THE POTENTIAL IMPORTANCE OF WATER PATHWAYS FOR SPENT FUEL TRANSPORTATION ACCIDENT RISK

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ABSTRACT

This paper analyzes the potential importance of water pathway contamination for spent fuel transportation accident risk using a "worst-case" water contamination scenario. The scenario used for the analysis involves an accident release that occurs near a reservoir. Water pathway doses are compared to doses for accident releases in urban or agricultural areas. The results of the analysis indicate that water pathways are not important for assessing the risk of transporting spent reactor fuel by truck or by rail.

INTRODUCTION

This paper discusses a worst-case analysis of potential water pathway exposures for transportation accidents involving shipment of spent fuel by truck or rail. A worst-case scenario was sought to provide an index for comparison of the potential dose from water pathways to all other exposure routes currently treated in transportation risk analyses. These analyses were used to determine if water pathways should be incorporated into assessments of spent fuel transportation risk. Historically, analyses have treated only "terrestrial" exposure pathways for accidents in urban, suburban, and rural areas[1]. These pathways include external exposure from a radioactive plume, external gamma exposure from radionuclide deposits on the ground, inhalation of radionuclides from a radioactive plume, inhalation of resuspended radionuclides, and ingestion of contaminated food products.

Surface waterbodies can be contaminated directly by a release from a damaged immersed cask or indirectly by a release from a nonimmersed cask (see Fig. 1). Indirect contamination would involve a radioactive aerosol release from a damaged shipping cask to the atmosphere. Following the release, some portion of the aerosol could be deposited directly onto a waterbody. A small fraction of any radionuclide deposit to land could ultimately be washed into a surface waterbody[2,3]. Direct contamination of a waterbody would involve radionuclede release from a damaged shipping cask immersed in the waterbody. For truck and rail shipments of waste, immersion of the cask would be limited to accidents which occur over or very near to surface waterbodies (e.g., accidents on bridges). Direct contamination of a waterbody is less likely to occur than is indirect contamination of a waterbody.

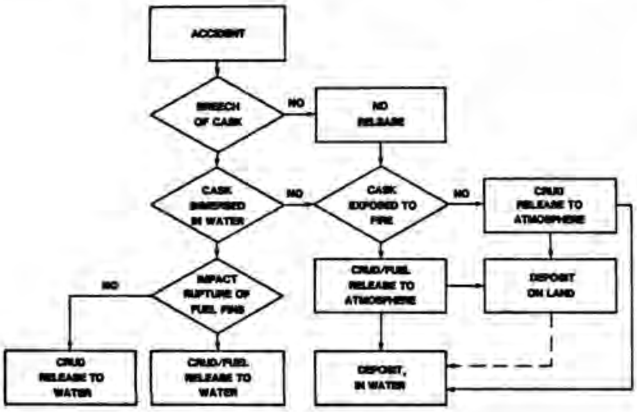

Fig. 1. Water Contamination Mechanisms for Credible Spent Fuel Transportation Accidents.

The largest levels of water contamination are likely to result for the indirect contamination scenarios. For accidents that do not lead to immersion of a damaged cask, the release would be principally reactor system activation products if there were no exposure of the cask to a fire[4]. These products are contained in "crud" deposits on the outside of the fuel elements that might be dislodged during the accident. For accidents involving prolonged exposure of the damaged cask to a significant fire, the fuel rods might rupture and yield a release of fission products[4]. Except for the inert gasses, a fission product release can occur only with sufficient heating of the fuel matrix. These radionuclides might be vented through a breech in the cask caused by the accident. Given the appropriate conditions, it is conceivable that most of a release to the atmosphere could be deposited onto a waterbody.

Following a truck or rail accident, the radionuclide release from an immersed cask is not likely to be larger than that for situations where the cask is not immersed in water. Given water immersion, the magnitude of the crud release is likely to be similar to that which might occur without immersion. However, because it is impossible for an immersed cask to be exposed to fire, the potential for fission product release is much reduced. Given cask immersion, the only process that could lead to release of fission products involves water leaching of fission products from the fuel matrix with subsequent release of these radionuclides from the cask. Release of fission products via the water leaching process would be minimal because 1) very few fuel pins would fail due to the accident impact[4], 2) leach rates for exposed fuel pellets are small[5], 3) cask breeching, which should be similar to that for situations not involving immersion of the cask, will, at worst, involve failure of a cask seal or a small hole in the cask body such as a crack[4], and 4) efforts will be made to recover the damaged cask within a reasonable period of time. In any case, the leach release of radionuclides for water immersion is likely to be much less than the release which might occur given prolonged exposure of a damaged cask to a fire. Therefore, for credible truck and rail accidents, the highest level of water contamination for any severity of accident is bounded by that which can occur for nonimmersion scenarios (i.e., indirect contamination).

The scope of this worst-case analysis was limited to a water contamination scenerio which involves deposition of radioactive aerosol onto a reservoir. The purpose of this approach was to determine if the issue of water pathway analysis should be further pursued in transportation risk assessment. This scenario is likely to result in the highest credible levels of water pathway contamination. The accident scenario, modeling approach, and results are discussed separately below.

ACCIDENT SCENARIO

The contamination scenario assumes a truck accident involving a shipment of spent reactor fuel. (The relative comparison for a truck accident is also applicable to rail shipments.) For this scenario, it was conservatively assumed that the accident occurs near the shore of a reservoir, that 100% of the aerosol release is deposited in the reservoir, that the reservoir is used exclusively as a municipal water source, and that water is not released from the reservoir. With respect to assuming that the reservoir is used as a municipal water source, water ingestion is considered to be the "critical" exposure pathway for freshwater contamination by radionuclides[6,7]. A river exposure was not included because the opportunity for prolonged exposures to limited populations is not realized.

Assuming that the reservoir is used exclusively as a municipal water source maximizes the population dose. Incorporation of assumptions regarding industrial, commercial, and agricultural uses of water into the analysis would act to reduce estimates of radiation dose to the human population.

In addition, it is highly unlikely that 100% of the aerosol release would actually be deposited onto the reservoir. Depending on the size of the reservoir and on the weather conditions at the time of the accident, the deposition fraction is likely to be much less than 100 percent of the release.

MIXED TANK MODEL

A mixed-tank lake model[8] was used to simulate the reservoir. For this model, it is assumed that radionuclides deposited onto the reservoir become uniformly mixed within the water volume. This mixed-tank assumption can occur only if the radionuclide deposit is in a water soluble chemical form. Insoluble deposits would likely settle to the lake bottom and ultimately would be covered by sediment. Processes that remove radionuclides from the mixed tank include radionuclide decay, sedimentation, and municipal withdrawal. For this scenario, inclusion of exposure pathways such as recreational fishing and swimming would have a negligible impact on the estimates of population dose[2,7]. Figure 2 provides a pictorial description to the mixed-tank model. This scenario assumes *maximum* usage of the reservoir for a drinking water source.

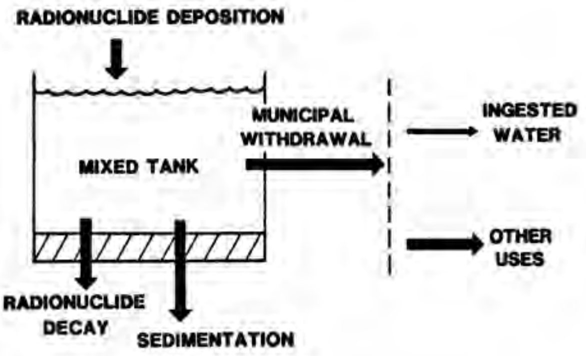

Fig. 2. Pictorial Description of the Mixed Tank Model.

Because lakes have small "flow velocities", most of the sediment introduced into lakes via streams or rivers will fall to the lake bottom. During this process, the sediment will sorb radionuclides from the water volume and carry these radionuclides to the lake bottom. Because of the high sedimentation rates characteristic of reservoirs[9,10], sediment deposits of radionuclides are effectively buried and become unavailable for recontamination of water.

Assuming a constant water volume, a constant withdrawal rate, and a constant sedimentation rate, the radionuclide concentration within the reservoir can be described by

$$dC(t)/dt = -(\lambda_R + \lambda_W + \lambda_S)C(t) \tag{1}$$

where C is the radionuclide concentration in water (Ci/m^3), λR is the radionuclide decay rate (yr^{-1}), λw is the loss rate due to municipal withdrawal (yr^{-1}), and λ_S is the loss rate due to sedimentation (yr^{-1}). Given a radionuclide deposit of magnitude A at time t=0.0, Eq. (1) can be solved to yield

$$C(t) = (A/V)\exp(-(\lambda_R + \lambda_W + \lambda_S)t) \tag{2}$$

where V is the reservoir volume (m^3) and A is the magnitude of the radionuclide deposit (Ci).

The rate of radionuclide ingestion for the manucipality is given by

$$IG(t) = C(t) \times \lambda_W \times V \times f_I \tag{3}$$

where f_I IS The fraction of municipal withdrawal used for human ingestion. Given Eq. (3), the time-integrated population exposure is given by

$$IE = \int_0^\infty IG(t)dt \tag{4}$$

or

$$IE = \lambda_W \times f_I \times A/(\lambda_R + \lambda_W + \lambda_S). \tag{5}$$

The population dose commitment is determined by multiplying the estimate of population ingestion exposure by a dose conversion factor.

The sedimentation loss rate, λ_S, is given by

$$\lambda_S = S \times \rho_S \times K_d/d_W \tag{6}$$

where S is average sedimentation rate for the reservoir (m/yr), ρ_S is the sediment density (g/cm^3), d_W is the average reservoir depth (m), and K_d is the radionuclide distribution coefficient for freshwater (cm^3/g). The distribution coefficient, K_d, is the ratio of the amount of radionuclide sorbed *on sediment* (Ci/g) to the amount of radionuclide left in solution (Ci/cm^3). For this model, ρ_s is taken to be 1.5 gm/cm^3, S is assigned a value of 0.02 m/yr and d_w is taken to be 7 m. Both the sedimentation rate and the average water depth are based on statistics in Reference 9 and 10. A sedimentation rate of 2 cm/yr reflects the lower limit of sedimentation rates for U.S. reservoirs. Sedimentation rates in excess of 10 cm/yr are common. The distribution coefficients used for the analysis are from Reference 8 and are median values for freshwater. The distribution coefficients should be considered highly uncertain due to variability in parameters such as radionuclide state and concentration, sediment type and concentration, the flow characteristics and water quality of a receiving surface waterbody, and contact time. Table I contains the values of K_d used for the analysis. The table also shows the variation in each K_d value, which is reported in Reference 8.

TABLE I

Sedimentation Removal Rates for Elements Considered in the Analysis

ELEMENT	K_d* (cm^3/g) RANGE	MEDIAN	$_s(y^{-1})$
Co	1,000-71,000	5,000	21
Sr	8-4,000	1,000	4.3
Eu	200-800	500	2.1
Cs	50-80,000	1,000	4.3
Pu	$100-10^7$	10,000	43
Ru	---	---	0.0

*These coefficients are from Ti-83.

The water ingestion fraction, f_I, is determined by dividing the average per capita ingestion of water by the average per capita usage of water in U.S. municipalities. For this model, the per capita ingestion of water used is 1.9 liter/day[11] and the per capita usage for municipalities is 630 liter/day[12]. The per capita usage of water reflects the average for the U.S. and does not incorporate commercial, industrial, and agricultural use of water. Based on the above data, the water ingestion fraction for municipalities is 0.003.

The reservoir was assumed to contain a two year supply for the municipality. Thus, the water withdrawal rate, λ_W, is assumed to be 0.5 yr^{-1}.

Finally, it was conservatively assumed that water treatment does not impact water contamination levels. Processes such as sand bed filtration and flocculation would, in fact, reduce contamination levels in the municipal water system.

CALCULATIONS/RESULTS

Population doses were calculated and compared for the worst case water contamination scenario and for the terrestrial accident scenarios treated by the RADTRAN III computer code[1]. RADTRAN III estimates population doses for accidents in urban, suburban, and rural areas. The exposure pathways treated by RADTRAN III include external gamma exposure from a radioactive plume, external gamma exposure from ground deposits, inhalation from the plume, inhalation of resuspended radionuclides, and ingestion of contaminated food. Ingestion of contaminated food is a factor only for accidents in rural areas.

The accident release fractions used for this analysis are those used for assessing the risk of transporting spent reactor fuel[13,14]. The release fractions are given for accidents in each of six severity categories (see Table II). Accident categories 1 and 2, which do not involve radionuclide release, account for more than 99.9% of the postulated truck accidents. Accident category 3 involves failure of the shipping cask followed by a release of "crud" deposits which are knocked loose from the fuel pins. Accident category 3 involves failure of cask containment and exposure of the cask to a fire of less than 0.5 hour duration. Impact failure of fuel pins is assumed for this scenario. Accident categories 5 and 6 involve failure of the cask and exposure of the cask to prolonged fires. In addition to the "crud" release, there is substantial release of fission products due to heating of the spent fuel. A detailed derivation of the release fractions is given in Reference 4.

TABLE II

Release Fractions as a Function of Accident Severity Category

	Accident Severity Category					
ELEMENT	1^B	2^B	3	4	5	6
Co	0	0	0.012	0.012	0.012	0.012
Kr*	0	0	0	0.01	0.1	0.11
Cs	0	0	0	$1x10^{-8}$	$2x10^{-4}$	$2.8x10^{-4}$
Eu,Sr,Pu	0	0	0	$1x10^{-8}$	$5x10^{-8}$	$5x10^{-8}$
Ru	0	0	0	$1x10^{-8}$	$1x10^{-5}$	$4.2x10^{-5}$

As noted earlier, a highway accident involving a shipment of spent PWR fuel was assumed for the analysis. The radionuclide inventory for the shipment, which is from[14], is given in Table III. This inventory is for a cask containing two PWR fuel assemblies that have been out of the reactor for 10 years.

TABLE III

Radionuclide Inventories

RADIONUCLIDE	CASK INVENTORY (Ci)
Co-60	48
Sr-90	$5.2(10^4)$
Ru-106	500
Eu-155	4200
Cs-Isotopes	$8.0(10^4)$
PU-Isotopes	$7.8(10^4)$

A comparison of the population doses calculated for the water contamination and the terrestrial accident scenarios is given in Table IV for accident categories 3 through 5. For each release category, the population doses are normalized to those for the urban accident. The RADTRAN III calculations for the urban, suburban, and rural areas incorporate protective action assumptions which act to reduce estimates of population dose (e.g., evacuation and decontamination). The water-pathway calculations do not incorporate assumptions regarding protective actions.

The results in Table IV suggests that the worst case reservoir doses are substantially less than those for the urban and suburban accident scenarios. For accident categories 3 and 4, the reservoir doses for the urban accident are a factor of 150 less than those for the suburban accident. The differences for accident categories 5 and 6 are less than those for categories 3 and 4. This results in part from the protective actions assumed for the urban and suburban accident scenarios. These actions act to reduce the estimates of population dose for the accident. No protective actions are incorporated into the water-pathway calculations. The smaller difference in dose for categories 5 and 6 is also a result of the fact that the mix of radionuclides differs for the releases. For accident categories 3 and 4, the releases are principally cobalt-60 while the releases for accident categories 5 and 6 are mostly cesium-137. Per unit release, cobalt-60 is more important than cesium-137 for external gamma doses, which are a factor for the terrestrial accidents, and less important than cesium-137 for the water-pathway doses where water ingestion is the only pathway.

Another important observation regarding the results in Table IV is that the worst case reservoir dose is roughly comparable to that for the RADTRAN III rural accident scenario. This is significant because 1) the rural scenario, althoudh improbable itself, is more probable than the water contamination scenario and 2) "best estimate" assumptions are used to calculate the rural accident dose (i.e., the rural accident assumptions do not "maximize" estimates of population dose as do those for the water contamination scenario).

ACCIDENT CATEGORY	Urban	Suburban	Rural	Reservoir
3	1.0*	0.31	0.0035	0.0019
4	1.0	0.31	0.0035	0.0019
5	1.0	0.31	0.018	0.023
6	1.0	0.31	0.017	0.021

*The estimates of population dose increase with increasing accident severity.

[B] Normalized to urban accident dose.

[a] Accident categories 1 and 2 do not involve the release of radionuclides

Variation in model parameters is not expected to have a substantial impact on the above observations. Although a worst-case contamination scenario was used for the water pathway analysis (i.e., 100% deposition of the radionuclide release onto a municipal reservoir), "typical" values were used for the model parameters (i.e., K_d values, sedimentation rates, etc.). However, variation in the model parameters that have the largest impact on the water pathway dose estimates, and are the most variable, include the distribution coefficients and the sedimentation rate. Given the range of K values shown in Table I, the estimates of water pathway dose can be a factor six larger to nearly two orders of magnitude smaller than those discussed above due to variation in the distribution coefficients. The sedimentation rate used for the analysis reflects the lower limit of sedimentation rates for U.S. reservoirs. Use of an average or median sedimentation rate could lead to estimates of dose that are a factor of four or more smaller than those discussed above.

The water-pathways model used in this study should not be used for the assessment of transportation accident risk since it reflects a worst case consequence scenario. The use of best estimate assumptions regarding the level of water contamination, protective actions, and water usage would lead to water-pathway doses that are one or more orders of magnitude smaller than those estimated using the above worst case model.

In addition, it is possible that water contamination levels could exceed contamination limits given in Title 10 of the Code of Federal Regulations (i.e., 10 CFR Part 20). In such an event, it is likely that use of the waterbody would be prohibited until contamination levels reach an acceptable level. However, contamination levels in excess of the limits is possible only for the largest accident releases (e.g., accident categories 5 and 6 in Table II) and for sufficiently small reservoirs. In the case of the water contamination scenerio assumed for this paper, water contamination limits could only be exceeded for reservoirs with volumes less than 1.5×10^6 m^3 (i.e., 1000 acre-ft or less). Given more credible assumptions regarding the fraction of the release deposited onto a waterbody, the critical volume could be 100 acre-ft or less. These do not represent reservoirs that serve a significant number of people.

Finally, incorporation of other exposure pathways such as consumption of contaminated fish and recreational uses of the reservoir could have a minor impact on the estimates of population dose. Recreational exposures, which include immersion of swimmers and shoreline exposures, will lead to very minimal contributions to radiation exposure (e.g., see Reference 6 and 7). Ingestion of aquatic food, game fish in this case, is not likely to be a significant contributor to population dose for the above scenario. Fish could be contaminated directly by exposure to contaminated water and indirectly by long-term "recycling" of radionculides from the sediment. Because 1) the concentration coefficients for fish are sufficiently small[8] and 2) because the annual harvest of fish (Kg) will be small relative to the reservoir volume (m^3), ingestion of fish that are directly contaminated will not be a significant contributor to population dose. Fish contamination via the "recycling" process would involve root uptake of radionuclides from shoreline sediment deposits with subsequent passage through the food chain to fish. Although this "recycling" process could result in long-term ingestion exposures to humans, it would make a negligible contribution to population dose because 1) only a small fraction of the contaminated sediment would be deposited near the shoreline where root uptake is possible, 2) the rate of radioactive decay is high relative to the root uptake rate, 3) only a small fraction of the radionuclides ingested by organisms in each level of the food chain is actually assimilated by that organism, and 4) the quantity of game fish is not expected to be large.

CONCLUSION

The worst case water-pathway analysis indicates that water-pathway contamination is not a significant contributor to the radiological risk of transporting spent nuclear fuel by truck or rail. In this case, accident risk is given by summing the products of accident consequence and probability. That is,

$$\text{Risk} = \sum_i \text{Consequence}_i \times \text{Probability}_i \qquad (7)$$

where i denotes the accident scenerio. Although a worst-case water contamination accident can have health impacts which are comparable to those for a "rural" accident, water pathways are not considered important for accident risk because of the low probability of significant water contamination. This conclusion is consistent with conclusions resulting from water-pathway analyses for postulated nuclear reactor accident releases (e.g., see Reference 2, 3, 6, and 7).

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