PRE-CLOSURE SAFETY ANALYSIS: SENSITIVITY STUDIES AND PRELIMINARY DOSE RESULTS

S. Kamas, T. Ahn, and M. Bailey

U.S. Nuclear Regulatory Commission, Washington, D.C. 20555-0001, tma@nrc.gov

INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for the design, construction, and operation of a permanent high-level waste (HLW) repository at the potential Yucca Mountain (YM) site. The potential YM functional lifetime will consist of a pre-closure period (construction and operation) and a post-closure period (long-term waste isolation). To proceed, DOE must submit a license application to the U.S. Nuclear Regulatory Commission for construction authorization. NRC will evaluate the application using the performance objectives of 10 CFR Part 63 [1].

Design of the pre-closure facilities at YM may include a dry transfer building where spent nuclear fuel assemblies (SFAs) will be transferred from the transportation cask to the waste package. Unless the dry transfer facility is inerted, this transfer is expected to occur in an oxidizing (i.e., air) environment. (Note: DOE recently announced plans to take a canister-based approach for spent nuclear fuel (SNF) at YM. This paper was developed prior to that announcement.)

Several event sequences may lead to a radioactive release from the dry transfer building. These events are characterized as Normal Operations, Category 1 (*Cat 1*), or Category 2 (*Cat 2*).

Normal Operations refers to the everyday operation of the facility. *Cat 1* event sequences are those that are expected to occur one or more times during the pre-closure period, and *Cat 2* event sequences are those that have at least one chance in 10^4 of occurring during the pre-closure period. This report analyzes event sequences from these three categories in which radionuclides are released into the atmosphere. These analyses are scoping in nature and are not intended to represent staff positions on methods and assumptions for consequence assessments. They represent an analytical testing methodology which NRC is investigating.

During *Normal Operations*, it is assumed that a certain number of SNF rods will arrive at YM with breached cladding. SNF pellets in rods with breached cladding may oxidize in air. Higher oxidation, which proceeds to U_3O_8, may lead to pellet pulverization and cladding unzipping [2].

In a dry transfer building, SFAs would be lifted out of the transportation cask and moved into a waste package. Bare SFAs are susceptible to damage from drops or collisions. Occasional drops or collisions of SFAs may initiate *Cat 1* event sequences.

A significant seismic event is assumed to be *Cat 2*. As part of severe Cat 2 seismic consequences, mechanical impacts on SFAs are studied here. During this event, all bare assemblies in the dry transfer building are assumed to be at risk. For the purposes of this paper, no credit is taken for building containment of radionuclides during *Cat 2* events.

The pre-closure performance objectives of 10 CFR Part 63 set dose limits for the public and workers. The annual worker dose from *Normal Operations* and *Cat 1* events cannot exceed 5 rem/year. For the public, the annual dose from Normal Operations and *Cat 1* events cannot exceed 15 mrem/year, and the dose from any *Cat 2* event sequence cannot exceed 5 rem.

This paper evaluates the source term of a radionuclide release from SNF and its potential consequences during the pre-closure period of the potential YM repository.

WORK DESCRIPTION

The Pre-closure Safety Analysis (PCSA) Tool was designed by the Center for Nuclear Waste Regulatory Analyses [3]. NRC will evaluate DOE's compliance with the pre-closure performance objectives of 10 CFR Part 63.111. The tool incorporates software packages that allow the user to perform consequence analysis of an atmospheric radionuclide release (RSAC) and calculations of building discharge fractions (MELCOR) [3] for confirmatory assessments.

This paper conducts scoping assessments of the atmospheric release of radionuclides from a hypothetical dry transfer facility at YM through consequence and sensitivity analyses. PCSA Tool, Version 3.0, was used to calculate doses for various event sequences and corresponding source terms. Doses were first calculated for a range of release heights, building sizes, filter efficiencies, and building discharge fractions. This sensitivity analysis gives perspective on the dose impact of these factors.

To assess scoping results in terms of pre-closure performance objectives, bounding release fractions (RFs) and downwind distances are coupled with expected values of release height, filter efficiency, and building discharge.

The outdoor worker dose is estimated by the maximum onsite dose and is obtained using the Worker Dose Consequence module of the PCSA Tool, Version 3.0.1. This maximum dose was assumed to occur in the cavity zone (the worker dose considering Wake effects is currently under further evaluation). The cavity zone is an area adjacent to the release building in which the recirculation of contaminated air may lead to increased dose (relative to the Gaussian plume model). The worker dose module computes ground surface, submersion, and inhalation dose components.

The downwind dose to the public is estimated by the public dose consequence module of the PCSA Tool, Version 3.0.1. The shortest distance from the proposed dry transfer facility to the western site boundary is 11 km (6.84 miles). The public dose module computes ground surface, submersion, inhalation, and ingestion doses. Ingestion dose is calculated for 1 year, assuming that the receptor eats some locally produced food that is grown at the site boundary (11 km from release). Most farming activity in the area takes place in the Amargosa Valley, about 30 km (18.65 miles) away.

Generating the Source Term

The source term for a given event sequence is the product of the material at risk (MAR), damage ratio, Release Fraction (RF), and leak path factor (LPF). The user of the PCSA tool may choose the number, type (BWR/PWR), and burnup of SFAs damaged, as well as the RF and LPF. The inventory of radionuclides in the SFA was determined for commercial SNF from a pressurized water reactor with a loading of 0.429 metric tons [0.473 tons] of uranium, a burnup of 49 GW-days/MTU [3.565×10^{12} Btu/ton], an enrichment of 4.0 percent, and a decay time of 25 years.

Material at Risk (MAR)

The MAR depends on the event sequence. Assuming that all SNF assemblies that arrive at YM will be handled in an environment that facilitates oxidation, the MAR for oxidation is equal to the number of rods that arrive at YM with breached cladding.

Current fuel failure rates are less than 0.1%, and, more conservatively, 1% of rods can be assumed to arrive at YM with breached cladding. The maximum throughput at YM is assumed to be approximately 6,400 SFAs per year. Up to one percent of 6,400, or 64 net SFAs per year, may arrive with breached cladding, and may be vulnerable to oxidation.

For an SFA drop or collision, it is assumed that the MAR is two PWR SFAs [4]. This would represent the failure of a mechanism carrying two SFAs or an assembly drop directly onto another assembly.

For the Cat 2 mechanical impact event, the MAR is equal to the number of vulnerable SFAs at the time of the seismic event. In this consequence analysis, 100 PWR SFAs are assumed to be at risk. The MAR is on the same order of magnitude as the capacity of a large SNF staging rack or 2-3 SNF transportation casks.

Damage Ratio

The damage ratio is the fraction of the material at risk that is damaged during the event sequence. For the purposes of this paper, the damage ratio in all event sequences is assumed to be one. For example, an assembly drop is assumed to cause every rod in the SFA to fail.

Release Fraction (RF)

The RFs used in the generation of the source term depend on the physical and chemical form of the material at risk, as well as the initiating stress. The methodology for formulating these factors draws upon empirical correlations, models, and experimental data [5, 6].

Material at Risk	Release Fraction		
	Drop	Oxidation	Seismic
Tritium	0.3	0.3	0.3
Noble Gases	0.3	0.3	0.3
Iodine	0.3	0.3	0.3
Crud	0.15	0.15	0.15
Ruthenium	0.0002	0.002	0.0002
Cesium	0.0002	0.002	0.0002
Strontium	2.0E-06	1.2E-03	8.5E-06
Fuel Fines	2.0E-06	1.2E-03	8.5E-06

Table 1- Release Fractions for Spent Nuclear Fuel

In Table 1, impact analysis results are the basis for the SFA drop/collision (Drop) and impact for part of seismic event (Seismic) RFs. The RF for the SFA drop/collision assumes an impact speed of 13 m/s [30 mph, equivalent to 9 m (29.5 ft) drop] and the seismic event assumes an additional impact speed of 27 m/s [60 mph, equivalent to 36 m (118.1 ft) drop] [6]. For SNF Oxidation, the RF is based primarily on experimental data involving the oxidation of SNF, leading to the pulverization of SNF pellets [2, 6]; and it is further enhanced by potential high burnup effects on a conservative basis.

SNF oxidation leading to pellet pulverization requires three conditions: exposure of fuel pellets to oxygen, high temperature of fuel pellets, and sufficient time for the fuel to oxidize and unzip the cladding. This could happen during the transfer of bare SFAs from the transportation cask to the waste package.

Leak Path Factor (LPF)

The Leak Path Factor (LPF) is the product of the building discharge fraction (BDF) and HEPA Filter Mitigation Factor (HMF). The BDF accounts for deposition and agglomeration as radionuclides travel through the building ventilation system. The HMF accounts for the presence of High Efficiency Particulate Air Filters that are capable of removing over 99% of particulate material from the air prior to atmospheric release.

During *Normal Operations* and *Cat 1* events, radionuclides are assumed to leave the building through a filtered ventilation system.

During *Cat 2* events, no credit is taken for the purposes of this paper for building deposition or HEPA filtration. The HMF and BDF for gaseous radionuclides are assumed to be 1 for all cases.

DOE's design is not finalized, and DOE's analyses are ongoing to determine the risk associated with assembly drops, collisions, SNF oxidation, and seismic events. Considering this current status of the application, this paper explores a range of inputs through sensitivity analyses. Potential doses are calculated for various building sizes, ventilation stack heights, filter efficiencies, and distances. Much of the risk associated with drops and oxidation of SFA would be mitigated if the pre-closure facility design is canister-based. And, therefore, the assumptions in these analyses would be highly conservative and the results upper bound.

RESULTS

Sensitivity Analysis

The doses presented in this sensitivity analysis are per assembly damaged. In the actual compliance assessment, the dose per assembly would be multiplied by the number of SFAs damaged, as determined by event sequence analysis.

	Normal Operations	**Cat 1**	**Cat 2**
Release Height	30 m	30 m	Ground
Material at Risk	64 SFAs/yr	2 SFAs/yr	100 SFAs
Damage Ratio	1	1	1
RF_{Gas}	0.3	0.3	0.3
$RF_{Volatiles}$	2×10^{-3}	2×10^{-4}	2×10^{-4}
RF_{Crud}	0.15	0.15	0.15
RF_{Fines}	1.2×10^{-3}	2×10^{-6}	8.5×10^{-6}
LPF_{Gas}	1	1	1
LPF_{Crud}	3×10^{-6}	3×10^{-6}	1
LPF_{Others}	6×10^{-7}	6×10^{-7}	1

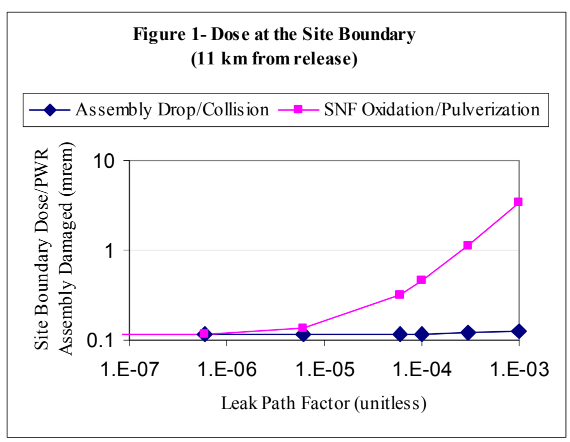
Table 2- Parameters used in the sensitivity analysis except where specified
(30 m = 98.43 ft, release height)

The default LPF values used in the PCSA Tool are 3×10^{-6} for Crud and 6×10^{-7} for other particulates. An LPF of 1 suggests that all radionuclides released from SNF leave the building.

The LPF may vary by event sequence. The BDF is sensitive to particle size, which may depend on the fuel burn-up and type of initiating stress. Assuming an event produces very small particles, the LPF for particulate radionuclides may increase by an order of magnitude (as calculated with MELCOR).

HEPA filters may be impaired, damaged, or bypassed during some postulated event sequences. Increasing the HMF would also increase the LPF.

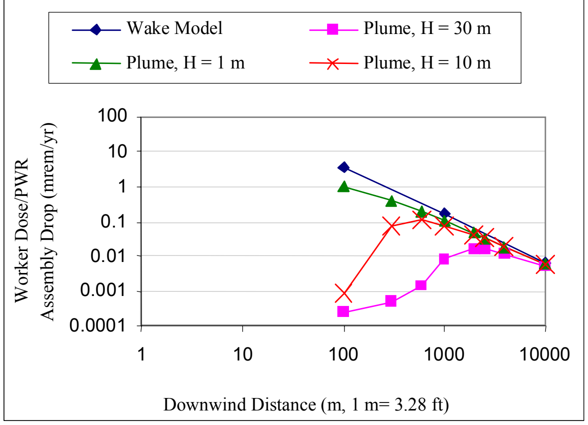
The potential downwind dose at the site boundary per assembly damaged is shown in Figure 1 as the LPF for solid radionuclides is varied. As seen in Figure 1, a small increase in particulate LPF does not affect the gas-dominated dose. The LPF for gases does not change, because of the assumption that all gas will leak (LPF = 1).



*100 mrem equals 1 mSv.

It is also of interest to calculate dose as a function of distance from the release. As the release travels downwind, radionuclides are dispersed and deposited. Figure 2 shows the onsite dose that may be expected when a PWR SFA is damaged in the dry transfer facility. The default LPF was used.

Figure 2. Worker Dose: Building Wake Effects vs. Standard Plume Model



* H is release height and varied for sensitivity (for example, 1m for breached container and 30 m for stack height).

Previous dose calculations assumed a cross-sectional building area 60 m (196.85 ft) wide by 20 m (65.62 ft) high, perpendicular to wind flow. Since the design is not finalized, these parameters may vary.

As the model for Wake effects (i.e., Wake Model) are under further evaluation and validation, some preliminary exercise results of the effects of building size, height and width, are not presented here. Figure 2 and the preliminary exercise results indicate that stack height and building size appear to be important near the release. Atmospheric releases from normal operations and Cat 1 event sequences are expected to be elevated stack release in the displacement zone rather than in the cavity zone of the building Wake Model. However, the “Wake Model” dose in Fig. 2 and preliminary dose results of the effects of building size were calculated using the PCSA Tool’s capability for estimating building Wake effects, assuming a ground release. “Plume” doses in Fig. 2 assume a Gaussian plume dispersion model for various release heights, H, that does not consider building Wake effects. The Gaussian dispersion model predicts small doses near the building for elevated releases.

Public dose calculations at the site boundary showed no dependency on building size. Dose at the site boundary decreased about 8% for a 30 m stack height relative to ground release.

Consequence Analysis

Using the values in Table 2, a deterministic scoping consequence analysis was performed.

Figure 3 shows that uninhibited oxidation of 1% of SNF rods may not be significant in terms of dose limits. However, the continuous accumulation of released radionuclides may increase the dose. On the other hand, chronic release of radionuclides in different wind directions may decrease the dose too. Also, a hot cell could be contaminated by oxidation. Assuming 1% of rods oxidize, there would be about 2 failed rods per assembly. Assuming 30-assembly casks were used, there would be approximately 60 failed rods per cask.

Figure 3- Normal Operations, SNF Oxidation: Building Wake effects considered for Worker Dose

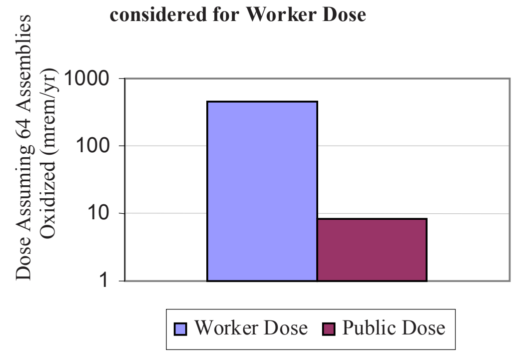
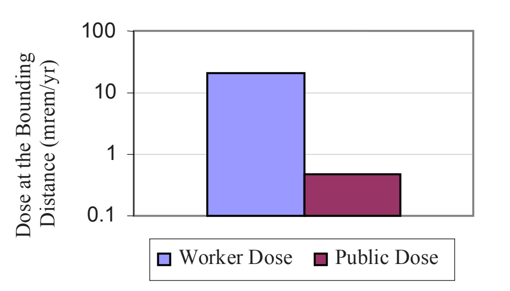


Figure 4 shows that the collision of two bare SFAs would have minimal dose consequences.

Figure 4- Category 1, Assembly Collision: 2 Assemblies Damaged, Credit is taken for deposition and filtration prior to release



Using the RF associated with additional impact events (as part of Cat 2 seismic study), an example calculation was made for the public dose consequence for RFs associated with 13 m/s [30 mph] and 27 m/s [60 mph] impacts [6] on SFAs. Equivalent speeds would be reached at drop heights of 9 m [29.5 ft] and 36 m [118.1 ft] respectively. There was about a factor of 3 increase in the maximum public dose, with 100 SFAs damaged in ground release without building, deposition and filtration.

CONCLUSIONS

The scoping calculation indicates that radionuclide release from a SFA drop or collision appears to be small for the assumed release scenarios.

In evaluating dose consequences from SNF oxidation, it is important to determine whether or not detrimental oxidation would occur in SNF rods with pinhole leaks or hairline cracks. The realistic risk of SNF oxidation will depend on the ability to prevent or mitigate oxidation through proper design.

The deposition, agglomeration, and filtration of particulate radionuclides prior to atmospheric release may greatly reduce the downwind dose.

An example dose consequence from a *Cat 2* impact event was assessed.

Work is ongoing systematically to develop more realistic source terms representative of *Cat 1* event sequences, *Cat 2* event sequences, and *Normal Operations*.

As previously stated, this paper was developed prior to DOE's announcement that it planned to take a canister-based approach for the pre-closure facility design. Such an approach could mitigate much of the risk associated with drops and oxidation of SFA. And, therefore, the assumptions in these analyses would be highly conservative and the results upper bound.

DISCLAIMER

The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a geologic repository at Yucca Mountain.

ACKNOWLEDGEMENTS

The authors wish to thank R. Benke and B. Dasgupta of the Center for Nuclear Waste Regulatory Analyses, and M. Waters, M. Nataraja and M. Shah of NRC, for their careful reviews.

REFERENCES

1. Code of Federal Regulations, "Disposal of High-Level Radioactive Wastes in a Proposed Geological Repository at Yucca Mountain, Nevada," Title 10-Energy, Chapter 1-NRC, Part 63, Washington, DC, U.S. Government Printing Office, (2002)
2. T. AHN. NUREG-1565: Dry Oxidation and Fracture of LWR Spent Fuels. U.S. Nuclear Regulatory Commission, Washington, D.C. (1996)
3. B. DASGUPTA, R. BENKE, B. SAGAR, R. JANETZKE, AND A. CHOWDHURY. PCSA Tool Development, Progress Report II. Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas (2002)
4. R. JOHNSON AND B. DASGUPTA. PCSA Tool and Example Application, 146th Meeting of Advisory Committee on Nuclear Waste, October 21–23, Nuclear Regulatory Commission (2003)
5. American Nuclear Society Standards Committee Working Group ANS 5.10. Airborne Release Fractions at Non-Reactor Nuclear Facilities, an American National Standard. American Nuclear Society, La Grange Park, Illinois (1998)
6. J. SPRUNG, et al. NUREG/CR-6672, Vol. 1: Reexamination of Spent Fuel Shipments Risk Estimates Main Report. Sandia National Laboratories, Albuquerque, NM (2000)

DEFINITIONS AND ABBREVIATIONS

BDF- Building Discharge Fraction. Fraction of radioactive material released from an event that enters the building ventilation and is released into the atmosphere assuming no filtration.

CFR- Code of Federal Regulations.

DOE- U.S. Department of Energy. The department responsible for the design, construction, and operation of a high-level waste repository in the United States.

HMF- High Efficiency Particulate Air Filter Mitigation Factor. The fraction of radioactive material which passes through the high efficiency particulate air filter system.

LPF- Leak Path Factor. The fraction of airborne, respirable material available for transport that successfully crosses the containment boundary. The product of the *Building Discharge Fraction* and the *HEPA Filter Mitigation Factor*.

MAR- Material-at-Risk. The amount of radioactive material available to be acted upon by the stresses generated during normal operations or accident conditions.

NRC- U.S. Nuclear Regulatory Commission. The agency responsible for licensing the proposed geological repository at Yucca Mountain.

PCSA- Pre-closure Safety Analysis. A systematic examination of the site; the design; and potential hazards, initiating events, and event sequences and their consequences (e.g. radiological exposures to workers and the public).

PWR- Pressurized Water Reactor.

RF- Release Fraction. The fraction of material of respirable size made airborne and available for transport during a given event sequence.

Source Term. The amount of radioactive material available for release from confinement if a leak were to occur at the confinement boundary.

SNF- Spent Nuclear Fuel. In this paper SNF refers to commercial spent nuclear fuel pellets or assemblies.

TEDE- Total Effective Dose Equivalent. For purposes of assessing dose to workers, the sum of the deep-dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures). For purposes of assessing doses to members of the public, the sum of the effective dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures)

YM- Yucca Mountain. The potential site of a permanent high-level waste repository.