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Isotopic Validation for PWR Actinide-Only Burnup Credit Using Yankee Rowe Data

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INTRODUCTION

Safety analyses of criticality control systems for transportation packages include an assumption that the spent nuclear fuel (SNF) loaded into the package is "fresh" or unirradiated. In other words, the spent fuel is assumed to have its original, as-manufactured U-235 isotopic content. The "fresh fuel " assumption is very conservative since the potential reactivity of the nuclear fuel is substantially reduced after being irradiated in the reactor core. The concept of taking credit for this reduction in nuclear fuel reactivity due to burnup of the fuel, instead of using the fresh fuel assumption in the criticality safety analysis, is referred to as "Burnup Credit." Burnup credit uses the actual physical composition of the fuel and accounts for the net reduction of fissile material and the buildup of neutron absorbers in the fuel as it is irradiated. Neutron absorbers include actinides and other isotopes generated as a result of the fission process. Using only the change in actinide isotopes in the burnup credit criticality analysis is referred to as "Actinide-Only Burnup Credit."

The use of burnup credit in the design of criticality control systems enables more spent fuel to be placed in a package. Increased package capacity results in a reduced number of storage, shipping and disposal containers for a given number of SNF assemblies. Fewer shipments result in a lower risk of accidents associated with the handling and transportation of spent fuel, thus reducing both radiological and nonradiological risk to the public.

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In May 1995, the U.S. Department of Energy's (DOE) Office of Civilian Radioactive Waste Management submitted the *Topical Report on Actinide-Only Burnup Credit for Pressurized Water Reactor Spent Nuclear Fuel Packages*[1] to the U.S. Nuclear Regulatory Commission (NRC). The objective of this topical report was to obtain the NRC's approval on a generic burnup credit methodology for use in designing criticality control systems of spent fuel shipping casks. As the result of its review, the NRC questioned the adequacy of the benchmark set used to perform isotopic depletion/generation computer code validation which is part of the methodology. The computer code package used to demonstrate the burnup credit methodology was the SCALE 4.2[2] with the 27BURNUPLIB cross section library. Consequently, additional isotopic benchmarking analyses for spent fuel with higher initial enrichment, higher burnup, and exposed to a non-typical spectrum (per NRC comment), along with other modifications, were added and Revision 1 of the topical report was submitted to the NRC in May 1997.[3]

As part of the additional isotopic benchmarking analyses, the isotopic data on a Yankee Rowe spent fuel assembly which had been chemically assayed in 1960's were used to augment the suite of isotopic benchmark set. This paper describes the modeling and the results of comparison between measured and calculated isotopic inventories for a selected number of samples taken from a Yankee Rowe spent fuel assembly. The complete description of this analysis is presented in the *Isotopic and Criticality Validation for PWR Actinide-Only Burnup Credit* [4] which was prepared and submitted to the NRC as one of the supporting technical documents referenced in the Actinide-Only Burnup Credit Topical Report, Rev. 1.

YANKEE ROWE SPENT FUEL SAMPLES USED IN ISOTOPIC VALIDATION

In the mid 1960's, extensive post-irradiation examinations, including radiochemical analyses, were performed on a selected set of spent fuel assemblies with relatively high enrichment (i.e., 3.4 wt.% U-235) discharged from Yankee Rowe Cores I, II, and IV.[5] The overall purpose of the program was to further the knowledge of physical processes that occur within an operating reactor. The program was carried out under three phases. Under Phase I, 56 fuel rods were removed from 14 Core I fuel assemblies. Seven fuel rods were removed from a Core I assembly recycled in Core II for Phase II post-irradiation examinations. The burnup for the rods from Core I and II ranged from 13 to 18 and 10 to 31 GWd/MTU, respectively. Under Phase III, eight rods from one assembly, E6, which had been cycled in Cores I, II, and IV, was selected for post-irradiation examination. The maximum burnup of these rods was 46 GWD/MTU. Initial enrichment for these assemblies was 3.4 wt% U-235. Therefore, because of the relatively high burnup and enrichment, it was decided to use the measurement data for isotopic validation from a selected number of rods from assembly E6 of Yankee Rowe.

In addition, the Yankee Rowe core design is significantly different from the typical PWR. Figure 1 shows the regional characteristics of the neutron spectra in the core as classified by the designers. As indicated in the figure, the spectrum close to the control rod cruciform is labeled as "perturbed." This spectrum could be harder or softer than the "intermediate" spectrum depending on whether the cruciform is in or out. Therefore, the benchmark set included data points from

fuel assemblies exposed to non-typical spectrum as stated by the NRC in their comments on the Rev. 0 of the topical report.

Figure 2 shows the assembly E6 from which fuel pins were removed for post-irradiation examination under Phase III program. Each Yankee Rowe assembly consists of six 6x6 subassemblies. With the assembly oriented as shown, the nine subassemblies are identified with a compass-point notation as indicated in the lower right corner of Figure 2. In each subassembly individual fuel rods are identified with an alpha-numeric notation whereby the columns of fuel rods, reading left to right, are headed with letters a through e in the case of subassembly NW, and a through f for the eight other subassemblies. Reading top to bottom in each subassembly, the rows of fuel rods are numbered 1 through 5 in the case of subassembly SE, and 1 through 6 for the eight other subassemblies.

As indicated by solid circles in Figure 2, eight rods were removed for examinations. Samples were taken at fixed axial heights along the entire rod length for radiochemical analysis. Out of the eight pins removed and analyzed under Phase III, the results of only three rods were used in this isotopic validation. Those three rods were selected in order to maximize diversity but at the same time stay within the modeling capabilities of 1-D codes such as SAS2H that will be used for standard fuel assemblies. The Yankee Rowe samples used for actinide-only burnup credit validation are four samples from rod E6-C-f6, two samples from rod E6-SE-c2, and two samples from rod E6-SE-e4 taken at different axial heights.

DEVELOPMENT OF ISOTOPIC GENERATION/DEPLETION MODEL

The SAS2H control module of SCALE 4.2 with the 27BURNUPLIB cross section library was used to perform the isotopic generation and depletion analysis in one-dimensional radial dimension under a set of specified reactor core conditions. The parameters needed to construct SAS2H input decks for Yankee Rowe samples are fuel density, temperature, and composition, moderator temperature, density, and boron content, fuel pin model for cross section averaging, fuel assembly physical characteristics, average power, burnup duration, cooling time per cycle, and the composition of non-fuel material in the fuel.

The information on fuel composition and design were obtained from Reference 5. Average boron concentration, specific power, cooling time, moderator, clad, and fuel temperatures were obtained from Reference 6. The SCALE 4.2 does not have the capability to use or update values for moderator, clad, and fuel temperature after each cycle. Therefore, burnup-weighted average values for moderator, clad, and fuel temperatures were calculated and used. The composition of light elements in the non-fuel components were assumed to be the same as that in the Trino Vercelles fuel assemblies. The mass of light elements per MTU was obtained from Reference 7.

Using the pellet and rod information provided in Reference 5, an infinite lattice of a fuel model (path A) was constructed. This model is used by SAS2H to calculate the average cross sections in a unit cell. Then the discrete ordinates one-dimensional transport calculations are performed to

determine the neutron flux in a unit cell. The cell-weighted cross sections produced using path A model are then applied to the fuel region of the entire fuel assembly model (path B). Path B accounts for the intera-assembly gap, instrumentation tube, and the region with additional moderator when the control rod cruciforms are withdrawn. The path B model is used to collapse the cross sections for use in the ORIGEN-S module of SCALE which performs the isotopic generation and depletion.

COMPARISON OF CALCULATED TO MEASURED VALUES

Table 1 provides the results of comparison between calculated values, using the SCALE 4.2 with 27BURNUPLIB cross section, which is based on ENDF/B-IV cross section library, and the measured values which had been reported in Reference 5. The comparison is shown in terms of % of measurement for nine of the actinide isotopes used in the actinide-only burnup credit methodology.

A negative value indicates an under prediction of the isotopic content in the fuel by the model, and a positive value means an over prediction when compared to the measurement results. A general conclusion that can be drawn is that the neutron spectrum to which fuel assemblies were exposed was slightly harder than what the SAS2H model calculated. This can be noticed by the fact that the U-235 and Pu-239 was consistently under predicted for six of the samples. The other two samples came from a rod exposed to a spectrum which was softer than what the SAS2H model calculated. This is because of the presence of moderator in the periphery of the assembly

E6 due to the withdrawal of the large control rod cruciforms. However, one should note that the difference between calculated and measured values for most of the samples are less than ten percent. Given the non-traditional design of the Yankee Rowe core and the reasonable difference between measured and calculated values by SCALE 4.2, it appears that this set of benchmarks is suitable, in terms of adding diversity to the entire benchmark set, for including in the benchmark set recommended for use in isotopic validation as part of the actinide-only burnup credit methodology.

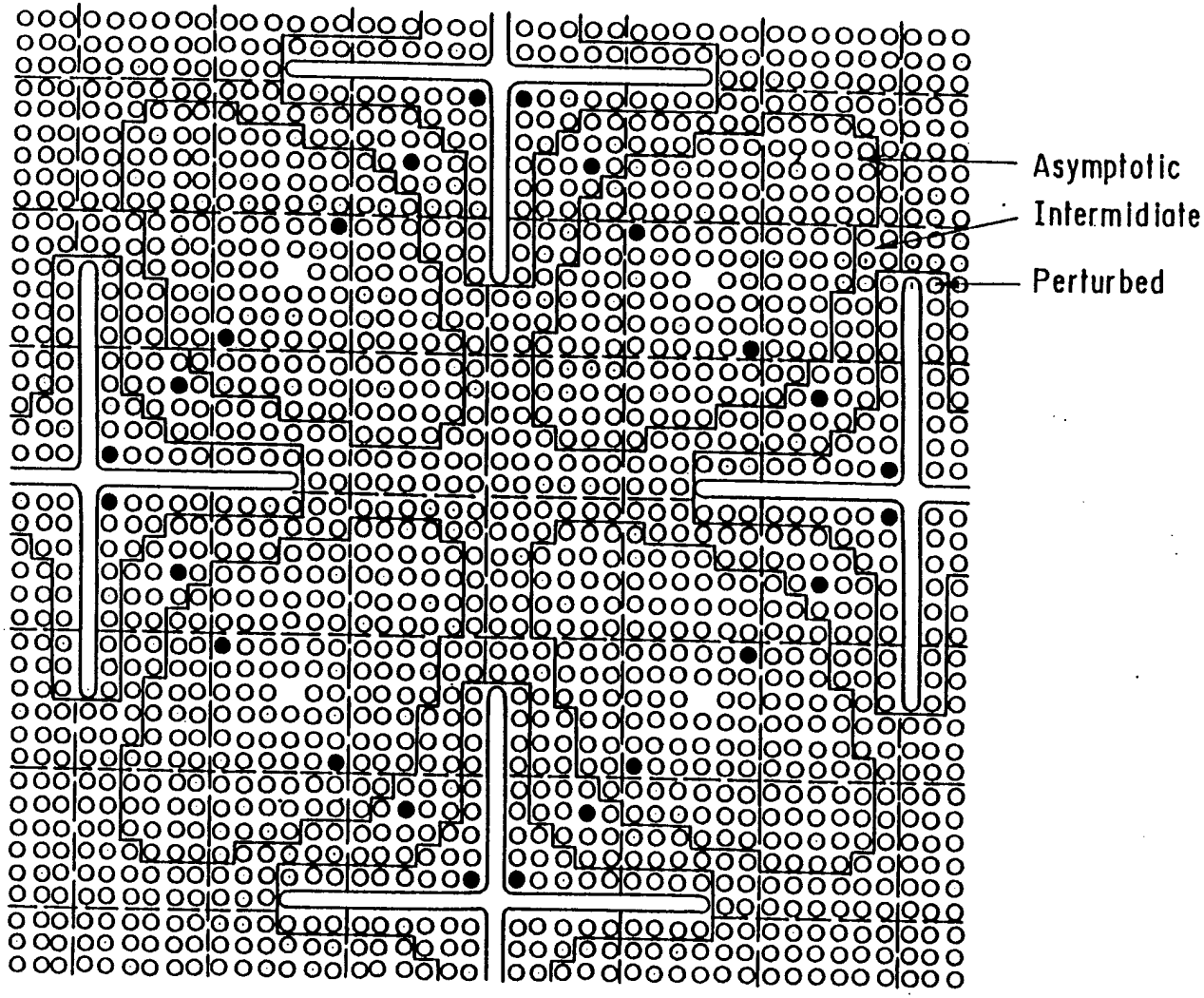

Figure 1. Junction of Four Yankee Rowe Fuel Assemblies Showing the Division of Lattice into Spectral Characteristic Region

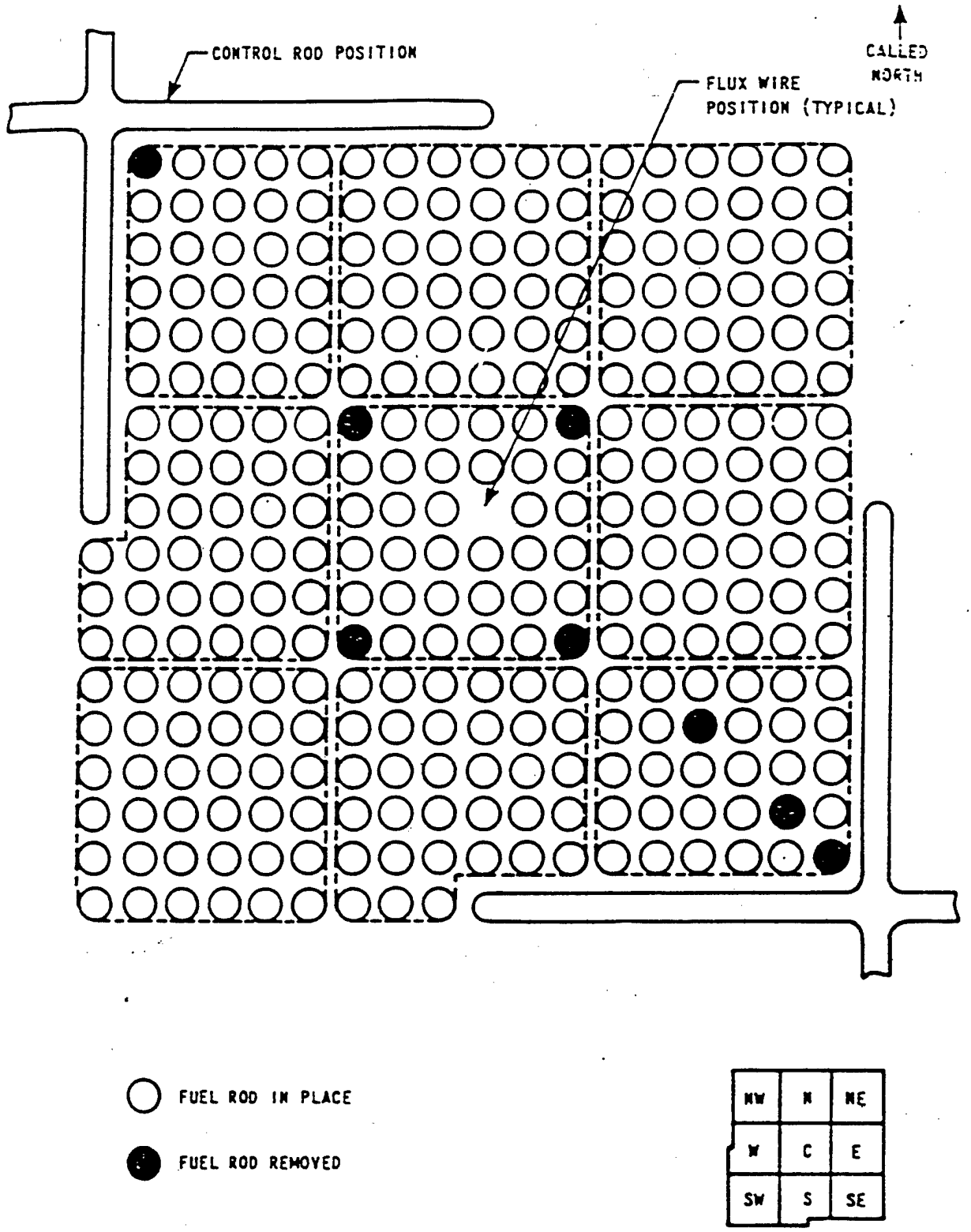

Figure 2. Locations of Fuel Rods Removed from Yankee Row Fuel Assembly for Chemical Analyses

Table 1. Difference Between Measured and Calculated Values for Yankee Rowe Samples (% of measured values)

Sample ID	E6-C-f6-1	E6-C-f6-3	E6-C-f6-5	E6-C-f6-6	E6-SE-c2-3	E6-SE-c2-5	E6-SE-e4-3	E6-SE-e4-5
Burnup (GWd/MTU)	15.95	30.39	31.33	20.19	32.03	31.41	35.97	35.26
Enrichment	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.40
Specific Power (MW/MTU)	14.22	27.09	27.93	18.00	28.56	28.00	32.07	31.44
U-234	1.15	-10.54	3.98	2.18	7.42	7.39	-2.79	-3.49
U-235	-1.05	-6.06	-5.31	-2.19	-5.82	-4.66	-1.74	-0.69
U-236	-0.79	0.84	0.43	0.52	0.70	1.73	-1.08	-1.55
U-238	0.38	0.30	0.51	1.47	0.48	0.46	0.24	0.24
Pu-238	-13.97	4.12	-11.29	-12.15	-9.63	-9.68	3.97	1.68
Pu-239	-4.78	-6.97	-9.35	-7.00	-7.07	-5.41	9.92	9.46
Pu-240	-5.94	-3.13	-7.15	-4.64	-9.23	-7.55	-8.26	-6.68
Pu-241	-3.45	-0.01	-4.41	-2.87	-2.21	-0.58	9.15	9.39
Pu-242	-10.42	3.32	-3.86	-7.50	-4.71	-3.83	-7.43	-6.92

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