BURNUP CREDIT ISSUES IN TRANSPORTATION AND STORAGE*

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ABSTRACT

Reliance on the reduced reactivity of spent fuel for criticality control during transportation and storage is referred to as burnup credit. This concept has attracted international interest and is being actively pursued in the United States in the development of a new generation of transport casks. An overview of the U.S. experience in developing a methodology to implement burnup credit in an integrated approach to transport cask design is presented in this paper. Specifically, technical issues related to the analysis, validation and implementation of burnup credit are identified and discussed.

INTRODUCTION AND BACKGROUND

Current practice for criticality analysis in spent fuel cask design is based on the assumption that the fuel is fresh. Spent fuel transportation and storage casks designed under this assumption have a limiting k_{eff} of 0.95 which represents a safety margin of 0.05 Δk. Using the fresh fuel assumption, it is necessary to control only one parameter, the initial enrichment, to prevent criticality. Criticality analyses using the burnup credit approach (accounting for the reduced reactivity of the spent fuel) will also have a limiting k_{eff} of 0.95 and, therefore, a safety margin of 0.05 Δk. Burnup credit reduces the conservatism in the cask design as a direct result of explicitly considering the actual fuel characteristics (i.e., initial enrichment, burnup and cooling time). The effects of these primary fuel characteristics on system reactivity are well known; reactivity increases with initial enrichment, and decreases with burnup and cooling time (Sanders et al. 1987, Cerne et al. 1987). In the U.S. approach, a minimum cooling time of 5 years is being considered with no additional reactivity credit for cooling times in excess of this value. The initial enrichment and burnup of the fuel are parameters that are used to qualify a fuel assembly for loading into a specific cask design. Use of these multiple-parameter limits for cask loading provide a substantial increase in cask capacity which translates to fewer shipments and directly reduces both occupational and public risk of exposure and transportation costs. However, the multiple-parameter limits also result in requirements for additional administrative controls to verify that the loading restrictions are met.

The U.S. has integrated analysis, validation and operations issues into a comprehensive strategy for the specification of design and operating criteria for the development of burnup credit casks. Factors that can affect design and safety have been identified and prioritized. Methods to validate the calculational methods and reduce data uncertainties are crucial to the successful implementation of burnup credit and are actively being pursued. Lessons learned are translated into design and operational guidance for the implementation of burnup credit.

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* This work performed at Sandia National Laboratories, Albuquerque, New Mexico, supported by the United States Department of Energy under Contract No. DE-AC04-76DP00789.

** A United States Department of Energy Facility

This paper identifies the current status in the resolution of physics and validation issues using the reference analysis methodology described below. Operational issues associated with the implementation of burnup credit are also discussed.

REFERENCE ANALYSIS METHODOLOGY

Evaluating a spent fuel system using the burnup credit approach has two fundamental requirements; predicting the isotopic composition of the spent fuel and analyzing the system reactivity based on these isotopics. The US-DOE Burnup Credit Program utilizes an analysis methodology developed at Oak Ridge National Laboratory (ORNL) based on the SCALE computer code system (NUREG/CR-0200 1992) which is primarily an away-from-reactor analysis tool. The reference analysis methodology is described in detail in Brady and Sanders (1992). In this methodology, the Monte Carlo code KENO V.a is used to perform criticality calculations. The ORIGEN-S code uses point depletion models (i.e., no spatial dependence) to predict the isotopic composition of the spent fuel. These codes are utilized via the automated sequences CSAS25 and SAS2H, respectively. The SCALE 27 group cross-section library, 27BURNUPLIB, is used in the calculations. Fission-product cross sections in this library are based on ENDF/B-V data; the actinide and light element (low Z materials such as those used in structural and moderator materials) cross-section data are primarily ENDF/B-IV data. Results using this reference methodology have been compared with independent calculations using in-core analysis tools such as PDQ7 (Brady and Sanders 1992) and CASMO-3/SIMULATE-3 (Napolitano 1990) and with alternative analyses performed by cask designers and national laboratories using codes such as MCNP, KENO-IV, and ORIGEN-2. The validation and sensitivity results presented in this paper are based on the SCALE reference methodology.

ANALYSIS ISSUES

Regardless of the computational tools utilized to evaluate burnup credit, there are specific analysis or physics issues which must be addressed. Factors which influence safety and design such as initial enrichment, fuel cycle history, etc. have been investigated and prioritized. The primary fuel characteristics affecting reactivity are initial enrichment, burnup and cooling time. Each of these is considered independently to provide the limiting criteria for loading spent fuel into a burnup cask.

Primary Fuel Characteristics

Infinite multiplication factors were calculated in Cerne, et al. (1987) for a pressurized water reactor (PWR) lattice were calculated for six initial enrichments, seven burnups, and five cooling times. The results were used to develop an equation for estimating k_∞ as a function of initial enrichment, E (weight percent ^{235}U); burnup, B [gigawatt days per metric ton uranium (GWd/MTU)]; and cooling time, C (years). This result, as given in Eq. 1, has been used to evaluate the sensitivity of the multiplication factor to the three primary fuel characteristics.

$$k_\infty = 1.060 - 0.010B - 0.002C + 0.114E + 7.081e\text{-}05B^2 + 7.565e\text{-}05C^2 - 0.007E^2 - 2.671e\text{-}04BE - 1.145e\text{-}04BC + 2.312e\text{-}04CE + 9.366e\text{-}06BCE \quad (1)$$

Based on partial derivatives, k_∞ is most sensitive to initial enrichment, then burnup and lastly, the cooling time. Since the multiplication factor increases with enrichment and is more sensitive to this parameter than any other, the initial enrichment should be used explicitly in any criticality calculation. Increasing the burnup has a negative effect on the multiplication factor and it is this fact that is the impetus for pursuing burnup credit. In an infinite array of PWR fuel, the reactivity difference between fresh fuel and fuel burned to 40 GWd/MTU is between 30 and 40% (assuming an initial enrichment of 4.2 wt % ^{235}U). In the U.S. approach, a minimum burnup is to be established as a function of initial enrichment for each cask design. Fuel assemblies with a burnup less than the minimum are unacceptable for transport in that cask design. All fuel assemblies whose burnup exceeds the minimum are permitted to be shipped, however no additional reactivity credit is allowed.

Obviously this is a conservative approach and there are many other options for integrating the burnup requirements into an implementation scheme. It is clear from Eq. 1 that k_∞ decreases with cooling time, there is also a significant influence from the burnup-cooling cross term. This means that for higher burnups the negative change in k_∞ with cooling occurs at faster rate. Since k_∞ is least sensitive to the cooling time, a minimum cooling time of 5 years was chosen as the design basis. The minimum cooling time requirement is independent of initial enrichment and burnup and is consistent with shielding requirements. As with the burnup restriction, fuel cooled less than 5 years is not acceptable and fuel with longer cooling times is acceptable with no allowance for the additional reactivity loss.

Fuel Uncertainties

Although initial enrichment, burnup and cooling time represent the major factors in determining the reactivity of spent fuel, there are several secondary parameters affecting spent fuel reactivity which should be addressed. These include variations in assembly design, differences in reactor operating histories (exposure histories of the assemblies), possible effects of low density moderation, and axial effects (reactivity effects due to the non-uniform axial burnup distribution for an assembly). Each of these factors is taken to represent an uncertainty in the spent fuel, i.e. they are not explicitly considered in the criticality analysis but are compensated for in terms of a penalty as a percentage Δk derived from sensitivity studies.

The largest of these uncertainties comes from the axial effect. Using conservative assumptions, studies (Brady et al. 1990, Turner 1989) have shown that the axial effect is on the order of 2-4% Δk and varies with burnup, cooling time and assumed profile. The axial effect generally refers to the difference in reactivity due to the axial distribution in burnup (profile) relative to the integral or assembly average burnup. This reactivity effect increases with both burnup and cooling time. The variation with cooling time can be neglected since no reactivity credit is sought for cooling times in excess of 5 years and the decrease in the overall multiplication factor with cooling exceeds any increase in the secondary axial effect. Variations with burnup and profile are interrelated as the profile varies with burnup. The most severe profiles are associated with the lower burnups as the distribution tends to flatten with increased burnup. Efforts are underway to compile a profile database in order to more clearly define a methodology which predicts the uncertainty due to the axial effect. The axial effect is also dependent on the specific cask design (relative leakage rates at the ends of the cask) and should be evaluated for each design.

The most reactive assembly design [e.g., Westinghouse (WE) 17x17, Babcock and Wilcox (BW) 15x15, Combustion Engineering (CE) 14x14, etc.] has been shown to vary with burnup (Napolitano 1990) based on three-dimensional calculations using the CASMO-3/SIMULATE-3 code system assuming an initial enrichment of 4.5 wt % ^{235}U. The most reactive fuel assembly in the burnup range of 0-20 GWd/MTU was determined to be the CE 14x14; from 20-35 GWd/MTU, BW 15x15; 35-50 GWd/MTU, WE 17x17. The least reactive assembly for all burnups was the WE 14x14 design. However, in the range of burnups used for the fuel loading criteria in the U.S. approach (approximately 25 GWd/MTU for 5 wt % enriched fuel), the differences observed between 7 U.S. PWR fuel assembly designs was less than 0.5%. The cask designer may choose any assembly type for the design basis (the WE 14x14 would not be recommended) and apply the biases given in Table 1 as a function of burnup. In burnup regions where the design basis assembly type is the same as the most reactive for the burnup region, no bias is necessary. The biases in Table 1 represent a 95 percent confidence level (2σ) derived from the CASMO-3/SIMULATE-3 calculations.

Table 1. Fuel assembly type Δk bias as a function of burnup

Burnup (GWd/MTU)	0	5	10	15	20	25
Most Reactive Assembly Type	CE 14x14	CE 14x14	CE 14x14	CE 14x14	BW 15x15	BW 15x15
Δk bias	0.006	0.006	0.006	0.005	0.004	0.003

Exposure history has been shown to have a minor second-order effect on assembly reactivity. Nine exposure scenarios, including several variations in the percentage uptime and specific power during the exposure cycles as well as power increases at the end of the last and next-to-last fuel cycles were evaluated using SAS2H for an integral burnup of 33 GWd/MTU (NUREG/0200 1992). Additional calculations were performed at a burnup of 50 GWd/MTU with four exposure scenarios. The maximum Δk (0.0034) was observed at discharge and decreased with cooling time and increasing burnup. The maximum value of k_∞ resulted from the fuel exposure history in which 100% uptime when a specific power based on the total fuel residence time and reactor power rating was assumed. Using this conservative exposure history would alleviate any need to add an uncertainty for exposure history, otherwise an exposure uncertainty value of 0.0015 (based on a 95 percent confidence level derived from the 33 GWd/MTU data at a 5 year cooling time) should be used. Effects due the presence of burnable poison rods (BPRs) during the fuel exposure were also investigated. Both CASMO-3/SIMULATE-3 and SAS2H(ORIGEN-S) calculations were utilized in this study. No dependence on cooling time was observed in either set of calculations for this effect. Both studies indicated that for burnups less than 15 GWd/MTU the presence of BPRs resulted in a lower k_∞ than similar cases without BPRs. For burnups greater than 15 GWd/MTU the inclusion of BPRs during the exposure resulted in an increase of approximately 0.01 in the infinite multiplication factor which decreased slightly with increasing burnup. Including the effect of two standard deviations in the results from both codes, the recommended bias for the presence of BPRs would be: no bias for burnups less than 15 GWd/MTU; 0.0128, 15-25 GWd/MTU; 0.0114, 25-35 GWd/MTU; and 0.0092, greater than 35 GWd/MTU.

Low-density moderation effects have also been investigated and have been found not to be a concern for closely packed arrays. Cask designs that have flux traps would require analyses to evaluate low-density moderation effects.

Another area of concern is determining which nuclides should be included in the analyses. The answer is dependent on the analysis method used. Isotopic depletion codes such as ORIGEN-S utilize data for about 800 fission products. However, more general purpose cross-section libraries such as the 27BURNUPLIB used in the reference analysis library have data for only a fraction of these (e.g., 191 fission-products and actinides are included in 27BURNUPLIB). Analyses (Sanders et al. 1987, Parks 1989) have been performed to identify and rank 37 nuclides that are considered important in the characterization of spent fuel reactivity. The US-DOE burnup credit program uses a subset of 25 of these (Brady and Sanders 1992). Volatile nuclides and those that are known to migrate in fuel are not considered since their presence in spent fuel can not be systematically assured. An additional criteria for including specific nuclides was the availability of experimental data verifying the ability of the depletion codes to accurately predict the quantity of a particular nuclide in spent fuel. An experimental chemical assay program is underway at Pacific Northwest Laboratory in Richland, Washington, USA, to produce isotopic measurements for each of the nuclides included in the analysis (Bierman 1990). The major fissile nuclides (^{235}U, ^{238}U, and ^{239}Pu) and the major actinide absorbers (e.g. ^{240}Pu and ^{241}Am) are among the 10 actinides included in the set of 25. Approximately two-thirds of the reactivity loss in spent fuel is due to the depletion and buildup of these actinides. There are 14 fission products included in the set of 25 nuclides. The buildup of these fission products account for approximately 80% of the remaining reactivity loss in spent fuel.

VALIDATION ISSUES

Three sources of experimental data have been identified for utilization in the validation of burnup credit analysis methodologies: (1) commercial reactor restart criticals; (2) fresh fuel critical experiments, including experiments with mixed-oxide fuels and neutron absorber materials; and (3) spent fuel chemical assay data. The validation of the reference analysis methodology against experimental data is discussed in detail in Brady and Sanders (1992). An additional goal is to develop and qualify a set of reference benchmark data to be utilized in the validation of independent analysis methods.

Results for five commercial reactor restart critical configurations were presented in Brady and Sanders (1992). Three additional calculations have been performed based on data for the Tennessee Valley Authority's Sequoyah Unit 2 reactor. This reactor was subject to an extended (31 month) downtime in the middle of cycle 3, after

which it was restarted with no refueling. This situation is one uniquely suited to the validation of burnup credit: the system reactivity is completely due to spent fuel since no fresh fuel is present, the fuel is cooled sufficiently to approximate the isotopic composition of the fuel to be shipped, and the soluble boron in the water is relatively low. The result for this middle-of-cycle (MOC) configuration at hot full power (HFP) is given in Table 2 along with results for HFP and hot zero power (HZP) conditions at the beginning-of-cycle(BOC) 3 which is before the extended shutdown. These calculations were performed using the SAS2H and KENO V.a methodologies as described in Brady and Sanders (1992). In total, eight reactor restart criticals have been analyzed using the reference analysis methodology. Two additional reactor restart configurations are being evaluated. These are for the Three Mile Island Unit 1 reactor which also experienced an extended outage and will have an isotopic content (particularly fission products) that is consistent with the spent fuel to be shipped. However the reactor was refueled before restart and approximately one-third of the core is fresh fuel which is typical of most reactor restart configurations. In this situation it has been shown that the spent fuel will contribute about two-thirds of the core reactivity and is still a reasonable benchmark for burnup credit.

Table 2. KENO V.a calculated results for Sequoyah Unit 2 Cycle 3

Burnup Conditions	Power Conditions	Boron (ppm)	k_{eff}	Neutron Histories
BOC	HZP	1685	1.00063+/-0.00093	286,000
BOC	HFP	1150	1.00259+/-0.00089	336,000
MOC	HZP	475	1.00014+/-0.00095	298,000

In addition to the reactor restart criticals which fulfill the role of spent fuel criticals, fresh fuel criticals are used to validate the performance of the analysis methodology for geometries representative of a spent fuel cask environment, i.e. assembly interaction, presence of neutron absorbers and shielding materials, etc. At present, 31 fresh fuel critical experiments have been evaluated using the reference analysis methodology. The calculated results for the 18 UO_2 and 13 mixed-oxide (MOX) criticals are summarized in Table 3. Twelve mixed-oxide critical configurations from Smith and Konzek (1976, 1978) and Taylor et al. (1965) have been added to the original data which was reported in Bowman (1991). Poor results obtained for the single MOX configuration that had been analyzed previously prompted the evaluation of additional MOX criticals to either refute or confirm these results. The more recent evaluation of MOX criticals give very good results as indicated in Table 3. Data used for the MOX configuration reported in ref. 12 is currently being reviewed in order to resolve the discrepancy in the performance of the analysis method for that problem relative to the current calculations.

Table 3. Summary of k_{eff} results for fresh fuel critical configurations.

Reference	Fuel Type	No. Configurations	Mean k_{eff}
EPRI NP-196 (Smith and Kinzek 1976, 1978)	UO_2	2	0.9925+/-0.0035
	MOX	6	1.0015+/-0.0061
WCAP-3385-54 (Taylor et al. 1965)	UO_2	2	0.9921+/-0.0027
	MOX	6	1.0042+/-0.0038
ORNL/M-1332 (Bowman 1991)	UO_2	14	0.9936+/-0.0036
	MOX	1	0.9801+/-0.0018*
Summary	UO_2	18	0.9933+/-0.0034
	MOX	13	1.0011+/-0.0079

* Calculation is currently being reviewed.

The final source of validation data is directly aimed at validating the depletion methodology against experimental assay data. Six principle sources of chemical assay data for light-water reactor (LWR) spent fuel have been identified (Brady and Sanders 1992). These are primarily data for fuel elements taken from the U.S. spent fuel inventory which have been identified for characterization as approved testing materials (ATMs) at the Materials Characterization Center at the Pacific Northwest Laboratory (Brady and Sanders 1992, Bierman 1990). Data for the German Obrigheim PWR have also been utilized in the validation analyses. Results for four cases were given in Brady and Sanders (1992), three additional cases will be evaluated in 1993. The U.S. program is also sponsoring measurements of the fission product content of the ATM samples, the first results are expected in late 1992.

In order to aid the validation of alternative methodologies, a "reference problem set" has been established (Brady and Sanders 1992). Also included are descriptions and references for a set of fresh fuel critical experiments validating geometries typical of a spent fuel cask environment and the cross-sections for the major fissile uranium and plutonium isotopes. A set of calculated reference isotopics, complete with a description of the physical and operating history information, etc. needed to generate such data, are given for various burnups and initial enrichments. In the final version of the reference problem set, these data will include at least one set of isotopics directly traceable to the reactor restart critical calculations used in the validation process. Calculational benchmarks have been established using these reference isotopics to represent spent fuel in the geometries described for the fresh fuel critical experiments. The burnup credit analysis methods established in the US-DOE program have been used to compute a reference k_{eff} for these spent fuel subcriticals. The final reference problem set will also include experimental data used in the isotopic validation studies and their references. Recommendations and guidelines for evaluating a calculation bias for the users' analysis methodology will also be included.

OPERATIONS ISSUES

Because burnup credit places restrictions on the spent fuel characteristics, it requires an integrated approach to assure efficiency in both the cask design and operations. Operational issues can directly influence cask design. For example, the likelihood and advantages of using automated systems for cask-handling operations at the receiving facility has prompted recommendations about cask closures, trunnions, tie downs, etc. Additional operational issues have been identified as a result of the development of verification and fuel acceptance procedures. Probabilistic risk assessment (PRA) tools are utilized to evaluate the impact of utilizing burnup credit on the overall package reliability and safety.

Operator error has been identified as one of the primary uncertainties associated with the implementation of burnup credit in cask design. Therefore, the technical feasibility of using automatic intelligent systems to validate crucial cask operations has been examined. These systems would monitor activities, verify that proper tools are used, verify that proper and acceptable measurements are taken in the course of cask operations, and automate the quality assurance procedures. The reliability of the monitoring system and its impact on criticality safety will be examined by : (1) identifying key operations during cask loading which could contribute to a criticality event, (2) identifying sensory devices that could monitor key operations and verify operational correctness, and (3) characterizing and collecting reliability data on sensory devices and supervisory computer operation.

Strategies (procedures and guidelines) for implementing burnup credit in the design and operation of spent fuel transport and storage casks are being analyzed using a relative risk methodology. Fault tree analyses of nuclear criticality safety issues indicate that the fresh fuel and burnup credit approaches to calculating criticality safety follow similar pathways, and both involve risks. In the case of burnup credit, the criticality control system consists of both an "external" control component that includes poisons in the cask or basket and an "internal" control component which is the compensation of the loaded spent fuel. Fault tree analyses have determined that exceeding the fuel reactivity limits could result from an error in the analysis used to develop fuel-loading procedures, or an error in the burnup characterization of the spent fuel (from erroneous in-core measurements or subsequent analyses). In theory, the number of opportunities for error increases with burnup credit because

the characteristics of spent fuel must be included in the cask design basis. However, an analysis of the actual inventory of spent fuel in the U.S. indicates that only a small fraction (on the order of 2 percent) of the existing spent fuel inventory is likely to be nonspecification for typical cask designs using burnup credit.

A nuclear criticality event during transport is highly unlikely because (1) it requires a failure in the control system, and also that (2) this failure occurs in conjunction with an accident severe enough to breach the cask which (3) must then be flooded with essentially pure water. The only credible source of error is a misloading event which would result from an error in the fuel-loading procedure or failure to correctly identify a fuel assembly during cask-loading operations. Errors of this type are mitigated by use of the automated intelligent systems described earlier. These dominant failure modes arise because of the significant time lapse between fuel discharge and transport. The initial enrichment and burnup of the fuel are parameters that are part of the required utility records for each fuel assembly and can be verified by measurement prior to cask loading. A measurement system to fulfil these requirements is being developed in a joint program by Sandia National Laboratories, Los Alamos National Laboratory, and the Electric Power Research Institute. It appears likely that standard gamma-ray and neutron yield measurements could be used to verify that a spent fuel assembly meets the minimum cooling time and burnup requirements. An appropriate on-site measurement and calibration system will be designed to minimize interference with loading operations and accurately verify the spent fuel characteristics against utility records for each fuel assembly. The FORK radiation detector, used by the International Atomic Energy Agency in safeguards inspections, is being tested to determine its applicability for this task. A detailed discussion is given in Ewing (to be published).

CONCLUSIONS

The current U.S. approach to the analysis and implementation of burnup credit is conservative and results in a two-parameter (burnup and initial enrichment) loading curve for fuel acceptance. Utility records for these parameters will be verified by a physical measurement as a part of the cask loading procedure. By designing casks that are optimized to the specifications of the older spent fuel that will be shipped, the new generation of spent fuel casks will be more efficient (with an increased capacity factor of four for a legal-weight truck cask design and an increase of nearly a factor of three for rail/barge casks) and at least as safe as current cask designs (Lake 1992).

The U.S. is also a participant in an international working group operating under the auspices of the Organization for Economic Cooperation and Development (OECD) to benchmark burnup credit for criticality safety analyses. A direct benefit from participation in this group is the independent verification of the U.S. analysis methodology. As work progresses in the development of the U.S. burnup credit program and via international cooperation, additional data will become available and many of the analysis and fuel uncertainties may be reduced. Future work includes moving towards optimizing cask design by balancing the burnup credit requirements and the relative reactivity worth of the cask basket (by reducing the neutron poisons in the basket). This could result in a reduction in the unit cost of the casks with no degradation in reliability and safety.

ACKNOWLEDGEMENTS

The US-DOE burnup credit program is dependent on a range of expertise, and the authors would like acknowledge S. M. Bowman, O. W. Hermann, C. V. Parks, J.-P. Renier and R. M. Westfall of ORNL for their substantial contributions to the different phases of the project. We would also like to express our appreciation for the technical expertise, assistance and advice from S. R. Bierman (Pacific Northwest Laboratory), R. I. Ewing (Sandia National Laboratories), C. R. Marotta (Marotta Consulting), D. Napolitano (Nuclear Assurance Corporation), O. Ozer and R. Williams (Electric Power Research Institute), and M. Smith (Virginia Power Company). This work is supported by the Office of Civilian Radioactive Waste Management of the US-DOE.

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