SYSTEM COST-EFFECTIVENESS FOR INCREASING CASK SHIELDING

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ABSTRACT

A methodology is developed for evaluating the cost-effectiveness for the federal waste management system of reducing the aggregate system radiation dose by increasing shielding on spent fuel transport casks. The methodology is evaluated for 100-ton rail casks which utilize steel, lead, and depleted uranium, respectively, for gamma shielding. For these examples, reducing the external radiation dose rate from the casks to less than one-half the current DOT limit does not appear to be cost-effective.

INTRODUCTION

One approach to reducing the cumulative radiation dose received by the waste disposal system workers and by the public as a result of the transport of spent fuel from the commercial power reactors to disposal sites is to increase the shielding on the transport casks. However, shield material is heavy and making the cask shield thicker increases the total weight of the cask. Since there are limitations on the maximum weight allowable for a given cask (legal-weight truck ~50,000 lbs., over-weight truck ~80,000 lbs., and normal rail ~200,000 lbs.), adding shielding can result in reducing the amount of payload that can be carried by a given cask, thereby requiring additional shipments to transport a given quantity of spent fuel. Therefore, it is useful to examine the relative cost-effectiveness of adding shielding to reduce the external dose rate of a cask to various levels, in terms of the change in system cost versus the change in system cumulative radiation dose. Relationships have been developed for use in comparing cumulative system transport cost and cumulative system radiation dose for various levels of cask exterior dose rate. The derivation and evaluation of these relationships for casks of different shield materials are the subjects of this paper.

METHODOLOGY DEVELOPMENT

The cumulative annual radiation dose to waste disposal system workers and to the general public resulting from loading, shipping, and unloading a cask containing spent nuclear fuel is approximately proportional to the product of the external radiation dose rate at a given distance from the side of the cask and the number of single cask shipments needed to transport an annual quantity of spent fuel. This cumulative dose can be expressed by:

$$D = NR(A + B + C) \tag{1}$$

where N is the number of shipments, R is the external dose rate from the cask, and A, B, C are the equivalent person-hours (public and occupational) of exposure per shipment to that radiation field incurred at the reactor, while in transit, and at the receiving facility, respectively.

To transport the annual amount of fuel in a reference cask/transport vehicle system having a fixed maximum gross vehicle weight, the total number of single cask shipments is given by:

$$N_{oa} = \frac{M}{K(R_o)} \tag{2}$$

where M is the number of fuel assemblies shipped annually and $K(R_o)$ is the number of assemblies contained in a single shipment for a given cask external dose rate R_o. The number of casks required in the fleet to transport M fuel assemblies annually in the reference cask is given by:

$$N_{of} = \frac{M}{nK(R_o)} \tag{3}$$

where n is the cask utilization factor, (cask trips per cask year). Thus, the size of the cask fleet is proportional to the inverse of the cask capacity. As more shielding is added to the reference cask, the capacity decreases and the number of casks having an external dose rate of R_i needed to transport the same quantity of fuel annually becomes:

$$N_{if} = \frac{M}{nK(R_i)} \tag{4}$$

The cumulative annual system radiation dose for the system using the reference rail cask becomes:

$$D_o = \frac{M}{K(R_o)} R_o(A + B + C) \tag{5}$$

and the cumulative annual system radiation dose for the system using a reduced capacity cask having an external dose rate R_i is given by:

$$D_i = \frac{M}{K(R_i)} R_i(A + B + C) \tag{6}$$

The change in annual system dose relative to the reference cask is given by:

$$\Delta \text{ Dose} = \left[\frac{R_i}{K(R_i)} - \frac{R_o}{K(R_o)}\right] M(A + B + C) \tag{7}$$

which can be rewritten to facilitate evaluation as:

$$\Delta \text{ Dose} = \left[\frac{R_i}{R_o K(R_i)} - \frac{1}{K(R_o)}\right] MR_o(A + B + C) \tag{8}$$

The annual system cost for the transport of the spent fuel is the sum of the annual amortized capital cost of the cask fleet, the annual cost of making N shipments, and the annual staff labor cost at the shipping and receiving facilities that are attributable to fuel transport operations. This annual system cost is given by:

$$ASC_o = \frac{M}{K(R_o)}\left[E(P + O) + S + \frac{T(R_o)}{nY}\right] \qquad (9)$$

where E is the average fully burdened staff labor cost per man-hour, P and O are the staff labor hours at the reactor and receiving facility, respectively, S is the cost per cask shipment, $T(R_o)$ is the capital cost of the cask and Y is its useful lifetime.

The increased disposal system cost associated with adding shielding to the cask is given by:

$$\Delta\$ = \left[\frac{1}{K(R_i)} - \frac{1}{K(R_o)}\right] M\left[E(P + O) + S + \frac{T(R_o)}{nY}\right] \qquad (10)$$

Since T(R) is only very weakly dependent upon R for a given type of cask, in this analysis it is assumed to be constant at the value for R_o.

Examining Eqs. (8) and (10), it is seen that only the terms in the left-hand square brackets are affected by the changes in the cask external dose rate and the associated changes in cask capacity. Thus, to a reasonable approximation, the change in cost divided by the change in dose is given by:

$$\frac{\Delta\$}{\Delta\ \mathrm{Dose}} = \left\{\frac{\frac{1}{K(R_i)} - \frac{1}{k(R_o)}}{\frac{R_i}{R_o K(R_i)} - \frac{1}{K(R_o)}}\right\} \cdot \left\{\frac{E(P + O) + S + [T(R_o)/nY]}{R_o(A + B + C)}\right\} \qquad (11)$$

EVALUATION

The constant term within the right-hand brackets of Eq. (11) is evaluated using data from a variety of sources, as listed below.

$E(P + O)$ = \$10,800 per shipment, based on an average man-year salary cost of \$50,000 and 54 man-days expended per shipment, (1).

S = \$39,700 per shipment, (1).

$T(R_o)$ = \$2.5 million, \$2.18 million, and \$2.91 million for a rail cask made of stainless steel (SS), SS + lead (Pb), or SS + depleted uranium (DU), respectively, based on (1) and (2).

n = 300 days per year/33 days per trip = 9.09 trips per year, (1).

Y = 25 year cask lifetime, (3).

$R_o(A + B + C)$ = 0.925 rem per shipment, based on (4).

Using these values, the constant has the values \$66,500 per rem (SS), \$65,000 per rem (Pb), and \$68,400 per rem (DU).

The terms in the left-hand brackets of Eq. (11), which are sensitive to cask capacity and external dose rate, are evaluated by performing a series of calculations using the CAPSIZE code (5), to examine the variation in this ratio as a function of the external dose rate from the cask. A maximum loaded cask weight of 200,000 lbs. was assumed, with a basket separator thickness of 1 inch, and with 10-year cooled, 33,000 MWD/MTU exposure PWR fuel.

For the examples given here, the external dose rates were varied from 10 millirem/hr (R_o), yielding cask capacities $K(R_o)$, down to 0.1 millirem/hr (lowest value of R_i) at 2 meters from the cask surface, with corresponding reductions in cask capacities, $K(R_i)$. The results of these calculations are presented in Table I and illustrated in Figs. 1, 2, and 3, for the SS, Pb, and DU casks, respectively. These results show that for the Pb and DU casks, sufficient shielding could be added to reduce the dose by about 30% without a corresponding reduction in cask capacity. Further shielding additions to reduce the external dose rate to the 4 to 5 millirem/hr range would reduce the cask capacities, with the resulting costs associated with these capacity reductions in the range of \$5000 to \$7000 per rem of system dose reduction. Subsequent dose rate reductions cause additional capacity reductions and corresponding system cost increases in the range \$15,000 to \$30,000 per rem of system dose reduction. The effects are even more marked for the SS cask.

TABLE I

Δ\$/Δ Dose and Cask Capacity as a Function of Cask External Dose Rate[a]

	Δ\$/ΔDose / Cask Capacity (K\$/rem) (PWR Assembly)		
Dose Rate[b] (mr/hr)	Stainless Steel	Stainless Steel Plus Lead	Stainless Steel Plus Depleted Uranium
10	0.0 / 19	0.0 / 22	0.0 / 27
9	73.9 / 18	0.0 / 22	0.0 / 27
8	23.8 / 18	0.0 / 22	0.0 / 27
7	14.1 / 18	0.0 / 22	0.0 / 27
6	23.8 / 17	8.5 / 21	6.8 / 26
5	17.7 / 17	6.7 / 21	5.3 / 26
4	14.1 / 17	5.5 / 21	15.1 / 24
3	19.4 / 16	16.1 / 19	23.9 / 22
2	23.8 / 15	19.6 / 18	20.0 / 22
1	35.9 / 13	36.4 / 15	21.8 / 21
0.9	35.3 / 13	35.8 / 15	21.5 / 21
0.8	34.8 / 13	35.2 / 15	21.2 / 21
0.7	34.2 / 13	34.6 / 15	31.1 / 19
0.6	42.9 / 12	34.0 / 15	36.5 / 18
0.4	41.4 / 12	49.4 / 13	35.4 / 18
0.2	62.2 / 10	47.7 / 13	40.4 / 17
0.1	93.7 / 8	56.5 / 12	54.2 / 15

(a) Intact PWR assemblies in a 100-ton rail cask.

(b) Calculated dose rate at a point 2 meters from the cask surface, at the cask midplane.

The actual shape of the curve for a given cask will depend on the details of the cask design. As can be seen from the figures, each time the cask capacity

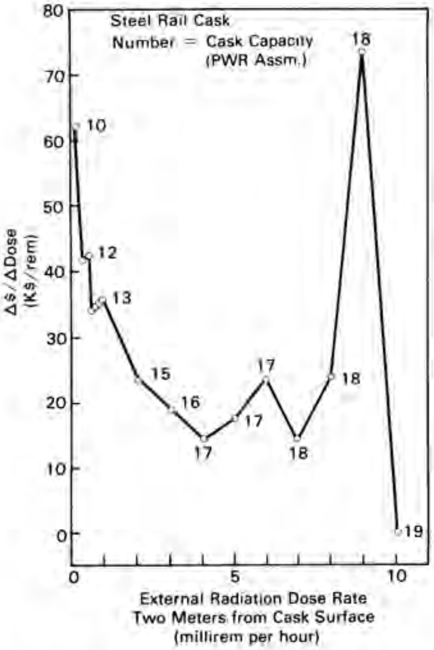

Fig. 1. System Cost Increases Associated with System Dose Reductions, as a Function of External Dose Rates from a Stainless Steel Spent Fuel Shipping Cask

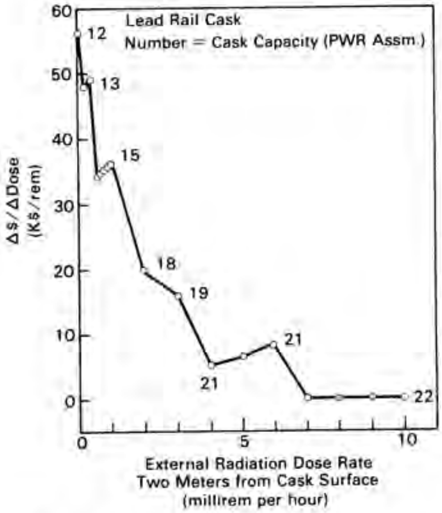

Fig. 2. System Cost Increases Associated with System Dose Reductions, as a Function of External Dose Rates from a Stainless Steel-Lead Spent Fuel Shipping Cask

is reduced, the cost per rem for system dose reduction increases. The magnitudes of the changes are related to the specifics of the geometry of the cask basket for a given capacity. It is obvious that a cask should be designed to have the maximum capacity achievable for a given external dose rate, within the constraints of the total system weight. However, in view of the rapidly increasing cost/dose ratios as the external dose rates and cask capacities are decreased, it appears that the cost penalty associated with reducing the cask external dose rates below the present DOT specifications by more than a factor of two would be prohibitive.

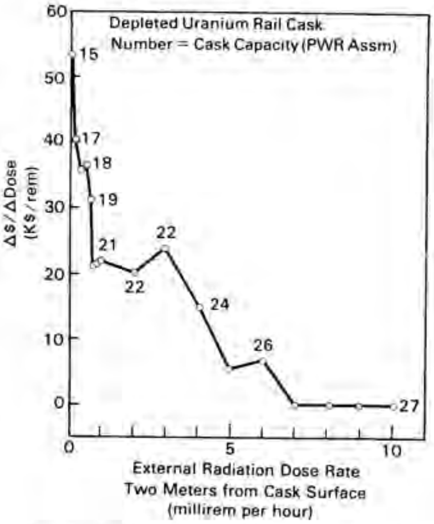

Fig. 3. System Cost Increases Associated with System Dose Reductions, as a Function of External Dose Rates from a Stainless Steel-Depleted Uranium Spent Fuel Shipping Cask

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