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AN ALARA ASSESSMENT OF SPENT FUEL AND NUCLEAR WASTE TRANSPORTATION SYSTEMS*

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The number of spent fuel and nuclear waste shipments per year may be expected to increase dramatically during the next few decades as the nuclear industry matures and waste management endeavors are expanded. Existing regulations specify allowable dose rates in the vicinity of such shipments. For example, under normal operating conditions the acceptable dose rate at 2 m from accessible surfaces of a spent fuel cask is 10 mrem/hr (IAEA Safety Series No. 6, para. 534.c and 537.c). As the number of shipments increases there may be pressure to restrict the allowable dose rates in accordance with the philosophy of "as low as reasonably achievable" (ALARA).

When changes are considered in the regulations, both the costs and the benefits of a given change should be addressed. In the past, the application of the ALARA concept in the transportation area has been investigated with almost exclusive emphasis on reducing occupational and public radiation exposure. Although radiation exposure is of paramount importance, ALARA effects on transportation system costs, including parameters such as physical dimensions and total lifetime shipping costs also must be determined to adequately justify using ALARA in transportation applications. During the past year some preliminary work in this area has been completed at Sandia National Laboratories.

The recent effort at Sandia evaluated the application of the ALARA concept to light water reactor (LWR) spent fuel, high-level commercial and defense wastes, and remote-handled transuranic waste transportation.[1] This evaluation included: (1) obtaining transportation hardware shield designs which comply with the regulatory 10 mrem/h, 2 m dose rate condition; (2) determining the additional shielding required to decrease the dose rate to 5 mrem/h; (3) determining the additional shielding required to decrease the dose rate to 2 mrem/h; and (4) investigating the effects of the additional shielding on system parameters such as cask weight and dimensions. This evaluation was done for wastes and LWR spent fuel of 1, 3, 5 and 10 years age and for casks with 1, 4 and 7 unit capacities. Gamma shield materials investigated were depleted uranium, lead and steel. The neutron shield material was water.

This study considered pressurized water reactor (PWR) spent fuel (SF) which was initially enriched to 3.3 wt.% ^{235}U. The irradiation sequence assumed for the fuel involved 3-year residence in the reactor with three separate burn cycles and an 80% capacity factor. The total burnup sustained was about 15,000 MW days per assembly (33,000 MW days/tonne of uranium).

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Current national policy in the USA does not authorize reprocessing of commercial reactor spent fuel. Since this policy could change in the future, ALARA impacts on the transportation of high-level commercial waste (HLCW) were investigated. The HLCW considered here was assumed to contain 0.5% of the uranium and plutonium and 100% of the fission products and other transuranics originally in the unprocessed LWR SF. Presently, in the USA, there are approximately 2 PWR reactors for each boiling water reactor (BWR). Since the radiation and thermal characteristics of PWR and BWR spent fuels differ, the HLCW considered was formulated to reflect this ratio of LWR types. The concentration of the waste in some suitable matrix (borosilicate glass for instance) was assumed to be such that the HLCW obtained from reprocessing 1 tonne uranium equivalent of the 2:1 PWR/BWR SF mix resulted in 0.085 m^3 (3 ft^3) of waste product.

High-level defense waste (HLDW), which is similar to but less radioactive than HLCW, is a by-product obtained during the reprocessing of military reactor SF. Large quantities of this waste currently are stored as salts, sludges, liquids and calcine at three US Department of Energy sites.[2] This waste will be concentrated and immobilized in a suitable matrix before being transported offsite. The radioactivity of the waste is quite variable from site to site and within a given site. The transportation of the most radioactive waste was investigated in this work.

Remote-handled transuranic waste (RH-TRU) is transuranic and fission product contaminated material which requires some radiation shielding for safe transport. Relatively small quantities of RH-TRU are in temporary storage at DOE sites. Generalizations concerning its physical characteristics are difficult to make since waste package sizes range from 30 gallon drums to round caissons 240 cm diameter by 300 cm high and larger. The volume of RH-TRU will increase considerably as decontamination and decommissioning programs of DOE facilities are begun in the coming decade and beyond. For the purposes of this study, the proposed Waste Isolation Pilot Project (WIPP) definition of an acceptable RH-TRU package[3] was used. The package assumed is 61 cm diameter, 460 cm long and has a maximum surface dose rate of 100 rem/hr.

Table I shows some of the physical parameters of the SF, waste material, and waste containers considered in this study. The radiation and thermal characteristics of each waste type were estimated using the SANDIA-ORIGEN[4] isotope generation and depletion code. The diameter of the HLCW canister was assumed to be 30.5 cm based on thermal considerations (i.e., possibility of waste melt along the canister centerline). This canister dimension could be too large for short cooled HLCW. The HLDW canister diameter was also selected to be 30.5 cm since, at one time, WIPP tests with such containers loaded with HLDW were proposed. The HLDW canister diameter could be increased to that of the RH-TRU container without any adverse thermal effects.

The cask hardware investigated in this study included a cask with a cavity sized to accommodate 1, 4 or 7 assemblies or canisters, a 2.5-cm-thick steel inner wall, a gamma shield zone of adjustable thickness, a 5.0-cm-thick steel structural wall, and a neutron shield zone of variable thickness if such a shield was necessary. Figure 1 shows idealized cross sections of the cask for each loading configuration. In each case, an aluminum basket was assumed to provide support for the waste canisters or fuel assemblies in the cask cavity. Table 2 lists the cask cavity diameters assumed for each configuration.

The thicknesses of the shield zones were varied for each waste type and cask capacity to obtain conceptual shield designs resulting in 10, 5 and 2 mrem/h dose rates at 2 m from the cask exterior. In order to obtain reasonably balanced shield designs, the acceptable primary gamma and neutron-secondary gamma dose rate contributions to the total dose rate as given in Table 3 were selected. The XSDRNPM[5]

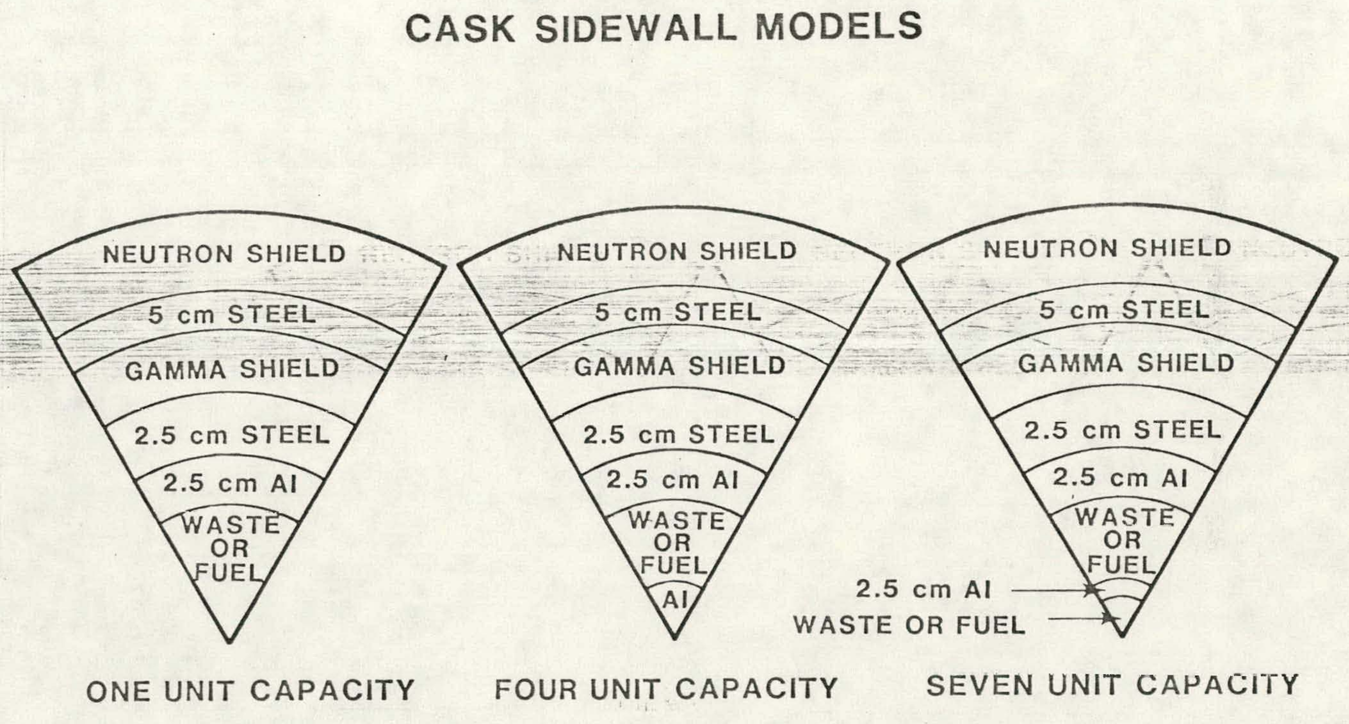

Figure 1. Cask Models for Various Loading Configurations

one-dimensional radiation transport code was used to estimate the required thicknesses of the neutron and gamma shield zones. The calculations were performed using an 11-group, P1 primary gamma cross-section set and a coupled 19-neutron, 13-secondary gamma P1 cross-section set. Past experience has shown that one-dimensional transport calculations performed using these cross section sets yield results which agree well with predictions obtained with more sophisticated Monte Carlo analyses using MORSE.[6] All calculations were done in cylindrical geometry using an S_6 quadrature.

Table 1. Physical Parameters of Spent Fuel and Waste

	PHYSICAL DIMENSIONS	WEIGHT (kg)	THERMAL POWER GENERATION RATE (Wth) 1-Yr-Old	3-Yr-Old	5-Yr-Old	10-Yr-Old
PWR Spent Fuel	21.7-cm dia 420-cm length	660	5000	1700	970	580
High-Level Commercial Waste Canister	30.5-cm dia 305-cm length	750	20000	6600	3600	2100
High-Level Defense Waste Canister	30.5-cm dia 305-cm length	750	230	200	180	150
Remotely Handled TRU Waste Container	61-cm dia 460-cm length	3200	100	95	90	80

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Table 2. Cask Cavity Dimensions and Capacities

TYPE	CAVITY DIAMETER (cm)	CAPACITY (Number of Assemblies or Canisters)
PWR Spent Fuel	39	1
	75	4
	91	7
HLCW	39	1
	87	4
	107	7
HLDW	39	1
	87	4
	107	7
RH-TRU	66	1
	137	4
	193	7

Table 3. Acceptable Primary Gamma and Neutron-Secondary Gamma Dose Rate Contributions

NOMINAL DOSE RATE AT 2 M FROM CASK EXTERIOR (mrem/h)	PRIMARY GAMMA (mrem/h)	NEUTRON-SECONDRY GAMMA (mrem/h)
10	7.0 ± 2.0	3.0 ∓ 2.0
5	3.5 ± 1.0	1.5 ∓ 1.0
2	1.5 ± 0.5	0.5 ∓ 0.5

The reasons for considering waste and SF cooled only for up to 10 years should be mentioned before considering the results obtained in this study. One reason is that a significant fraction of the SF stored in the USA is approaching 10 years since being discharged. A more fundamental reason is that the radiation source associated with each waste changes dramatically during the first 10 years of cooling but much more slowly thereafter. This is indicated in Figure 2, which shows the ratio of the neutron and gamma sources for each year decay to that at 20 years cooling time as a function of cooling time for PWR SF. The curves are quite steep for the first 10 years of cooling and nearly flat during the subsequent 10 years. Thus the shielding requirements of the material do not change significantly during the second 10 years.

The results obtained in this study for each waste type, cooling time, cask capacity, and dose rate are too extensive to detail in full here. To indicate trends, only the results for the 7 element capacity PWR cask will be given. In Figure 3 are shown the estimated radii (not including cooling fins) of conceptual spent fuel casks designed to transport 7 PWR fuel assemblies as a function of fuel age and 2 m dose rate. The left portion of the figure is for casks in which depleted uranium provides the necessary gamma shielding. The center portion illustrates similar results for lead shielded casks. On the right are shown the results for steel casks. In general, the radii of the depleted uranium casks are less than the corresponding lead and steel shielded casks because uranium is the best gamma shield material of the three considered. The radius of the cask is important since transportation-imposed constraints limit this dimension to probably no more than 105 cm (without cooling fins). From the figure it is seen that the lead and steel shielded casks for short cooled fuel which yield 2 mrem/h dose rates and the steel shielded cask with the 5 mrem/h dose rate for 1 year cooled fuel do not meet this requirement.

Figure 4 shows the estimated empty weights of the casks indicated in Figure 3. Again, three sets of curves are given: the left for uranium shielded casks, the center for casks with lead gamma shielding, and the right for steel casks. The weights of the lead and steel casks are more sensitive to waste age and 2 m dose rate than are the uranium casks.

The percentage increases in the weight of each cask when the design dose rate is decreased from 10 mrem/h to 5 or 2 mrem/h as a function of cooling time for each gamma shield material are shown in Figure 5. By halving the regulatory dose rate, the cask weight increases by about 6 to 10% in each case. A further reduction of the acceptable dose rate by a factor of 2.5 causes an additional 10% increase in the weight of the uranium and steel casks relative to the corresponding 10 mrem/h casks. The additional weight percent increase is even higher for the lead shielded casks, being around 15%. The reason the lead casks weight

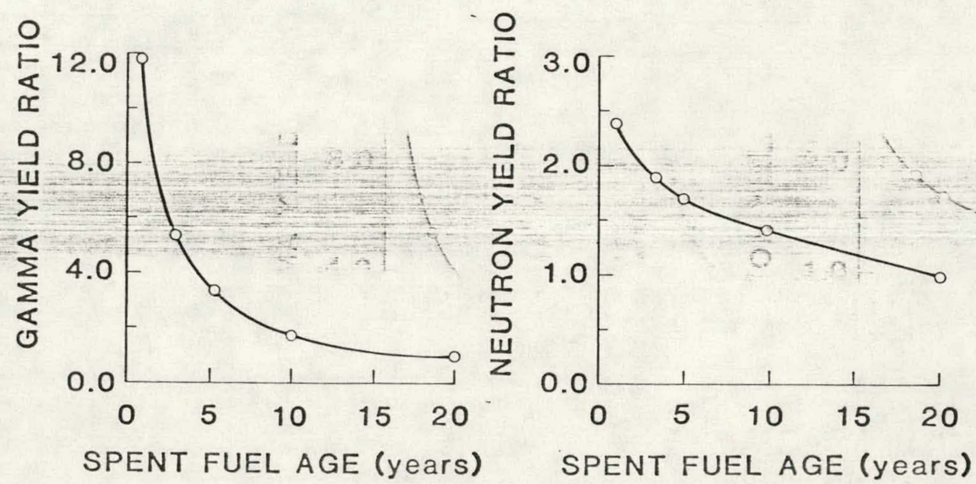

Figure 2. Temporal Variation of Radiation Source Strength for PWR Spent Fuels

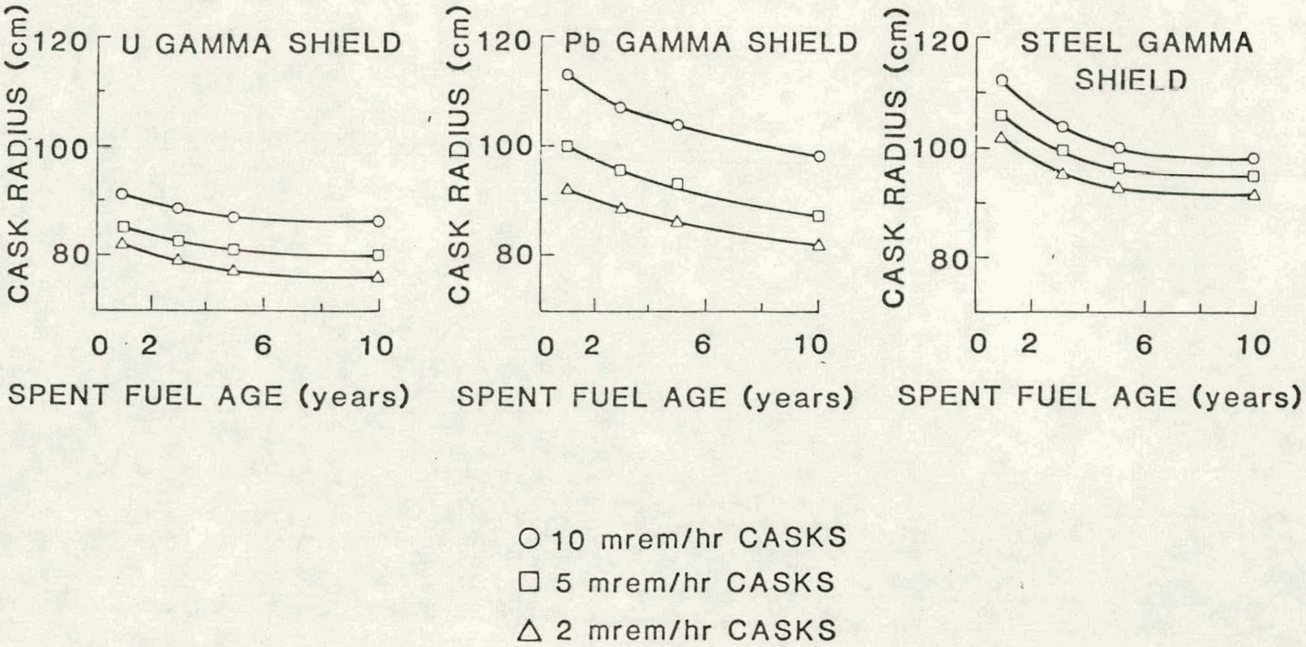

Figure 3. Estimated Radii of Seven Element Spent Fuel Casks

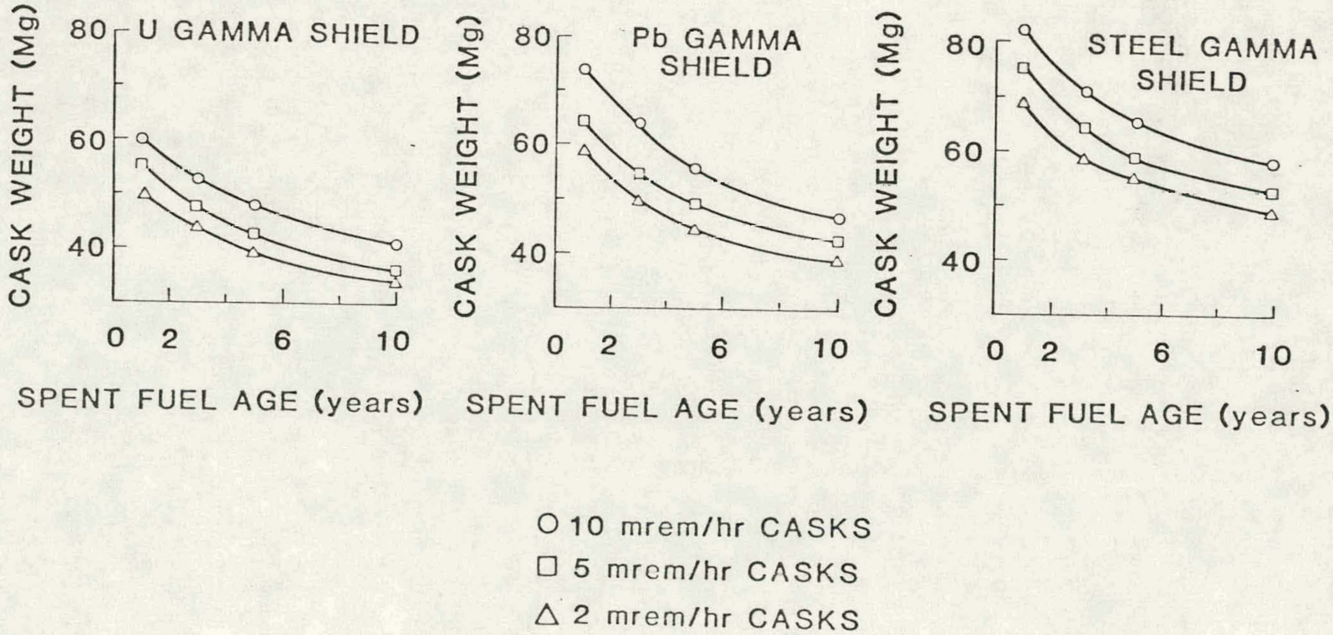

Figure 4. Estimated Weights of Empty Seven Element Spent Fuel Casks

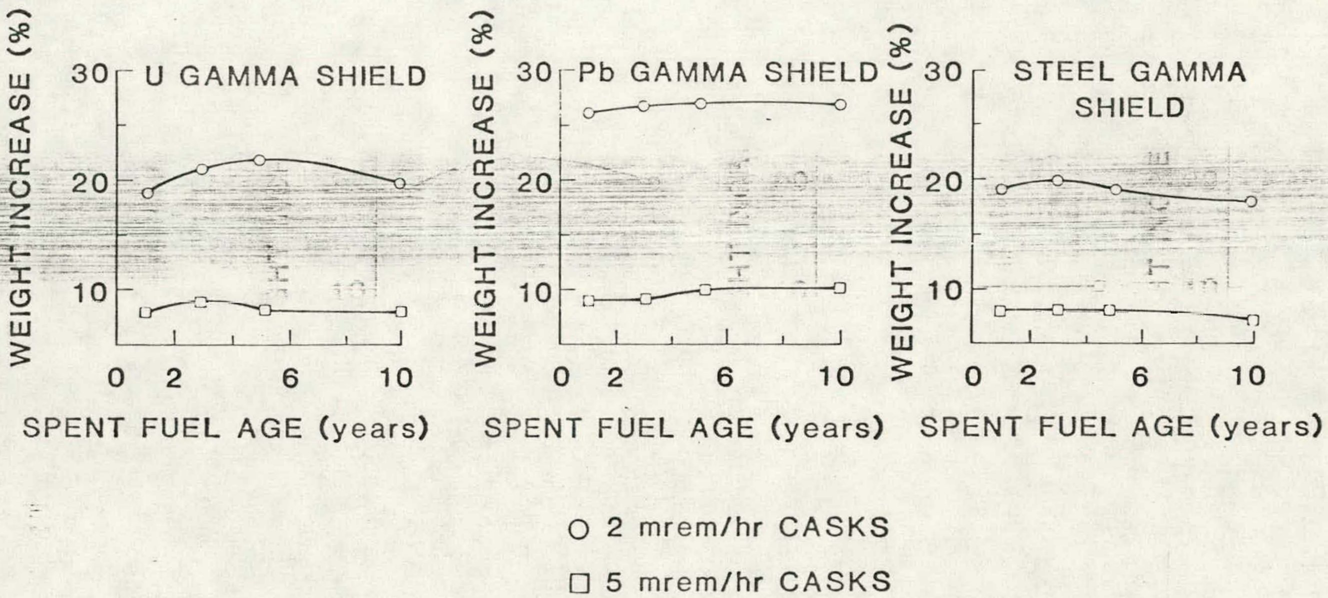

Figure 5. Weight Increase in Empty Seven Element Spent Fuel Casks Due to Reduction in Allowable Dose Rate

percent increases are higher apparently is because lead is the poorest neutron shield material of the three gamma shields considered. The neutron shielding problem is more important at the lower dose rate.

Figure 6 gives estimates of the lifetime transportation costs of the casks, in 1978 U.S. dollars, based on the weight estimates of Figure 4. These cost estimates do not include fabrication costs. Assuming a 20 year lifetime and roundtrip distances of 3200 km with 15 roundtrips per year at 9.3 cents/Mg-km including both haulage and usage fees, the estimates for lifetime transportation costs, as given in Figure 6, are obtained. From the figure it is apparent that a lead shielded cask would cost approximately \$1 million and a steel cask \$2 million more to operate over their lifetimes than a corresponding uranium shielded cask. Such additional operating cost may be recovered since lead and, particularly, steel casks are less expensive to fabricate than uranium casks.

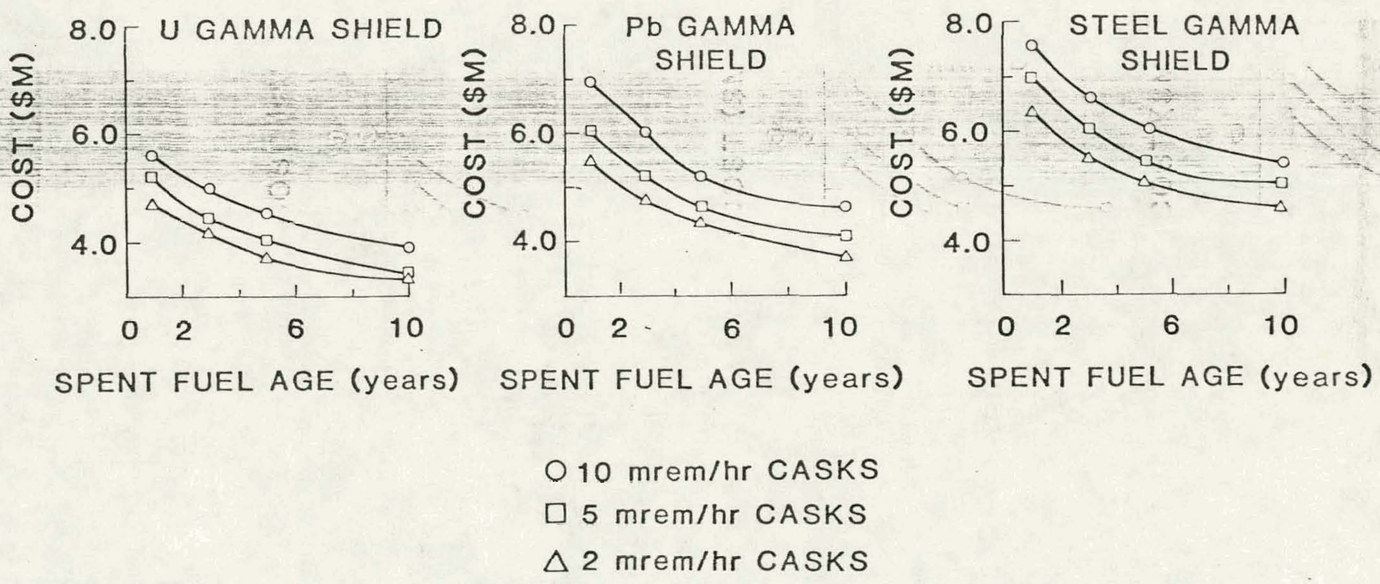

Figure 6. Estimated Lifetime Transportation Cost of Seven Element Spent Fuel Casks

Similar results are obtained for the 1 and 4 element SF casks and for the other waste casks considered in this study. Some of the overall significant results may be summarized as follows: (1) some low dose rate cask designs may be oversize or overweight if lead or steel provide the gamma shielding, (2) designing for 5 instead of 10 mrem/h increases the cask weight by about 10% and for 2 mrem/h adds another 10% or more to the weight, and (3) the increased weight of the low dose rate casks results in an estimated \$1 to \$2 million increase in the cask lifetime transportation costs.

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