Automated Depletion Analysis of PBMR Fuel Using SCALE

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INTRODUCTION

The SCALE 5 code system [1] includes sequences to perform automated fuel depletion and decay analyses by coupling one-dimensional (1-D) and two-dimensional (2-D) neutron transport codes with ORIGEN-S to predict the time-dependent variation of isotopic contents in fuel for about 2000 nuclides. In the 1-D depletion analysis sequence, SAS2H, cross sections for ORIGEN-S are developed with a two-step neutronic analysis involving two separate 1-D transport calculations using the XSDRNPM code: the first step develops cell-weighted cross sections for the unit cell, and the second step applies homogenized unit cell materials and cross sections from the first step in a larger system model. The current version of the sequence permits either cylindrical fuel rods or plate-type fuel as the unit cell. The model employed for the second larger cell geometry used to represent an assembly or other fuel configuration is limited to cylindrical geometry.

This two-step procedure is well suited for the analysis of spent fuel properties for the Pebble Bed Modular Reactor (PBMR). A common approach to developing cross sections for PBMR fuel is to first generate homogenized (cell-weighted) cross sections at the fuel grain level, and secondly apply the grain materials and cross sections in the analysis of the entire pebble. Additionally, a third level of homogenization may be used to include heterogeneity of different pebbles or core structures.

This paper describes modifications that have been made to the SAS2H depletion analysis sequence of SCALE to permit the automated burnup analysis of spherical PBMR fuel pebbles. Preliminary results have been compared to independent calculations.

CODE ENHANCEMENTS

Relatively few modifications were required in SAS2H to fully implement an analysis capability for spherical geometry at both the grain and pebble geometry levels. Some coding towards this aim was already present, although not functional. Changes were made to support spherical triangular pitch (SPHTRIANGP) and spherical square pitch (SPHSQUAREP) unit cell lattice types. In the second geometry level an option was made to permit either cylindrical or spherical geometry. Modifications were also made that simplified the input to provide full user control of the options used in the second level XSDRNPM calculation.

ANALYSIS PROCEDURES

One of the more difficult phenomenon related to analysis of PBMR fuel is the effects of the double-heterogeneity of the grain and pebble geometry on the resonance self shielding of cross sections. Previous work [2] has identified deficiencies in the ability of the SCALE modules to accurately calculate a Dancoff correction factor for the fuel grains. To circumvent this limitation, the Dancoff factors for the fuel may be entered manually by the user. These factors are generally calculated by means of Monte Carlo methods and published values for some pebble geometries are available [2,3].

Another issue, found to be very important to the analysis of PBMR spent fuel isotopic compositions, is how the treat that fact that a fresh pebble is introduced to a core of previously irradiated pebbles. In the analysis procedure of SAS2H, the model is restricted to that of a single fuel pebble. The default procedure assumes that all other pebbles are identical in composition (i.e., burnup) to the reference pebble by applying reflective boundary conditions. In an actual equilibrium core with a continuous reloading scheme, a fresh pebble introduced to the core will be surrounded by pebbles with a substantial burnup on average. In previous studies [4] the flux spectrum in the fuel pebble was found to be dominated by the burnup of the surrounding spheres, rather than the burnup of the pebble itself.

Using this finding, an alternate scheme was investigated that would provide a better representation of the surrounding fuel pebbles in a SAS2H type of procedure. The XSDRNPM model of the pebble was modified to perform a fixed boundary source calculation (with fissions enabled), rather than the standard eigenvalue calculation with a reflective boundary. The boundary flux for the pebble was determined from a previous XSDRNPM calculation using estimated equilibrium PBMR fuel compositions at 45,000 MWd/MTU.

RESULTS

To benchmark the procedure burnup simulations were performed assuming the following PBMR fuel

specifications: fuel enrichment of 8.07%, uranium mass of 9 g U per pebble, UO_2 grain diameter of 500 μm, and effective grain pitch of 1.834 mm. All SAS2H calculations were performed using the SCALE 44-group transport library. The SAS2H results were compared to results [4] from the VSOP code, a three-dimensional diffusion code used for core analysis, for an 874 day irradiation and 10-cycle discharge burnup of 80,000 MWd/MTU. The PBMR core contained a region of mixed fuel and graphite pebbles, and a region of all fuel pebbles. A VSOP Dancoff factor of 0.405 for an infinite system of fuel spheres was applied in the SCALE calculation. The results, listed in Table I, show excellent overall agreement for the major uranium and plutonium isotopes.

Table I. Actinide mass (grams) calculated for 80,000 MWd/MTU burnup.

Isotope	VSOP	SCALE
^{235}U	0.119	0.119
^{238}U	7.92	7.92
^{239}Pu	0.0374	0.0372
^{241}Pu	0.0199	0.0183
Total	8.15	8.25

The results however proved to be highly sensitive to the surface angular flux applied at the pebble boundary. A boundary flux calculated for the core region containing all fuel pebbles was found to be highly undermoderated, whereas the flux for the mixed graphite and fuel region was overmoderated, with respect to the VSOP core average. The results in Table I were derived using a boundary flux for a core-average pebble model with fuel and graphite pebbles that included a fraction of the external graphite moderator. Additional work is required to develop an effective core model that will better account for the moderating effects of the central graphite region of the core and the graphite reflector.

CONCLUSIONS

The one-dimensional SAS2H depletion sequence of SCALE has been modified to perform automated burnup analyses of a PBMR fuel using physics analysis at the pebble geometry level. The double heterogeneity of the fuel currently necessitates that the Dancoff factor is calculated outside of SCALE and manually applied in the SAS2H analysis. Comparisons with spent fuel compositions computed using the VSOP code (with similar Dancoff values) show good agreement, indicating that the new methods provide an accurate representation of the pebble physics.

An important feature of SAS2H is that the burnup-dependent cross sections computed during the irradiation can be saved for later use with the ORIGEN-ARP code [5]. ORIGEN-ARP, used with the Windows graphical user interface developed for burnup analysis, allows spent fuel properties to be computed with relative ease and in a small fraction of the time required using traditional physics methods. Upon completion of further testing and benchmarking, the SAS2H code modifications to support PBMR fuel analysis described in this paper are expected to be distributed in a later release of SCALE 5.

REFERENCES

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