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Isotopic Biases for Actinide-Only Burnup Credit

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In May 1995, the U.S. Department of Energy's (DOE's) Office of Civilian Radioactive Waste Management (OCRWM) submitted a topical report on actinide-only burnup credit for pressurized water reactor (PWR) spent-nuclear fuel packages[1] to the Nuclear Regulatory Commission (NRC). The purpose of this topical was to obtain the NRC's approval on a generic burnup credit methodology in designing criticality control systems of spent fuel shipping casks.

A major part of this methodology is the validation of the neutronics model. The Standardized Computer Analyses for Licensing Evaluation (SCALE 4.2)[2] computer code package was used to demonstrate the proposed methodology in the topical report. To perform burnup credit criticality analysis using SCALE 4.2, the isotopic generation/depletion part of the Shielding Analyses Sequence (SAS2H) and Criticality Safety Analysis Sequence (CSAS) are used.

The isotopic validation methodology presented in the burnup credit topical report consisted of establishing a set of isotopic correction factors (i.e., a bias factor with a 95% confidence level) by comparison between a set of isotopic measurements and the corresponding calculated values. The NRC has commented on the isotopic validation in Rev. 0 of the Topical Report by stating that the amount of experimental data needs to be augmented and investigation for presence of any possible trends with respect to pertinent parameters needs to be performed.

In response to the NRC's comments, Rev. 1 of the Topical Report contains additional chemical assay data and a methodology in deriving isotopic correction factors which includes trends with respect to initial enrichment, burnup, and a spectral index. The purpose of this paper is not so much to discuss the results of additional isotopic benchmarks, but to present the new methodology for establishing bias and uncertainty associated with isotopic prediction in spent fuel assemblies for burnup credit analysis.

TRENDING ANALYSIS

A total of 54 spent fuel samples which had been measured were modeled and analyzed using SAS2H.[3] Table I shows the results of benchmarks in terms of measured/calculated values for the nine burnup credit isotopes. Am-241 is also one of the isotopes which credit is being taken for its presence in spent fuel. It is assumed that 100% of Pu-241 decay results in Am-241. Therefore, the bias for Am-241 is assumed to be the same as that for Pu-241. The majority of benchmark cases (i.e., 36) were modeled and analyzed by Oak Ridge National Laboratories.[4,5] The remaining cases were modeled and calculated by the authors.

Using the isotopic ratios in Table I, multiple regression analysis as a function of initial enrichment, burnup, and average lethargy for absorption (ALA) for nine actinide isotopes were performed.

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Then, a trending test was performed to determine, with 95% confidence, if there is a trend associated with any of the parameters (initial enrichment, burnup, and ALA). If the test does not indicate a trend with respect to the particular parameter, that parameter is eliminated and regression analysis with respect to the remaining parameters are performed. Then the bias would be in the form of a linear equation as a function of one or more parameters. If the test does not indicate any trends with respect to any of the three parameters, the bias would be equal to the average of measured/calculated values.

An uncertainty term associated with the regression equation (or the bias) was also developed. The uncertainty term is a function of trending parameters and the sample size. This approach would allow the range of applicability to expand but, of course, with a penalty in terms of larger uncertainty.

RESULTS

The resulting bias and uncertainty were added together for the nine isotopes and were called isotopic correction factors. These correction factors are basically multiplicative biases which can be used to correct any future isotopic calculations performed by SAS2H of SCALE 4.2 with 27BURNUPLIB cross section. The followings are the correction factors for the ten actinide burnup credit isotopes.

$$f_{U\text{-}234} = 0.736$$

$$f_{U\text{-}235} = -(1.622E\text{-}1)+(4.180E\text{-}2)X_1+(2.284E\text{-}3)X_2+(6.199E\text{-}2)X_3 +(2.954E\text{-}2)*[(1.529E+2)+(3.642E\text{-}1)X_1^2+(3.119E\text{-}4)X_2^2+(4.568E\text{-}1)X_3^2 -(1.122E+1)X_1-(1.200E\text{-}1)X_2-(1.652E+1)X_3+(8.132E\text{-}3)X_2X_1 +(5.452E\text{-}1)X_3X_1+(4.892E\text{-}3)X_3X_2]^{1/2} * (1.676)$$

$$f_{U\text{-}236} = +(1.776)-(1.460E\text{-}3)X_2-(4.569E\text{-}2)X_3 - (3.454E\text{-}2)*[(6.648E+1)+(2.834E\text{-}4)X_2^2+(2.528E\text{-}1)X_3^2 +(4.756E\text{-}3)X_2-(8.124)X_3-(1.221E\text{-}3)X_3X_2]^{1/2}*(1.676)$$

$$f_{U\text{-}238} = +(8.082E\text{-}1)+(1.196E\text{-}2)X_3-[(1.549E\text{-}5)+(4.001E\text{-}6)*(X_3-1.611E+1)]^{1/2} *(1.679)$$

$$f_{Pu\text{-}238} = 0.841$$

$$f_{Pu\text{-}239} = +(8.474E\text{-}1)+(5.703E\text{-}2)X_1-(1.426E\text{-}3)X_2 +(3.826E\text{-}2)*[(3.499)+(2.015E\text{-}1)X_1^2+(2.988E\text{-}4)X_2^2 -(1.361)X_1-(3.160E\text{-}2)X2+(5.340E\text{-}3)X_1X_2]^{1/2}*(1.675)$$

$$f_{Pu\text{-}240} = +(4.126E\text{-}1)+(4.520E\text{-}2)X_1+(1.766E\text{-}3)X_2+(2.886E\text{-}2)X_3 -(2.954E\text{-}2)*[(1.529E+2)+(3.642E\text{-}1)X_1^2+(3.119E\text{-}4)X_2^2+(4.568E\text{-}1)X_3^2 -(1.122E+1)X_1-(1.200E\text{-}1)X_2-(1.652E+1)X_3+(8.132E\text{-}3)X_2X_1 +(5.452E\text{-}1)X_3X_1+(4.892E\text{-}3)X_3X_2]^{1/2} * (1.676)$$

$f_{Pu\text{-}241} = 1.089$

$$f_{Pu\text{-}242} = -(8.889E\text{-}1)+(1.108E\text{-}1)X_1+(1.018E\text{-}1)X_3 -(2.583E\text{-}2)*[(1.406E+2)+(3.581E\text{-}1)X_1^2+(4.304E\text{-}1)X_3^2 -(1.016E+1)X_1-(1.474E+1)X_3+(4.940E\text{-}1)X_1 X_3]^{1/2} * (1.678)$$

$f_{Am\text{-}241} = 0.899$

where:

X_1 = initial enrichment
X_2 = burnup
X_3 = ALA

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Table I

Measured/Calculated Ratios for 54 Benchmark Cases

	Sample	U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Mihama	1	1.046	1.025	0.939	1.000	0.914	0.970	1.023	0.928	1.016
Mihama	2		1.022	0.951	1.001	0.950	0.985	1.058	0.975	1.109
Mihama	3		1.054	1.001	0.999	1.089	1.075	1.081	1.040	1.141
Mihama	4		1.052	1.000	1.000	1.059	0.998	1.058	0.965	1.082
Mihama	5		1.050	0.933	1.001	1.056	1.028	1.101	1.022	1.144
Mihama	6		1.099	0.943	1.000	1.045	1.034	1.102	1.022	1.122
Mihama	7	0.936	1.041	0.971	1.003	1.010	0.943	1.088	0.921	1.099
Mihama	8	0.954	1.048	0.970	1.001	1.019	0.949	1.108	0.944	1.135
Yankee	9	0.991	1.006	1.010	0.995	1.165	1.046	1.061	1.075	1.129
Yankee	10	1.115	1.056	0.995	0.998	0.963	1.069	1.033	1.100	0.977
Yankee	11	0.946	1.043	0.989	0.996	1.148	1.087	1.076	1.076	1.036
Yankee	12	0.975	1.016	0.997	0.985	1.158	1.071	1.056	1.069	1.091
Yankee	13	0.929	1.052	0.994	0.995	1.127	1.069	1.105	1.061	1.058
Yankee	14	0.934	1.041	0.982	0.996	1.127	1.053	1.082	1.042	1.051
Yankee	15	1.029	1.006	1.014	0.997	0.983	0.904	1.095	0.949	1.087
Yankee	16	1.029	0.997	1.020	0.998	1.004	0.909	1.073	0.947	1.088
C. Cliffs	17	0.875	1.015	1.008	1.012	1.216	1.014	1.072	1.009	1.124
C. Cliffs	18	0.852	1.045	1.003	1.016	1.075	1.008	1.083	0.979	1.086
C. Cliffs	19	0.930	1.026	1.012	1.010	1.009	0.947	1.083	0.939	1.099
C. Cliffs	20	1.264	1.010	0.986	1.008	0.970	0.944	1.060	0.982	1.117
C. Cliffs	21	1.144	1.046	1.010	1.013	0.969	0.940	1.065	0.978	1.125
C. Cliffs	22	0.761	0.983	1.007	1.004	0.980	0.895	1.061	0.939	1.157
C. Cliffs	23	0.994	1.059	0.969	1.007	1.032	0.996	1.068	0.961	1.043
C. Cliffs	24	1.007	1.095	0.972	1.003	1.005	0.988	1.082	0.968	1.038
C. Cliffs	25	0.952	1.106	0.984	1.001	1.000	0.955	1.096	0.962	1.069
Robinson	26		0.997	1.011	0.998	0.996	0.944	1.022	0.950	
Robinson	27		0.992	1.022	1.006	1.000	0.937	1.049	0.950	
Robinson	28		1.062	0.979	0.995	1.077	0.957	1.058	0.999	
Robinson	29		0.979	1.007	1.009	0.983	0.896	1.046	0.921	
Obrigheim	30		1.028	0.984		0.994	0.983	1.086	0.951	1.190
Obrigheim	31		1.033	0.989		0.940	0.957	1.053	0.931	1.135
Obrigheim	32		1.049	0.979		0.913	0.968	1.058	0.938	1.122
Obrigheim	33		1.027	0.986		0.973	0.935	1.046	0.914	1.135
Obrigheim	34		1.026	0.981		0.920	0.968	1.043	0.928	1.127
Obrigheim	35		1.029	0.987		0.923	0.964	1.063	0.940	1.171
T. Point	36	0.957	1.076	0.971	1.001	0.935	0.952	1.054	0.915	0.975
T. Point	37	0.826	1.043	0.937	1.001	0.909	0.971	1.069	0.953	1.016
T. Point	38	0.957	1.030	0.972	1.001	0.944	0.953	1.072	0.929	1.035
T. Point	39	0.971	1.074	0.965	1.001	0.903	0.941	1.045	0.908	0.977
T. Point	40	0.901	1.076	0.939	1.001	0.920	0.969	1.048	1.012	1.005
T. Vercelles	41		0.971	1.082	1.000		1.021	1.055	0.982	1.141
T. Vercelles	42		0.955	1.026	1.000		1.020	1.043	0.957	1.153
T. Vercelles	43		0.989	0.000	1.001		1.025	1.052	1.014	1.159
T. Vercelles	44		1.009	1.029	1.000		0.987	1.041	0.955	1.067
T. Vercelles	45		0.985	1.017	0.999		1.007	1.038	0.942	1.058
T. Vercelles	46		0.998	1.057	1.001		0.979	0.989	0.935	1.043
T. Vercelles	47		0.984	1.053	1.000		0.994	1.041	0.975	1.096
T. Vercelles	48		0.967	1.059	1.000		0.981	1.045	0.945	1.097
T. Vercelles	49		0.988	1.051	1.000		1.025	1.074	0.964	1.096
T. Vercelles	50		1.029	1.003	1.000		1.000	1.029	0.938	1.038
T. Vercelles	51		0.985	1.032	0.998		1.008	1.053	0.964	1.064
T. Vercelles	52		1.002	1.094	0.999		1.005	1.059	0.955	1.093
T. Vercelles	53		0.980	1.001	0.999		1.013	1.058	0.950	1.097
T. Vercelles	54		0.989	1.117	0.999		1.045	1.086	1.059	1.254