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Regulatory Research on Use of Burnup Credit for Criticality Safety in BWR Spent Fuel Transportation Packages

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Abstract

The U.S. Nuclear Regulatory Commission (NRC) performs reviews of applications for spent nuclear fuel transportation packages and storage casks to ensure pertinent safety regulations are met. Among other acceptance criteria, these regulations require that the package be subcritical under a variety of normal, off-normal and accident conditions. Currently, all spent nuclear fuel transportation packages and storage casks assume fresh fuel (i.e., the fuel is un-irradiated) in their criticality safety analyses for boiling water reactor (BWR) fuels. Reviews using this conservative assumption are less complex. The fresh fuel assumption for BWR fuel does not allow any credit for the presence of gadolinium (often called the “fresh fuel no-Gad” assumption), an integral burnable absorber present in nearly all BWR fuel assemblies. More recently, applicants began requesting credit for the reactivity reduction due to depletion. This credit is commonly referred to as “burnup credit” (BUC). As of today, NRC recommends that only analyses for Pressurized Water Reactor (PWR) spent fuel implement BUC. This is due to the fact there is limited directly applicable data available to benchmark codes for depletion and reactivity calculations for BWR BUC analyses, and determining the most reactive irradiation conditions is much less straightforward than for PWR BUC analyses. Similar to what was done for PWR BUC, the NRC staff and its contractors have begun identifying and prioritizing significant technical issues so that a technical basis for the allowance of BWR BUC can be developed. NRC is implementing a two-phased approach in investigating BWR BUC. Phase 1 investigated peak reactivity credit and Phase 2 evaluates BUC at a typical discharge exposure. This paper discusses current progress made in Phase 2 and future work to address challenges.

Introduction

The Nuclear Regulatory Commission (NRC) reviews applications for spent nuclear fuel (SNF) transportation packages and storage casks to ensure that they meet the applicable regulations. Title 10 of the Code of Federal Regulations (10 CFR) Part 71 contains the regulations for radioactive and fissile material transportation packages. The regulations in 10 CFR 71.55 have the specific requirements for fissile material packages. The requirements in 10 CFR 71.55 require that a package be subcritical during normal conditions of transport, as defined in 10 CFR 71.71, and hypothetical accident conditions, as defined in 10 CFR 71.73.

The NRC performs its reviews by following the procedures in the Standard Review Plan (SRP). For SNF transportation packages, the NRC follows the guidance in NUREG-1617 [1], "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel," March 2000. The SRP contains guidance for the NRC staff in reviewing the transportation package designs, including thermal, structural, confinement, and shielding considerations, as well as criticality safety. When there are updates to a certain area of review that do not coincide with the full SRP update, the NRC has issued an Interim Staff Guidance (ISG) document. These documents have been called "interim" because the intent is to incorporate them into the full SRP during the next update. The NRC has an ISG document containing guidance for its staff in reviewing applications for transportation packages which use burnup credit in the design of criticality safety systems.

Burnup Credit

Taking credit for the reduction in reactivity as a result of fuel burnup during reactor operations is referred to as burnup credit (BUC). Accounting for reduced reactivity due to burnup is not only technically more accurate but also serves in the interest of public health and safety in several ways. BUC for transportation packages increase packaging payload capacity which results in fewer shipments. Spent fuel pool criticality analyses have been incorporating BUC in their analyses for much longer than storage and transportation casks, which historically used a very conservative approach by assuming the fuel was fresh, i.e. unburned within the reactor. The challenges in approving applications for BUC are mostly related to ensuring the computational codes used to evaluate reactivity as a result of fuel burnup are accurate. This includes depletion codes and reactivity (criticality) codes and the nuclear data (cross sections) used within these codes. Until recently, there has been limited experimental data to adequately validate these codes for BUC.

Spent fuel pool criticality analyses share the same validation challenges as criticality analyses for spent fuel transportation packages. However, the NRC has typically required more conservatism in criticality analyses for storage casks and transportation packages, for several reasons. First, there is less control over the SNF once it leaves the spent fuel pool in a cask, or leaves the controlled area (i.e. nuclear power plant site) in transportation and enters the public domain. Second, there is no ability to actively detect and mitigate a criticality in a storage cask or a transportation package, as there is in a spent fuel pool. Finally, there are more severe analytical accident conditions that storage cask and transportation package criticality analyses must take into consideration.

Modern computational resources and an increase in the quantity and fidelity of experimental data have made it possible to reduce the conservatism of the "fresh fuel" assumption for transportation packages. BUC has been accepted by the NRC staff for PWR SNF transportation packages and dry storage casks criticality analyses for over a decade.

The NRC staff currently reviews applications for transportation packages and storage casks requesting BUC using the guidance in ISG-8. The most recent revision is Revision 3, "Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transportation and Storage Casks," published in 2012 [2]. This ISG only addresses BUC for pressurized water reactor (PWR) fuel. The NRC developed review guidance for BUC for PWR fuel because there is less of a demand for boiling water reactor (BWR) fuel BUC. In addition, the more complex BWR design introduces more analytical challenges and there is less BWR-specific experimental data for code validation. ISG-8 is applicable for storage casks as well, however the NRC typically receives requests for BUC for transportation packages.

The NRC, Division of Spent Fuel Management, updated ISG-8 to Revision 3 to incorporate the latest results for BUC studies completed since the publication of Revision 2 in 2002. Major updates include the option for credit for fission product and minor actinide neutron absorbing isotopes in the SNF composition, misload analyses in lieu of burnup measurements, and an increase in credited maximum assembly average burnup. This was possible because of new radiochemical assay (RCA) data for the benchmarking of depletion codes for minor actinides and fission products, and new critical experiment data for criticality code validation of minor actinides and some fission products. In addition, Oak Ridge National Laboratory (ORNL) had furthered the development of sensitivity and uncertainty analysis tools (e.g., the TSUNAMI code) within the SCALE [3] computational package, that enabled the evaluation of bias and bias uncertainty for isotopic depletion and criticality codes without enough data for a traditional validation.

The work used to support ISG-8, Rev. 3 was performed by ORNL and published in two NUREG/CR reports. NUREG/CR-7108 [4], "An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Isotopic Composition Predictions", published in 2012, describes an approach for establishing depletion code uncertainty for PWR BUC analyses including major and minor actinides and fission products. NUREG/CR-7109 [5], "An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Criticality (k_{eff}) Predictions," describes an approach for determining criticality code bias and bias uncertainty of major and minor actinides and fission products.

Since the Division of Spent Fuel Management has completed Revision 3 to ISG-8, it is now planning its next update to ISG-8 to include some guidance on reviewing BWR BUC applications for storage and transportation casks. The NRC is anticipating transportation and storage cask applications using limited BWR BUC, in order to increase assembly average enrichments allowed for transportation, and to maintain sub-criticality considering fuel reconfiguration analysis requirements for high burnup fuel. In addition, there is more data available to support validation of BWR BUC analyses, and the availability of computational tools, such as TSUNAMI, make it more practical to issue staff guidance for reviewing BWR BUC applications at this time.

BWR Burnup Credit

Currently, for BWR fuel, the NRC has only approved spent fuel storage casks and transportation packages with criticality analyses that assume the fuel is fresh with no gadolinium. This is a conservative assumption when considering nuclear criticality safety margins. In reality, during the depletion process neutron absorbing nuclides are produced, thus, decreasing the reactivity of the fuel. In addition, BWR fuel assemblies typically contain gadolinium, a neutron absorber, and neglecting its presence is conservative with respect to criticality safety analyses. In addition to the contract work with ORNL to support ISG-8, Revision 3, ORNL performed scoping work to begin investigating BWR BUC. This work was published in two NUREG/CR reports in 2013. NUREG/CR-7157 [6], "Computational Benchmark for Estimated Reactivity Margin from Fission Products and Minor Actinides in BWR Burnup Credit," discusses the estimation of additional reactivity margin available in SNF from fission products and minor actinides in a BWR burnup-credit storage and transportation environment. NUREG/CR-7158 [7], "Review and Prioritization of Technical Issues Related to Burnup Credit for BWR Fuel" builds on the work in NUREG/CR-7157 and identifies and prioritizes issues associated with BWR burnup credit.

The BWR BUC project is divided into two phases. As part of the first phase, the results of ORNL's work on peak reactivity credit are summarized in NUREG/CR-7194 [8], "Technical Basis for Peak Reactivity Burnup Credit for BWR Spent Nuclear Fuel in Storage and Transportation Systems." The second phase of the project will be studied over several years outlining a complete burnup credit methodology for higher burnup BWR fuel beyond peak reactivity. Once completed, NRC staff will be able to update its review guidance to recommend general information on limits for the licensing basis, recommend assumptions regarding reactor conditions, and provide guidance on code validation.

Peak Reactivity Credit

The NRC Division of Spent Fuel Management has begun its investigations on BWR BUC by looking into what is called "peak reactivity credit." BWR fuel assemblies contain gadolinium, an integral neutron absorber, in some fuel rods. Unlike PWR fuel where the maximum reactivity of the fuel is at the beginning of life, maximum activity of BWR fuel occurs after the gadolinium has largely burned out. This peak typically occurs, on average, from 10- 20 GWD/MTU. Evaluating BWR fuel with gadolinium at beginning of life would produce a lower reactivity and therefore it is more conservative to assume that the fuel assembly is at its most reactive time in life. Since peak reactivity credit considers the presence of the gadolinium, this approach has also been called "gadolinium credit."

Phase 1 of the BWR BUC research project is complete. The NRC Division of Spent Fuel Management is currently reviewing an application for "gadolinium credit" and has been notified of additional applications intending to use credit for "peak reactivity." The NRC presented a summary of NUREG/CR-7194 at the

International Conference for Criticality Safety (ICNC) 2015 [9].

Extended BWR Burnup Credit

The NRC Division of Spent Fuel Management is now in Phase 2 of the BWR BUC research which applies to "extended" BWR BUC, which is the term used for BUC beyond peak reactivity. The research phase of this work includes the publication of four NUREG/CR documents before the staff updates ISG-8. The first NUREG/CR document is complete and pending publication by the NRC [10]. The title of this NUREG/CR is: "Axial Moderator Density Distributions, Control Blade Usage and Axial Burnup Distributions for Extended BWR Burnup Credit."

This NUREG/CR evaluates the impact of moderator density distribution, control blade usage and axial burnup profiles on extended BWR BUC. Axial moderator densities in BWRs can vary by 80% or more within a fuel assembly at a single location during core operations. The frequency with which moderator density calculations must be updated during depletion calculations in order to obtain accurate results is studied. Furthermore, the NUREG/CR discusses the use of control rod blades on discharge reactivity given the varied use of control blades in BWR operations. The third area of study for this NUREG/CR is on the axial burnup distribution and its effect on reactivity. This NUREG/CR uses data from core follow data from a recent cycle of a BWR/6 core. The combined effect of these parameter changes will be studied in future work.

Future Work

ORNL will continue to study the use of reactor operating parameters in fuel depletion calculations as it applies to the extended BWR BUC. Also, ORNL will aim to identify correlated reactor conditions that may affect the reactivity of spent BWR fuel. The combined effect of moderator density distribution, control blade usage and axial burnup distributions will be studied in future work.

The third and fourth NUREG/CRs will be on code validation. Similar to what ORNL and the NRC have done in the past to form a technical basis in support of reviewing PWR burnup credit applications, these NUREG/CRs will focus on validation of calculated nuclide composition as a result of BWR fuel depletion and validation of codes evaluating reactivity (k_{eff}).

Once all four NUREG/CRs are complete, expected in 2018, ORNL will produce a technical basis document to the staff that will inform the update of ISG-8. The staff will use the research information provided by ORNL plus its review experience to date on BWR peak reactivity and extended BWR burnup credit to update ISG-8 to include its recommendations on the allowance of BWR burnup credit.

In addition to the on-going work at ORNL in support of extended BWR BUC, the NRC and ORNL are still engaged in research activities related to peak reactivity credit. The NRC is currently providing partial support for obtaining measurement data to support validation for nuclide concentrations from the Rod Extremity and

Gadolinia AnaLysis (REGAL) program underway at the Belgian nuclear research center Studiecentrum voor Kernenergie (SCK·CEN) []. Such measurements will help measure residual gadolinium nuclides to validate gadolinium depletion and reduce level of nuclide uncertainty in the burnup range of peak reactivity.

Conclusions

NRC is seeking a technical basis for reviewing applications applying credit for burnup for criticality safety analysis of BWR storage casks and transportation systems. NRC has engaged with ORNL to produce a technical basis document that will help inform NRC reviews of applications requesting BWR burnup credit. The NRC is engaging in research to further its knowledge of BWR BUC. All of this work will support a revision to ISG-8 where the NRC will make recommendations on performing reviews of BWR BUC for storage and transportation systems.

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