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The Uncertainty Analysis of a Liquid Metal Reactor for Burning Minor Actinides from Light Water Reactors

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ABSTRACT

The neutronics analysis of a liquid metal reactor for burning minor actinides has shown that uncertainties in the nuclear data of several key minor actinide isotopes can introduce large uncertainties in the predicted performance of the core. A comprehensive sensitivity and uncertainty analysis was performed on a 1200 MWth actinide burner designed for a low burnup reactivity swing, negative doppler coefficient, and low sodium void worth. Sensitivities were generated using depletion perturbaton methods for the equilibrium cycle of the reactor and covariance data was taken ENDF-B/V and other published sources. The relative uncertainties in the burnup swing, doppler coefficient, and void worth were conservatively estimated to be 180%, 97%, and 46%, respectively.

1. INTRODUCTION

The long-term nuclear waste from the commercial power plant has been a hinderence on the nuclear community to promote nuclear industry and, therefore, people have studied ways of transmuting nuclear waste either in a power reactor or accelerator-driven system.[1] One of the principal problems in the design and analysis of a minor actinide transmuting system has been the lack of accurate nuclear data for the principal minor actinide isotopes.[2] The effect of nuclear data uncertainty on the design of a minor actinide burner is particularly important because the key safety performance parameters are very sensitive to the poorly known minor actinide data.

Specifically, the computed values of the burnup reactivity swing, the void coefficient, and the doppler coefficient of a minor actinide burner are highly sensitive to the minor actinde data. The purpose of the work reported here was to analyze the effect of nuclear data uncertainties on the predicted performance of a minor actinide burner. In this paper, the design of actinide burner will be briefly reviewed. Then, the sensitivity and uncertainty analysis of such a system will be discussed.

2. MINOR ACTINIDE BURNER (MAB)

2.1 Design Characteristics

One of the principal innovations used in the design of MAB is to maintain a homogeneous core layout but to employ two core zones; an inner core consisting of minor actinide fuel and an outer core containing standard plutonium fuel. The plutonium outer core offsets much of the poor core safety performance caused by the presence of minor actinides in the inner core. The B_4C blocks were employed in the center of the core, as suggested by several studies as a means of further reducing the sodium void worth.[3] The horizontal configuration of the core is shown in Fig.1 and the general characteristics of fuel assembly is summarized in Table I. The inner core fuel is composed of 70% Np-237 and the outer core fuel is enriched to 50% with fissile plutonium. The plutonium fuel pin diameter is smaller to keep the peak linear power less than 40.0 kW/m. Because the outer core fuel is highly enriched and the inner core contains fertile Np-237, the power shifts from the outer to the inner core during the cycle.

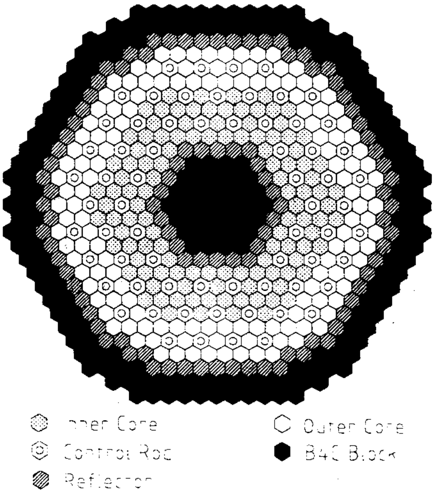

Fig.1 Horizontal View of MAB Model

Table I. Fuel Assembly Design Parameter

	Inner Core	Outer Core
Fuel composition	U/Np/Am/Cm+25% Zr 5/71/15/9	U/Pu/Np/Cm+25% Zr 1/90/8/1
Volume ratio (Fuel/coolant/strucure)	38/36/26	13/72/15
Number of pins per assembly	271	169
Fuel pin diameter (cm)	0.724	0.544
Cladding thickness (cm)	0.056	0.043
Pitch/diameter ratio	1.18	2.01
Fuel smear density (% T.D.)	75	75
Assembly lattice pitch (cm)	15.47	15.47

2.2 Fuel Cycle Model

The MAB was designed to operate using three fuel batches and a 10 month cycle length. The relatively short cycle length is used to maintain an acceptable burnup reactivity swing. It was assumed that the feed material for the minor actinide burner is provided by a typical 1000 MWe LWR after cooling for 3 years. At the completion of each burnup cycle, the discharged fuel is recovered and fabricated with the external feed material in the fabrication plant. The external feed material is assumed to be provided as separate plutonium and minor actinide streams. The MAB accepts 689 kg of minor actinides and 557 kg of plutonium per year. The minor actinides are continuously recycled in the core, however 70% of the fissile plutonium is surplus material and is assumed to be used as fissile makeup in another reactor.

2.3 Safety Performance

The reactivity of the inner core increases substantially with burnup, since the minor actinide fuel consists mostly of Np-237 (η=0.94) which results in Pu-238 (η=2.46) after a neutron capture. As the core depletes, this reactivity gain is compensated by the decrease in the fissile plutonium in the outer core resulting in a small positive reactivity burnup swing for the core (1.19 %Δk). The dominant contribution to the sodium void worth is spectral hardening which we mitigate to some extent by using the HT-9 rods in the control rod sites. The isotope most responsible for the increase in reactivity upon coolant voiding in the inner core is Np-237, however, as the coolant voids in the outer core the neutron leakage increases and the power level decreases. Because the outer core is predominantly fissile material, a reduction in the power reduces neutron production more than absorption, which provides a negative coolant void worth in this region. The net effect is still a small positive void worth, however it is comparable to void worths allowed in conventional LMR designs. The doppler effect of MAB is smaller than a conventional LMR, but remains negative ($-0.32\times10^{-3}\Delta k$). The safety parameters are summarized in Table II for both the BOEC and the EOEC core conditions.

Table II. Reactivity Worth

	BOEC	EOEC
Burnup swing (%Δk)	1.19	
Void worth (%Δk)	0.74	1.17
Doppler coefficient ($10^{-3}\Delta k$)	-0.35	-0.32

3. SENSITIVITY AND UNCERTAINTY ANALYSIS

The prediction error due to nuclear data can be evaluated using the data covariances and sensitivity coefficients such as $V = S\ \boldsymbol{M}\ S^t$ where V, S and $\boldsymbol{M}$ are the prediction error, the sensitivity coefficient vector, and the covariance matrix, respectively. The covariance data were taken from ENDF/B-V for U-235, U-238, Np-237, Pu-239, Pu-240, Pu-241, Pu-242 and Am-241. The data were generated in 9 energy groups by the NJOY system. The covariance data not contained in ENDF was taken from other published results. The sensitivity coefficient with respect to the group cross section in region k, σ_{kg}, is given as $S^R_{\sigma_{kg}} = \frac{\delta R}{R} / \frac{\delta\sigma_{kg}}{\sigma_{kg}}$ where R is the response to be evaluated. The sensitivity coefficients to the group-wise cross-sections were computed using depletion perturbation theory.[4] Because the actinide burner is operated in the closed fuel cycle, these sensitivities were formulated as constrained ones.[5]

The estimates of the uncertainty (1σ) in the burnup reactivity swing, the EOEC void worth, and the EOEC doppler coefficient are given in Table III. It should be emphasized that these values account only for the uncertainty due to data covariance and utilize only the covariance data that is availiable in the open literature. Some data, such as the neutron yield per fission of Np-237 and the fission cross-section of Pu-238, have large sensitivities but were not included in the uncertainty estimate because there was no published covariance data. Of the reactions for which covariance data was available, the largest contribution to the uncertainty in the burnup reactivity swing, the sodium void worth, and the doppler coefficient comes from the fast fission (0.183-1.35MeV) of Np-237, which is the most abundant isotope in the reactor. The standard deviation of the Np-237 fission cross-section in this energy range is about 10%.

Because there is so much data missing from the covariance library, the uncertainty estimates shown in Table III should be considered a lower bound estimate of the uncertainty. The actual values of the uncertainty could be much higher, particularly for the reactivity burnup swing and the void worth, once the data for other reactions are included. For example, if we assume just a 10% standard deviation for the Pu-238 fast fission cross-section, the burnup swing uncertainty would increase to about 220% and the void worth uncertainty would increase to over 100%. Such large uncertainties seriously compromise our confidence in the ability to predict the safety performance of an actinide burner design.

Table III. Uncertainty in Core Performance Parameter

Parameter	Reactivity worth	Relative Uncertainty	Absolute Uncertainty(σ)
Burnup swing	1.19 %Δk	180 %	2.14 %Δk
Void worth(EOEC)	1.17 %Δk	97 %	1.13 %Δk
Doppler coefficient(EOEC)	-0.032 %Δk	46 %	0.015 %Δk

4. CONCLUSION

Uncertainties in the nuclear data of several key minor actinide isotopes can introduce large uncertainties in the predicted performance of a minor actinide burning liquid metal reactor. A comprehensive sensitivity and uncertainty analysis was performed on a 1200 MWth MAB designed for a low burnup reactivity swing, negative doppler coefficient, and low sodium void worth. Sensitivities were generated using depletion perturbaton methods for the equilibrium cycle of the reactor and covariance data was taken ENDF-B/V and other published sources. The relative uncertainties in the burnup swing, doppler coefficient, and void worth were conservatively estimated to be 180%, 97%, and 46%, respectively. These large uncertainties reduce confidence in the ability to predict the minor actinide burner performance and motivate further experiments to reduce the uncertainties.

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