INCENTIVES FOR THE ALLOWANCE OF "BURNUP CREDIT" IN THE DESIGN OF SPENT NUCLEAR FUEL SHIPPING CASKS*

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ABSTRACT

An analysis has been completed which indicates that the consideration of spent fuel histories ('burnup credit') in the criticality design of spent fuel shipping casks could result in considerable public risk benefits and cost savings in the transport of spent nuclear fuel. Capacities of casks could be increased considerably in some cases. These capacity increases result in lower public and occupational exposures to ionizing radiation due to the reduced number of shipments necessary to transport a given amount of fuel. Additional safety benefits result from reduced non-radiological risks to both public and occupational sectors. In addition, economic benefits result from lower in-transit shipping costs, reduced transportation fleet capital costs, and fewer cask handling requirements at both shipping and receiving facilities.

INTRODUCTION

The design of a spent fuel shipping cask is an iterative process considering many variables. Generally, the ultimate limit on cask capacity is defined by the weight restrictions of the particular transport mode. Cask weight is primarily affected by shielding and basket spacing requirements. The basket is the structure in the cavity of a spent fuel cask that supports the assemblies and provides criticality control. Basket spacing requirements are determined by thermal, structural, and criticality concerns and it is generally difficult to identify the limiting variable without actually performing an entire cask design. For a given payload (i.e., fuel assemblies), increasing assembly-to-assembly spacing increases the inner cavity diameter, thereby increasing the volumes of the shield and structural components of the cask regardless of cask shape. Similarly, for a given cask weight, reducing web spacing may allow additional assemblies in the cavity because total cask weight is a weak function of the assembly weights.

It is apparent that previous generation cask capacities have been primarily thermal and/or shielding limited. For casks designed for much older spent fuels with longer decay times, shielding and heat transfer requirements are reduced sufficiently with respect to payload such that a considerable weight margin may be available to the designer for increasing the capacity by reducing assembly spacing requirements. Excess margin in cask capacity then, is essentially limited by criticality and structural concerns since fuel assembly spacing (and requirements for poison configurations) is dictated by requirements to both control neutron multiplication and ensure the structural integrity of fuel support components.

Criticality control of loaded spent fuel shipping casks is one of the primary safety considerations in the cask design. Traditional criticality analyses for both storage and shipping casks have assumed the package to be loaded with fresh, unburned fuel. This conservative assumption presumably provides a significant criticality design margin, since a fresh fuel loading is the most reactive state possible for criticality purposes. The conservatism in this approach is justifiable where economic penalties are not severe, but needs re-evaluation when resulting criticality control measures are not consistent with the risks involved.

Parametric Analyses of the Impacts of Various Reactivity Control Measures on Cask Capacities

A parametric analysis was conducted to evaluate the impact of various reactivity control measures or strategies on basket web spacing requirements and, in addition, the impact of web spacing requirements on cask capacities. All the evaluations were conducted using a standard Westinghouse 17 x 17 pressurized water reactor (PWR) assembly with the fuel enriched to 3.75 weight percent ($^{w}/_{o}$) U-235. A generic cask model was used that is based on a previous cask optimization analysis (1). This analysis defined the heavy metal shield thicknesses required to meet dose criteria and weight constraints. The design basis model includes one or more Westinghouse assemblies, one of three types of heavy metal shields (lead, steel, depleted uranium), a borated ethylene glycol

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** A United States Department of Energy Facility solution neutron shield, and a variable thickness basket of stainless steel and neutron absorber and moderator materials where applicable.

A representative result of the cask capacity versus web thickness analysis is illustrated by Fig. 1 for a 200,000 pound rail cask. This part of the analysis does not consider criticality. As indicated, a combination of shield and web thickness optimizations could result in a considerably higher payload than existing cask designs. For example, the latest steel or lead shielded dry storage cask designs with similar weights in the U.S. have capacities from 21 to 24 PWR assemblies respectively (2). With a uranium shield, Fig. 1 indicates that if the web spacing could be reduced to 0.2 inches for mainly structural purposes, cask capacity could be increased to 32 PWR assemblies, a 23 percent increase. The combination of changing shielding material from lead to uranium and reducing the web thickness results in a 45 percent capacity increase.

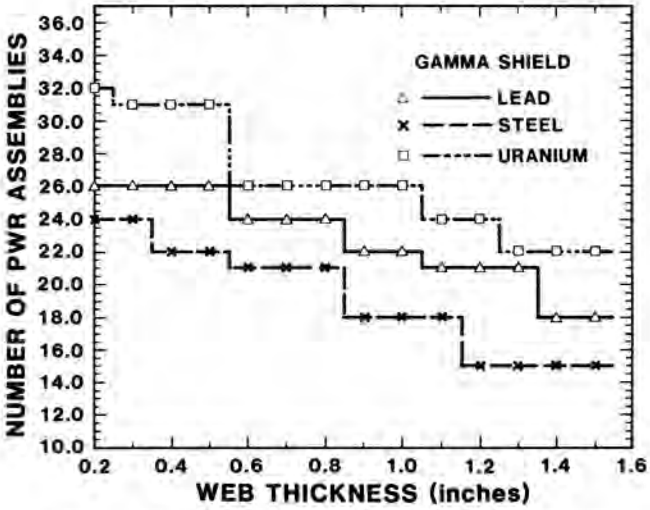

Fig. 1. Cask Capacity vs. Basket Web Thickness; Burnup = 33 GWD/MTU, Age = 10 years, Cask Weight = 100 tons.

The criticality analysis approach involved the following major steps. First, a reactivity analysis was performed on an infinite lattice using a pin cell model to determine the equivalent negative reactivity worth of the burnup (Δk) in terms of the decrease in the pin-lattice multiplication factor (k_∞). Next, infinite lattices of both fresh and irradiated fuel assemblies at various burnups, separation distances, and absorber densities and geometries were analyzed to determine the reactivity effect of variations in basket web thicknesses and absorber controls. Finally, three-dimensional analyses of complete cask, basket, and fuel systems were performed to demonstrate the merits of burnup credit in actual cask geometries.

Only the most important non-gaseous fission product absorbers were considered in the criticality analyses. The infinite multiplication factor, k_∞, and reactivity components associated with fissile fuel depletion, Δk_{fd}, fission and activation product poisons, Δk_{fp}, and total negative reactivity, Δk_t, are illustrated as functions of cooling time in Fig. 2 for a 33 GWD/MTU exposure history. Negative reactivity is a measure of the reduction in the infinite multiplication factor $(k_{\infty,t} - k_{\infty,t=0})$. The fission and activation product contribution to negative reactivity is about three-fifths of the total. Several conclusions were derived from the infinite multiplication analysis. First, fission and activation product poisons represent a very stable and significant source of negative reactivity for criticality control of spent fuel lattices. Second and of particular importance to criticality safety, reactivity variations with time are always such that the net result is a significant negative reactivity addition over the period of concern to spent fuel transportation.

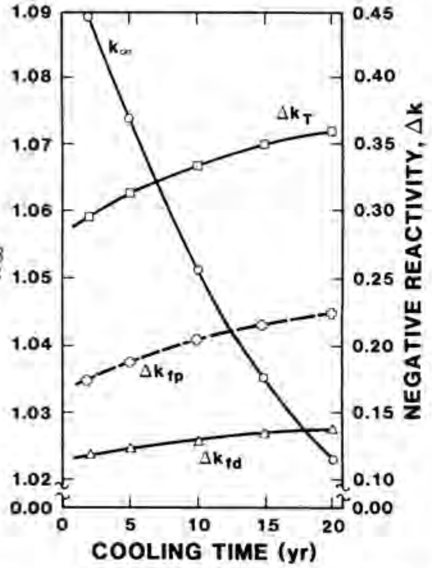

Fig. 2. Infinite Multiplication Factor, k_∞, and Total Negative Reactivity, Δk_t, Resulting From Fissile Fuel Depletion, Δk_{fd}; and Fission and Activation Product Poisons, Δk_{fp}; Burnup = 33 GWD/MTU.

The infinite multiplication analysis was extended to evaluate the effects of basket web thicknesses and materials on criticality and to derive minimum web thickness requirements for several different fuel/basket configurations. An infinite array of the 17 x 17 fuel assemblies was analyzed to determine the reactivity worth of the array for various thicknesses of hypothetical stainless steel and poison combinations used for separation of the fuel assemblies. The analyses were conducted for both fresh and irradiated fuel. It must be recognized that there are numerous alternatives available for designing an external neutron poison system. These include varying boron (or other poison) enrichments and basket materials as well as different approaches for incorporating the poison into the basket. Particular combinations of fuel and basket/absorber configurations analyzed are illustrated in Fig. 3. Fresh fuel arrays were evaluated using several poison strategies to estimate the minimal web spacing achievable using a fresh fuel assumption for criticality purposes. It should be noted that an assessment of basket structural requirements was not included in this analysis.

The results of the analyses of all seven different combinations are presented in Fig. 4. The numbers on the curves correspond with the configuration numbers on Fig. 3. Fuel exposure and decay histories (burnup credit) were used in the analysis of Case 1 and Case 2. All other case evaluations were based on a fresh fuel assumption. As indicated, the case with

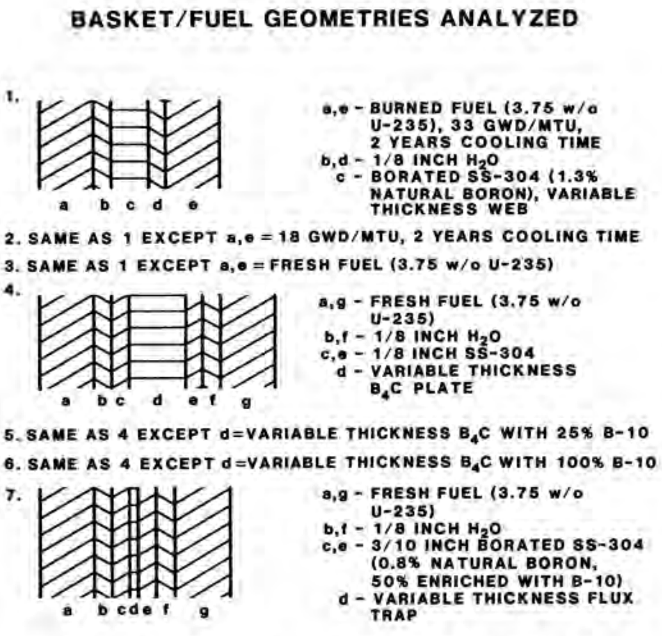

Fig. 3. Basket/Fuel Geometries Analyzed.

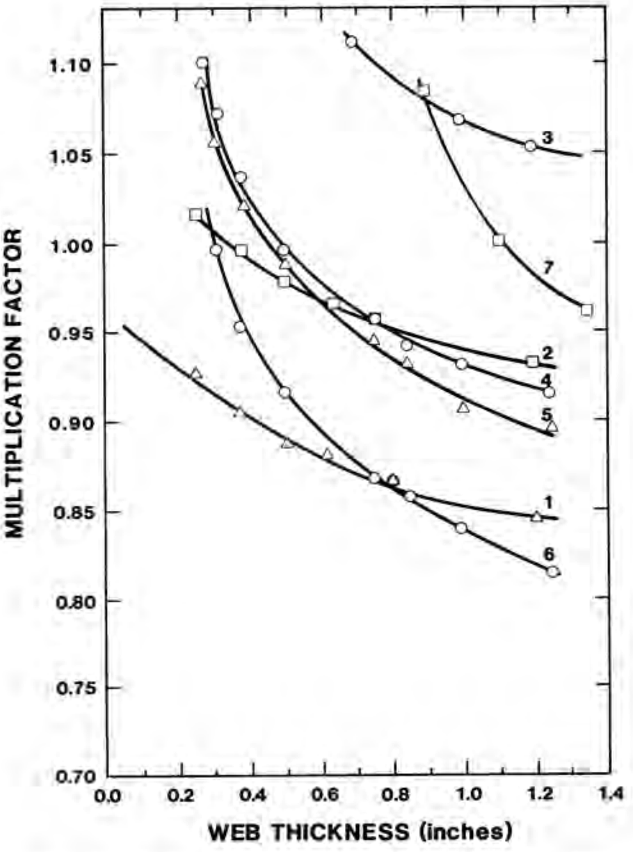

Fig. 4. Criticality Analysis Results for Various Infinite PWR Assembly Arrays.

typically irradiated fuel (Case 1-33,000 GWD/MTU, 2 year cooled) yields a significantly thinner web than a fresh fuel assumption except for the case with a very high external poison concentration, a B_4C plate enriched with 100 percent Boron-10 (Case 6). Also, while the addition of flux traps increases the efficiency of the absorbers (Case 7), the major impact is a potential reduction of absorber combined with an increase in web thickness.

Several model cask and basket configurations were also analyzed for both fresh fuel and burned fuel using some of the same basket geometries considered in the infinite assembly array analysis (Fig. 3). The results for all cases indicate that the reduction to a finite geometry results in approximately a 3-8% reduction in the array multiplication factor, for a rail and legal weight truck cask respectively.

Several conservative assumptions were used in the analyses for simplification purposes. Only major fission products were considered and their two-year decay inventories were used. Material properties were evaluated under "worst case" conditions (i.e., dense moderator, etc.). Maximum reflectivity was assumed. Also, the highest burnup evaluated, 33 GWD/MTU, is only 85 percent of the design burnup value for the fuel analyzed. Higher burnups would result in even lower reactivities. Since the cask capacity is essentially optimized to the maximum extent possible, it appears that there is still a considerable margin for criticality control remaining in the model evaluated. The closeness of spacing is limited by the requirements for maintaining structural integrity of the basket.

In summary, both the feasibility of and justification for employing burnup credit in cask criticality analysis has been demonstrated. Benefits occur in two ways; capacity can be increased over casks not based on burnup credit and basket geometries may be simplified, possibly resulting in a more structurally sound configuration.

Economic Incentives for Maximizing Cask Capacities

Any increase in cask capacity results in a corresponding decrease in the number of shipments required to transport a fixed amount of spent fuel between any two points. Handling costs and, to some extent, maintenance costs at shipping and receiving facilities are inversely proportional to cask capacity; i.e., higher capacities result in proportionately fewer cask handling operations (except for actual spent fuel transfer operations, which are constant over the lives of both facilities). Capacity may also have some impact on receiving facility capital costs via reductions in handling area requirements. Fleet procurement and in-transport operating costs for both the truck and rail scenarios are also inversely proportional to capacity.

A sensitivity analysis was performed to evaluate the impact of cask capacity on total transportation system life cycle costs. Assumed shipping rates were 1000 MTU/year for truck shipments and 2000 MTU/year for rail shipments. Several discount rates were also analyzed. While discounting does affect the total dollars, the relative importance of the cost parameters is essentially unchanged. The results for a legal weight truck (LWT) system and a 100-ton rail system are illustrated by Fig. 5 and Fig. 6 respectively.

The baseline (zero) for the LWT system is a 2 PWR/5 BWR cask and the baseline for the rail system is a 14 PWR/36 BWR cask. Costs are in 1987 dollars. The non-shaded areas represent an estimate of cost savings that are available from other capacity optimization strategies such as shield materials and requiring longer decay periods prior to shipment. These capacity increases are believed to be possible

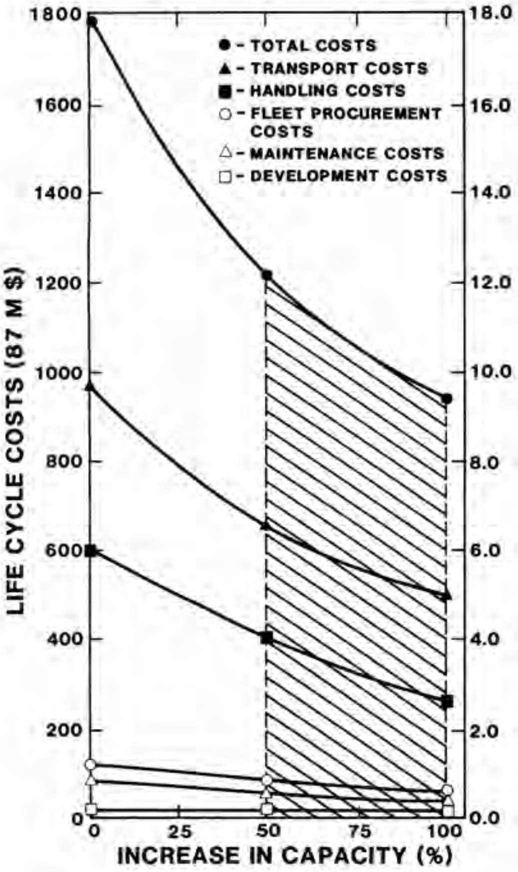

Fig. 5. Impact of Cask Capacity on Legal Weight Truck System Life Cycle Costs; 1000 MTU/Year Shipping Rate, 25 Year Repository Operation.

without burnup credit. The shaded areas of both figures represent where the allowance of burnup credit may contribute to cask capacity increase. Thus, the total savings as a result of burnup credit over a 25 year period using a 33 percent truck, 67 percent rail system could be as much as $500,000,000.

Risk Reduction Incentives for Maximizing Cask Capacities

The total risk resulting from radioactive material shipments is a combination of several factors including both radiological and non-radiological components. Both of these components also include normal transport and accident risks as well as occupational and non-occupational categories. In addition to actual in-transit risks, there are occupational risks (both radiological and non-radiological) that result from in-facility spent fuel cask handling operations.

An estimate of the impact of cask payload capacities on public and occupational exposures and risks was conducted to determine the approximate magnitude of risk reduction that may accrue. A sensitivity analysis was performed with truck and rail cask capacities as the independent variable. For truck cask shipments, the major contribution to the total risk to the public comes from the non-radio-logical accident component (i.e., highway accidents). Along any specific route, the non-radiological accident risk is proportional to the number of cask-miles occurring for a given mass quantity shipping rate and, therefore, is inversely proportional to cask capacities. The non-radiological transport risk to the public resulting from normal transportation pollutants is also proportional to cask-miles. The majority of the radiological risk results from stops during transit. Radiological risks are also proportional to the number of cask-miles.

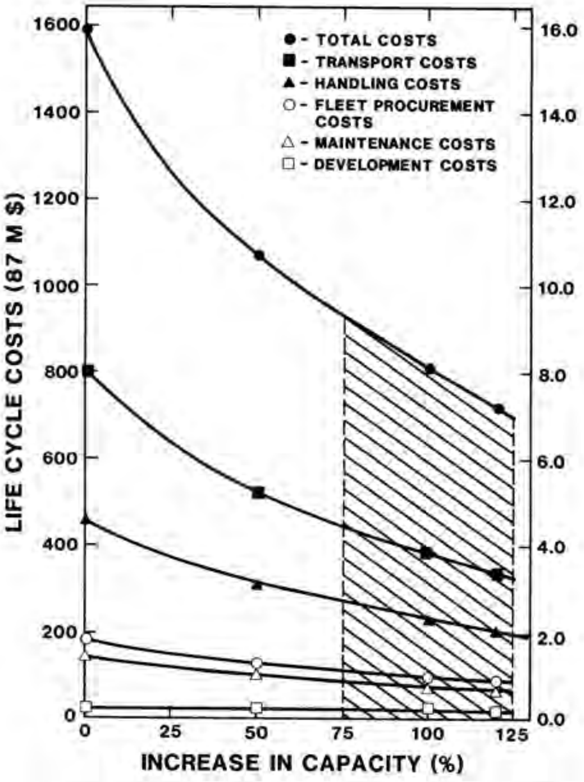

Fig. 6. Impact of Cask Capacity on Rail System Life Cycle Costs; 2000 MTU/Year Shipping Rate, 25 Year Repository Operation.

For normal, incident-free rail transport, the major part of radiological risk to the public occurs as a result of stops for inspections and maintenance. These stops are directly proportional to the number of individual shipments along a specific route, which, in turn, are inversely proportional to individual cask capacities. All other impacts of cask capacity on radiological and non-radiological risks from individual route-specific shipment-miles by rail are essentially the same as those outlined for truck shipments.

For the occupational population, the impact of a reduction in the number of individual shipments needed to transport a given amount of spent fuel is much more significant in terms of radiological exposure reduction. Fewer cask handling (loading, unloading) operations, as a result of increased cask capacities, will result in proportionately lower worker exposures, consistent with ALARA goals. The dose to facility workers during cask loading operations in spent fuel pools or unloading operations in a shielded hotcell is a function of the total number of individual assemblies shipped and is independent of cask capacities over the life of the facility. However, the frequency of all other cask receiving, preparation, and release operations is dependent on capacities. Any reductions in those operations will result in a directly proportional reduction in total occupational exposure over the life of the facility.

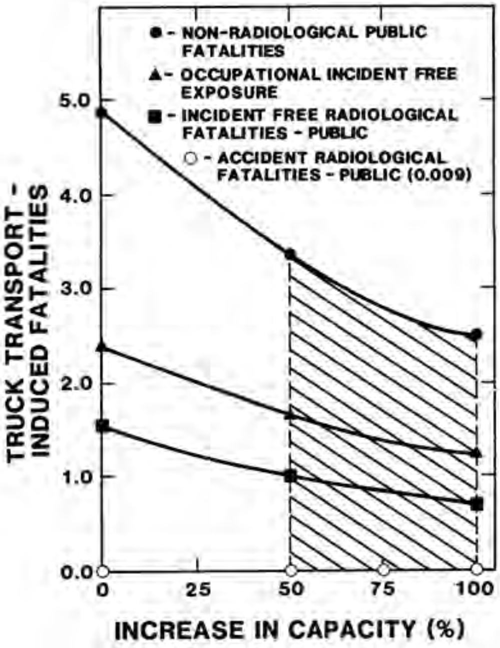

Fig. 7. Impact of Cask Capacity on Total Public and Occupational Risk From Truck Transport; 1000 MTU/Year Shipping Rate, 25 Year Repository Operation.

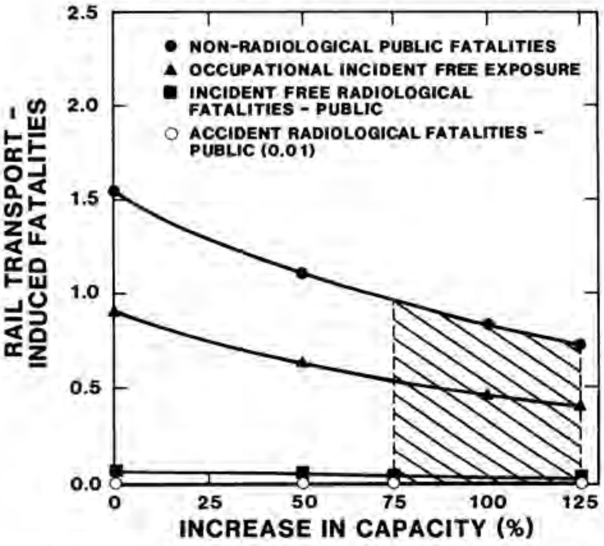

Fig. 8. Impact of Cask Capacity on Total Public and Occupational Risk From Rail Transport; 2000 MTU/Year Shipping Rate, 25 Year Repository Operation.

The impacts of cask capacities on both public and occupational fatalities over 25 years are illustrated by Fig. 7 and Fig. 8 for truck and rail systems, respectively. Occupational exposure estimates were extrapolated from existing data (3). The in-transit exposures were calculated using the RADTRAN-III risk analysis code (4). Again, the baseline casks were the 2/5 truck and 14/36 rail cask systems. Also, the shipping rate was again 3000 MTU/year with 33 percent truck and 67 percent rail components. Interestingly, there is little impact of increased capacity on accident-related radiological fatalities even though it was conservatively assumed that cavity releases were directly proportional to the volume of the spent fuel contents. Exposure fatalities were based on 100 latent cancer fatalities (LCF) per 10^6 person-rem population dose. Non-radiological occupational fatalities were not considered, although, clearly, that number should also be proportional to cask capacity.

The shaded areas of the two figures again represent the expected contributions of burnup credit allowance to cask capacities. Thus, burnup credit allowance could result in about one to two fewer deaths as a result of truck transport and about one fewer death as a result of rail transport over 25 years of repository operation.

Probabilistic Risk Assessment of Spent Fuel Cask Criticality

A variety of scenarios were identified and analyzed which could lead to a spent fuel shipping cask critical event either during cask loading or transport. A probabilistic risk assessment methodology was used to estimate the likelihood of inadvertent loading of non-specification fuel into a shipping cask and the possibility of subsequent critical events. In addition, the probability of a critical event with specification fuel was examined for comparative purposes. Non-specification fuel is defined as fuel, new or exposed, with reactivity in excess of that used for cask criticality analyses based on burnup credit. Specification fuel is defined as fuel, new or exposed, with reactivity equal to or less than that used for the cask criticality analysis based on burnup credit or the fresh fuel assumption. A fault tree format was used for the assessment of the various scenarios. Equipment, operational, and accident causes were considered for both specification and non-specification fuel loading errors. On the basis of expected cask usage rates it may be concluded that the occurrence of a critical event during spent fuel transport is not credible, regardless of the allowance of burnup credit. The highest likelihood of a critical event appears to be during fuel loading operations at a reactor facility and the most likely cause is an equipment selection error. Such an error appears to be independent of the fresh fuel vs. burnup credit argument. The likelihood of this occurring is very small and can be further reduced by implementing uniform cask loading procedures that require strict secondary checks on crucial operations such as fuel identification and cask draining, drying, and sealing. The consequences of such an event do not appear to be greater than potentially exist with other non-transportation related spent fuel handling activities. [5] Also, the risk potential to the public from spent fuel cask critical events appears to be negligible.

Conclusions

It is apparent, then, that the allowance of the consideration of spent fuel histories in the criticality analysis and design of spent fuel shipping casks could result in significant benefits to virtually all parties affected by the transport of spent nuclear fuel. Capacities of casks may be increased considerably in some cases. These capacity increases result in lower public and operational exposures to ionizing radiation. Additional significant safety benefits result from reduced non-radiological risks to both public and occupational sectors.

Economic benefits of capacity increases result from both lower in-transit shipping costs and reduced transportation fleet capital costs. Additional costs savings result from reduced cask handling requirements at both shipping and receiving facilities. In addition, capital cost savings may occur for interim storage, repository, and cask maintenance facilities as a result of both a fewer number of required shipments and a reduced number of individual casks.

The criticality analysis of a model infinite lattice containing spent PWR fuel leads to some significant conclusions. In particular, the vast majority of non-gaseous fission product neutron poisons represent a very stable and major source of negative reactivity for criticality control of spent fuel lattices. The combined effects of fissile fuel depletion and fission and activation product absorption are roughly proportional to in-core burnup. Reactivity effects in PWR lattices are always negative over the 20 year cooling time investigated with the highest rate of negative reactivity addition occurring between 2 to 15 years after discharge from a reactor. Separation distances as small as 0.20 in. for 33 GWD/MTU burned fuel appear to be acceptable for criticality control of PWR spent fuel in a stainless steel basket with low boron fractions, either homogeneously mixed or in equivalent plates. Extension of the analysis to a finite model cask geometry indicates 31 assemblies of fuel exposed to 33 GWD/MTU could be safely accommodated in a 100 ton rail cask.

A fault tree analysis of various cask loading and transport scenarios indicates that the probability of occurrence of a critical event during transport is incredible. The highest potential for a critical event occurs during cask loading operations at reactor facilities. The likelihood of this occurring is very small and can be further reduced by implementing uniform cask loading procedures that require strict secondary checks on crucial operations such as fuel identification and cask draining, drying, and sealing. Finally, the risk potential to the public from spent fuel cask critical events appears to be negligible, regardless of the use of burnup credit in the criticality design.

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