetrated	1	1	3	1	3
Cask Wall(s) Penetration	Through	Front	Front	Front	Front
Surrogate Pins Affected	10	111	142	90	234
Respirable Aerosol Released (grams)	0.78	2.93	1.05	0.962	0.375
Estimated Average Pellet Mass within HEDD-Produced Cavity (grams)	170	3820	3190	3130	6250
Respirable Aerosol Mass per Average Cavity Mass Produced by HEDD	4.6×10^{-3}	7.7×10^{-4}	3.2×10^{-4}	3.1×10^{-4}	6.0×10^{-5}
As Above, But Relative to One Assembly		7.7×10^{-4}	9.6×10^{-4}		1.8×10^{-4}
Initial Cask Pressure Relative to Ambient (bar)	0	0	0	0	-0.2
Estimated Pin Plenum Gas Volume / Cask Free Volume (VR)	0	0	0.11	0.07	0.18

However, two problems arise in using the data:

- The first problem is that the two sets of data, despite being consistent produce results that are somewhat different in ways not easily explained. The GRS 1 test respirable mass release is a factor of three lower than the SNL FS test despite the fact that 3 assemblies were penetrated (versus only 1 in the SNL FS) and there was release of significant pin plenum gas in the GRS 1 test that would be expected to act to increase the released aerosol mass even further.

- The second problem occurs when it is desired to apply the results to estimate the likely release resulting from an HEDD attack on a modern multi-element shipping cask. The SNL results apply best to a single assembly cask, but would have to be adjusted to allow for the effect of blowdown of pin plenum gas released from broken pins. This was done for an analysis of sabotage events affecting spent fuel shipments [4] (referred to hereinafter as the "Sabotage Report"). The GRS 1 data would be a better choice for estimating release for a multi-assembly cask, but the data applies to a cask that has a somewhat larger free volume than modern casks used in the USA and, hence, relatively smaller ratio of pin plenum gas volume to cask free volume (VR) than those evaluated in the Sabotage Report.

To develop a method for using all the test data effectively and to help resolve issues relating to the consistency of the two experiments, a model was developed based on the concept that consistency would be demonstrated if the GRS 1 mass release data were predicted by applying the basic information and phenomenology derived from the SNL experiments to the GRS experiments. A collateral benefit of such a model would be that it provides a calculation scheme to account for a range of values for VR that covers the potential range in modern transport casks.

MODEL DEVELOPMENT

Conceptually it was clear that the GRS experiments were different from the SNL experiments in two key areas:

- multiple assemblies were confined within a basket that provided significant containment of each assembly exposed to HEDD action, and
- surrogate fuel pins were pressurized as is actual spent fuel.

The basic assumption of the model developed here ("GRS Model") is that the SNL data for single assembly casks describes the early time phenomena occurring in the first compartment penetrated by the HEDD in the GRS cask. That is, each GRS basket cavity is similar to the single assembly cask used in the SNL tests. In particular, the SNL tests are used to provide estimates of the prompt aerosol release from the cask and, more importantly, the quantity of aerosol created in the first assembly that is swept into the parts of the cask basket occupied by the second and subsequent fuel assemblies impacted by HEDD action. At later times the effects of pin plenum gas blowdown and initial cask pressurization (if any) are taken into account in the same manner as in the Sabotage Report. Thus, the goal of the GRS Model was to derive parameters that allow prediction of the two components of the GRS experiments total release data, prompt and blowdown releases.

The initial design for the GRS Model was based on the fact that the ¼ scale test performed by SNL achieved full penetration of both walls of the cask and achieved a release fraction (relative to swept mass) that was a factor of 6 larger than the full scale test that only penetrated one wall. From that observation it was conceived that the effect of an HEDD that penetrated a multi-assembly cask (3 assemblies in the GRS 1 test) would be to produce a prompt release of 1/6 of the SNL ¼ scale test release through the entry hole with 5/6 of SNL ¼ scale test release (created in the first cavity) being swept into the basket cavities holding the second and third assemblies affected by the HEDD. The aerosol created in the first cavity moves at a relatively high speed both radially and axially relative to the line of action of the HEDD. The radial motion carries aerosol into the surface-rich areas of the remaining mostly-intact fuel assembly where deposition can occur. This process is treated parametrically in the GRS Model by removing a fraction of the aerosol remaining in cavity 1. The axial transfer of momentum from the particles of fuel rod and wall moving along the line of action of the HEDD creates the gas current that sweeps the aerosols further into deeper partitions of the cask basket.

Later in the release process there are opportunities for additional aerosol to be swept from the cask by the release of any pre-pressurization of the cask and by the release of the high-pressure pin plenum gas from pins that are broken by the action of the HEDD. The timing of these blowdown sources is a relatively important issue. The action of any initial pressurization of the cask is likely to occur shortly after the time frame of the prompt release, and will be referred to here as a mid-term release in the model. The release from pin plenum gases occurs at a later time depending on the condition of the fuel rods. For the GRS experiments pellets were slipped into cladding tube and could slide relatively freely. As a result, the plenum gas could flow in the cladding-pellet annulus relatively quickly into the cask (within a few seconds) after the pins were disrupted by the HEDD. This could put the pin plenum gas release for the GRS experiments into the "mid term" period. For actual spent fuel, where the pellets are held firmly by the cladding, the gas flow path would be through the fractures of the fuel pellets that could take minutes to occur. For the GRS Model it is assumed that the plenum gas release occurs enough later in time that it is separated from the prompt release process; thus, it is a late term source.

As might be expected from the discussion above, the basket cavity holding the first assembly is expected to have a relatively small remaining fraction of the aerosol originally created from HEDD interaction with the first assembly. Most of the material generated by HEDD action on the first assembly is swept into the basket volumes for assemblies 2 and 3 or deposited on nearby surfaces. As a result there is little remaining aerosol in the basket partition of assembly 1 to be swept out by the relatively slow release of the pin plenum gases. Virtually none of the aerosol around assembly 2 and 3 is expected to be swept out into cavity 1 and thence out to the environment because the flow path from cavity 2 to cavity 1 is small compared to the flow area along the axis of the spent fuel assembly. As a result that contribution is assumed to be zero.

For GRS 1, the SNL FS relationship linking the mass of respirable aerosol to swept mass was used to get the prompt release. Also following the SNL ¼ scale test, it was estimated that an amount of respirable aerosol mass 5 times the prompt aerosol release was swept into the basket partition for assemblies 2 and 3. The amount of aerosol remaining in cavity 1 was obtained by subtracting these two releases from the amount of respirable aerosol created in cavity 1 by the action of the HEDD. The respirable aerosol mass was estimated using data from the relatively recent experiments performed for the International Consortium that suggest that about 2% of the swept mass of surrogate fuel ends up in respirable aerosols. As indicated above much of this aerosol moves radially into the area of intact fuel rods surrounding the cavity produced by the HEDD where much of it (about 65%) is assumed to be deposited by impaction, diffusion and/or thermophoretic effects.

Within the GRS Model conceptual framework, the known data on swept volume, pin plenum gas volume, cask free volume, estimated 2% respirable aerosol generation from the International Consortium experiments and an assumption of 0.65 deposition on cavity 1 surfaces was used to calculate a total release of 1.02 grams of respirable aerosol release for the GRS 1 experiment. This compares with the 1.05 grams that is published in the GRS report. The features of the model calculations are shown in Table II.

Using the same model and variables to predict GRS 2 and GRS 3 gives estimates of 1.3 g and 0.42 g versus the published values of 0.962 g and 0.375 g. These are also shown in Table II and

are close enough to the actual measured values to believe that the model captures the essential features of the experiments, given that these experiments were radically different from GRS 1.
In experiment GRS 2, only 1 surrogate assembly was penetrated by the HEDD (probably a result of misfire or manufacturing defect), but the affected mass was larger than in GRS 1. The lack of penetration depth and greater area affected suggested reduced energy input to the pins and a yield of respirable aerosol about 20% of that for GRS 1. In experiment GRS 3 full penetration of three assemblies occurred as in GRS 1 (but with a larger damage area), but the inflow of air caused by the initial below-atmospheric pressure caused a significant decrease in release by pushing aerosol into the cask and further away from the release point at the entry hole.

Table II. Principal Features and Results of the GRS Model

Test Identifier Model Estimates	GRS 1 (g)	GRS 2 (g)	GRS 3 (g)
Respirable Aerosol Created in Cell 1	18.8	3.45	26.1
Swept to other Cells	3.59	0	7.98
Released immediately to environment	0.719	1.28	1.28
Prompt Deposition in Cell 1	9.4	1.41	10.9
Aerosol Left in Cell 1	5.06	0.76	5.88
Mid term Blowdown Release	0.0	0.0	-1.28
Left in Cell 1	5.06	0.76	4.6
Late Blowdown Release	0.301	0.0298	0.423
Model Estimated Respirable Release	**1.02**	**1.31**	**0.422**
Measured Respirable release	**1.05**	**0.962**	**0.375**

For effective use of the GRS 1 data, the ability to account for differences in blowdown fraction between the GRS 1 test and the blowdown fractions for casks likely to be used for large-scale transport campaigns is needed. Fig. 1 indicates the projected potential effect of variable blowdown fraction on the projected release in the GRS 1 experiment.
The GRS Model described here provides a method for using the key features of the existing experiments using surrogate spent fuel in cask configurations together with data on respirable aerosol production from the experiments of the WGSTSC. However, the GRS Model is far from the ideal predictive model that treats all of the physical phenomena potentially affecting the process of aerosol release. As a result caution in applying the results to situations that are greatly different is required. However, given the difficulty in developing a truly omnibus model, this simple model can be used for situations that are not too different from the conditions of the GRS, SNL, and International Consortium experiments on whose data it is based. In the event that the release from a cask involved in a postulated terrorist attack must be precisely and reliably defined, investment in a full-scale test or perhaps in development of a detailed first principles model may be a reasonable, but costly, alternative.

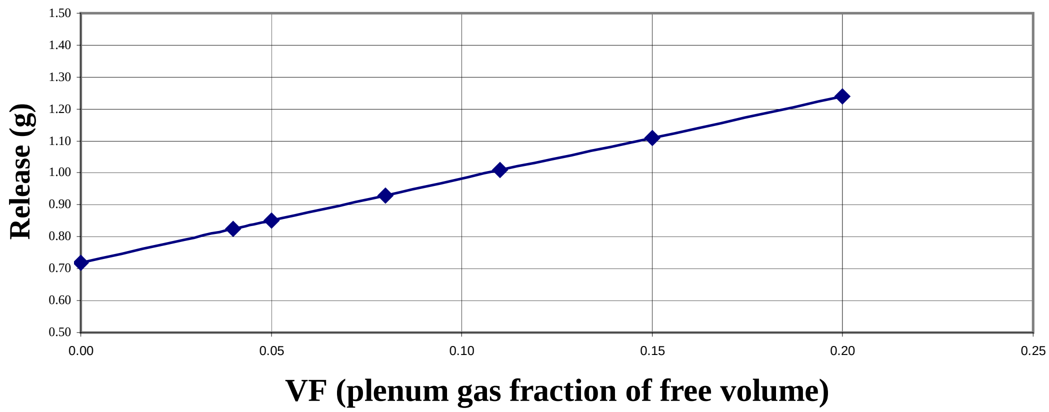

Fig. 1. Released mass vs. Plenum gas volume fraction for GRS 1

GRS MODEL APPLICATION

The 1999 Sabotage Report by Luna, Neuhauser, and Vigil[4] provided an estimate of the potential release of aerosols that might result from an attack using either of 2 HEDDs on representative truck and rail spent fuel casks that might be used for shipment of spent fuel to a repository at Yucca Mountain. That report was based on extrapolating the results from the SNL FS experiment conducted in the early 1980s. Although the GRS experiments had been conducted in 1994, the authors of the Sabotage Report did not know the existence of the data at the time their work was being completed. However, using the GRS Model described above, it is possible to reevaluate the estimates made earlier in light of the experimental data obtained from the in GRS 1 experiment.

The basic calculational process that was used in the Sabotage Report is quite similar to that used in the GRS model so it was relatively straightforward to alter the spreadsheet to accommodate the information from the GRS Model. Changes affected several areas:

- Production of respirable aerosol from the swept mass was reduced from 5% to 2% to reflect the recent experiments of the International Consortium.
- Aerosol produced from any assembly other than the first acted upon by the HEDD cannot contribute to the aerosol released to the environment. It is captured and held within the basket surrounding the interior spent fuel elements.
- An amount of aerosol 5 times that released to the environment is carried from the first fuel assembly’s basket partition into the interior of the cask where it is unavailable for release to the environment (based on data from the SNL ¼ scale test).
- A fraction of the remaining aerosol generated by the HEDD interaction with the first fuel assembly moves laterally within the first assembly and is deposited on surfaces and becomes unavailable for release. In the GRS Model a deposit fraction of 65% was found to reproduce the GRS 1 test result.

Retained from the original calculation were:

- The basic calculational flow from the 1999 estimation process as well as the data that the calculation drew upon relating to cask dimensions, nuclide inventory, etc.
- Prompt aerosol release estimation using the SNL FS respirable release to swept mass of fuel ratio (also a feature of the GRS Model).
- Blowdown estimation based on the ratio of plenum gas released to cask free volume (also a feature of the GRS Model).
- Use of an SFR value of 3 to relate the amount of HEDD-generated aerosol from spent fuel to that from a comparable event that involved surrogate spent fuel.

Changes in the original calculation were:

- Correction of an error in the original calculation relating to non-respirable CRUD.

DISCUSSION OF RESULTS

The results of the recalculation of the releases from the casks are in Tables III.b and III.c shown below. Table III.a is provided to show the results contained in the original report (note that there is a correction in the last row that was discovered while preparing this paper). The Yucca Mountain EIS [5] derived the potential consequences of an optimally successful sabotage attack against casks in transit to the site based on values for release fraction shown in Table III.a. Since the release fraction values for respirable matrix material in the first two rows of each table dominated the consequence calculation as a result of the very high dose conversion factors for the actinide nuclides, these are the principal focus of this report.

For the information of the reader unfamiliar with the 1999 report the following is noted:

- HEDD1 was a large device that was similar to that used in the full scale experiments at Sandia in the early 1980's
- HEDD2 was representative of modern anti armor devices in the arsenals of many nations.
- The truck cask held 4 PWR assemblies and was similar to the GA-4/9 cask
- The rail cask held 26 PWR assemblies with a wall construction containing layers of depleted uranium and lead for gamma attenuation.

Table III.b contains the revised estimate for the release fractions obtained by modifying the original spreadsheet calculation to mirror the calculation method used in the GRS Model that closely estimated the release from GRS 1 and reasonable agreement with results from GRS 2 and GRS 3.

Table III.c shows the ratio of the new estimates of release fraction to those from the 1999 report. The ratio format shows clearly the effect of the revised calculation process. For the respirable release fraction of fuel matrix material the revised values are between 8% and 40% of the prior values (reduction factors of 12 to 2.5).

The immediate effect of basing the prompt release on the swept mass from the first assembly affected by the HEDD is a reduction by a factor of 2. This holds, in fact for all of the results except for the noble gas release, which is unchanged as expected.

After the prompt release, there is an additional release from blowdown of the residual aerosol in the basket cavity occupied by the 1st fuel assembly. The blowdown component is affected by a factor of 2.5 decrease in aerosol production (going from 5% to 2%) and from deposit of 65% of the generated aerosol in the first fuel assembly's basket partition. These two factors lead to as much as a factor of 7.5 potential reduction in blowdown release, depending on blowdown fraction. For the case with the lowest blowdown fraction (HEDD2 and rail cask), the effect is to decrease the release fraction relative to prior values from a factor of 2 lower to a factor of 2.5 lower. For the case with the highest blowdown fraction (HEDD1 and truck cask), the effect is to decrease the release fraction relative to prior values from a factor of 2 lower to a factor of 12 lower.

Table IIIa. Release Fraction Results from Reference 4

Release Fraction Component	Original Values (ref 4)			
	HEDD1		HEDD2	
	Truck	Rail	Truck	Rail
Total Max Respirable. Fraction Fuel Matrix Released to Environment	1.63E-04	4.02E-06	2.35E-05	2.98E-07
Total Avg. Respirable. Fraction Fuel Matrix Released to Environment	1.24E-04	3.08E-06	1.80E-05	2.28E-07
Total Respirable Fraction Co as Crud Released to Environment	7.45E-05	1.28E-06	9.11E-06	4.68E-08
Total Fraction Cs as Released to Environment	1.03E-03	1.73E-05	1.43E-04	7.20E-07
Total Fraction Te Released to Environment	1.03E-03	1.73E-05	1.43E-04	7.20E-07
Total Fraction Noble Gases Released to Environment	2.01E-02	4.05E-04	6.20E-03	3.92E-05
Maximum Fuel Mass Fraction Ejected (not respirable)	3.04E-03	4.23E-04	6.87E-04	5.57E-05
Average Fuel Mass Fraction Ejected (not respirable)	2.33E-03	3.24E-04	5.26E-04	4.26E-05
Crud Fraction Ejected by HEDD (not respirable)	2.33E-03	3.24E-04	5.26E-04	4.26E-05

Table IIIb. Release Fraction Results Using GRS Model Parameters

Release Fraction Component	GRS Model			
	HEDD1		HEDD2	
	Truck	Rail	Truck	Rail
Total Maximum Respirable. Fraction Fuel Matrix Released to Environment	1.36E-05	7.19E-07	2.35E-06	1.18E-07

Total Average Respirable. Fraction Fuel Matrix Released to Environment	1.05E-05	5.50E-07	1.80E-06	9.03E-08
Total Respirable Fraction Co as Crud Released to Environment	3.73E-05	5.17E-07	4.56E-06	2.65E-08
Total Fraction Cs as Released to Environment	5.15E-04	7.15E-06	7.16E-05	4.17E-07
Total Fraction Te Released to Environment	5.15E-04	7.15E-06	7.16E-05	4.17E-07
Total Fraction Noble Gases Released to Environment	2.01E-02	4.05E-04	6.20E-03	3.92E-05
Maximum Fuel Mass Fraction Ejected (not respirable)	1.52E-03	1.75E-04	3.44E-04	3.23E-05
Average Fuel Mass Fraction Ejected (not respirable)	1.16E-03	1.34E-04	2.63E-04	2.47E-05
Crud Fraction Ejected by HEDD (not respirable)	1.16E-03	1.34E-04	2.63E-04	2.47E-05

Table IIIc. Ratio of Revised Release Fraction Estimates to Values in Reference 4

Release Fraction Component	GRS Model / Original Values			
	HEDD1		HEDD2	
	Truck	Rail	Truck	Rail
Total Maximum Respirable. Fraction Fuel Matrix Released to Environment	8%	18%	10%	40%
Total Average Respirable. Fraction Fuel Matrix Released to Environment	8%	18%	10%	40%
Total Respirable Fraction Co as Crud Released to Environment	50%	40%	50%	57%
Total Fraction Cs as Released to Environment	50%	41%	50%	58%
Total Fraction Te Released to Environment	50%	41%	50%	58%
Total Fraction Noble Gases Released to Environment	100%	100%	100%	100%
Maximum Fuel Mass Fraction Ejected (not respirable)	50%	41%	50%	58%
Average Fuel Mass Fraction Ejected (not respirable)	50%	41%	50%	58%
Crud Fraction Ejected by HEDD (not respirable)	50%	41%	50%	58%

CONCLUSION

The application of the GRS Model to the 1999 release fraction calculations contained in the Sabotage Report that were the basis of the Yucca Mountain Project EIS suggests that the potential consequences assessed in the EIS could have been overstated by a factor of 2.5 to 12.

Availability and use of the 1994 GRS test data provided a means to assess the effects of aerosol blowdown resulting from pin plenum gas release, which was not a feature of the SNL experiments. Because blowdown of pin plenum gas was not included in the SNL experiments, the model constructed for the 1999 Sabotage Report added a blowdown term that assumed that a fraction (blowdown fraction) of all aerosols created in the cask interior would be swept out to the environment when the pin plenum gases were released. What the WGSTSC data on respirable aerosol production from HEDD action and the process of fitting the GRS Model to the data from the GRS 1 test (and GRS 2 and GRS 3, as well) suggested was that:

- The estimate of HEDD aerosol production used in the Sabotage Report (5%), which was intended to be conservative, was too conservative a factor of about 2.5.
- The assumption that all of the aerosol produced would be available for release form the cask as a result of blowdown of pin plenum gas was too conservative by about a factor of 3 (because of immediate deposition).
- The assumption that the aerosol from all fuel assemblies impacted by the action of the HEDD would be equally available for release in the blowdown of the cask did not recognize the impact of the cask basket dividers in limiting the access of those aerosols to the exit hole to the environment during the blowdown process.

REFERENCES

1. Sandoval, R. P., et al, "An Assessment of the Safety of Spent Fuel Transportation in Urban Environs", Sandia National Laboratories, Report SAND82-2365, June 1983.
2. Pretzsch, G. and Lange, F., "Experimental Determination of the Release of UO_2 from a Transport Container for Spent Fuel Elements after shaped Charge Bombardment", Gessellshaft fur Anlagen- und Reaktorsicherheit, Report GRS A-2157, May 1994.
3. Luna, R. E., "Comparison of Results from Two Spent Fuel Sabotage Source Term Experiments" International Journal of Radioactive Materials Transport, V11, No. 3 pp 261-265, 2000.
4. Luna, R. E., Neuhauser, K. S. and Vigil, M. G. "Projected Source Terms for Potential Sabotage Events Related to Spent Fuel Shipments" Sandia National Laboratories, Report SAND99-963, June 1969.
5. USDOE, "Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada": Final Environmental Impact Statement", U.S. Department of Energy Office of Civilian Radioactive Waste Management, DOE/EIS-0250, February 2002.