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MULTI-FACET APPROACH FOR EVALUATING CRITICALITY RISKS DURING TRANSPORTATION OF COMMERCIAL SPENT NUCLEAR FUEL

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ABSTRACT

The U.S. industry's limited efforts at licensing transportation packages characterized as "high-capacity," or containing "high-burnup" (>45 GWd/MTU) commercial spent nuclear fuel (CSNF), or both, have not been successful considering existing spent fuel inventories that will have to be eventually transported. A holistic framework is proposed for resolving several CSNF transportation issues. The framework considers transportation risks, spent fuel and cask-design features, and defense-in-depth in the context of present regulations as well as in the context of future potential revisions of regulations that would reflect a risk-informed, technically state-of-the-art approach. Within the boundary limits of the cases analyzed, the EPRI-sponsored work shows that there are no credible combinations of accident events, accident locations, and fuel misloading or reconfiguration that would result in a critical configuration during the transportation of spent nuclear fuel. The non-mechanistic criticality evaluation performed in the as-loaded or as-designed configuration can be considered the bounding case for all conditions of transportation because this hypothetical reactivity case bounds all those normal and hypothetical accident cases that can credibly exist for a spent fuel transportation packages. Criticality during hypothetical transportation accidents should be a regulatory non-issue, as misallocation of regulatory requirements can lead to greater risks by overly restricting payloads.

INTRODUCTION

The packaging and transportation of radioactive material in the United States is regulated by the U.S. Nuclear Regulatory Commission (NRC) under Part 71 of Title 10 in the Code of Federal Regulations (10 CFR 71). The NRC grants a 10 CFR 71 certificate of compliance (CoC) for radioactive material transportation packages upon successful review and approval of the CoC application. The Part 71 regulations include generic requirements for all radioactive material packages as well as unique requirements for specific types of packages. Only those requirements applicable to the criticality control functions and analyses of packages used to transport fissile material in the form of commercial spent nuclear fuel (CSNF) are of interest in this study.

The 10 CFR Part 71 regulations are largely deterministic. That is, they provide specific design features, test requirements, and package performance criteria. In the areas where the regulations do not specifically call out the design or performance requirement, guidance has been published by the NRC. The guidance comes in two forms. The first is in the form of guidance tailored for the cask designer and analyst, such as Regulatory Guides and NUREG documents. The second is review guidance used by the NRC staff to scope and structure their reviews of submitted applications for package design certification, i.e., the standard review plan (SRP) [1]. In several areas, and in particular in the area of criticality control and analysis, the research, data, and the state-of-the-art of the analysis work have been evolving rapidly. Thus, the NRC has chosen to make interim changes to the SRP[1] using Interim Staff Guidance (ISG) documents.

The regulatory guidance, comprised of the SRP and ISGs, includes numerous conservatisms. Whereas the regulations are not specific as to the acceptance criteria for the package criticality evaluation [10 CFR 71.55(d) and 10 CFR 71.55(e) require the package to be "subcritical" under normal and accident conditions, respectively], the SRP establishes a specific reactivity acceptance criterion of $k_{eff} < 0.95$ with a 95% confidence factor. This effectively establishes a five percent minimum safety margin irrespective of the specific contents or design features of the package or the likelihood of the package ever having the fuel cavity flooded with pure water. Other conservatisms include limited burnup credit; limits on neutron absorber credit, such as 75% or 90% depending on material; maximum moderator density, or 1 g/cm^3; flooding of the pellet-cladding gap; etc.

There are several key unresolved criticality safety issues that affect the analyses performed by transportation cask certificate applicants and the reviews of these analyses by the NRC staff. They include incomplete, inconsistent, or overly conservative regulatory guidance in the areas of transportability of high-burnup CSNF, burnup credit, fuel assembly burnup measurement, and moderator exclusion.

In the absence of practical and predictable regulatory acceptance criteria for addressing these issues, regulatory reviews of CSNF transportation package CoC amendment submittals in general, and burnup credit applications in particular, require long periods of time (years rather than months), and result in extremely limited approved contents for those applications that are approved. This leaves the U.S. nuclear industry without the confidence that their high burnup, higher enrichment spent fuel, currently being placed into storage in dual-purpose canisters and casks will be able to be transported off site. The problem intensifies on a regular basis as more high-capacity dual-purpose casks and canister are loaded and placed into spent fuel storage facilities at the reactor sites.

ISSUES

Transportability of High Burnup CSNF

Most of the debate (and R&D) has centered about cladding integrity/performance under transportation accident conditions, as being the key to satisfying the regulatory requirement contained in Part 71.55(e) stipulating that the transportation package contents have to remain subcritical under hypothetical accident conditions.

High burnup (HBU) CSNF is understood to mean fuel burned in a reactor to greater than 45 GWd/MTU. For burnup less than or equal to 45 GWd/MTU, the NRC has concluded that hypothetical transportation accidents do not result in significant damage to, or reconfiguration of, the spent fuel. This is based on the fact that sufficient evidence exists to provide reasonable assurance that fuel burned to lesser levels will remain structurally intact under hypothetical accident conditions, and will, therefore, be bounded by the criticality analysis performed to demonstrate compliance with §71.55(b) (i.e., for "as-loaded" or "as-designed" configuration). For burnup greater than 45 GWd/MTU, the NRC has concluded that they could no longer assume that no significant fuel damage and reconfiguration would result. Therefore, changes in the packaging under hypothetical accident conditions that could cause the nuclear reactivity to increase need to be addressed.

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[1] Revisions to the SRP are infrequent.

Clearly, assuming all other relevant parameters being similar, a higher discharge burnup results in higher radiation fields (shielding is more challenging) and in larger source terms (maintaining waste package integrity becomes even more important). But as far as nuclear reactivity is concerned, the higher the burnup, the better it is for criticality safety![2]

Burnup Credit Methodology

Burnup is a physical reality. How much credit can be claimed for this physical reality is the main issue. It can cover the range from none ("fresh fuel" assumption) to best-estimate "full" (actinides + fission products) burnup credit. The negative reactivity effect of burned fuel is used throughout the nuclear industry in areas such as wet storage rack design and reactor core re-load analyses. The regulatory environment has a long history with the use of burnup credit in these areas. The level of maturity with the preparation and NRC review of burnup credit analyses has allowed the methodology to evolve to include full fission product credit.[3]

Burnup credit has been sought for the transportation of CSNF for over two decades. NRC's review guidance for spent fuel storage and transportation casks practically prohibited any use of burnup credit until 1999. As a result, cask designers have historically assumed unirradiated fresh fuel in every storage location in the cask in the criticality analyses. As time passed, cask designers increased capacity and fuel enrichment limits for their spent fuel cask product lines to respond to the market in the late 1990s. The first issuance of the ISG dealing with burnup credit was issued in 1999. Its latest revision, issued in 2002 [5], endorsed actinide-only burnup credit. Another revision, Revision 3, is expected in 2011. Experimental data necessary for validation of the isotopic compositions and the nuclear cross sections of fission products have not been deemed adequate thus far, and approval of full burnup credit for transportation applications has been subsequently delayed. High-capacity PWR casks and dual-purpose canisters have been loaded for storage since 2000 and, except for the Holtec MPC-32 that can accommodate a limited range of fuel enrichment/burnup, none have been licensed for transportation [6].

Fuel Assembly Burnup Measurement

ISG-8 requires in-pool measurement of the burnup of fuel assemblies chosen for emplacement in a transportation or storage cask licensed with burnup credit to confirm the reactor burnup record for the assembly. However, in most instances, fuel assembly burnup information is already well characterized and quality records corroborated by *in-core measurements* already exist.

Moderator Exclusion

Fissile material transportation packages, including CSNF transportation casks, by regulatory fiat, must be assumed to be flooded with unborated water and analyzed to be subcritical. This condition is not considered a normal condition of transportation or a result of a hypothetical accident. It is a

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[2] Commercial nuclear fuel is limited an initial ^{235}U enrichment of 5% or less. Therefore, a large fraction of its nuclear reactivity will have been consumed at a burnup greater than 45 GWd/MTU.

[3] Over the past year, NRC guidance in the area of spent fuel pool criticality has been changing and as a result, significant uncertainty and unpredictability has been introduced into the licensing process, specifically with regard to the staff reliance on the "Kopp memo" [2]. The NRC has characterized the situation as "Experiencing short term licensing uncertainty in order to achieve long term predictability" [3], and has developed a draft interim staff guidance on spent fuel pool criticality [4].

non-mechanistic requirement that leaves the cask designers with no way to design any CSNF transport cask to exclude moderator and permit the criticality analysis to be performed accordingly. The NRC staff has made it clear that exceptions to the moderator intrusion requirement, as permitted by the regulations, will not be granted on a package *design* basis. Further, the NRC Commission has disapproved an NRC staff recommendation to revise the regulations to allow some flexibility in the moderator intrusion requirement.

The NRC issued ISG-19 [7] permitting cask designers the ability to credit design features for providing the moderator exclusion function during hypothetical accident conditions provided testing was performed. However, this guidance is of limited use for cask designers given the moderator intrusion requirement of §71.55(b). The position in ISG-19 is inconsistent to the extent that the guidance shows a regulatory willingness to accept moderator exclusion under accident conditions, i.e., under loss-of-control conditions (accidents typically result from loss of control), but not normal configuration conditions, when operational controls are assumed to be respected.

ISSUE RESOLUTION ELEMENTS

Risk Assessment

Risks during transportation of CNSF have been addressed by the NRC in References [8] and [9]. These studies assess the risks of accidents capable of breaching the transportation package and resulting in the release of radioactive material to the environment, but do not quantify the frequency of a criticality event.

The only mechanistic manner in which pure water could unexpectedly infiltrate a spent fuel transportation package would be during an accident condition that occurs near a body of water. A detailed analysis of the probability of a criticality event during railroad transportation of CSNF was performed [10] [11], and the results are summarized hereafter.

Probability of a Critical Event during Transportation

To assess the probability of a critical event during railroad transport of CSNF, the following were considered:

1. Probability that fuel assemblies in the transportation package have sufficient nuclear reactivity to produce criticality
2. Frequency of railroad transportation accident
3. Probability of the transportation package suffering damage sufficient to permit in-leakage of water
4. Probability of becoming submerged in water resulting in internal flooding that would produce the geometry, moderation, and reflection conditions necessary to produce criticality.

Table 1 shows that the likelihood of a criticality event during transportation of a 32-PWR spent fuel assembly package is equal to ~10^{-16}/shipment, which is well below any credible event probability historically considered in regulatory practice. This result arises from a number of independent factors:

- The extremely low likelihood that a railroad accident will produce the damage and immersion needed to achieve criticality, as determined by the U.S. NRC-sponsored research.

- The very low likelihood of an error in the recorded burnup of fuel assemblies due to flux mapping measurements and use of fuel assembly burnup to predict and verify core performance during active fuel cycles in the core.
- The low likelihood of a misload due to the controls and verification requirements followed when loading fuel assemblies into the spent-fuel cask.
- The ability to access core burnup and Special Nuclear Material accountability data at any time prior to shipment of a spent fuel cask offsite in order to verify compliance to the cask's CoC.

Table 1. Summary of the Risk of Criticality during Railroad Transportation [10]

Description	**Freight Trains**
Train Accidents per Train-Mile (All Accidents, All Speeds, All Track Classes), 2000 - May 2006.	2.7E-06
Probability of Accident of Interest, Given Any Accident (>2% Strain and Immersion) per Modal Study	7.8E-09
Frequency of Accidents of Interest for Criticality/Train-Mile	2.1E-14
Assumed Average Number of Miles per Shipment	2,000
Frequency of Accidents of Interest for Criticality/Shipment	4.2E-11
Likelihood of Shipping a Misloaded Spent Fuel Cask	2.6E-06
Likelihood of an Accident with a Potential for Criticality/Shipment	1.1E-16

A number of operational safeguards and controls would further reduce the risks, such as more closely controlling and monitoring the trains transporting spent nuclear fuel than the generic population of freight trains evaluated in the risk assessment. For example, train speed limits can be established below a threshold speed needed to produce damage. They could be further reduced selectively for those stretches of track that have the close proximity to water deep enough to fully immerse a spent fuel cask. A NAS committee also recommended that no other traffic should be allowed in tunnels during transit of spent fuel through the tunnel. [20]

Critical Configuration

The potential for a critical configuration will depend on:

- Amount of nuclear reactivity inadvertently introduced as a result of misloading, and
- Reconfiguration of fuel that would result in a higher nuclear reactivity

Misloads

The likelihood of shipping a misloaded spent fuel cask, equal to $2x10^{-6}$ as shown in Table 1, carries the assumption that a *single* misloaded fuel assembly would introduce sufficient reactivity for resulting in a critical event.

EPRI examined the impact of misloading both “under-burned” and fresh fuel into a 24-PWR-assembly cask design[4] containing fixed boron neutron absorbers [12]. “Under-burned” fuel is spent fuel that has not achieved the burnup obtained from the reactor core-follow calculations used to plan reactor operations and reloading schemes. The calculations accounted for actinide depletion and buildup of five neutron-absorbing fission products. The results are shown in Figure 1 for spent PWR fuel with a discharge burnup of 45 GWd/MTU from a hypothetical fuel cycle utilizing 5% enriched fuel. The value for k_{eff} of ~0.88 with no misloaded fuel assemblies indicates that there is considerable margin for uncertainty in the calculations when the presence of neutron absorbers actually in the fuel is accounted for.

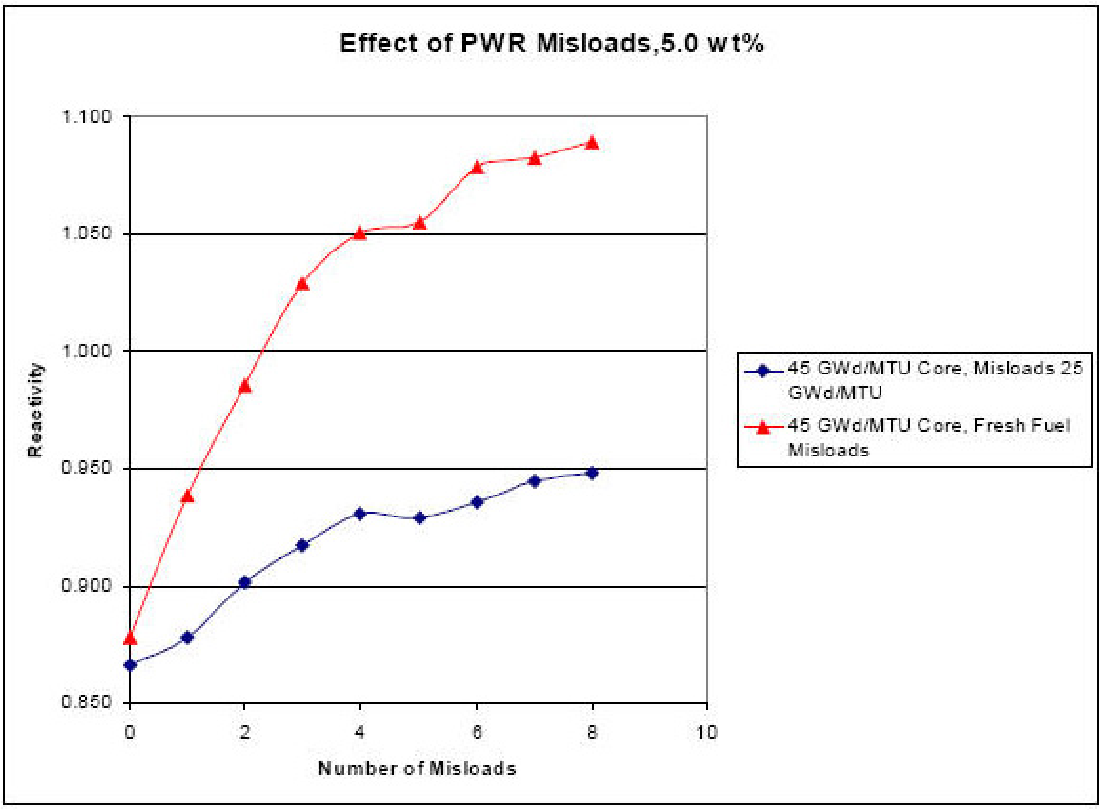

Figure 1. Effect of misloaded fuel assemblies on the k_{eff} of a conceptual 24-PWR spent fuel cask [12]

The two sensitivity cases in Figure 1 show the impact of the substitution of up to eight assemblies (i) with a burnup of only 25 GWd/MTU (about 56% of the design burnup), and (ii) consisting of fresh fuel. For both cases, the substitution of these assemblies is made by grouping them together in

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[4] A sensitivity study shows that cask size does not significantly alter the k_{eff} of the package. For the calculations using spent fuel with the same burnup, the criticality calculations for a 32-PWR assembly cask produce essentially the same k_{eff} as a 24-PWR assembly cask. This results from the fact that the calculation groups all the under-burned assemblies in the center of the cask in their most reactive configuration. The misloaded fuel acts like a small core surrounded by a reflector of the more highly burned assemblies directly adjacent to the misloaded fuel. Addition of assemblies beyond the adjacent assemblies increases k_{eff} only to the extent that net neutron leakage out of the misloaded region is reduced. As the immediately adjacent assemblies provide the vast majority of reflection back into the misloaded group, the overall effect on k_{eff} of using a larger cask is insignificant.

the middle of the cask, which produces the highest increase in k_{eff}. It can be seen that the substitution of up to eight fuel assemblies with a burnup of 25 GWd/MTU results in a maximum k_{eff} of only ~0.95. Furthermore, it shows that more than one assembly of fresh fuel must be misloaded into the cask to result in a k_{eff} greater than 0.95, while three are needed to produce criticality. As expected, the consequences of a misload with fresh fuel would be more significant. Misloading a single fresh assembly with 3, 4, or 5 wt% ^{235}U enrichment would result in an increase in k_{eff} of ~0.02, 0.04, and 0.06, respectively [13].

Therefore, even assuming the worst possible nuclear reactivity to start with, i.e., $k_{eff} = 0.95$, the assumption that a *single* misloaded fuel assembly would introduce sufficient reactivity ($\Delta k_{eff} \geq 0.05$) necessary for a critical event is true only when the misload involves a fresh 5% enrichment assembly. However, there is a very low likelihood that fresh fuel would be in the spent fuel pool when spent fuel casks are loaded. Since all fuel is handled by one group within a plant and spent fuel pool space is limited, spent fuel cask loading would typically be scheduled to be made early in a fuel cycle run to make room for the next refueling operation. The new fuel is received into the new fuel storage area, where it is inspected and stored to just prior to refueling.[5] In addition, there is a distinct difference in the appearance of fresh and once-burned fuel assemblies, as illustrated in Figure 2. This figure shows an arrangement of fuel assemblies during a refueling operation. The fresh fuel assemblies have their original metallic color, while the once-burned assemblies have been darkened by corrosion. The risk assessment takes no credit for the ability of members of the

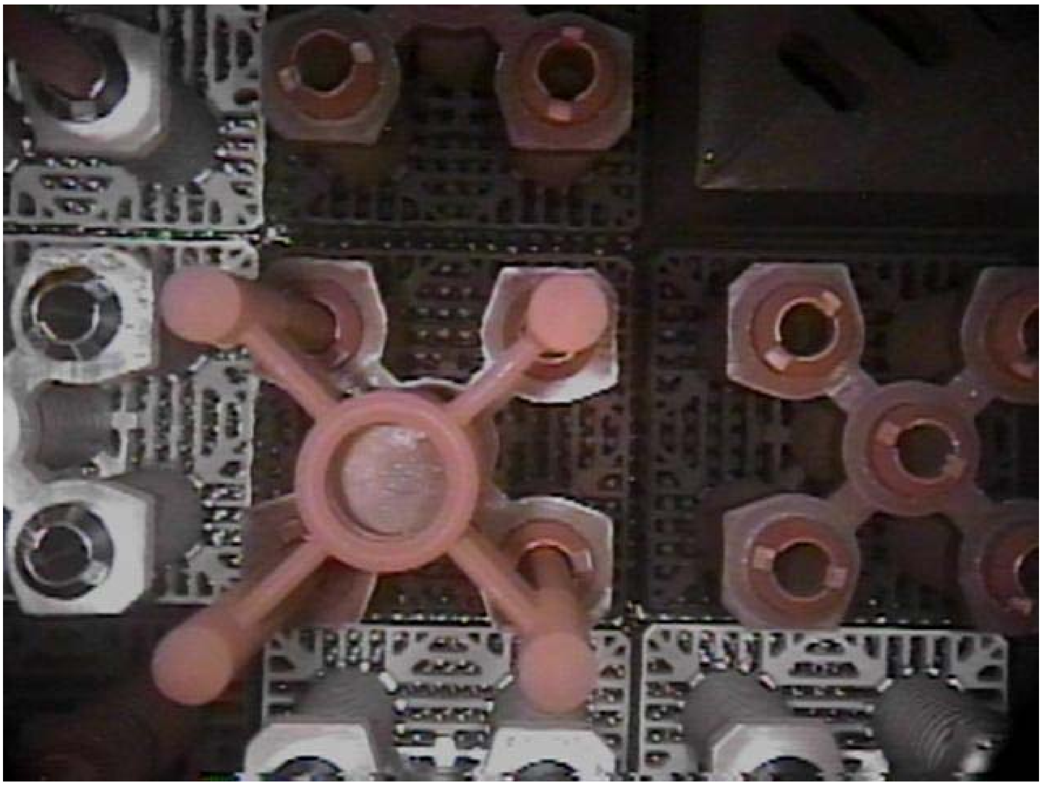

Figure 2. New and Once-Burned Fuel in a Reactor Core

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[5] Some plants that changed from a three to two cycle shuffle may have to transfer new fuel to the spent fuel pool to make room for the last shipment of new fuel, but the work necessary for processing the new fuel will take priority over any loading of spent fuel casks.

refueling team to recognize the differences between a fresh fuel assembly and a once-burned fuel assembly. However, the readily recognizable difference in appearance provides additional assurance that the likelihood of a misload will not involve a fresh fuel assembly.

High Burnup Fuel Reconfiguration

One of the U.S. NRC spent fuel transportation system requirements is that criticality calculations be performed with the fuel geometry in its most credible configuration that would maximize k_{eff}. If the spent fuel were to become severely damaged during a transportation accident, it would be difficult to define what that maximum credible geometry would be. As long as the cladding remains sufficiently ductile, damage to the spent fuel in a transportation accident would be minor. Today's high burnup fuel designs are expected to be burned in excess of 45 GWd/MTU. According to ISG-19 [7]:

> *"Due to effects of irradiation, the cladding of spent fuel, and particularly high burnup fuel (i.e., fuel with a burnup greater than 45,000 MWD/MTU) may become brittle. If excessively brittle, the cladding could fracture under impact loads currently associated with hypothetical accident free drop test conditions. Consequently, criticality safety of the reconfigured fuel assembly must be demonstrated."*

Worst-case Scenarios

The effects of "worst-case" accident scenarios were surveyed in Reference [14]. The survey used scenarios that were postulated to provide theoretical upper limits for reactivity effects of fuel relocation, although they were described as going "beyond credible conditions."

In order to provide credible estimates of the probability and maximum reactivity changes, EPRI delved deeper into the physical conditions that make up the theoretical scenarios and applied physical limits based on current cask design practices [15]. The scenarios involved physical changes either to fuel assembly rod arrays or to collections of fuel pellets with the fuel skeleton removed. These scenarios were deconstructed into a set of scenarios and the physical phenomena required to create the scenario were identified. The boundary between credible (but unlikely) and incredible scenarios is easily discernible with this methodology.

The study showed that the unyielding cask basket structure prevents fuel rod arrays from attaining optimum moderation conditions, thus limiting reactivity increases. The study concluded that the maximum reasonable reactivity increase for unlikely, but perhaps credible, "worst-case" scenarios was either less than the administrative margin of 0.05 for scenarios involving physical changes to fuel assembly rod arrays (Figure 3), or a substantial reactivity decrease for scenarios involving physical changes to free pellet arrays.

Figure 3 shows the most reactive case corresponding to fuel rods expanding within the basket fuel cell with all rods remaining parallel and equally spaced (without grids), with increasing water moderation. The maximum reactivity increase can be calculated by expanding the fuel basket cells and unrealistically allowing the cask diameter to grow to accommodate the larger basket, as shown in Figure 3. The reactivity increases until optimum moderation is reached, and then it decreases as the array becomes over-moderated. Alternatively, if the cask basket is unyielding (i.e., is not capable of expanding), which is a much more reasonable assumption, then fuel rods must be removed from the array to provide the space needed for expansion, and optimum moderation is reached with a smaller array within the fixed basket cell. This case is more pertinent for spent fuel casks, and the maximum reactivity is reduced by half, from ~0.06 to ~0.03.

Best-estimate Case Scenarios

Transportation accidents postulated for spent fuel shipments are bounded by the regulatory hypothetical accident of a 9-meter drop of a rail transport cask onto an unyielding surface. Of the three possible drop orientations of the cask at impact, namely the end-on drop, the corner drop with slap-down and the side drop; the latter is the most severe because it activates the cladding failure mode with the highest failure potential.

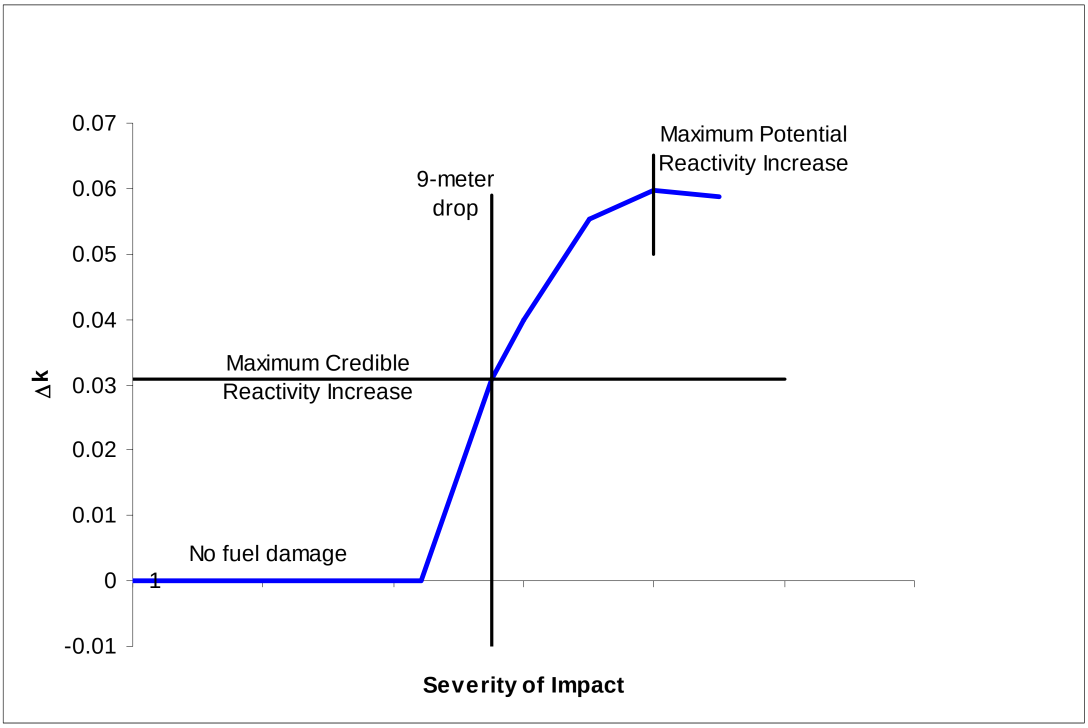

Figure 3. Cask System Reactivity versus Cask End Drop Severity

The source-term study conducted by Sandia National Laboratories nearly two decades ago for the spent fuel inventory known at the time, which was in the low-to-medium burnup range (~ 35 GWd/MTU), showed that the effects of transportation accidents on spent fuel failures, and consequential radioactivity release to the environment, were relatively benign [16]. The results from these Sandia studies have provided the justification for ignoring significant damage and potential reconfiguration as a result of accident conditions. However, with today's discharged fuel burnup routinely greater than 45 GWd/MTU, potential hydride reorientation during interim dry storage and its effects on cladding properties have become one of the primary cladding performance concerns for spent fuel transportation.

Laboratory tests of un-irradiated and irradiated cladding specimens subjected to heat treatments promoting hydride dissolution followed by re-precipitation in the radial direction have shown that relatively moderate concentrations of radial hydrides can significantly degrade cladding ductility, at least at room temperature. The absence of specific data that are relevant to high-burnup spent fuel under dry storage conditions have led to the conjecture, deduced from those tests, that massive cladding failures, possibly resulting in fuel reconfiguration, could be expected during cask drop events. Such conclusions are not borne out by the findings in the EPRI studies [17] [18] [19], as discussed below.

There are three types of physical and material conditions of spent fuel rods at the end of dry storage that could have an effect on cladding failure behavior under transportation accident conditions. These are:

(a) Burnup-dependent conditions, such as the dependence of cladding mechanical properties on irradiation and cladding thickness loss due to corrosion, which affect the magnitude of cladding deformations.

(b) Dry-storage conditions, such as creep-induced fuel-cladding gap and hydride re-orientation, which affect cladding resistance and vulnerability to failure.

(c) Cladding defects, such as hydride lenses and incipient cracks, which behave as precursors for cladding failure initiation.

These are incorporated in the EPRI methodology, and their effects are reflected in the results. The results indicate that type (a) conditions play an indirect role in cladding failure behavior, namely, through their effects on cladding deformations. Type (b) conditions play a very direct role in cladding failure behavior in two ways: firstly, through the effects of radial hydrides on cladding fracture resistance, and, secondly, through the effect of the fuel-cladding gap size on limiting cladding deformations due to fuel pellets participation in resisting the load. This latter effect of gap size plays a similar role in the behavior of type (c) defects, where cladding contact with the fuel pellets prevents the propagation of cracks or surface defects to through-wall failures.

The analysis results indicate that cladding failure is bi-modal: a state of failure initiation at the inside wall of the cladding remaining as part-wall damage with less than 2% probability of occurrence, and a through-wall failure at a probability of $\sim 10^{-5}$. It is important to note in this regard that the through-wall cladding failure probability of $\sim 10^{-5}$ is of the same order of magnitude as calculated in the Sandia study for lower burnup fuel.

In summary, the EPRI studies showed that significant breakage is not likely in the nine-meter drop transportation hypothetical accident scenarios and fuel reconfiguration of a magnitude discussed in worst-case scenarios are not credible.

Moderator Exclusion and Burnup Credit

Risk information supports the concept of defense-in-depth when considering that moderator exclusion or burnup credit could be used singly or in combination in the design of transportation package:

1. For a “burnup-credit” package design, it is highly unlikely that fuel would be exposed to water during transportation because of the low frequency of severe enough accidents in the proximity of a water body [10] [11].
2. For a “moderator-exclusion” package design, it is highly unlikely that even if water flooded the package, the package could ever form a critical configuration. A companion requirement could impose a condition that k_{eff} be shown to be below 1 when using a *best-estimate* burnup credit methodology.

Of the two options, moderator exclusion would seem to hold the promise of an easier, less-costly path to success, particularly for advanced and next-generation technology. However, for general application of moderator exclusion, rulemaking may be required to relieve the NRC of having to use the exception approach to certification. Moderator exclusion may be possible within the current regulatory framework through an interpretation of current regulations and development of guidance documents to allow moderator exclusion under certain conditions in which it can be demonstrated that water in-leakage is not credible [21].

ISSUES RESOLUTION APPROACH SUMMARY

Risk information indicates that the probability of a critical event during transportation is essentially zero.

1. Casks are designed and their contents so limited that under the most reactive conditions, with pure water in the fuel cavity, the k_{eff} for the reactivity system must be calculated to be less than or equal to 0.95 using very conservative assumptions. The criticality analysis assumes that each fuel assembly in the cask is at its minimum required burnup for its enrichment as specified in the loading curve contained in the CoC. This is required to ensure that the licensing basis criticality analyses for the cask are bounding for all combinations of fuel permitted by the CoC for loading. Other physical parameters used in the criticality analysis are also assumed to be at their limiting value that maximizes the reactivity of the system. In a properly-loaded cask at least some of the fuel is burned to higher levels than the minimum CoC requirement, which provides additional safety margin beyond that shown in the criticality analyses. EPRI work shows that the actual reactivity of a properly loaded 24-assembly cask with fixed neutron absorbers and considering the burnup credit from five fission products would be on the order of $k_{eff} = \sim 0.85$, as illustrated in Figure 1. This represents significant additional criticality safety margin before any misloading event is considered.
2. Transportation accidents that are severe enough to result in an opening in the transportation package in the presence of water are very low probability events.
3. Assuming that the package contents maintain their normal configuration during the accident, misloading of under-burned fuel does not result in a critical configuration, except under extremely unlikely assumptions (misloading of *fresh* fuel enriched at ~5%).
4. Assuming that the package contents experience reconfiguration as a result of the accident, it is highly likely that reconfiguration will result in a lower k_{eff}. Reconfiguration may lead to slightly higher k_{eff} under extremely unlikely assumptions. However, (1) best-estimate evaluation of fuel damage under accident conditions indicates that damage is limited and far from approaching the type of damage assumed for extremely unlikely scenarios; and (2) the potential for any reconfiguration is tied to high burnup values, and therefore, low residual nuclear reactivity.

CONCLUSIONS

Within the boundary limits of the analyzed cases, the EPRI-sponsored work shows that there are no credible combinations of accident events, accident locations, and fuel misloading or reconfiguration that would result in a critical configuration during the transportation of spent nuclear fuel. For most transportation package designs, criticality during hypothetical transportation accidents should be a regulatory non-issue given the extraordinarily low probability of the concomitant occurrence of the conditions required for providing a situation conducive to criticality in the cask. The non-mechanistic criticality evaluation performed in the as-loaded or as-designed configuration can be considered the bounding case for all conditions of transportation because this hypothetical reactivity case bounds all those normal and hypothetical accident cases that can credibly exist for a spent fuel transportation packages.

In the U.S., the present lack of regulatory guidance for analyzing hypothetical transportation accident conditions is largely based on the paucity of mechanical property data available for spent fuel irradiated above 45 GWd/MTU. The reactivity of a spent fuel transportation package with re-configured fuel and water in the fuel cavity is of particular concern to the regulators. However, realistic and achievable configurations of nuclear fuel materials following an impact accident are more likely to have no impact or result in a reactivity decrease.

Non-radiological events, while very low risk themselves, provide the over-riding level of comparative risk. These non-radiological risks are directly proportional to the number of spent fuel shipments; that is, a higher number of shipments means a higher risk of accidents and other events. To minimize the number of shipments and related risk, the number of spent fuel assemblies per shipment should be maximized. High-capacity rail casks represent the lowest risk method of transporting spent nuclear fuel, regardless of the enrichment or burnup of the fuel.

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