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for EBR-II Core-Follow Analysis

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*Validation of the REBUS-3/RCT Methodologies
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One of the many tasks to be completed at EBR-II/FCF (Fuel Cycle Facility) regarding fuel cycle closure for the Integral Fast Reactor (IFR) is to develop and install the systems to be used for fissile material accountancy and control [1]. The IFR fuel cycle and pyrometallurgical process scheme determine the degree of actinide buildup in the reload fuel assemblies. Inventories of curium, americium and neptunium in the fuel will affect the radiation and thermal environmental conditions at the fuel fabrication stations, the chemistry of reprocessing, and the neutronic performance of the core. Thus, it is important that validated calculational tools be put in place for accurately determining isotopic mass and neutronic inputs to FCF for both operational and material control and accountancy purposes. The primary goal of this work is to validate the REBUS-3/RCT codes [2,3] as tools which can adequately compute the burnup and isotopic distribution in binary- and ternary-fueled Mark-III, Mark-IV, and Mark-V subassemblies.

The validation procedure has involved obtaining the available loading information for an EBR-II configuration which sufficiently preceded the runs of EBR-II into which were loaded driver/test subassemblies that were ultimately analyzed for discharge compositions. Detailed REBUS-3 modeling of the core loading and core power level history for that EBR-II run is used to calculate the burnup history. This process is then extended through a series of all subsequent EBR-II runs, where input to the REBUS-3 burnup calculations utilizes the known heavy metal loadings for freshly-loaded subassemblies and the calculated (REBUS-3) number densities for the remainder of the subassemblies. This procedure should approximate the energy and spatial distribution of the neutron flux for the freshly-loaded subassemblies. Therefore, after a series of EBR-II runs have been analyzed, the effect of the initial conditions (i.e., the coarse initial reactor loading data) should diminish. Depletion analysis for a series of EBR-II runs is then repeated for specific experimental test subassemblies using the RCT code to obtain local values (e.g., values for an axial segment of a single element within a subassembly) of the burnup and isotopic compositions. Validation of these analytical methods and procedures is then determined via comparison of calculated element discharge compositions with experimentally measured burnup indicators (such as ^{139}La and ^{148}Nd measurements and U and Pu isotopic ratio measurements).

Methods and Models

Cross sections for this study are based on the ENDF/B Version V.2 nuclear data files. Region-dependent multigroup cross sections in 9 broad energy groups have been generated using the MC^2 -2/SDX cell homogenization codes [4,5] for each of the EBR-II cell types. The REBUS-3 reactor model of EBR-II is a three-dimensional (hexagonal-Z) full core model which explicitly models each hexagonal subassembly through Row 16. An additional row of hexagons (Row 17) is included in the REBUS-3 model representing the sodium pool. The reactor model includes three axial depletion regions in each of the core and blanket subassemblies. The neutronics solution uses DIF3D nodal diffusion theory [6]. The control rods and safety rods are modeled explicitly with time-dependent positions. The REBUS-3 calculation for each EBR-II run is a single burn step non-equilibrium calculation in which all loading changes from the preceding reactor run have been modeled. The power is assumed to be constant over the burn step. The series of EBR-II runs included in the present study started with Run 130A (August, 1984) and extended through 67 reactor sub-runs to Run 154F, that is, analysis of these runs required 67 separate REBUS-3 non-equilibrium calculations.

EBR-II has been utilized as an irradiation facility to test IFR metal fuels. Irradiated test subassemblies have included binary (U-10Zr) and ternary (U-xPu-10Zr) fuel elements of various designs. Because all three of the lead IFR test subassemblies (X419, X420, and X421) are mixed fuel types, direct comparison cannot be made between the REBUS-3 results and the analytical chemistry measurements of burnup and U and Pu isotopic fractions for these three subassemblies. That is, the compositions of the different element types in these subassemblies have been homogenized within the node (hexagon) in the REBUS-3 analysis. Furthermore, the depletion in REBUS-3 has been zone or block depletion, thereby lacking point values. And finally, the not uncommon procedure of reconstitution and further irradiation of many test assemblies (including these three experimental assemblies) is well beyond the standard abilities of REBUS-3. The RCT code has been developed to reconstruct the intra-nodal distributions of power density, burnup, nuclide densities, group fluxes, and fast and total fluences from nodal-diffusion/depletion calculations performed in hexagonal-Z geometry using REBUS-3/DIF3D.

Discussion of Results

The EBR-II experimental data available for comparison with REBUS-3/RCT calculations include burnup measurements, U and Pu isotopic fraction measurements, and gamma scan data. The current study focuses only on chemistry measurements performed by personnel of the Argonne-West Analytical Laboratory on *metal* fuel. This limits the database, at this time, to measurements on four experimental assemblies, namely, the three lead IFR test assemblies X419, X420, and X421, and the experimental assembly X425. Assembly X425 contains 61 new HT9 clad IFR metal fuel elements with as-built fissile loadings designed to closely match those of X419, X420, and X421.

The burnup measurements are based on Isotope Dilution Mass Spectroscopic (IDMS) analysis of fission products ^{139}La and ^{148}Nd . The overall accuracy of the Analytical Laboratory's determination of burnup on irradiated IFR fuel (U-10Zr or U-xPu-10Zr) up to 20 atom percent burnup is estimated to be $\pm 4\%$ provided the diffusion of La and Nd is only in the radial (and not axial) direction. Furthermore, there is an absolute uncertainty of 4% in the measurement of the power level of EBR-II. Because the power level is a direct normalization to the burnup values obtained in the REBUS-3/RCT analysis, the 4% uncertainty in the reactor power contributes a 4% uncertainty to the calculated values in addition to other nuclear data, methods, and modeling uncertainties. Therefore, agreement between calculated and experimental burnup values within about 6% should be considered good.

There are data for 14 samples -- each measured with La and Nd burnup monitors. The agreement between the calculated and measured burnup values for the IFR metal fuel is very good. The mean value $\pm 1\sigma$ spread of all 28 C/E values is 1.029 ± 0.032 . The range of the 28 C/E values is from 0.960 to 1.087, these extreme values being La burnup measurements of two samples of the same U-8Pu-10Zr ternary pin in X419 at $\sim 1.9\%$. The mean and 1σ spread in the C/E values according to fuel type are shown below.

	Burnup C/E's Mean Value $\pm 1\sigma$
U-10Zr	1.024 ± 0.012
U-8Pu-10Zr	1.027 ± 0.038
U-19Pu-10Zr	1.036 ± 0.033

The slight differences in the mean C/E values according to fuel type are not significant. In fact, there are *no significant* trends in the C/E biases. The set of six C/E values for the binary pin in X419 at $\sim 1.8\%$ burnup are the best and most consistent set (i.e., closest to unity and to each other). However, the best C/E's for a single sample were for the U-19Pu-10Zr ternary pin in

X419B at ~12% burnup, which was the highest burnup measured.

Burnup data is available at different axial positions for only three elements of IFR metal fuel, namely, for elements T167, T013, and T119 of test assembly X419. For these three elements, the C/E value is lower near the top of the fuel column than at the middle and bottom. It is natural to question (i) whether this distributional bias is real, and (ii) does it portend a misprediction in the axial flux or power profile. Because these C/E values all agree within $\pm 6\%$, the first question cannot be answered unequivocally without additional data (i.e., more comparisons of measured burnup distributions). However, one can still consider the second question. For the U-19Pu-10Zr element T167 of assembly X419, the gamma scan of ^{95}Nb has been measured. These data have been compared with the REBUS-3/RCT calculated values of axial power density and burnup for element T167. The calculated distributions are more convex or "buckled" than the measured data, that is, the calculated values are lower at both the top and bottom of the fuel column. However, it must again be noted that the differences are small ($<4\%$).

U and Pu isotopic analyses have also been performed by the Analytical Laboratory on the same four IFR test assemblies. The determinations are again obtained from mass spectrometer measurements. The overall accuracy of performing isotopic measurements on irradiated IFR fuel is estimated to be $\sim 0.2\%$ for ^{235}U , ^{238}U , and ^{239}Pu , and $\sim 1.0\%$ for ^{234}U , ^{236}U , and ^{240}Pu .

In the case of X419, X420, and X421, isotopic data have been measured from radial drilling of the irradiated samples. As might be expected, the radial variation within the samples was determined to be quite small. The experimental values used in this study represent average values for the entire axial section of the samples. The comparison of calculated and measured values of the U and Pu isotopic fractions as a function of burnup for U-10Zr, U-8Pu-10Zr, and U-19Pu-10Zr IFR fuel have been made. The agreement between measured and calculated values is quite good.

U and Pu isotopic fractions have also been measured for the two burnup samples of element T456 (U-8Pu-10Zr) in test assembly X425A. Again, agreement is quite good, except for ^{242}Pu , which represents a very small component of the Pu in element T456. One of the two C/E values for the ^{242}Pu weight fraction is $\sim 9\%$ high and the other $\sim 27\%$ low. The measurements in X419, X420, and X421 did not report the ^{242}Pu weight fractions.

Conclusions

The principle conclusions from the present study are:

1. REBUS-3 analysis using nodal diffusion theory with a three-dimensional hexagonal-Z full core model and ENDF/B-V.2 nuclear data can adequately follow EBR-II fuel management and depletion.
2. Details of nuclide density, burnup, power density, and fluence within the node or hexagonal subassembly can adequately be reconstructed using the RCT code.
3. Comparisons have been made of REBUS-3/RCT analyses with experimental values, including the analysis of mixed fuel type test assemblies that have had complex irradiation histories (such as multiple reconstitutions, multiple core insertions/removals, and multiple core locations and subassembly orientation).
4. Results of these comparisons for burnup and U and Pu isotopic fractions are quite good (i.e., generally within experimental uncertainties) and indicate the REBUS-3/RCT methodologies can meet both operational and material control and accountancy requirements for the IFR.

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