DISPOSAL CRITICALITY ANALYSIS METHODOLOGY'S PRINCIPAL ISOTOPE BURNUP CREDIT

T.W. DOERING
Electric Power Research Institute,
Palo Alto, California

D.A. THOMAS
Framatome Cogema Fuels,
Las Vegas, Nevada

United States of America

Abstract

This paper presents the burnup credit aspects of the United States Department of Energy Yucca Mountain Project's methodology for performing criticality analyses for commercial light-water-reactor fuel. The disposal burnup credit methodology uses a "principal isotope" model, which takes credit for the reduced reactivity associated with the build-up of the primary principal actinides and fission products in irradiated fuel. Burnup credit is important to the disposal criticality analysis methodology and to the design of commercial fuel waste packages.

The burnup credit methodology developed for disposal of irradiated commercial nuclear fuel can also be applied to storage and transportation of irradiated commercial nuclear fuel. For all applications a series of loading curves are developed using a best estimate methodology and depending on the application, an additional administrative safety margin may be applied. The burnup credit methodology better represents the "true" reactivity of the irradiated fuel configuration, and hence the real safety margin, than do evaluations using the "fresh fuel" assumption.

1. INTRODUCTION

The United States Department of Energy (DOE) Yucca Mountain Project's (YMP) methodology for performing disposal criticality analyses includes the use of principal isotope burnup credit for commercial light-water-reactor fuel [5]. Burnup credit involves taking credit for the reduced reactivity associated with irradiated fuel, compared to unirradiated fuel, in criticality safety evaluations. Principal isotope burnup credit takes credit for the reduced reactivity associated with the presence of the principal actinides and fission products in the irradiated fuel. DOE plans to use principal isotope burnup credit for the criticality evaluations of waste packages loaded with irradiated fuels from commercial boiling water reactors and pressurized water reactors.

Burnup credit does not eliminate safety margin but provides a better representation of the "true" reactivity of the spent nuclear fuel. Development of a burnup credit program based on best-estimate evaluations allows the applicant, and regulator, to understand the real margin of safety of the configuration, and to make an informed decision regarding the application of an additional administrative margin.

The implementation and demonstration of burnup credit methods require an understanding of reactor core physics, reactor operations, and traditional out-of-reactor criticality safety. Unlike the traditional out-of-reactor criticality approach of a "fresh fuel" assumption, burnup credit requires an understanding of a fuel assemblies irradiation conditions and history. Knowledge of reactor physics and reactor operations is needed to simulate the way the fuel is irradiated and understand how this affects the isotopic composition, and hence the reactivity, of the irradiated fuel. Knowledge of traditional out-of-reactor criticality safety is needed for applying the information on irradiated fuel's reduced reactivity for the out-of-reactor environment.

In addition to a better understanding of the reactivity of the irradiated nuclear fuel configurations, burnup credit for transport, storage, or disposal of irradiated commercial fuel provides design flexibility that may provide economic and ALARA benefits. Burnup credit facilitates increased assembly loading in casks, which leads to reduced cumulative radiological risks (less packages) and associated cost savings. For existing systems, burnup credit would allow the loading, transport, or storage of irradiated fuel that could not be readily handled with the fresh fuel assumption.

The use of burnup credit in disposal applications has an additional value compared to transportation and short-term storage applications. Over the long time period considered for disposal, active criticality control features such as moderator exclusion barriers, neutron absorbing (poison) plates, and geometry features will degrade and change. The reduced reactivity associated with the presence of actinide and fission product absorbers in irradiated fuel is the only feature that may last.

2. METHOD

The disposal criticality analysis methodology is a risk-informed, performance-based methodology. One part of the methodology is concerned with identifying potentially critical configurations. The principal isotope burnup credit method is part of this portion of the overall methodology.

Two system models are used in the burnup credit method, an isotopic model and a criticality model. The isotopic model is used to calculate the concentrations of actinides and fission products in irradiated fuel. The criticality model is used to calculate the keff for the various configurations of irradiated fuel, using the isotopic concentrations from the isotopic model. The YMP isotopic model uses the SAS2H sequence of the SCALE computer code system [6]. The SAS2H sequence is used with a 44-energy group cross-section library. The YMP criticality model uses the MCNP computer code [7]. The MCNP code is used with its point-wise/continuous energy cross-sections. Both cross-section sets are based on ENDF/B libraries.

The isotopic model uses reactor operating parameters and fuel assembly information to model the fuel irradiation and depletion. The reactor operating parameters modeled include fuel temperature, moderator temperature/density, void histories (for boiling water reactors), soluble boron concentrations (for pressurized water reactors), specific power histories, and the presence of control mechanisms (control rods, control blades, axial power shaping rods, etc.). The fuel assembly information includes items such as the initial enrichment, the assembly burnup, the time since discharge from the reactor (cooling time), dimensional and mass information, and information about burnable poisons (removable and integral) that may have been present during irradiation cycles. The specific values used for these depletion parameters are conservative for waste package loading calculations for the specific fuel and reactor type being modeled. Sensitivity evaluations have been performed to determine how each of the depletion parameters affects the reactivity of irradiated fuel in a waste package or cask system.

For risk-informed disposal applications, the isotopic model is used to generate isotopic concentrations over large ranges of cooling times, not just conservative ones. Also, in long-term disposal applications, the isotopic concentrations in the irradiated fuel are modified to account for geochemical processes that can remove, transport, and deposit isotopes under certain conditions (i.e., fuel cladding breached).

In addition to the concentrations of actinides and fission products from the isotopic model, the criticality model uses detailed geometry and material information for the fuel assembly and waste package. The criticality model accounts for the spatial variations in burnup that occur in fuel assemblies (e.g., axial burnup profiles).

The isotopic and criticality models must be validated prior to use in evaluations. Benchmark calculations of measured data are an important part of the validation process. The validation of the models used for principal isotope burnup credit relies on three types of benchmarks: Commercial Reactor Criticals (CRCs), Radiochemical Assays (RCAs), and Laboratory Critical Experiments (LCEs). Each of these types of benchmarks is discussed below.

CRCs are measured critical configurations of commercial light-water-reactor fuel. The critical conditions for CRCs are measured under zero power conditions (isothermal) to minimize thermal gradients and to eliminate the concern over xenon in the benchmark. The CRC cases (state points) analyzed include all fresh fuel (initial cores), mixed fresh and irradiated fuel (beginning of cycle cores), and all irradiated (middle/end of cycle cores). To date, approximately 45 PWR and 20 BWR CRC state points have been calculated, each state point consists of many the detailed reactor power histories. The CRC state points include fuel with a large range of expected fuel characteristics (axial blankets, multiple axial and radial enrichments, burnable poison rods, integral fuel burnable absorbers, etc.). At present the assembly average enrichments from 1.93 weight percent (wt %) U-235 to 4.02 wt % U-235 and core average burnups from 0 GWd/tU to 33 GWd/tU have been evaluated [2]. Additional cases are currently being evaluated that will extend the range well above 4.5 wt % U-235 initial enrichment.

Evaluations of the neutronic conditions in CRCs and the neutronic conditions in waste packages have confirmed the applicability of CRC as benchmarks for waste packages containing irradiated commercial nuclear fuel [4]. The evaluations of neutronic conditions included consideration of neutron spectrum, reflection, and leakage as well as the materials present in the fuel.

Radiochemical assays are isotopic concentration measurements made with samples of irradiated fuel. The majority of the measurements are for small (fraction of a fuel pellet) measurements, but a few measurements were made on samples from half assemblies. For the principal isotope burnup credit work, approximately 85 samples (BWR and PWR) have been measured for fuel assemblies with enrichments from 2.45 wt % U-235 to 3.87 wt % U-235 and burnups from 2.16 GWd/tU to 46.46 GWd/[1]. Additional samples (26) with enrichments up to 4.64 wt % U-235 and burnups up to 70.4 GWd/tU are currently being evaluated.

LCEs are the standard critical experiments performed in laboratories and designed to replicate particular geometry or material combinations of interest to real-world applications. Nearly 500 LCEs have been analyzed so far for various disposal applications [3]. Only about 91 apply to irradiated commercial nuclear fuel in intact configurations, and 66 of these are fresh UO2. The LCEs are generally much smaller than waste packages and do not contain true representations of irradiated commercial nuclear fuel.

CRCs and LCEs are used for estimating bias and uncertainty for the criticality model. In addition, CRC data are used, with RCAs, to estimate bias and uncertainty for the isotopic model for intact configurations of irradiated commercial nuclear fuel. RCAs will also be used for confirming the adequacy of the isotopic model used for the waste package design analyses.

CRCs represent irradiated commercial fuel in known critical configurations. Although the CRC evaluations provide excellent criticality benchmarks for irradiated fuel in a reactor, they do not provide benchmarks for isotopic concentration of individual isotopes and they do not have some of the characteristics of a waste package (e.g., leakage, fuel temperature, moderator temperature, fixed absorbers). However, CRC evaluations provide valuable information on the integral capability of the models (SAS2H and MCNP) to predict the keff of a measured system containing similar fuel geometry. The neutronic characteristics that differ between CRCs and waste packages have been evaluated and the effect can be accounted for. Evaluations of both LCEs and RCAs will be performed to supplement the CRC evaluations and complete the model validations for principal isotope burnup credit applications.

Principal isotope burnup credit only includes a subset of the isotopes present in irradiated commercial fuel. The process for choosing this subset considers the nuclear, physical, and chemical properties of the irradiated commercial fuel isotopes. The nuclear properties are cross sections and half-lives of the isotopes; the physical properties are concentration (amount present in the irradiated fuel) and state (solid, liquid, or gas) of the isotopes; and the chemical properties are the volatility and solubility of the isotopes. Isotopic decay and build-up, as well as relative importance of isotopes for criticality (combination of cross sections and concentrations), are also considered in this selection process. No isotopes with significant positive reactivity effects (fissile isotopes with significant concentrations) are removed from consideration. Thus, the selection process is conservative. The process results in selecting 14 actinides and 15 fission products. Table I lists these isotopes.

Table I. Principal Isotopes.

^{95}Mo	^{145}Nd	^{151}Eu	^{236}U	^{241}Pu
^{99}Tc	^{147}Sm	^{153}Eu	^{238}U	^{242}Pu
^{101}Ru	^{149}Sm	^{155}Gd	^{237}Np	^{241}Am
^{103}Rh	^{150}Sm	^{233}U	^{238}Pu	^{242m}Am [a]
^{109}Ag	^{151}Sm	^{234}U	^{239}Pu	^{243}Am
^{143}Nd	^{152}Sm	^{235}U	^{240}Pu	

[a] Half Life = 152 years

For design applications, two aspects of the isotopic model for irradiated commercial fuel must be addressed. First, values for the discharged isotopic concentrations must be conservative with respect to their contribution to criticality. Second, changes to the discharged isotopic concentration values as a function of time must also be conservative with respect to their contribution to criticality. Three requirements have been developed as part of the methodology for principal isotope burnup credit to ensure these conservatisms:

1. Reactor operating histories and conditions must be selected together with axial burnup profiles such that the isotopic concentrations used to represent irradiated commercial fuel assemblies shall produce values for keff that are conservative in comparison to any other expected combination of reactor history, conditions, or profiles.

2. These bounding reactor parameters will be used to predict isotopic concentrations that, when compared to best-estimate isotopic predictions of the measured RCA data and the measured radiochemical data itself, must produce values for keff that are conservative.
3. The values for the isotopic concentrations representing irradiated commercial fuel must produce conservative values for keff for all time periods for which criticality analyses are performed.

3. SUMMARY

The use of principal isotope burnup credit provides for a more realistic prediction of the potential for criticality within the long repository time frames over which the fuel remains intact. Thereby allowing the applicant and regulator a more realistic understanding of the potential criticality scenarios and consequences. In addition, this methodology can be applied to storage or transportation system. A methodology for implementing principal isotope burnup credit has been developed by the YMP for use in disposal of all irradiated commercial light-water-reactor fuel. The methodology addresses operating history effects and includes validation requirements that will ensure that the results are conservative.

The presentation will explain the methodology and summarize the work performed to validate the models via use of CRCs, LCEs and RCAs. The lessons-learned and data obtained through implementation of this methodology to disposal should have benefit to the understanding and implementation of burnup credit in transportation and storage of irradiated commercial nuclear fuel. This process has been reviewed and approved by the US Nuclear Regulatory Commission for disposal.

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