Radioactive Materials Transport Accident Analysis

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ABSTRACT

Over the last 25 years, one of the major issues raised regarding radioactive material transportation has been the risk of severe accidents. While numerous studies have shown that traffic fatalities dominate the risk, modeling the risk of severe accidents has remained one of the most difficult analysis problems. This paper will show how models that were developed for nuclear spent fuel transport accident analysis can be adopted to obtain estimates of release fractions for other types of radioactive material such as vitrified high-level radioactive waste. The paper will also show how some experimental results from fire experiments involving low level waste packaging can be used in modeling transport accident analysis with this waste form. The results of the analysis enable an analyst to clearly show the differences in the release fractions as a function of accident severity. The paper will also show that by placing the data in a database such as ACCESS™, it is possible to obtain risk measures for transporting the waste forms along proposed routes from the generator site to potential final disposal sites.

INTRODUCTION

In one of the first transportation risk studies, it was shown that the transport accident risk for plutonium oxide shipments was much less than the risks associated with the operation of nuclear power reactor (Ref. 1). That study relied on an analysis performed by Sandia National Laboratory that specified the accident environment for truck and rail (Ref. 2). For a variety of reasons, perhaps the most severe being computing cost associated with modeling the behavior of spent fuel casks in the accident environment, it wasn't until 1988, with the publishing of what has been termed the Modal Study (Ref. 3), that the behavior of the spent fuel cask in the accident environment was modeled in detail. While this study updated the earlier Sandia study by looking at the characteristics of transportation routes, the focus of the Model Study was determine the behavior of the cask in a broad spectrum of rail and truck transportation environments. The analysis did not model the fuel behavior in much detail and did not evaluate the consequences of radioactive material releases from the failed cask. It was not until 2001with the publishing of NUREG/CR 6672, (Ref. 4), that a comprehensive analysis integrated the behavior of the fuel, clad, and cask in the transport accident environment with the characteristics of representative transport routes. This paper begins with the results shown in NUREG/CR-6672 and shows a technique that can be used to determine the radiological accident risk for other radioactive material shipments.

ANALYTICAL FRAMEWORK

The analytical framework has remained relatively unchanged since the publishing of the plutonium transportation studies in the mid 1970's. The accident environment is divided into a series of cases that consider the coupled effects of ranges of impact velocities and fire durations. For each case, the accident severity probability and release fractions are estimated. These are then coupled with the characteristics of possible transport routes to estimate accident impacts, expressed as accident consequences or accident risk.

Figure 1 shows the NUREG/CR-6672 case numbers, failure mechanisms and accident probabilities for a Steel-Lead-Steel Rail Cask containing PWR spent fuel using a format first used in the Modal Study. On one axis is velocity and on the other is temperature rise. It can be seen that the 21 rail accident severity cases analyzed in NURGE/CR 6672 consider impact velocities ranging from zero to greater than 120 mph and fire cases ranging from no fire to fires that result a final temperature, $T_{f,}$ of 1000 °C. The intermediate break points in the temperature regime are the temperatures at which various component failures are postulated. The cask seal is assumed to fail at $T_s = 350°C$ and the fuel clad not ruptured by impact is assumed to burst at $T_b = 750°C$. It is also conservatively assumed that as a result of the decay heat loading, the interior of the cask is at 300°C at the time of the accident. The two columns on at the right of the figure show the same heat-up temperature range, 300 to 1000°C. The one labeled A assumes no egress of air and therefore no oxidation of radioactive materials, specifically ruthenium. The latter assumes the breach of the cask is sufficient for both egress of radionuclides and ingress of air. As shown in Table 1, for each of the 21 cases, release fraction are estimated for particulates (Part), ruthenium (Ru), cesium (Cs), inert gases (Kr), and crud (Crud).

Figure 1. PWR Steel Lead Steel Rail Cask Accident Severity Matrix, Case Numbers, Failure Mechanism and Probability

Equivalent Impact onto an unyielding surface (mph)

>120 mph	3 Seal Failure on Impact Prob 4.49E-09	13 Seal Failure on Impact Prob 3.70E-11	14 Seal Failure on Impact Prob 1.03E-12	15 Seal Failure on Impact Prob 1.37E-13	19 Failure by Shear/Puncture Seal Failure from Fire Prob 1.37E-16
90 – 120	2 Seal Failure on Impact Prob 5.68E-07	10 Seal Failure by Impact Prob 4.68E-09	11 Seal Failure by Impact Prob 1.31E-10	12 Seal Failure by Impact Prob 1.74E-11	18 Failure by Shear/Puncture Seal Failure from Fire Prob 1.74E-14
60 – 90	1 Seal Failure on Impact Prob 8.20E-06	7 Seal Failure by Impact Prob 6.76E-08	8 Seal Failure by Impact Prob 1.88E-09	9 Seal Failure by Impact Prob 2.51E-10	17 Failure by Shear/Puncture, Seal Failure from Fire Prob 2.51E-13
30 – 60		4 Seal Failure by Fire Prob 2.96E-05	5 Seal Failure by Fire Prob 8.24E-07	6 Seal Failure by Fire Prob 1.10E-07	16 Failure by Shear/Puncture, Seal Failure from Fire Prob 4.15E-10
No Impact	21 No Release Prob 0.99996			20 Seal Failure by Fire Prob 4.91E-05	
	No Fire (300 ºC)	$T_a – T_s$ (300 to 350 ºC)	$T_a - T_b$ (300 to 750 ºC)	A $T_a – T_f$ (300 to 1000 ºC)	B $T_a – T_f$ (300 to 1000 ºC)

Initial and Final Temperature Associated with Cells

In the PWR accident model, releases are controlled by gas thermal expansion and deposition or plate-out on the inside of the cask. In a fire environment, as the cask heats up, radioactive material is released from the failed fuel and the breached cask as a result of gas thermal expansion. In addition to these continuous releases from heating, release pulses occur whenever a component barrier fails. One pulse occurs when the cask seal and fuel clad fail on impact or if these barriers have not failed on impact, when the cask seal temperature in the fire reaches 350°C. A second pulse occurs when the clad on any fuel not failed by impact bursts at 750°C. The first step in modeling the HLW canister shipments is to determine if similar releases can be postulated.

The same cask can be used to ship PWR fuel can also be used to ship HLW canisters. Thus the cask failures postulated for shipping PWR fuel can also be used to model the behavior of a cask shipping HLW canisters. The ceramic fuel and vitrified waste forms, both being brittle solids, are anticipated to have similar particulate release fractions. When cesium and ruthenium are placed in a glass matrix, their volatility is greatly reduced so for HLW, the particulate release fraction will be used to estimate the cesium and ruthenium release fractions. There will be no crud containing Cobalt 60 on the outer surfaces of the HLW canister so the release fractions for crud are set to zero. Similarly, any volatile gases are removed when the vitrified waste is cast into the canisters.

Table 1. Spent Fuel Release Fractions for the 21 Rail Accident Severity Categories

Case	Probability	Release Fraction				
		Kr	Cs	Ru	Part	CRUD
1	8.20E-06	4.14E-01	1.24E-08	2.49E-07	2.49E-07	1.40E-03
2	5.68E-07	8.00E-01	8.64E-06	1.32E-05	1.32E-05	4.40E-02
3	4.49E-09	8.00E-01	1.78E-05	1.92E-05	1.92E-05	6.40E-02
4	2.96E-05	1.35E-01	4.05E-09	1.01E-07	1.01E-07	1.35E-03
5	8.24E-07	1.80E-01	5.40E-09	1.35E-07	1.35E-07	1.80E-03
6	1.10E-07	8.35E-01	3.60E-05	1.37E-05	1.37E-05	5.36E-03
7	6.76E-08	4.28E-01	1.29E-08	2.57E-07	2.57E-07	1.45E-03
8	1.88E-09	4.92E-01	1.47E-08	2.95E-07	2.95E-07	1.67E-03
9	2.51E-10	8.45E-01	2.66E-05	6.75E-06	6.75E-06	4.51E-03
10	4.68E-09	8.16E-01	8.81E-06	1.35E-05	1.35E-05	4.49E-02
11	1.31E-10	8.88E-01	9.59E-06	1.47E-05	1.47E-05	4.88E-02
12	1.74E-11	9.10E-01	1.36E-05	1.50E-05	1.50E-05	5.08E-02
13	3.70E-11	8.16E-01	1.81E-05	1.96E-05	1.96E-05	6.53E-02
14	1.03E-12	8.88E-01	1.97E-05	2.13E-05	2.13E-05	7.10E-02
15	1.37E-13	9.10E-01	2.17E-05	2.18E-05	2.18E-05	7.35E-02
16	4.15E-10	8.35E-01	9.59E-05	8.39E-05	1.82E-05	6.35E-03
17	2.51E-13	8.45E-01	5.51E-05	4.95E-05	8.89E-06	5.38E-03
18	1.74E-14	9.10E-01	1.36E-05	1.77E-05	1.50E-05	5.10E-02
19	1.37E-16	9.10E-01	2.17E-05	2.30E-05	2.18E-05	7.38E-02
20	4.91E-05	8.39E-01	1.68E-05	2.52E-07	2.52E-07	9.44E-03
21	0.99991	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

The major difference between the HLW canisters and a PWR fuel rod is that the HLW canister is not pressurized when it is sealed. As a result, when an intact canister is heated to 1000°C in an accident, stress analyses shows that the pressure build-up from thermal heating of the gas in the canister void volume above HLW glass will not result in canister failure. Thus if the clad on the HLW canister does not fail from impact, it will not fail in any the subsequent fire. Thus the releases for case 20, the fire only scenario, are zero.

It would be expected that the canister would behave differently from the PWR fuel clad in the impact accident environment. Impact tests were performed on simulated canisters of vitrified high level waste (Ref. 5) and these provide the basis for the failure thresholds for the clad on the high level waste capsules. These studies showed that a 40 mph impact 2 out of 12 capsules failed and at 80 mph impacts 5 out of 7 failed. Since the NUREG/CR-6672 analysis divided the impacts categories beginning at 30, 60, 90 and >120 mph, these results were translated into a 20% probability of a breach for the 30 to 60 mph bin and 70% for the 60 to 90 mph bin. For impacts above 90 mph, a 100% probability of a breach was used. For impacts below 30 mph, no breach was assumed. When these similarities and differences between PWR fuel and HLW are incorporated into the release model, the resultant HLW release fractions are shown in Table 2.

A comparison of the particulate release fractions in Table 1 with those in Table 2, show that the release fractions for HLW are always below those of PWR spent fuel for the same case. Subsequent sections will show that the release risk is less as well.

Table 2. HLW Release Fractions for the 21 Rail Accident Severity Categories

Case	Probability	Release Fraction				
		Kr	Cs	Ru	Part	CRUD
1	8.20E-06	0.00E+00	1.63E-07	1.63E-07	1.63E-07	0.00E+00
2	5.68E-07	0.00E+00	7.86E-06	7.86E-06	7.86E-06	0.00E+00
3	4.49E-09	0.00E+00	1.14E-05	1.14E-05	1.14E-05	0.00E+00
4	2.96E-05	0.00E+00	3.33E-08	3.33E-08	3.33E-08	0.00E+00
5	8.24E-07	0.00E+00	7.89E-08	7.89E-08	7.89E-08	0.00E+00
6	1.10E-07	0.00E+00	9.29E-08	9.29E-08	9.29E-08	0.00E+00
7	6.76E-08	0.00E+00	1.84E-07	1.84E-07	1.84E-07	0.00E+00
8	1.88E-09	0.00E+00	2.76E-07	2.76E-07	2.76E-07	0.00E+00
9	2.51E-10	0.00E+00	3.05E-07	3.05E-07	3.05E-07	0.00E+00
10	4.68E-09	0.00E+00	8.55E-06	8.55E-06	8.55E-06	0.00E+00
11	1.31E-10	0.00E+00	1.17E-05	1.17E-05	1.17E-05	0.00E+00
12	1.74E-11	0.00E+00	1.26E-05	1.26E-05	1.26E-05	0.00E+00
13	3.70E-11	0.00E+00	1.24E-05	1.24E-05	1.24E-05	0.00E+00
14	1.03E-12	0.00E+00	1.70E-05	1.70E-05	1.70E-05	0.00E+00
15	1.37E-13	0.00E+00	1.83E-05	1.83E-05	1.83E-05	0.00E+00
16	4.15E-10	0.00E+00	9.29E-08	9.29E-08	9.29E-08	0.00E+00
17	2.51E-13	0.00E+00	3.05E-07	3.05E-07	3.05E-07	0.00E+00
18	1.74E-14	0.00E+00	1.26E-05	1.26E-05	1.26E-05	0.00E+00
19	1.37E-16	0.00E+00	1.83E-05	1.83E-05	1.83E-05	0.00E+00
20	4.91E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21	0.99991	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

LLW RELEASE FRACTION ESTIMATES

The response of a shipment of 55 gallon (208 liter) drums of Low Level Radioactive Waste in the accident environment was determined by going back to the basic accident data that were used to estimate the accident probabilities for impacts and fires of various durations. Based on drum deformations performed in a previous analysis, (Ref 1) it was assumed that if a drum experienced a crush force of 100,000 pounds then the deformation would be sufficient for the lid to pop off the drum. Based on this failure mechanism, and assuming the drums weigh 500 pounds (227 kgs) and are arranged 4 across in the back of the truck, then at an impact of 30 mph the front 25 percent of the drums will fail, at 60 mph 55% will fail, at 90 mph 75% will fail, and at ≥ 120 mph all are assumed to fail. The fire duration is assumed to be independent of the impact severity. It was assumed that fire occurred in 1.6% of all accidents (Ref. 2) and of those fires, 85% of the fires have a duration of less than 15 minutes and 99% of the fires have a duration of less than 30 minutes. Regarding thermal failures, fire experiments using simulated waste drum arrays (Ref. 6), show that if drums are directly exposed to a fire, they will fail by lid loss in about 70 seconds. However if they are not directly exposed to the fire, but directly adjacent to drums that are exposed the fire, the venting begins after about 5 minutes and about 6% of the waste is consumed every minute. This means that after about 20 minutes, most of the waste in the adjacent drums will be completely combusted. The wall of the truck or rail car, if it is still intact following the crash, will probably be an effective barrier for some of that time. For these reasons, it will be assumed that half the drums not failed by impact will fail after being exposed to a 15 minute fire and none will survive a fire that lasts longer than 30 minutes. The release fractions for impact releases and fire releases are based on the estimates provided in DOE-HDBK-3010, (Ref. 7). Section 4.4.3.3.2 of that reference provides an estimate for impact only releases from waste and Section 5.3.1 provides an estimate for fire releases fractions for the combustible waste materials packed in standard 55 gallon (208 liter). The resultant release fraction and accident severity probability estimates are shown in Table 3.

Table 3. Accident Severities and Release Fractions for Truck Transport of LLW in 55 Gallon (208 liter) Steel Drums

Cases	Probability	Release Fraction				
		Kr	Cs	Ru	Part	CRUD
< 30 mph, no fire, no drum failure	3.11E-01	0.00000	0.00E+00	0.00E+00	0.00E+00	0.00000
30 – 60 mph, no fire	6.52E-01	0.00E+00	1.20E-05	1.20E-05	1.20E-05	0.00E+00
> 60 mph, no fire	2.82E-02	0.00E+00	9.22E-04	9.22E-04	9.22E-04	0.00E+00
< 30 mph impact ≤ 15 minute fire	2.32E-03	0.00E+00	2.13E-04	2.13E-04	2.13E-04	0.00E+00
> 30 mph impact ≤ 15 minute fire	2.56E-04	0.00E+00	7.30E-03	7.30E-03	7.30E-03	0.00E+00
> 30 mph impact > 15 minute fire	6.12E-03	0.00E+00	3.80E-01	3.80E-01	3.80E-01	0.00E+00

The major difference between packages used for shipping Class A type waste and high-level radioactive waste is shipped in a heavily shielded cask. This difference is best shown in the results from some fire tests involving Class A packages. A HLW cask can be exposed to a pool fire for more than an hour and the internal temperature will still not reach 700 °C. If a Class A package is exposed to a pool fire, it takes less than 70 seconds to heat the drum to 700 °C. When the HLW cask reaches 700 °C the cask seals will have failed but no other damage is postulated. In the case of the Class A drum, experiments show that at 700 °C the pressure buildup in the drum is sufficient for the drum containing combustible materials to vent. At that point all the material inside the drum will burn and release the radioactive material associated with the waste.

APPLICATION TO OTHER WASTE FORMS

Similar estimates have been made for other fuel forms such as HTGR, TRIGA reactor, and various clad uranium metal and uranium metal alloy fuels. In these cases, the biggest uncertainty is the likelihood of canister and clad failure. Once failure rates for these components have been estimated, the same principles that were used to translate the PWR releases into HLW releases can be applied.

MODELING TRANSPORTATION SYSTEMS

In the United States of America it has long been recognized that spent nuclear fuel and high level waste will not be stored at reactor and processing sites forever but eventually will be shipped to a suitable site for geologic disposal. Thus, at some point in the future these materials will have to be shipped in relatively large quantities. As part of the approval process, Environmental Impact Statements have been prepared that estimate the impacts of these future shipments. The risk of transport accidents is one of the impacts assessed. As described in a paper at PATRAM 2001, (Ref. 8) it has been found that databases provide an excellent platform for performing these assessments. In the database, rather than model all the cases, probability weighting is used to reduce the number of cases to a more manageable number, in this case six. The resultant collapsed tables are shown in Tables 4 and 5 for the HLW truck and rail casks.

Table 4. Simplified Truck Accident Severity Table for HLW

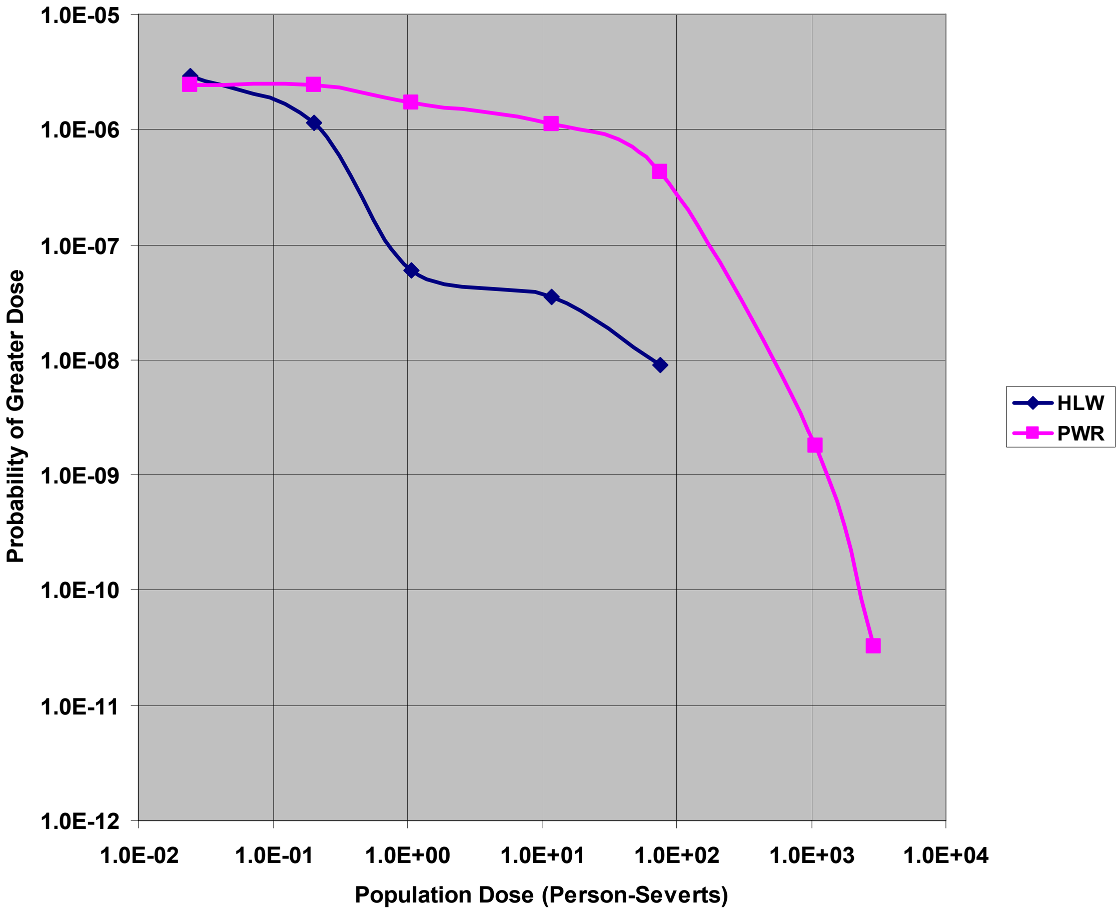
Cases	Probability	Release Fraction				
		Kr	Cs	Ru	Part	CRUD
19	0.99993	0.00000	0.00000	0.00000	0.00000	0.00000
2, 3	6.22E-05	0.00E+00	1.42E-08	1.42E-08	1.42E-08	0.00E+00
18	5.59E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1, 5, 6, 8	5.16E-07	0.00E+00	4.34E-08	4.34E-08	4.34E-08	0.00E+00
4	6.99E-08	0.00E+00	8.69E-08	8.69E-08	8.69E-08	0.00E+00
7,9,10,11,12,13, 14,15,16,17	2.24E-10	0.00E+00	7.62E-08	7.62E-08	7.62E-08	0.00E+00

To demonstrate the flexibility of this assessment tool, a query was used to estimate the accident risk spectrum for two of the waste types that might eventually be shipped to the proposed geologic repository at Yucca Mountain, Nevada. The PWR curve in Figure 2 is for 125 rail shipments of PWR fuel, about 3200 PWR fuel assemblies or 1500 metric tons of fuel. The HLW curve is based on 600 rail shipments of HLW, 3000 total canisters. This is a fabricated case in that there is no place in the United States where similar quantities of these materials coexist. The route chosen for the comparison was from West Valley in New York State, the former site of a nuclear fuels reprocessing plant to the proposed Yucca Mountain Repository in the State of Nevada, a distance of over 4000 kilometers.

Table 5. Simplified Rail Accident Severity Table for HLW

Cases	Probability	Release Fraction				
		Kr	Cs	Ru	Part	CRUD
21	0.99991	0.00000	0.00000	0.00000	0.00000	0.00000
1, 4, 5, 7, 8	3.87E-05	0.00E+00	1.43E-08	1.43E-08	1.43E-08	0.00E+00
20	4.91E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2, 3, 10	5.77E-07	0.00E+00	1.09E-06	1.09E-06	1.09E-06	0.00E+00
6	1.10E-07	0.00E+00	8.69E-08	8.69E-08	8.69E-08	0.00E+00
9,11,12,13,14, 15,16,17,18,19	8.52E-10	0.00E+00	1.66E-06	1.66E-06	1.66E-06	0.00E+00

Figure 2. Comparison of HLW and PWR Transport Accident Risk Spectra



Since there are almost 5 times more HLW shipments than PWR shipments, it would be expected that at the top end of the curve the HLW curve would be higher than the PWR case by this factor. The results are similar because for the HLW case there is no risk contribution from the fire only scenario. The PWR curve extends to higher doses because of fuel pressurization and because the failure of the fuel clad at 750 °C results in a greater release. Additionally, in HLW, the cesium and ruthenium are assumed to be bound up in the glass and are released as particulates.

The true advantage of using databases is that the same query can be applied to all waste types being modeled in the database. This makes validation of the calculations much easier. Validate the results for one fuel type shipment traveling through one state, check that all states are being included in the query and the results have been validated.

SUMMARY

It has been shown that the release models developed in NUREG/CR-6672 can be applied to casks carrying other fuel forms by making reasonable assumptions regarding the difference in behavior of the waste forms during a severe transport accident. The flexibility of databases to perform queries of the data to determine accident consequences and likelihoods and to develop insightful risk curves has been shown. Many additional queries could easily be developed to identify other in-bedded characteristics of the transportation routes and the transport accident environment.

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