NUREG/CR-6672: ACCIDENT SEVERITY AND RELEASE FRACTIONS

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ABSTRACT

Simple models for severe accident source term severity and release fractions are described. Severity fraction equations are developed for collision accidents that do not initiate fires, for collision accidents that do initiate fires, and for fires not initiated by collisions. Rod-to-cask and cask-to-environment release fraction equations are developed for noble gases, for vapors that contain Cs or Ru, for CRUD, and for fuel fines. The rod-to-cask release fractions for fuel fines treat fuel pellet fracturing, particle bed formation, and particle filtering by those particle beds. The effects of fuel oxidation on Cs and Ru release fractions are discussed. Also discussed are the use of GIS methods of analysis to develop improved occurrence frequencies for shipment route wayside surfaces and the use of tank car accident data to develop probabilities for cask failure by puncture or shearing. Finally, the set of severity and release fractions developed for the transport of PWR spent fuel in a steel-lead-steel rail cask are presented to illustrate the results obtained using these severity and release fraction expressions.

INTRODUCTION

The spent fuel transportation accident risks presented in NUREG/CR-6672 [1] were calculated using Version 5 of the RADTRAN code [2,3]. To calculate accident risks, RADTRAN 5 must be provided input data that define a representative set of accident source terms and their probabilities of occurrence. The accident source term (ST_k) for each important radionuclide k in spent fuel was calculated for NUREG/CR-6672 as the product of (a) the cask inventory (I_k) of radionuclide k calculated using ORIGEN [4,5]; (b) the fraction of the spent fuel rods in the cask (f_{rod}), calculated as described in the third paper in the session, that are failed by the accident; and (c) the fraction ($f_{release,k}$) of radionuclide k in a spent fuel rod that escapes to the environment, if the rod is failed by the accident. Thus, $ST_k = I_k f_{rod} f_{release,k}$. Values of f_{rod} were calculated as described in the third paper of this session. The probability (P) per shipment that this release occurs was calculated as the product of the shipment route length (L), the accident rate on that route (R), and the fraction (F_i) of all possible accidents that would cause the release of the accident's source term. Thus, $P = LRF_i$, where F_i is called a severity fraction.

Four types of representative accidents were examined by the NUREG/CR-6672 study: collisions that fail the cask seal but do not initiate fires (Category 4 accidents), collisions that fail the cask seal and also initiate fully engulfing optically dense, long-duration fires (Category 5 accidents), collisions that fail both the cask seal and the body of the cask and also initiate an optically dense, slightly offset, long-duration fire (Category 6 accidents), and fire-only accidents.

Four unyielding surface impact speed ranges (30-60, 60-90, 90-120, and 120-150 mph) and three temperature ranges (T_a-T_s, T_s-T_b, and T_b-T_f) were examined, where T_a = 300?C is the internal temperature of the spent fuel cask under ambient conditions [6], T_s = 350?C is the temperature at which elastomeric cask seals fail due to thermal degradation [7,8], T_b =750?C is the temperature

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at which spent fuel rods fail by burst rupture [9,10], and T_f = 1000?C is the average temperature of a hydrocarbon fuel fire [11]. Figure 1 shows that these speed and temperature ranges produce 21 accident cases, 4 collision only cases, 12 collision + fire cases, 4 cask double-failure cases, and 1 fire-only case.

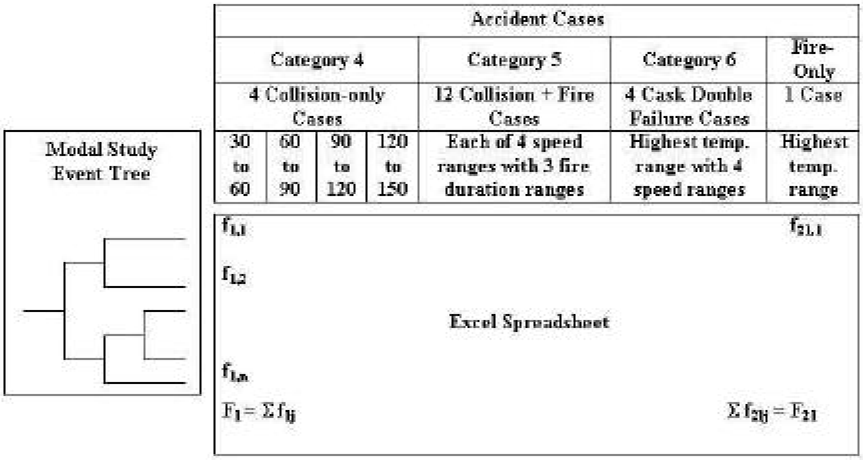

Figure 1. Scheme for calculating Severity Fractions for the 21 representative accident cases

SEVERITY FRACTIONS

Severity fractions (F_i where i is an accident case index) were developed by estimating the chance of reaching each of these 21 accident cases from the each of the endpoints on either the truck or the train accident event tree published in the Modal Study [12]. Thus, $F_i \; ? \; \underset{j}{?} \; f_{ij}$ where j denotes a scenario (accident path) endpoint on one of these Modal Study accident event trees. Figure 1 schematically depicts this process.

For Category 6 accidents, collisions that fail both the cask seal and the cask body and also initiate an optically dense, long-duration fire, f_{ij} is calculated using the following expression:

$$f_{ij} = f_{\text{scenario } j} P_{\text{speed } j} P_{\text{fire/collision } j} P_{\text{severe fire}} P_{\text{puncture/shear}}$$

where $f_{\text{scenario } j}$ is the fraction of all accidents that follow scenario j, $P_{\text{speed } j}$ is the probability that accident scenario j takes place at a speed that falls, for example, into the speed range v_{30}-v_{60}, $P_{\text{fire/collision } j}$ is the probability that scenario j initiates a fire, $P_{\text{severe fire}}$ is the chance that the fire is an optically dense, fully engulfing fire that last long enough to heat the cask and its contents to temperatures that fall within one of the three temperature ranges (the highest temperature range for Category 6 accidents), $P_{\text{puncture/shear}}$ is the chance that the collision fails not only the cask seal but also the cask body by puncture or shearing, and v_{30} and v_{60} are the cask impact speeds onto the real world yielding impact surface (e.g., soft rock, hard soil, clay, silt, ….) specified by Modal Study accident scenario j, that cause the same damage to the cask as is done by 30 and 60 mph impacts onto an unyielding surface. Values of impact speeds onto yielding surfaces that produce the same damage as, 30, 60, 90, and 120 mph impacts onto an unyielding surface were calculated as described in the third paper in this session [13]. The time periods required by fully engulfing, optically dense, hydrocarbon fueled fires to heat each of the four generic casks examined by NUREG/CR-6672 to the three temperatures of concern, T_s, T_b, and T_f, were determined as described in the second paper in this session [14]. The probability of cask failure by puncture or shearing was estimated from failure data from rail tank cars [15]. Other probabilities were estimated from accident data or taken from the Modal Study.

Expressions for f_{ij} for other accident categories are obtained by dropping parameters from the Category 6 expression for f_{ij}. The following table shows the parameters in the Category 6 expression for f_{ij} that are retained in the expressions for f_{ij} for other accident categories (Category 4 or Category 5 or the Fire-Only accident category).

Terms in the expression for f_{ij} used for each accident category

	$f_{ij} = f_{scenario\ j}$	$P_{speed\ j}$	$P_{fire/collision\ j}$	$P_{severe\ fire}$	$P_{puncture/shear}$
Category 6 Accidents	x	x	x	x	x
Category 5 Accidents	x	x	x	x	
Category 4 Accidents	x	x			
Fire-Only Accidents	x			x	

The finite element impact calculations described in the third paper of this session [13] indicated that only a high-speed impact onto an unyielding surface could threaten the integrity of a spent fuel cask. Therefore, the occurrence frequencies of hard rock route wayside surfaces were estimated using U.S. Agriculture Department data [16] and Geographic Information System (GIS) methods of analysis [17] for three long routes: (1) a very densely populated route, the Maine Yankee nuclear plant to Savannah River; (2) a very long transcontinental route, the Crystal River nuclear plant to Hanford; and (3) a route with properties similar to the means of the route parameter distributions described in the fifth paper in this session [18], the Kewaunee nuclear plant to Savannah River. These GIS analyses suggested that the frequencies of occurrence of hard rock route wayside surfaces may be somewhat larger than was assumed in the Modal Study.

RELEASE FRACTIONS

The release of radionuclide k from a failed spent fuel rod to the environment was modeled in NUREG/CR-6672 as a two step process, where the first step was release from the failed rod into the cask interior, and the second step was transport through the cask to the cask leak and escape through that leak to the environment. Thus, the release fraction ($f_{release,k}$) for radionuclide k was calculated as $f_{release,k} = f_{RCk}f_{CEk}$, where f_{RCk}, the Rod-to-Cask release fraction, is the fraction of radionuclide k in the failed rod that escapes from the rod to the cask interior, and f_{CEk}, the Cask-to-Environment release fraction, is the fraction of the amount of each radionuclide released to the cask interior that escapes from the cask interior through the cask leak to the environment.

Cask-to-Environment Release Fractions. Depressurization of a leaking cask after pressurization due to failure of spent fuel rods will cause gases, vapors, and particles to be transported from the leaking cask to the environment. Once depressurized, release by diffusion will occur but can be neglected. Cask-to-Environment release fractions (f_{CE}) for release due to cask depressurization were calculated as

$$f_{CEk} = (1 - f_{deposition,k})\left(1 - \frac{p_{atm}T_a}{p_{acc}T_{acc}}\right)$$

where the first term corrects for deposition of condensible vapors and particles onto cask interior surfaces, p_{atm} is atmospheric pressure, T_a is the internal temperature of the cask under ambient conditions, p_{acc} is the maximum pressure attained inside of the cask upon rod depressurization, and $T_{acc} = T_a$, T_s, T_b, or T_f depending on the temperature range of the accident scenario.

Figure 2 presents the dependence of f_{CEk} on the cross-sectional area of the cask leak as calculated using MELCOR [19] for a TN-12 cask failed by a collision that doesn't initiate a fire [20]. Leak areas for collision accident cases were calculated as described in the third paper of this session [13]. Since all fire accidents were assumed to destroy the cask's elastomeric seal, the leak area for fire accidents was taken to be the product of the cask circumference and the surface roughness height of the cask closure surfaces.

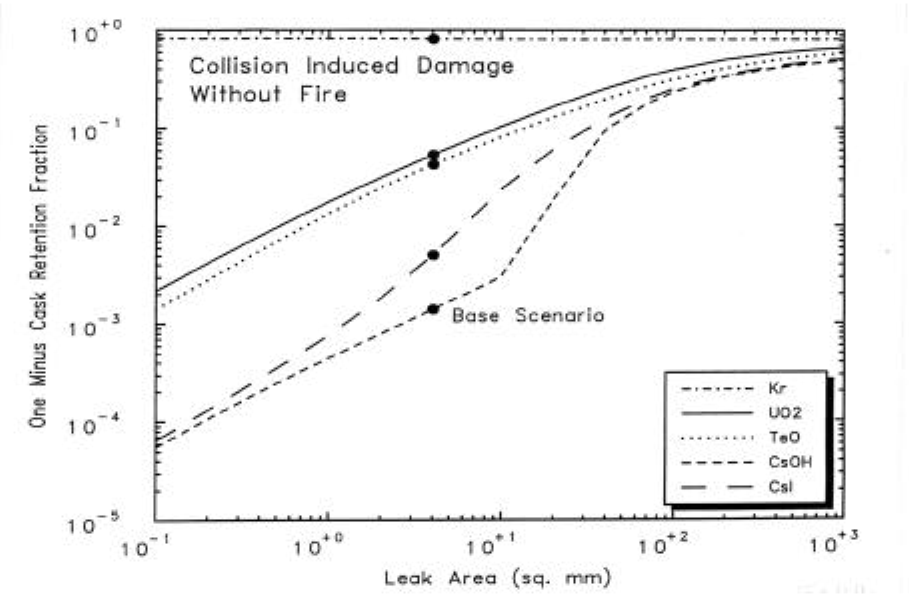

Figure 2. Dependence of Cask-to-Environment Release Fractions (1.0 – Retention Fraction) on the Size of the Cask Failure (leak area).

For the MELCOR calculations for TN-12 cask collision-only accidents,

$$f_{CEk} \; ? \; ?1 ? f_{deposition,k} \, ?? 1 ? \frac{p_{atm}}{p_{acc}} ?$$

Therefore, since, f_{CEk}, p_{atm} and p_{acc} are known, $f_{deposition,k}$ could be calculated for particles and CsI for any cask leak area.

Rod-to-Cask Release Fractions. ORIGEN [4,5] calculations provide results for about 800 radionuclides. For NUREG/CR-6672, radionuclides not important for population dose were eliminated from the ORIGEN output using the RADSEL code [21] which screens radionuclides using A_2 values [22,23] as a measure of importance. This yielded BWR and PWR inventories for a single fuel assembly that respectively contained 20 and 21 radionuclides. To simplify the estimation of f_{RCk} values, these radionuclides were divided into five chemical element groups: noble gases (Kr-85), Cs compounds (CsI), Ru compounds (RuO_2 and RuO_4), CRUD which contains CO-60, and particles, which contain all the remaining radionuclides. Expressions for

f_{RCk} for each of these five chemical element groups were developed using models and data identified by literature reviews, especially the experimental results of Lorenz et al. [24-27], who measured the release of fuel fines (as Eu-154), Cs-134, and Ru-106 from sections of spent fuel rods upon failure by burst rupture.

Noble Gases. PWR spent fuel rods are pressurized with helium to about 30 atmospheres and BWR rods to about 15 atmospheres. Thus, when a spent fuel rod fails and depressurizes to atmospheric pressure, almost all of the gasborne species will be carried out of the rod with the depressurization flow of helium. Thus, if the occlusion of noble gas atoms in fuel fines is unimportant or neglected, rod-to-cask release fractions for noble gas fission products should have values close to 1.0.

Particles. In order to develop particle release fractions that apply to transportation accidents, the release fraction for fuel fines determined by Lorenz [24] must be adjusted to account for impact fracturing caused by impact loads, particle bed formation, and filtering of respirable particles during transport through particle beds. The fraction of the UO_2 fuel mass converted to respirable fuel fines by pellet fracturing due to impact loads during collision accidents was modeled [28] as $F_{respirable} = A?gh = 0.5\ A?(v_{impact})^2$. Because the dependence of A on v_{impact} was not available, v_{impact} was assumed to be 120 mph for all collisions even though collapse of assembly structures is expected to absorb much of the energy associated with the cask impact. Impact fracture data for depleted UO_2 shows [29] that 99 percent of the total particle mass is in particles with diameters ? 200 ?m. Because the internal cracks in spent fuel pellets and the shrunken fuel cladding gap in spent fuel rods have widths much smaller than 200 ?m, fuel fine particle beds should form in these spaces and be augmented by fuel fracturing during collision accidents. Interception will be the dominant particle capture mechanism by a bed of 200 ?m particles [30]. If the total bed capture efficiency is equated to the interception efficiency, solution of the resulting equation shows that bed lengths of about 0.3 cm will collect 99 percent of the 10 ?m particles that pass through the bed [31]. Accordingly, for collision accidents, efficient filtering was assumed to occur along almost the entire length of the rod. For fire-only accidents, the release fraction for particles determined by Lorenz by examination of 1 ft sections of spent fuel rods was applied to the 1 ft portion of the full rod that contains the rod failure and particle bed formation and efficient filtering was assumed to apply to the remaining 11 feet of active fuel.

Cesium. Although the equation for release of Cs determined by Lorenz et al. [26,27] has the form A exp (? C/T) and thus has the form of a vapor pressure equation, the experimental value of C, 7420 K^{-1}, it not similar to the value of C for any reasonable Cs vapor species. For example, the value of C for CsI, when the vapor pressure equation for CsI is expressed as an exponential, is 22862 K^{-1}, not 7420 K^{-1}. This discrepancy is explained as follows. Lorenz et al. measured total Cs, not Cs in vapor species. Since their experiments released Cs as a constituent, not only of vapors, but also of particles, Cs release should have been modeled as the sum of a particle release expression and a vapor release expression. If the Cs release expression of Lorenz et al. is equated to the sum of a release fraction for CsI vapor and a release fraction for particles, the following equation is obtained:

$$a\,V_{burst}\,?\frac{M_{gap}}{A_{clad}}?^{0.8}\;\exp ??\;?C/T_b\;??\;?\;MW_{CsI}\,\frac{V_{rod}}{RT_b}\,10^{?a/T_b\;?b}\;?\;M_{inventory}F_{particles}$$

Substitution of CsI values for MW_{CsI} and for a and b [32] and values developed by Lorenz et al. [26,27] for all other parameters in this expression except C, allows a value of C = 7960 K-1 to be calculated. Since this agrees well with the experimental value determined by Lorenz et al., Cs release was assumed to occur both as CsI (or CsOH) vapor and was modeled using the two terms on the right side of the preceding equation.

Oxidative Release Fractions. The double cask failure assumed for Category 6 accidents allows combustion gases and air to flow through the cask. This flow was assumed to have two effects. First, it was assumed to transport out to the environment all materials released from failed rods to the cask interior (i.e., for Category 6 accidents, deposition of particles and vapors onto cask interior surfaces was neglected). Second, the O_2 and CO_2 in this gas flow was assumed to oxidize any exposed fuel pellet surfaces. Lorenz et al. [24] found that Cs release and Ru release were increased respectively by factors of 54.6 and $2.02x10^4$ when the experimental atmosphere was dry air rather than steam. The increase is believed to be caused by the oxidation of involatile RuO_2 to volatile RuO_4 and of UO_2 to U_3O_8, which increases the pellet surface area and facilitates the escape of Cs vapors. If, as is shown in Figure 3, this oxidation is assumed to occur in a small disc of UO_2 with a height h_{ox} and a volume V_{ox}, that is located below the burst rupture failure hole in the rod section, and, in addition, release of Cs and Ru from this oxidized disc is assumed to be total, then use of either the Cs or the Ru enhancement factor allows the height of this disc to be estimated to be about 0.1 mm and its volume to be 0.3 mm^3. Therefore, the ratio of the oxidized volume of spent fuel in a failed rod to the volume of all of the pellets in that rod gives the release for Cs and Ru, that is caused by oxidation of spent fuel, when that fuel is exposed to oxygen at temperatures ? T_b, the burst rupture temperature of spent fuel rods [33].

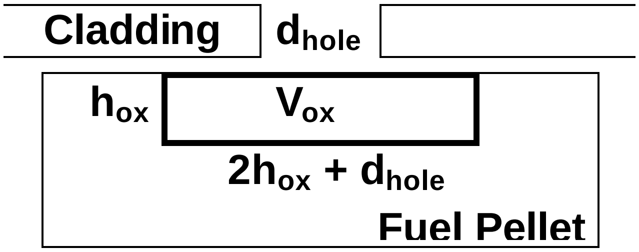

Figure 3. Schematic of Oxidized Spent Fuel Disc

CRUD. Reactor water chemistry causes deposits that contain Ni to form on the surface of spent fuel rods. Activation of Ni then produces Co-60, which can be released if these CRUD deposits spall off of rod surfaces due to mechanical or thermal loads during transportation accidents. There is almost no data on CRUD spallation. Sandoval et al. [34] estimated that CRUD spallation might cause 15 percent of the CRUD deposits on a spent fuel rod to be released during transportation accidents. In the absence of additional data, the NUREG/CR-6672 study assumed that spalled CRUD would deposit onto cask interior surfaces like fuel fines (e.g., same deposition fractions) and that the fraction of the CRUD deposits on rod surfaces released by spallation would be 0.1 for collision accidents, 0.05 for fires initiated by collisions, and 0.15 for fires not initiated by collisions.

TYPICAL RELEASE AND SEVERITY FRACTIONS

Substitution of values into the expressions developed for source term release and severity fractions and rounding of values in order to be conservative allowed values to be developed for these source term parameters for PWR and BWR spent fuel when transported in each of the generic casks described in the second paper in this session [14]. Table 1 presents the release fraction and severity fraction values developed for PWR spent fuel when transported in a steel-lead-steel Type B rail cask.

Steel-Lead-Steel Rail Cask						
Number of PWR Fuel Assemblies: 24						
Case	**Severity Fraction**	**PWR Release Fractions**				
		Kr	**Cs**	**Ru**	**Particulates**	**CRUD**
1	3.59E-03	0.0	0.0	0.0	0.0	0.0
2	8.20E-06	4.1E-01	1.2E-08	2.5E-07	2.5E-07	1.4E-03
3	5.68E-07	8.0E-01	8.6E-06	1.3E-05	1.3E-05	4.4E-02
4	4.49E-09	8.0E-01	1.8E-05	1.9E-05	1.9E-05	6.4E-02
5	2.96E-05	1.4E-01	4.1E-09	1.0E-07	1.0E-07	1.4E-03
6	8.24E-07	1.8E-01	5.4E-09	1.3E-07	1.3E-07	1.8E-03
7	1.10E-07	8.4E-01	3.6E-05	1.4E-05	1.4E-05	5.4E-03
8	6.76E-08	4.3E-01	1.3E-08	2.6E-07	2.6E-07	1.5E-03
9	1.88E-09	4.9E-01	1.5E-08	2.9E-07	2.9E-07	1.7E-03
10	2.51E-10	8.5E-01	2.7E-05	6.8E-06	6.8E-06	4.5E-03
11	4.68E-09	8.2E-01	8.8E-06	1.3E-05	1.3E-05	4.5E-02
12	1.31E-10	8.9E-01	9.6E-06	1.5E-05	1.5E-05	4.9E-02
13	1.74E-11	9.1E-01	1.4E-05	1.5E-05	1.5E-05	5.1E-02
14	3.70E-11	8.2E-01	1.8E-05	2.0E-05	2.0E-05	6.5E-02
15	1.03E-12	8.9E-01	2.0E-05	2.1E-05	2.1E-05	7.1E-02
16	1.37E-13	9.1E-01	2.2E-05	2.2E-05	2.2E-05	7.4E-02
17	4.15E-10	8.4E-01	9.6E-05	8.4E-05	1.8E-05	6.4E-03
18	2.51E-13	8.5E-01	5.5E-05	5.0E-05	8.9E-06	5.4E-03
19	1.74E-14	9.1E-01	1.4E-05	1.8E-05	1.5E-05	5.1E-02
20	1.37E-16	9.1E-01	2.2E-05	2.3E-05	2.2E-05	7.4E-02
21	4.91E-05	8.4E-01	1.7E-05	2.5E-07	2.5E-07	9.4E-03
22	0.99632	0.0	0.0	0.0	0.0	0.0
	1.00000					

Table 1. Severity and Release Fractions for PWR Spent Fuel Transported in a Steel-Lead-Steel Type B Rail Cask

In Table 1, the release fractions for Accident Cases 1 and 22 all have values of zero. Accident Case 1 has values of zero because the finite element calculations described in the third paper in this session [13] indicate that a steel-lead-steel Type B rail cask will not fail due to impact at speeds below 60 mph regardless of the hardness of the impact surface. Accident Case 22 has values of zero because it represents all of the accidents that might occur that are characterized by conditions less severe than the conditions which define Accident Cases 1 through 21. Thus, by definition, it is the “nothing happens” accident case.

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