Alternatives for Implementing Burnup Credit in the Design and Operation of Spent Fuel Transport Casks*

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INTRODUCTION

The traditional assumption used in evaluating criticality safety of a spent fuel cask is that the spent fuel is as reactive as when it was fresh (new). This is known as the "fresh fuel assumption." It avoids a number of calculational and verification difficulties, but could take a heavy toll in decreased efficiency. The alternative to the fresh fuel assumption is called "burnup credit." That is, the reduced reactivity of spent fuel that comes about from net depletion of fissile radionuclides and net increase in neutron absorbers (poisons) is taken into account.

It is recognized that the use of burnup credit will in fact increase the percentage of unacceptable or non-specification fuel available for misloading. This could reduce individual cask safety margins if current practices with respect to loading procedures are maintained. As such, additional operational, design, analysis, and validation requirements should be established that, as a minimum, compensate for any potential reduction in fuel loading safety margin.

There are numerous approaches toward developing design and operational constraints that together ensure the criticality safety margin in each cask is optimized. Some approaches, however, could negatively affect the potential benefits of burnup credit without a substantial increase in verifiable safety margin. A comparative methodology has been developed for the purpose of evaluating tradeoffs between these various implementation strategies (Lake and Sanders, 1989).

This method is based on a probabilistic (PRA) approach and is called a relative risk comparison. The method assumes a linear risk model, and uses a selected probability function to compare the system of interest and an acceptable reference system by varying the features of each to assess effects on system safety. While risk is the product of an event probability and its consequence, the consequences

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** A United States Department of Energy Facility of criticality in a cask are considered to be both unacceptable and the same, regardless of the initiating sequence. Therefore, only the probability of the event is considered in a relative risk evaluation.

FACTORS AFFECTING THE CRITICALITY SAFETY MARGIN IN A SPENT FUEL TRANSPORT CASK

One governing "ground rule" provides the basis for assuring criticality safety. No single event, loss, or failure, whether operational or component-related, should result in compromised criticality safety. Under the fresh fuel assumption, the cask criticality control system consists of a single "external" component that includes neutron absorbers (poisons) incorporated in the cask or basket web, void spaces or "flux traps" incorporated in the basket for moderator requirements, and structural support members. These features are "external" to the fuel. Flux traps are required to ensure that any neutron absorptions that occur do so in the external poison rather than in the fuel. These are "hardware" subcomponent(s) of the criticality control system. Loss of either hardware subcomponent, be it the poison, the flux trap, or spacing support, could render the total system ineffective or, at a minimum, result in reduced reliability.

Additional safety margin results from other aspects of the design basis. For example, the criticality design basis normally assumes maximum water moderation and reflection, although shipments are intended to be dry. Also, the reactivity of the actual fuel loaded will be significantly less than the design basis fresh fuel value. The criticality safety margin associated with the fresh fuel assumption is generally assumed to be independent of the reliability of fuel loading operations. This is indeed true if future fuel is designed to the same reactivity limit over the life of the cask. If future fuel is made more reactive (higher initial enrichments), the system is no longer passive and active operational requirements will be necessary to preclude loading nonspecification fuel into the cask. Nonspecification fuel is any fuel (fresh or irradiated) that exceeds the design basis reactivity.

In the case of burnup credit, the criticality control system will consist of two separate components with the reliability of each being important. The first is an external control component similar to that used in a fresh fuel assumption design basis, and includes poisons in the cask or basket web and geometric spacing and support. The second "internal" component is the loaded spent fuel. Burned fuel reduces external criticality control requirements due to net depletion of the fissile material and the production of poisons which deprive remaining fissile nuclei of available neutrons.

From a broad perspective, the major events that could lead to reduced subcritical margin during cask loading or transport are unchanged with burnup credit. However, the number of opportunities for error leading to one of those events, excessive fuel reactivity, will increase. Exceeding fuel reactivity limits could result from a fuel loading error, an error in the analysis used to develop fuel loading procedures, or an error in the burnup characterization of the spent fuel (from error in in-core measurements or subsequent analyses). Some minimal acceptance criteria for demonstrating the reliability of spent fuel analysis and operational activities is needed. This does not mean that the reliability or quality of current spent fuel operations is questionable; however, any uncertainties associated with those operations need to be defined.

For a transportation system with a specific task (fixed spent fuel shipping rate and transport distance), the use of burnup credit could result in significantly lower total system risk (Sanders et al., 1987). The reduced risk occurs primarily as a result of higher cask capacities and fewer transport requirements. This results in reductions in both normal transport exposure risks and radiological and nonradiological accident risks.

Although burnup credit can be seen as a means of reducing system risks it is also evident that if burnup credit is introduced with no other changes in the cask design or operations, individual cask criticality risks must increase. The increased cask risk is not due to increased probabilities of criticality control failure, but rather from the introduction of a new opportunity for error (i.e., loading nonspecification fuel). A nonspecification fuel loading error can also occur under the fresh fuel assumption if fuel designs are introduced that have higher reactivity than cask design limits. This idea weakens, but does not dismiss the value of the fresh fuel assumption. These thoughts raise some important questions. What exactly is the risk that we are concerned with? Is the increase in individual cask criticality risk with burnup credit significant? If the increased risk is significant, do we simply choose not to allow it, or determine what can be done to eliminate the net increase? The first of these questions will be answered qualitatively in the next paragraph. The others will be answered quantitatively in the next section.

Casks are designed to remain subcritical within a specific margin (by precedent a 5 percent margin is used on k_{eff}, the measure of criticality). The regulatory design conditions assume multiple independent failures. The fresh fuel assumption is not introduced by regulation, but by precedent and does result in a perception that the reactivity margin is much greater than 5 percent. Because the multiple failures necessary to even approach criticality are covered by regulation, loading of nonspecification fuel under burnup credit has the practical affect of reducing this perceived margin rather than introducing a risk of criticality.

METHODS FOR REDUCING THE PERCEIVED RISK OF BURNUP CREDIT

A qualitative relative risk comparison can be conducted to compare safety margins or reliabilities that result from various design and operational strategies for implementing burnup credit. Relative risk by definition is simply the ratio of the probability of a less-than-adequate burnup credit criticality control system existing to the same probability for a system based on the fresh fuel assumption. Alternatively, it could also be defined as the ratio of the criticality control reliabilities associated with each of those systems.

Some reasonably simple models of the effect of various system strategies can be developed for the criticality control functions of a spent fuel shipping cask. This is possible because (1) a shipping cask is a rather straightforward system and the various human activities and failure modes which can reduce its functional reliability can for the most part be identified; and (2) all of the failure modes affecting criticality control reliability can be traced to human errors (whether design, fabrication or operational) that have similar probabilities of occurrence (on the order of some small number δ which lies in the range 10^{-5} to 10^{-3}) (Sanders et al., 1987).

The relative risk of implementing burnup credit without any additional controls is the ratio of the failure probabilities for the fresh fuel case and the burnup credit case, assuming the consequences are the same for both cases. This is given by (Lake and Sanders, 1989):

$$RR = 1.0 + \Delta \tag{1}$$

where Δ is the ratio of the failure probability of the internal criticality control feature to that for a system based on the fresh fuel assumption.

Regardless of the magnitude of Δ, the relative risk is greater than one because other sources of error or failure combine to increase the potential for a reduction in the overall criticality safety margin. The "lost" margin is associated only with the nonspecification fuel inventory and its characteristics and the system reliability is no longer perceived to be totally passive to operational loading errors.

There are several options which, if implemented in a burnup credit system, could result in a criticality control reliability at least equal to that provided by the fresh fuel assumption case. The first option is simply to recognize that the "increase" involves a very small number and is negligible although the "relative risk" is slightly greater than one. The probability of a criticality event occurring is still much less than one.

Another option available to achieve equivalent safety between the fresh fuel assumption and burnup credit cases is to implement additional controls on the internal and external components of the system. When such additional controls are used, independent steps, components, or operations are added that must also fail for reduced reliability to result. An example could be an additional overcheck of a specific operational step that must be performed independently. Design conservatism or operational margin that compensates for a single error source are other examples. The relative risk is significantly reduced if a criticality safety feature (e.g., test, operation, or hardware verification) is added that is independent of the fuel and cask components. Such a safety or control feature is known as a system level feature, i.e., it results in an additional feature that must fail independently of the cask and fuel features before criticality safety is reduced.

Thus, there are basically three generic options for implementing burnup credit which result in some relative risk value. A single functional relationship for the relative risk for all options has been developed. This function is given by:

$$RR = \left[\frac{\sigma_n + \varepsilon}{P_o} \right] \pi \tag{2}$$

RR is the ratio of the failure probability of a burnup credit design basis to that for an accepted fresh fuel reference design basis. The terms σ_n and ε are failure probability distributions for the external (cask) and internal (spent fuel) features of the criticality control system, respectively. For example, the spent fuel basket is an external control feature and the analysis used to characterize the spent fuel is an internal control feature. P_o is the failure probability for a system based on the fresh fuel assumption. The first term on the right side of Equation (2) is the relative risk function for a burnup credit case without system level controls and varies between some value greater than 1.0, and some minimum. The function π represents the failure probability for system level control features. If no system level control features are added, the value of π is 1.0.

If no changes are made to the cask component control features, then σ_n is equal to P_o and equation (2) reduces to equation (1). In this case then, the relative risk can become less than 1.0 only if burnup credit implementation results in an external control system with higher reliability than that for the fresh fuel assumption case. This is possible if an inherent failure source such as a flux trap requirement can be eliminated from the system.

As additional external and internal component control features are added, σ_n and ε of equation (2) are reduced accordingly, and the system failure probability approaches zero (system reliability approaches 1.0). Some of these additional controls at the component level could already be in place. For example, a transport cask based on burnup credit is clearly analogous to a burnup credit storage rack system when the cask is placed in a spent fuel storage pool. The cask becomes a separate region of the pool that takes credit for fuel burnup. Regulations are in effect that place constraints both on the procedures used while loading fuel in a burnup credit region and the storage rack design (Brooks, 1987). For example, the criticality criterion ($k_{eff} \leq 0.95$) must be met assuming unborated water is used in the pool. The criticality analysis and the design of the storage rack system must be performed using calculational methods and procedures that have been verified. Methods have been developed to ensure that only spent fuel assemblies having required burnups are placed in burnup credit rack systems. Acceptable methods include (1) measuring the average burnup of each assembly, (2) measuring the reactivity of each assembly, or (3) independently validating the analysis and procedure that result in the choice of a particular assembly for placement in a burnup credit rack region. Each of these methods results in an additional independent control on the internal component that must fail for system reliability to decrease.

Even more options exist. A fuel misloading error in a burnup credit rack system can result from fresh fuel storage in reactor pools. To preclude error, some utilities have implemented positive locking devices on racks containing fresh fuel. These locking devices require that an operator perform an active independent operation in addition to misidentifying an assembly in order to remove the assembly from its location. All fresh fuel moving into a pool is immediately locked into place or placed in a specific region that has barriers which prevent accidental removal. This is a redundant and independent component level control. Other utilities videotape the movement of all fuel to and from the reactor vessel and the storage pool. This strategy provides a time-independent and irrefutable fuel location history. Videotaping serves as a second source of information for use in evaluating fuel tracking data and reduces the uncertainty of administrative controls after a long time period.

Other distinguishing differences between fresh and spent fuel are available for use as additional controls. For example, there are obvious visible differences. The very low gamma flux (if any) emanating from fresh fuel allows a very simple measurement to identify quickly fuel that has not been irradiated.

Also transport campaigns could be discouraged during periods when fresh fuel is indeed in the pool. Finally, it is very unlikely that a fresh fuel batch or even a single assembly would inadvertently either be left in a pool or transferred out by cask. A rail cask loaded with fresh fuel transported from a utility represents a loss of about $15 million to the utility; therefore, there are obvious economic reasons to ensure that the reliability of the fresh fuel accounting system is high.

For any system control application, the magnitude of π is governed by the error rate for trained operators and will be approximately 10^{-3} to 10^{-4}. The resulting relative risk is less than or equal to 1.0 even if $\sigma_n + \varepsilon >> P_o$ (NUREG/CR-1228, 1980). An additional control employed at the system level reduces the probability of system failure by a considerable amount and further ensures that multiple independent failures are required to result in reduced criticality safety. Note also that a single additional system level control feature results in relative risk of similar magnitude to the minimum for component level features which occurs when additional controls are implemented on all element level features. An example of a system level control is a pre-use validation of all operational and design components of the cask system. This "acceptance test" would validate utility procedures, cask procedures, utility evaluations of fuel characteristics, cask hardware, and other factors.

Another system level control that could be implemented readily is a cask "dryness measurement" prior to transport. Ensuring that a cask is both dry and properly sealed prior to transport significantly reduces the in-transport criticality probability, results in substantial subcritical margin during transport, and ensures that a minimum of three unlikely, independent events must occur for criticality to become a credible event. An accident must occur, a body of water must be present, and the accident must be severe enough to result in water inleakage.

RESULTS AND CONCLUSIONS

It is possible to develop an optimal strategy for implementing burnup credit in spent fuel transport casks. For transport, the relative risk is rapidly reduced if additional pre-transport controls such as a cavity dryness verifications are conducted prior to transport. Some other operational and design features that could be incorporated into a burnup credit cask strategy are listed in Table 1. These examples represent many of the system features and alternatives already available for use in developing a broadly based criticality safety strategy for implementing burnup credit in the design and operation of spent fuel transport casks.

REFERENCES

T. L., Sanders, R. M. Westfall, and R. H. Jones, Feasibility and Incentives for the Consideration of Spent Fuel Operating Histories in the Criticality Analysis of Spent Fuel Shipping Casks, SAND87-0151, TTC-0713, Sandia National Laboratories (August 1987).

W. H. Lake and T. L. Sanders, "Evaluating Alternative Design Philosophies for Spent Nuclear Fuel Transport Casks Using a Comparative Probabilistic Risk Assessment Approach," Proceedings, PSA'89 International Topical Meeting: Probability, Reliability, and Safety Assessment, Volume 2, 1186, April, 1989.

"Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications," U.S. Nuclear Regulatory Commission, NUREG/CR-1228, April, 1980.

W. L. Brooks, "Credit for Burnup in Spent-Fuel Storage Rack Design - Regulatory Perspective," Transactions of American Nuclear Society, 55, 400, November 1987.

Table 1

Cask Operational and Design Options Available for Implementing Burnup Credit in the Design and Operation of Spent Fuel Transport Casks

Cask Design Basis Options

A Validated Criticality Analysis Method Should Be Used
Design Assumptions
- The Cask/Fuel Analysis Must Assume Fully Reflected and Moderated Conditions
- Short-lived Fission Product Poisons in the Fuel Should be Neglected
- Gaseous Fission Product Poisions in the Fuel Should be Neglected
- Manufactured Poison Components of the Fuel Should be Neglected Unless Including Them Results in a More Reactive Condition

Acceptance Test Requirements
- Basket Poisons Included in the Design Should be Verified by Measurement Prior-to-First Use of the Cask
- Subcritical Verification on First Loading Could be Performed Prior-to-First Use

The Following Uncertainty Analyses Should be Performed:
- Axial Burnup Distribution Effects
- The Effects of Water Density Variations on System k_{eff}
- The Effect of the Presence of a Single Fresh Assembly on k_{eff}

The Following Operational Design Considerations Could be Evaluated:
- Human Factor Features That Prevent Errors in Cask Operations
- Overcheck Validation Requirements

Cask Operational Procedures

A Method for Utility Analysis of Shipment k_{eff} Could be Incorporated in Pre-shipment Evaluations
A Method for a Preshipment Verification of Cavity Dryness Could be Required
A Reliable Procedure for Checking Successful Completion of all Cask Operations Should be Required
A Preloading Discriminating (GO-NO GO) Measurement for Fresh Fuel Could be Required

Utility Operational Considerations

Utility Fuel Analysis and Management Methods and Systems Should be Validated by an Acceptance Test
Sites Should be Licensed for Burnup Credit Operations
Cask Loading Personnel Should be Trained and Certified in Accordance with Specific Requirements
Whenever Possible Spent Fuel Shipping Activities Should not be Conducted When Fresh Fuel is Stored in the Pool
All Non-Specification Fuel Available in a Pool Should be Actively Segregated (behind barrier, locked in place, etc.) from the Specification Fuel Population