NUREG/CR-6798
ORNL/TM-2001/259

Isotopic Analysis of High-Burnup PWR Spent Fuel Samples From the Takahama-3 Reactor

Oak Ridge National Laboratory

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Isotopic Analysis of High-Burnup PWR Spent Fuel Samples From the Takahama-3 Reactor

Manuscript Completed: May 2002
Date Published: January 2003

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U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code W6479

ABSTRACT

This report presents the results of computer code benchmark simulations against spent fuel radiochemical assay measurements from the Kansai Electric Ltd. Takahama-3 reactor published by the Japan Atomic Energy Research Institute. Takahama-3 is a pressurized-water reactor that operates with a 17 × 17 fuel-assembly design. Spent fuel samples were obtained from assemblies operated for 2 and 3 cycles and achieved a maximum burnup of 47 GWd/MTU. Radiochemical analyses were performed on two rods having an initial enrichment of 4.11 wt %, and one integral burnable absorber rod containing Gd_2O_3. These measurements represent the highest enrichment and highest burnup samples currently available in the United States. The benchmark results are important to burnup credit initiatives in the United States since the lack of available benchmark data has led to restrictions on the allowable credit beyond 4.0 wt % and 40 GWd/MTU. Although the primary objective of the measurements was support of burnup credit, radiochemical analyses were also available for a number of actinide and fission product nuclides important to decay heat and radiation source term analysis. Isotopic predictions from both the SCALE 4.4a and HELIOS-1.6 code systems were used in this benchmark study. The results indicate that the level of agreement between predictions and measurements is very good. The results, for the most part, are consistent with the findings of earlier studies for lower enrichment and lower burnup samples and yield similar biases and levels of uncertainty.

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FOREWORD

In 1999 the United States Nuclear Regulatory Commission (U.S. NRC) issued initial recommended guidance for using reactivity credit due to fuel irradiation (i.e., burnup credit) in the criticality safety analysis of spent pressurized-water-reactor (PWR) fuel in storage and transportation packages. This guidance was issued by the U.S. NRC Spent Fuel Project Office (SFPO) as Revision 1 to Interim Staff Guidance 8 (ISG8R1) and published in the *Standard Review Plan for Transportation Packages for Spent Nuclear Fuel*, NUREG-1617 (March 2000). With this initial guidance as a basis, the U.S. NRC Office of Nuclear Regulatory Research (RES) initiated a program to provide the SFPO with technical information that would:

- enable realistic estimates of the subcritical margin for systems with spent nuclear fuel (SNF) and an increased understanding of the phenomena and parameters that impact the margin, and
- support the development of technical bases and recommendations for effective implementation of burnup credit and provide realistic SNF acceptance criteria while maintaining an adequate margin of safety.

ISG8R1 recommends limiting the amount of credit for burnup to 40 GWd/MTU or less, and recommends a loading offset (additional reactivity penalty) for fuel with enrichment values above 4 wt %. These restrictions were based largely on the lack of experimental data in these regimes to validate computer code predictions of the nuclide concentrations in spent fuel. In a parallel research effort initiated by RES in 1999, work is progressing towards an increased understanding of predicted source terms (e.g., decay heat, radiation sources) for high-burnup SNF in order to provide guidance on improved models and predictive methods. Recently, new radiochemical assay measurements on PWR SNF samples having enrichments and burnups that exceed the limits in ISG8R1 have been published. This report presents the results of predictive analyses performed to help assess the uncertainty associated with current predictive methods. The benchmark results represent an important addition to the isotopic assay database to support computer code validation for higher burnup regimes.

This research in combination with ongoing research will also be use to develop the technical basis for regulatory guidance on loading of high burnup fuel (>45 GWd/MTU) in storage and transportation packages. This research will allow NRC to maintaining safety and enhance public confidence, especially criticality safety for storage and transportation packages. It will also contribute to NRC in making effective, efficient and realistic regulatory decisions with respect to allow unloading high burnup fuel from reactor spent fuel pools.

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1 INTRODUCTION

The nuclide composition of spent nuclear fuel determines its properties and radiological characteristics in transportation, interim storage, and final disposal. The accurate prediction of the time-dependent nuclide inventory in spent fuel is necessary to evaluate many issues, including (1) the neutron multiplication factor in criticality safety, (2) decay heat sources for thermal analysis, (3) neutron and gamma-ray sources for radiation shielding and dose rate analysis, and (4) radionuclide concentrations and toxicities for assessment of long-term environmental waste management concepts. Validation of the predicted isotopic concentrations and aggregate properties of spent fuel, and the evaluation of the computational bias and uncertainties, is an essential step to support use of the predicted characteristics in a safety analysis or licensing evaluation.

Japan Atomic Energy Research Institute (JAERI) recently published spent fuel radiochemical assay measurements from the Kansai Electric Ltd. Takahama-3 reactor.[1] Takahama-3 is a pressurized-water reactor (PWR) with a power rating of 2652 MWt and operates with assemblies having a 17 × 17-fuel lattice design. Spent fuel samples were obtained from two assemblies, NTG23 and NTG24, irradiated for 2 and 3 cycles, respectively. Both assemblies operated with fixed gadolinia (Gd_2O_3) burnable poison rods (BPRs). Radiochemical analyses were performed on ten spent fuel samples obtained from one rod in each assembly. In addition, a BPR from assembly NTG23 was analyzed. The fuel rods each had an initial enrichment of 4.11 wt % and achieved a maximum burnup of 47 GWd/MTU. This report presents results of benchmark simulations performed with computer codes SAS2H and HELIOS against spent fuel samples from Takahama-3.

The Takahama-3 data represent the highest enrichment and highest burnup spent fuel measurements publicly available and considerably extend the range of previously available isotopic assay data.[2] A majority of the previous measurements involved spent fuel samples having a maximum enrichment of 3.4 wt % (one 3.9 wt % sample was available). The maximum burnup of the higher enrichment samples was 36 GWd/MTU. The Takahama-3 fuel samples are the only publicly available samples from assemblies that operated with Gd_2O_3 integral burnable poison rods (IBPRs). Integral burnable poisons are routinely employed in the higher enrichment assemblies currently in use. Therefore, the data are more representative of modern spent fuel assemblies than are earlier data.

The Takahama-3 radiochemical assay data are potentially highly important to burnup credit initiatives in the United States. Revision 1 of Interim Staff Guidance 8 (ISG-8), issued by the United States Nuclear Regulatory Commission (U.S. NRC) in July 1999, provides guidance on the application of actinide burnup credit in criticality safety analyses for PWR spent fuel in transportation and storage casks.[3] The guidance recommends that burnup credit be limited to a maximum of 40 GWd/MTU and recommends a loading offset method to be used for fuel enrichments in the 4–5 wt % range. The offset method assesses an additional reactivity margin equal to 1 GWd/MTU for every 0.1 wt % initial enrichment above 4 wt %. This penalty is recommended because of the lack of experimental isotopic assay data above 4 wt %, and is designed to compensate for potentially larger isotopic uncertainties in extrapolating beyond the range of the data.

Radiochemical analyses of the Takahama-3 fuel samples were performed for a wide array of actinides and fission products. Although primarily designed to support validation for burnup credit analyses, the experiments also measured nuclides important to decay heat and radiation source terms. Specifically, all samples included measurements for ^{244}Cm, the dominant neutron source nuclide. Fission product measurements included ^{137}Cs, ^{144}Ce, ^{106}Ru, (decay parents to the dominant gamma radiation source nuclides ^{137m}Ba, ^{144}Pr, and ^{106}Rh), ^{134}Cs, ^{154}Eu, and all of the Nd and Sm isotopes important to burnup credit.[4]

The calculations reported in this benchmark study were performed using the one-dimensional (1-D) SAS2H depletion analysis sequence of the SCALE 4.4a code system, and the two-dimensional (2-D) HELIO-1.6 code system.

2 FUEL AND ASSEMBLY SPECIFICATIONS

2.1 TAKAHAMA-3 DESCRIPTION

The Takahama-3 reactor is a PWR with a rated thermal power of 2652 MW and operates with 17 × 17 fuel assembly design. Isotopic assay measurements of spent fuel samples from Takahama-3 were recently published in Ref. 1, by the JAERI. Oak Ridge National Laboratory (ORNL) has translated this report and published the English version in Ref. 5. Subsequently, additional information on the Takahama-3 reactor operations and design was published in a revision to the SFCOMPO isotopic assay database.[2] A summary of the Takahama-3 reactor and fuel assembly design data is given in Table 1.

Radiochemical isotopic assay measurements were performed on two different Takahama-3 fuel assemblies: NT3G23 and NT3G24. Both fuel assemblies feature 14 integral burnable gadolina-bearing (Gd_2O_3) fuel rods containing 2.6 wt % ^{235}U and 6.0 wt % gadolinia while the standard fuel rods contain 4.11 wt % ^{235}U enrichment. The assemblies also had 25 water-filled guide tubes. A summary of the initial composition of Takahama-3 fuel assemblies is given in Table 2.

Spent fuel samples were obtained from two standard fuel rods and one gadolinia-bearing fuel rod of fuel assemblies NT3G23 and NT3G24. The standard fuel rods, designated SF95 (assembly position A-Q) and SF97 (assembly position I-Q), were irradiated in assemblies NT3G23 and NT3G24, respectively. The gadolina-bearing fuel rod, SF96 (assembly position C-M), was irradiated in assembly NT3G23. Figure 1 shows the positions of assay fuel rods SF95, SF96, and SF97 in assemblies NT3G23 and NT3G24.

The fuel assembly NT3G23 (SF95 and SF96 samples) resided in the Takahama-3 core during operating cycles 5 and 6, and assembly NT3G24 (SF97 samples) resided in the reactor core during operating cycles 5, 6 and 7, and achieved the highest burnup. The reactor operating history is summarized in Table 3. The Takahama-3 reactor operates with soluble boron in the moderator that decreases in concentration during an operating cycle. The variation in the boron concentration during cycles 5, 6, and 7 is shown in Table 4.

Five samples each were taken from various axial locations of fuel rods SF95 and SF96, and six samples were taken from fuel rod SF97. A summary of the basic parameters (e.g., initial enrichment, axial locations, burnup, cooling time) of the three measured spent fuel rods is listed in Table 5. The standard fuel samples (SF95 and SF97) covered a wide burnup range, from 7.8 GWd/MTU to 47.3 GWd/MTU. The IBPR achieved a maximum sample burnup of 24.2 GWd/MTU. The irradiation history for each measured axial point of each fuel rod is shown in Tables 6–8.

Table 1 Design data for Takahama Unit 3 reactor and fuel assemblies

Parameter	Data
Takahama Unit 3 reactor core data	
Operating power (MWt)	2652
Core diameter (m)	3.04
Active core height (m)	3.66
Number of assemblies	157
Soluble boron, cycle average ppm[a]	630
Inlet coolant temperature (°C)	284
Outlet coolant temperature (°C)	321
Fuel assembly design data	
Lattice	17 × 17
Number of fuel rods	264
Number of fuel rods containing burnable poisons	14
Number of guide tubes	25
Assembly fuel mass, kg U	~ 460
Assembly pitch, cm	21.4
Total assembly length, m	4.06
Water pressure, psi (kg/cm^2)	2250 (32)
Fuel rod data	
Fuel material	UO_2
Enrichment, wt % ^{235}U (see Table 2)	4.11 (fuel rods), 2.61 (burnable poison rods)
Fuel density, g/cm^3	95% theoretical density[b]
Fuel temperature, K	900 K
Rod pitch, cm	1.259
Fuel diameter, cm	0.805
Rod OD, cm	0.950
Rod ID, cm	0.822
Active fuel length, cm	~ 364.8
Total fuel rod length, cm	~ 403.6
Clad material	Zircaloy-4 (1.4–1.7 wt % Sn)
Clad density, g/cm^3	6.44
Clad temperature, K	570[c]
Guide tube data[d]	
Inner radius, cm	0.5715
Outer radius, cm	0.6121
Material	Zircaloy-4

[a] Time-dependent soluble boron data obtained from Ref. 2.
[b] Theoretical density assumed to be 10.96 g/cm^3.
[c] Clad temperature was estimated.
[d] Guide tube data not available. Dimensions for a Westinghouse 17 × 17 design assumed.

Table 2 Initial composition of Takahama-3 fuel assemblies

	Isotopic composition (initial wt %)	
Isotope ratio	Fuel rods	Burnable poison rods
$^{234}U/U$	0.04	0.02
$^{235}U/U$	4.11	2.63
$^{238}U/U$	95.85	97.25
Gd_2O_3/Fuel	N/A	6.0

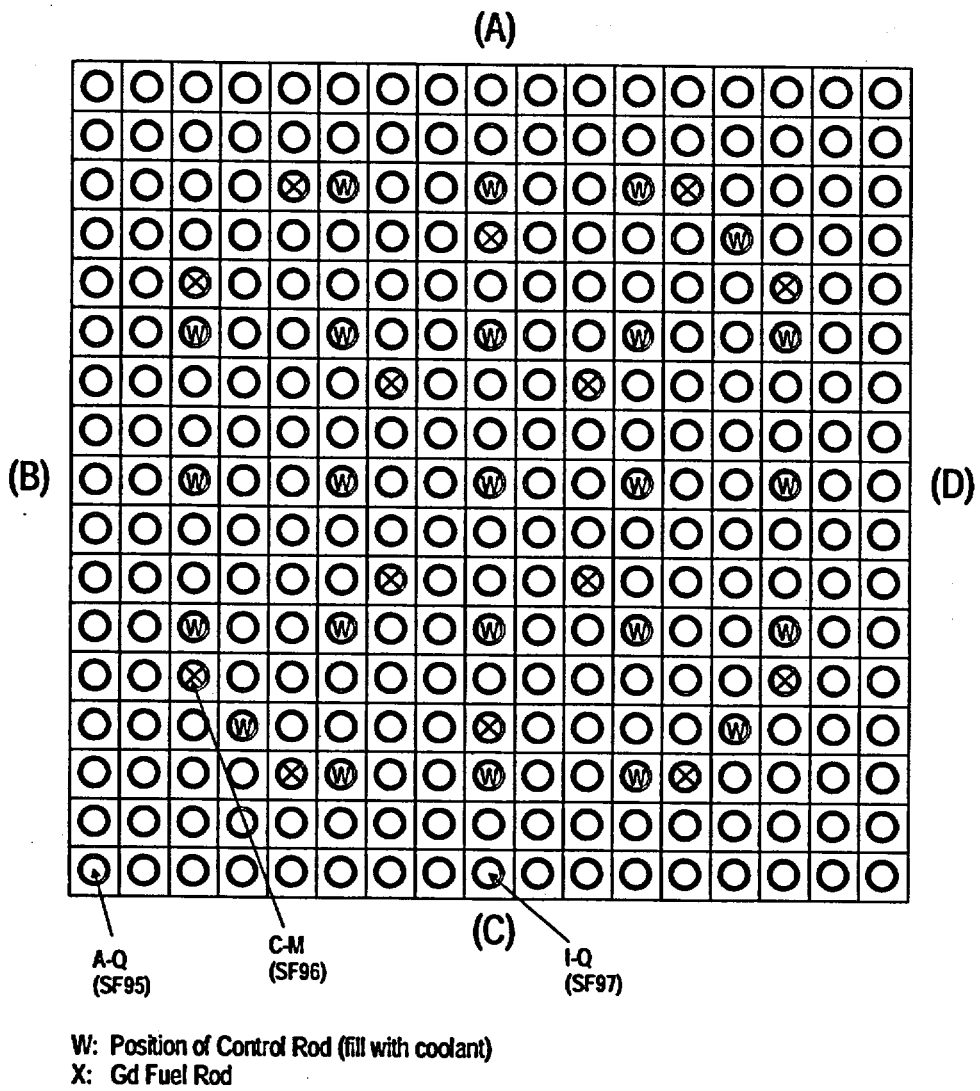

Figure 1 Positions of assay fuel rods in Takahama-3 assemblies NT3G23 and NT3G24

Table 3 Operation history of Takahama-3

Start	Stop	Days	Status	Cycle
1990/01/26	1991/02/15	385	Burnup	5
1991/02/15	1991/05/14	88	Cool	
1991/05/14	1992/06/19	402	Burnup	6
1992/06/19	1992/08/20	62	Cool	
1992/08/20	1993/09/30	406	Burnup	7

Table 4 Variation in boron concentration in Takahama-3 cycle 5, cycle 6, and cycle 7

Cycle 5	
Day	Boron (ppm)
0	1154
106	894
205	651
306	404
385	210

Cycle 6	
Day	Boron (ppm)
473	1132
592	864
704	613
817	358
875	228

Cycle 7	
Day	Boron (ppm)
937	1154
996	1001
1048	867
1100	732
1152	598
1204	463
1256	329
1308	195
1342	104

Table 5 Basic parameters of the measured spent fuel samples

No.	Unit name	Assembly (pin No.)	Sample ID	Initial enrichment (wt % ^{235}U)	Axial location[a] (cm)	Burnup[b] (GWd/MTU)	Cooling time[c] (years)
1	Takahama-3	NT3G23	SF95-1	4.11	20.1	14.30	0
2		(A-Q)	SF95-2		36.1	24.35	
3			SF95-3		88.1	35.52	
4			SF95-4		216.1	36.69	
5			SF95-5		356.1	30.40	
6	Takahama-3	NT3G23	SF96-1	2.63	17.6	7.79	0
7		(C-M)	SF96-2		33.6	16.44	
8			SF96-3		85.6	28.20	
9			SF96-4		213.6	28.91	
10			SF96-5		353.6	24.19	
11	Takahama-3	NT3G24	SF97-1	4.11	16.3	17.69	0
12		(I-Q)	SF97-2		35.0	30.73	(3.96 Sm isotopes)
13			SF97-3		62.7	42.16	
14			SF97-4		183.9	47.03	
15			SF97-5		292.6	47.25	
16			SF97-6		355.6	40.79	

[a] Distance measured from top of fuel.
[b] Burnup determined from ^{148}Nd analysis.
[c] Isotopic measurements were adjusted to discharge time, with the exception of Sm isotopes, and ^{239}Pu (adjusted to include ^{239}Np precursor).

Table 6 Irradiation history of SF95 samples

Days	Power (MW/MTU)				
	SF95-1	SF95-2	SF95-3	SF95-4	SF95-5
0	0.00	0.00	0.00	0.00	0.00
12	5.08	8.65	12.59	13.04	10.80
8	20.32	34.61	50.34	52.15	43.20
27	20.33	34.62	50.36	52.17	43.22
35	20.42	34.78	50.59	52.40	43.42
28	20.22	34.44	50.09	51.89	42.99
21	20.09	34.23	49.78	51.57	42.73
35	20.02	34.10	49.60	51.37	42.73
35	19.71	33.57	48.83	50.58	41.90
28	19.72	33.59	48.85	50.61	41.93
27	19.60	33.39	48.57	50.31	41.68
49	19.33	32.92	47.89	49.60	41.10
15	19.07	32.47	47.23	48.93	40.54
37	18.80	32.03	46.59	48.26	39.98
19	18.61	31.71	46.12	47.77	39.58
9	18.50	31.51	45.84	47.48	39.34
88	0.00	0.00	0.00	0.00	0.00
10	4.36	7.43	10.80	11.19	9.27
11	17.52	29.85	43.42	44.97	37.26
20	17.69	30.14	43.84	45.41	37.62
23	17.78	30.28	44.04	45.62	37.79
28	17.75	30.23	43.97	45.55	37.74
28	17.72	30.17	43.89	45.46	37.67
28	17.68	30.12	43.80	45.37	37.59
35	17.65	30.06	43.72	45.29	37.52
28	17.61	30.00	43.63	45.20	37.45
34	17.57	29.93	43.53	45.09	37.35
43	17.50	29.81	43.36	44.91	37.21
28	17.34	29.53	42.95	44.49	36.86
28	17.17	29.25	42.54	44.06	36.51
35	17.08	29.09	42.31	43.82	36.31
15	17.00	28.96	42.12	43.63	36.15
8	16.97	28.91	42.05	43.56	36.09

Table 7 Irradiation history of SF96 samples

Days	Power (MW/MTU)				
	SF96-1	SF96-2	SF96-3	SF96-4	SF96-5
0	0.00	0.00	0.00	0.00	0.00
12	0.99	2.09	3.59	3.68	3.08
8	3.97	8.37	14.37	14.73	12.32
27	4.21	8.88	15.24	15.62	13.07
35	4.47	9.44	16.19	16.60	13.89
28	5.04	10.64	18.25	18.70	15.65
21	5.64	11.90	20.42	20.93	17.52
35	6.39	13.48	23.13	23.71	19.84
35	7.97	16.82	28.85	29.57	24.75
28	8.90	18.78	32.21	33.02	27.63
27	9.84	20.76	35.61	36.50	30.55
49	10.71	22.59	38.75	39.72	33.24
15	11.42	24.10	41.34	42.37	35.46
37	12.13	25.59	43.90	44.99	37.66
19	12.34	26.04	44.68	45.79	38.32
9	12.61	26.59	45.62	46.76	39.14
88	0.00	0.00	0.00	0.00	0.00
10	5.61	11.84	20.32	20.83	17.43
11	11.30	23.84	40.90	41.92	35.08
20	11.45	24.16	41.45	42.48	35.55
23	11.57	24.41	41.88	42.93	35.93
28	11.64	24.56	42.13	43.18	36.14
28	11.71	24.70	42.37	43.43	36.35
28	11.78	24.86	42.64	43.71	36.58
35	11.86	25.01	42.91	43.99	36.81
28	11.93	25.16	43.16	44.24	37.02
34	11.99	25.29	43.38	44.46	37.21
43	12.06	25.44	43.65	44.74	37.44
28	12.06	25.44	43.65	44.74	37.44
28	12.04	25.40	43.57	44.66	37.38
35	12.07	25.45	43.67	44.76	37.46
15	12.08	25.48	43.72	44.81	37.50
8	12.09	25.50	43.74	44.83	37.52

Table 8 Irradiation history of SF97 samples

Days	Power (MW/MTU)					
	SF97-1	SF97-2	SF97-3	SF97-4	SF97-5	SF97-6
0	0.00	0.00	0.00	0.00	0.00	0.00
12	3.54	6.15	8.44	9.42	9.46	8.17
8	14.24	24.74	33.94	37.86	38.04	32.84
27	14.37	24.96	34.24	38.20	38.38	33.13
35	14.57	25.31	34.72	38.73	38.91	33.59
28	14.73	25.59	35.10	39.16	39.34	33.96
21	14.81	25.74	35.31	39.39	39.58	34.17
35	14.93	25.95	35.60	39.71	39.90	34.44
35	15.02	26.09	35.80	39.93	40.12	34.63
28	15.12	26.27	36.04	40.21	40.40	34.87
27	15.43	26.81	36.78	41.03	41.22	35.58
49	15.66	27.21	37.33	41.64	41.84	36.12
15	15.65	27.20	37.31	41.62	41.82	36.10
37	15.64	27.18	37.29	41.60	41.79	36.08
19	15.62	27.14	37.23	41.53	41.72	36.02
9	15.59	27.09	37.17	41.46	41.66	35.96
88	0.00	0.00	0.00	0.00	0.00	0.00
10	8.39	14.58	20.00	22.31	22.42	19.35
11	16.72	29.06	39.87	44.47	44.68	38.57
20	16.61	28.85	39.58	44.16	44.37	38.30
23	16.49	28.65	39.30	43.84	44.05	38.02
28	16.29	28.31	38.84	43.32	43.53	37.57
28	16.12	28.00	38.42	42.86	43.06	37.17
28	16.03	27.85	38.21	42.62	42.82	36.97
35	15.94	27.70	38.00	42.39	42.59	36.76
28	15.93	27.69	37.98	42.37	42.57	36.75
34	15.91	27.64	37.91	42.30	42.49	36.68
43	15.76	27.39	37.58	41.92	42.12	36.36
28	15.58	27.08	37.14	41.44	41.63	35.94
28	15.53	26.99	37.03	41.31	41.50	35.83
35	15.54	27.01	37.05	41.33	41.53	35.85
15	15.47	26.88	36.87	41.13	41.33	35.67
8	15.44	26.83	36.81	41.06	41.25	35.61
62	0.00	0.00	0.00	0.00	0.00	0.00

Table 8 (continued)

Days	Power (MW/MTU)					
	SF97-1	SF97-2	SF97-3	SF97-4	SF97-5	SF97-6
12	6.97	12.11	16.62	18.54	18.63	16.08
8	13.96	24.25	33.27	37.11	37.29	32.19
49	14.03	24.39	33.45	37.32	37.49	32.37
28	14.14	24.57	3.70	37.60	37.77	32.61
29	14.22	24.70	33.89	37.80	37.98	32.79
34	14.21	24.69	33.87	37.79	37.96	32.77
28	14.20	24.68	33.86	37.77	37.95	32.76
28	14.27	24.79	34.01	37.94	38.11	32.90
35	14.25	24.75	33.96	37.88	38.06	32.85
27	14.21	24.69	33.87	37.79	37.96	32.77
29	14.22	24.72	33.91	37.82	38.00	32.80
35	14.19	24.66	33.82	37.73	37.91	32.73
28	14.21	24.69	33.88	37.79	37.97	32.77
19	14.25	24.75	33.96	37.88	38.06	32.85
17	14.22	24.72	33.91	37.83	38.00	32.81

2.2 EXPERIMENTAL MEASUREMENTS AND METHODS

Destructive analysis of the spent fuel samples was performed to determine the isotopic compositions of U, Np, Pu, Am, Cm and a number of fission product isotopes important to burnup credit, decay heat, and radiation source term applications. This section summarizes the radiochemical analysis procedures used to determine the concentrations of different isotopes, and the methods used to estimate the burnup of the samples. A detailed discussion of the radiochemical analysis procedures is given in the original JAERI report, Ref. 1 (English translation published in Ref. 5).

2.2.1 Burnup Determination

The burnup of the fuel samples was determined experimentally by the ^{148}Nd method.[6] The integral number of fissions in the sample is determined using the ^{148}Nd fission product yields for ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu. The effective fission yield is derived by weighting the yields from each of the four fissionable nuclides by the fractional fissions from each nuclide as determined by calculation. The error in the burnup determined by the ^{148}Nd method is given as 3% or less.[4] The experimentally determined burnup value was applied in all depletion analysis calculations.

2.2.2 Measurement Methods

The samples were collected from 0.5 mm thick sections cut from the spent fuel rods and dissolved. Nuclide compositions were determined using anion exchange separation. Isotopic dilution mass spectrometry (IDMS) was used to determine the concentrations of the Nd and Sm fission products, and the U and Pu isotopes. Mass spectrometry (MS) and alpha-spectrometry (α-s) were used to determine isotopic ratios for the Am and Cm isotopes. The concentration of ^{237}Np was determined using alpha-ray spectrometry after its

isolation and purification. The isotopic ratios of Gd nuclides were determined by mass spectrometry. The quantities of gamma-ray emitting radionuclides with relatively long half lives (^{137}Cs, ^{154}Eu, ^{144}Ce, and ^{106}Ru) were determined by gamma-ray spectrometry using an intrinsic Ge semiconductor detector. Spectra were also measured for ^{106}Ru and ^{125}Sb to determine the amount of these nuclides as insoluble residues, and whose total amounts do not exist in the dissolved solution. A summary of the different analytical techniques and the relative standard deviation associated with the measurements is given in Table 9.

The reported radiochemical assay results for all isotopes except Sm are given as discharge values (immediately after irradiation). The results for ^{239}Pu, however, include ^{239}Np (decay parent) due to the difficulty separating these actinides. Therefore calculated values of ^{239}Pu + ^{239}Np were used for comparisons with the experimentally determined value for ^{239}Pu.

Table 9 Analytical measurement techniques and uncertainty

Nuclide	Measurement technique	Relative standard deviation
^{234}U	IDMS	< 1%
^{235}U, ^{238}U	IDMS	< 0.1%
^{236}U	IDMS	< 2%
^{238}Pu	IDMS	< 0.5%
^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu	IDMS	< 0.3%
Nd, Sm isotopes	IDMS	< 0.1%
^{241}Am, ^{243}Cm, ^{244}Cm	α-s, MS	< 2%
^{243}Am, ^{246}Cm	α-s, MS	< 5%
^{242m}Am, ^{242}Cm, ^{247}Cm	α-s, MS	< 10%
Gd isotopes	MS	< 0.1%
^{237}Np	α-s	< 10%
^{134}Cs, ^{137}Cs, ^{154}Eu	γ-s	< 3%
^{106}Ru	γ-s	< 5%
^{125}Sb, ^{144}Ce	γ-s	< 10%

IDMS: Isotopic dilution mass spectrometry
α-s: Alpha-ray spectrometry
MS: Mass spectrometry
γ-s: Gamma-ray spectrometry

2.3 DEPLETION ANALYSIS MODELS

Isotopic concentrations were calculated using the SAS2H depletion analysis sequence[7] of the SCALE 4.4a code system[8] as well as the HELIOS code system.[9] This section describes the analyses performed for the various fuel rods as modeled in SCALE and HELIOS.

2.3.1 SCALE Analysis

The SCALE calculations were performed using the SAS2H depletion analysis sequence from SCALE 4.4a. All calculations used the 44-group ENDF/B-V-based cross-section library.[10] The 44-group library is collapsed from the 238-group ENDF/B-V library using a light-water-reactor neutron spectrum.

The analyses of fuel rods A-Q (SF95) and I-Q (SF97) were made using a standard modeling approach for fuel assemblies containing burnable absorbers, described in Ref. 7. This approach places the burnable absorber rod at the center of the model and places a proportional amount of fuel around the central rod, thus conserving the ratio of fuel to absorber in the assembly model. The NT3GT23 and NT3GT24 assemblies also contain guide tubes with water. The additional water moderator was placed outside of the fuel region in the assembly model. The SAS2H methodology requires that all fuel in the model have the same enrichment, since it is a point-depletion model. Consequently, the uranium enrichment of the BPRs (2.63 wt %) was increased to equal that of the fuel rods (4.11 wt %). SAS2H sample input files of SF95 and SF97 can be found in Appendix A.

Modeling of rod C-M (SF96), a Gd-bearing rod, using SCALE presents a significant challenge. The SAS2H sequence is primarily designed to calculate assembly-average fuel compositions. BPRs, and rods adjacent to poison rods or other strong absorbers, may have neutronic characteristics that deviate significantly from those of the assembly average. Nevertheless, the isotopic assay data widely used to validate the codes and data used for predicting isotopic compositions in spent fuel[11,12,13] are generally available only for specific fuel rods and not (with some notable exceptions[12]) for the assembly average. The increasing use of burnable poisons with the higher enrichment fuels now widely used means that an increasing percentage of fuel rods in spent fuel assemblies are either poison rods or reside in close proximity to poison rods. The BPRs in assemblies NT3GT23 and NT3GT24 represent only about 5% of the total fuel inventory.

Accurate analysis of these rods generally requires using multidimensional depletion methods that permit different fuel regions (enrichments, compositions, etc.) in an assembly to be represented explicitly and depleted independently of one another in the burnup analysis. Within the SCALE system the multidimensional depletion sequence SAS2D (to be released in SCALE 5) that uses the 2-D NEWT generalized-mesh discrete ordinates transport code is designed to perform this type of analysis.[14] Nevertheless, some efforts have been made to model more heterogeneous regions of an assembly to obtain pin-specific information using 1-D methods in SCALE. However, many of these modeling approaches deviate significantly from standard approaches and the results may therefore be of limited relevance to code validation of production models and methods. An attempt was made in this work to model the BPR C-M (SF96) using an approach similar to the standard approach used above. In this model the BPR was placed at the center and surrounded by the fuel region as performed with the other samples. However, the enrichment of the surrounding fuel region was set equal to that of the poison rod (2.63 wt %) due to the point-depletion restriction in SAS2H. To generate cross sections for the depletion analysis calculation that were more representative of the absorber rod rather than the entire assembly model, the cross-section weighting was performed only over the inner region of the model containing the absorber rod. This was accomplished using an advanced input option (INPLEVEL=3) of SAS2H that allows the user to override many of the default model options. This approximation allows a more accurate representation of the absorber rod region,

however, it provides only an approximate representation of the surrounding fuel region. A SAS2H sample input file of SF96 can be found in Appendix A.

Calculations performed with the boron concentration letdown curve were compared to those obtained using the average boron concentration calculation. It was noted that the differences in the results were very minor. Therefore, depletion calculations performed in this study used the average boron concentration 630 ppm.

The coolant density at the axial locations corresponding to each sample was calculated from the coolant temperature assuming a reactor operating pressure of 2250 psi (32 kg/m^2) using standard pressure/temperature tables.[15] The coolant temperatures for each sample location were calculated based on the core inlet and outlet temperatures according to the following equation:

$$T(z) = T_{inlet} + \frac{\pi \Delta T}{2H} \int_0^z \cos\left(\frac{\pi}{2H} z\right) dz,$$

where

T_{inlet} is the coolant temperature at the reactor core inlet,

H is the effective fuel length,

ΔT is the increase in coolant temperature at the reactor core outlet, and

z is the coolant temperature at the sample position measured from the bottom of the fuel.

2.3.2 HELIOS Analysis

The HELIOS-1.6 code package[5] primarily consists of three programs: AURORA, HELIOS, and ZENITH. HELIOS is a 2-D, generalized-geometry transport theory code based on the method of collision probabilities with current coupling. AURORA, the input processor, is used to define the geometry, materials, and calculational parameters. ZENITH, the output processor, reads the results saved by HELIOS (in a binary database) and outputs the results in text format.

HELIOS was employed for this analysis because of its capability to explicitly model the relatively complicated, heterogeneous assembly lattices associated with integral burnable absorbers. The various structures within the assembly model were coupled using angular current discretization (interface currents). The fuel assembly was modeled using quarter symmetry. All calculations are for an infinite array of fuel assemblies and utilize the 45-group neutron cross-section library, based on ENDF/B-VI, which is distributed with the HELIOS-1.6 code package. A HELIOS sample input file can be found in Appendix B.

In addition, HELIOS was used to investigate the potential importance and influence of the surrounding fuel assemblies on the isotopic concentrations of fuel samples SF95 and SF97. These rods resided at the outer edge of the assembly and were therefore potentially subject to the effects of adjacent assemblies as fuel was reloaded and relocated between cycles.

Although the soluble boron concentration curve was provided (data in Table 4), the calculations were performed using an average boron concentration. As with the SAS2H analyses described previously, the results from calculations using the average boron concentration were compared with those using an explicit boron concentration letdown curve, and the differences were found to be very minor.

3 RESULTS

Comparison of measurements and calculations of Takahama-3 SF95 samples 1–5 (assembly NT3G23, rod A-Q) are presented in Tables 10–14. The SF95 samples are taken from the fuel pin located in the corner of the fuel assembly, which was not subject to local flux perturbations from the water holes or the BPRs in the assembly during irradiation (i.e., all adjacent rods were standard fuel pins). The percentage difference between measured and calculated isotopic concentrations of SF95 samples 1–5 for U and Pu isotopes are plotted in Figure 2 (HELIOS) and Figure 3 (SAS2H).

Comparisons of Takahama-3 SF96 samples 1–5 (assembly NT3G23, rod C-M) are presented in Tables 15-19. These samples were obtained from a burnable poison (Gd_2O_3) rod. The SAS2H model was a non-standard type assembly model used to approximate the heterogeneous region around the poison rod, and the results are therefore included for illustration only. The HELIOS code used a 2-D model to explicitly model the BPRs and standard fuel rods of the assembly. The deviation from average of SF96 samples 1–5 for U and Pu isotopes are plotted in Figure 4 (HELIOS) and Figure 5 (SAS2H).

Comparisons of Takahama-3 SF97 samples 1–6 (assembly NT3G24, rod I-Q) are presented in Tables 20–25. This rod was a standard fuel rod, similar to SF95, located at the outer edge of the assembly. However assembly NT3G34 was exposed for an additional cycle (3 cycles in all) to achieve higher burnups. The SF97 samples 1–6 for U and Pu isotopes are plotted in Figure 6 (HELIOS) and Figure 7 (SAS2H).

Overall, the SAS2H and HELIOS predictions for standard fuel samples SF95 and SF97 are in good agreement with the measurements. Both codes predict the majority of the U and Pu isotopes accurately, except for sample SF97-1 where both codes significantly overestimate the Pu and higher actinides concentrations. Sample SF97-1 was obtained from an axial location (see Table 5) 16.3 cm from the top of the fuel rod, or approximately 4 mm from the end of the active fuel length. The large deviations in the results using both SAS2H and HELIOS suggest that the neutronic environment very near the end of the fuel is not characteristic of the majority of fuel. The overestimation of ^{239}Pu is consistent with a neutron flux spectrum in the calculations that is harder than that actually experienced by the fuel. This is consistent with a high leakage near the ends of the fuel that is not modeled by the codes. For this reason, the results for the SF97-1 sample are not typical of most fuel and could be excluded in spent fuel benchmark studies. The results for the end samples were included here to evaluate the extent of the fuel end effect. For criticality safety studies using burnup credit, it is important to note that the predicted isotopic concentrations will yield a conservative estimate of the neutron multiplication factor with respect to the fuel near the ends of the assembly.

A summary of the Takakama-3 results for the SF95 and SF97 samples (the SF97-1 sample excluded) is given in Table 26 showing the number of measurements available, the average calculated-to-experimental (C/E) ratio, and the average standard deviation (% uncertainty) of the results. A comparison with other recent evaluations of these quantities using previously available data[11] indicates the results are generally consistent with the earlier studies. In addition, a previous validation study of the ORIGEN-S code for predicting radionuclide inventories in used CANDU fuel[16] shows that ^{125}Sb was overpredicted to a similar amount as seen in this study. However, some nuclide C/E ratios were significantly improved compared to earlier results, such as ^{134}Cs, ^{154}Eu, and many of the Sm nuclides.

The results for the integral Gd_2O_3 burnable absorber rod SF96 show that the HELIOS code somewhat underestimates the Pu isotopes while the SAS2H code significantly overestimates the Pu isotopes. This rod was situated adjacent to two water holes. The 1-D SAS2H model underestimates the degree of moderation in the vicinity of the rod, leading to the overprediction of Pu. The results indicate that 2-D transport methods are required to accurately predict the inventories in such heterogeneous regions of the assembly.

Table 10 Comparison of analyses and calculations of Takahama-3 SF95-1

	Measured[a] g/MgU				
Nuclide	SF95-1 Measured	SF95-1 SAS2H	SF95-1 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.987E+02	3.299E+02	2.74E+02	1.10	0.92
^{235}U	2.674E+04	2.673E+04	2.67E+04	1.00	1.00
^{236}U	2.672E+03	2.672E+03	2.65E+03	1.00	0.99
^{238}U	9.499E+05	9.495E+05	9.50E+05	1.00	1.00
^{238}Pu	1.718E+01	1.626E+01	1.66E+01	0.95	0.97
^{239}Pu	4.227E+03	4.393E+03	4.61E+03	1.04	1.09
^{240}Pu	7.802E+02	8.083E+02	7.88E+02	1.04	1.01
^{241}Pu	3.690E+02	3.776E+02	3.78E+02	1.02	1.02
^{242}Pu	3.790E+01	4.071E+01	3.47E+01	1.07	0.92
^{241}Am	1.378E+01	1.161E+01	1.23E+01	0.84	0.89
^{242m}Am	1.840E–01	1.953E–01	1.78E–01	1.06	0.97
^{243}Am	2.682E+00	3.128E+00	2.56E+00	1.17	0.96
^{242}Cm	1.510E+00	1.143E+00	1.21E+00	0.76	0.80
^{243}Cm	1.451E–02	1.128E–02	1.01E–02	0.78	0.70
^{244}Cm	2.712E–01	2.810E–01	2.44E–01	1.04	0.90
^{245}Cm	5.519E–03	4.370E–03	5.45E–03	0.79	0.99
^{246}Cm	2.560E–04	1.488E–04	1.09E–04	0.58	0.43
^{137}Cs	5.405E+02	5.401E+02	5.20E+02	1.00	0.96
^{134}Cs	2.343E+01	2.041E+01	1.69E+01	0.87	0.72
^{154}Eu	4.093E+00	4.058E+00	4.16E+00	0.99	1.02
^{144}Ce	1.937E+02	1.902E+02	1.80E+02	0.98	0.93
^{125}Sb	1.471E+00	2.628E+00	3.42E+00	1.79	2.33
^{106}Ru	4.447E+01	4.366E+01	4.25E+01	0.98	0.96
^{142}Nd	3.429E+00	2.703E+00	N/A	0.79	N/A
^{143}Nd	4.631E+02	4.555E+02	4.47E+02	0.98	0.97
^{144}Nd	3.276E+02	3.303E+02	3.27E+02	1.01	1.00
^{145}Nd	3.328E+02	3.348E+02	3.29E+02	1.01	0.99
^{146}Nd	2.809E+02	2.866E+02	2.82E+02	1.02	1.00
^{148}Nd	1.592E+02	1.601E+02	1.58E+02	1.01	0.99
^{150}Nd	7.200E+01	7.071E+01	7.01E+01	0.98	0.97
Burnup (GWd/MTU)[b]	14.30				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 11 Comparison of analyses and calculations of Takahama-3 SF95-2

Nuclide	Measured[a] g/MgU				
	SF95-2 Measured	SF95-2 SAS2H	SF95-2 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.850E+02	2.850E+02	2.56E+02	1.00	0.90
^{235}U	1.927E+04	1.932E+04	1.92E+04	1.00	0.99
^{236}U	4.024E+03	3.946E+03	3.96E+03	0.98	0.98
^{238}U	9.424E+05	9.423E+05	9.42E+05	1.00	1.00
^{238}Pu	7.102E+01	6.140E+01	6.92E+01	0.86	0.97
^{239}Pu	5.655E+03	5.563E+03	5.66E+03	0.98	1.00
^{240}Pu	1.539E+03	1.539E+03	1.50E+03	1.00	0.97
^{241}Pu	9.578E+02	9.038E+02	9.56E+02	0.94	1.00
^{242}Pu	1.844E+02	1.824E+02	1.72E+02	0.99	0.93
^{241}Am	2.344E+01	2.649E+01	2.66E+01	1.13	1.13
^{242m}Am	5.201E–01	5.391E–01	5.17E–01	1.04	0.99
^{243}Am	2.289E+01	2.545E+01	2.16E+01	1.11	0.94
^{242}Cm	7.672E+00	4.992E+00	6.98E+00	0.65	0.91
^{243}Cm	1.240E–01	8.723E–02	1.11E–01	0.70	0.89
^{244}Cm	5.042E+00	4.278E+00	4.32E+00	0.85	0.86
^{245}Cm	1.962E–01	1.104E–01	1.72E–01	0.56	0.88
^{246}Cm	1.900E–02	7.164E–03	1.59E–02	0.38	0.84
^{137}Cs	9.336E+02	9.198E+02	8.94E+02	0.99	0.96
^{134}Cs	7.012E+01	5.832E+01	5.69E+01	0.83	0.81
^{154}Eu	1.306E+01	1.220E+01	1.35E+01	0.93	1.03
^{144}Ce	3.160E+02	3.110E+02	2.99E+02	0.98	0.95
^{125}Sb	2.900E+00	5.025E+00	7.28E+00	1.73	2.51
^{106}Ru	8.340E+01	9.678E+01	9.49E+01	1.16	1.14
^{142}Nd	8.887E+00	8.129E+00	N/A	0.91	N/A
^{143}Nd	7.149E+02	7.003E+02	6.97E+02	0.98	0.97
^{144}Nd	6.046E+02	6.029E+02	5.96E+02	1.00	0.99
^{145}Nd	5.384E+02	5.394E+02	5.35E+02	1.00	0.99
^{146}Nd	4.925E+02	4.974E+02	4.91E+02	1.01	1.00
^{148}Nd	2.736E+02	2.718E+02	2.71E+02	0.99	0.99
^{150}Nd	1.258E+02	1.245E+02	1.24E+02	0.99	0.99
Burnup (GWd/MTU)[b]	24.35				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 12 Comparison of analyses and calculations of Takahama-3 SF95-3

	Measured[a] g/MgU				
Nuclide	SF95-3 Measured	SF95-3 SAS2H	SF95-3 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.873E+02	2.401E+02	1.92E+02	1.28	1.02
^{235}U	1.326E+04	1.299E+04	1.36E+04	0.98	1.02
^{236}U	4.911E+03	4.904E+03	4.95E+03	1.00	1.01
^{238}U	9.338E+05	9.340E+05	9.34E+05	1.00	1.00
^{238}Pu	1.539E+02	1.491E+02	1.53E+02	0.97	1.00
^{239}Pu	6.194E+03	6.043E+03	6.54E+03	0.98	1.06
^{240}Pu	2.186E+03	2.219E+03	2.21E+03	1.02	1.01
^{241}Pu	1.486E+03	1.413E+03	1.51E+03	0.95	1.01
^{242}Pu	4.516E+02	4.571E+02	4.16E+02	1.01	0.92
^{241}Am	3.310E+01	3.732E+01	3.93E+01	1.13	1.19
^{242m}Am	7.877E–01	8.130E–01	8.14E–01	1.03	1.03
^{243}Am	8.047E+01	9.360E+01	7.98E+01	1.16	0.99
^{242}Cm	1.964E+01	1.178E+01	1.64E+01	0.60	0.83
^{243}Cm	3.720E–01	3.006E–01	3.02E–01	0.81	0.81
^{244}Cm	2.562E+01	2.507E+01	2.36E+01	0.98	0.92
^{245}Cm	1.396E+00	8.783E-01	1.30E+00	0.63	0.93
^{246}Cm	1.049E–01	9.553E–02	8.97E–02	0.91	0.86
^{137}Cs	1.347E+03	1.338E+03	1.31E+03	0.99	0.97
^{134}Cs	1.404E+02	1.204E+02	1.06E+02	0.86	0.76
^{154}Eu	2.525E+01	2.476E+01	2.76E+01	0.98	1.09
^{144}Ce	4.560E+02	4.359E+02	4.22E+02	0.96	0.92
^{125}Sb	3.733E+00	7.952E+00	1.01E+01	2.13	2.69
^{106}Ru	1.360E+02	1.713E+02	1.67E+02	1.26	1.23
^{142}Nd	2.116E+01	1.802E+01	N/A	0.85	N/A
^{143}Nd	9.299E+02	9.046E+02	9.10E+02	0.97	0.98
^{144}Nd	9.347E+02	9.457E+02	9.29E+02	1.01	0.99
^{145}Nd	7.392E+02	7.395E+02	7.35E+02	1.00	0.99
^{146}Nd	7.340E+02	7.418E+02	7.34E+02	1.01	1.00
^{148}Nd	3.979E+02	3.946E+02	3.97E+02	0.99	1.00
^{150}Nd	1.896E+02	1.866E+02	1.87E+02	0.98	0.99
Burnup (GWd/MTU)[b]	35.42				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 13 Comparison of analyses and calculations of Takahama-3 SF95-4

Nuclide	Measured[a] g/MgU				
	SF95-4 Measured[a]	SF95-4 SAS2H	SF95-4 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.870E+02	2.372E+02	1.88E+02	1.27	1.01
^{235}U	1.230E+04	1.203E+04	1.23E+04	0.98	1.00
^{236}U	4.999E+03	4.992E+03	5.00E+03	1.00	1.00
^{238}U	9.335E+05	9.337E+05	9.34E+05	1.00	1.00
^{238}Pu	1.588E+02	1.533E+02	1.57E+02	0.97	0.99
^{239}Pu	6.005E+03	5.816E+03	6.14E+03	0.97	1.02
^{240}Pu	2.207E+03	2.243E+03	2.23E+03	1.02	1.01
^{241}Pu	1.466E+03	1.397E+03	1.47E+03	0.95	1.00
^{242}Pu	4.803E+02	4.895E+02	4.40E+02	1.02	0.92
^{241}Am	2.351E+01	3.620E+01	3.41E+01	1.54	1.45
^{242m}Am	7.282E–01	7.630E–01	7.53E–01	1.05	1.03
^{243}Am	8.472E+01	1.002E+02	8.52E+01	1.18	1.01
^{242}Cm	2.328E+01	1.216E+01	1.74E+01	0.52	0.75
^{243}Cm	3.976E–01	3.102E–01	3.05E–01	0.78	0.77
^{244}Cm	2.837E+01	2.717E+01	2.59E+01	0.96	0.91
^{245}Cm	1.587E+00	9.228E–01	1.38E+00	0.58	0.87
^{246}Cm	1.251E–01	1.095E–01	1.05E–01	0.88	0.84
^{137}Cs	1.400E+03	1.387E+03	1.36E+03	0.99	0.97
^{134}Cs	1.471E+02	1.262E+02	1.20E+02	0.86	0.82
^{154}Eu	2.657E+01	2.528E+01	2.76E+01	0.95	1.04
^{144}Ce	4.301E+02	4.514E+02	4.31E+02	1.05	1.00
^{125}Sb	3.169E+00	8.239E+00	9.14E+00	2.60	2.88
^{106}Ru	1.401E+02	1.784E+02	1.75E+02	1.27	1.25
^{142}Nd	2.222E+01	1.949E+01	N/A	0.88	N/A
^{143}Nd	9.373E+02	9.175E+02	9.20E+02	0.98	0.98
^{144}Nd	1.024E+03	1.001E+03	9.88E+02	0.98	0.96
^{145}Nd	7.598E+02	7.642E+02	7.57E+02	1.01	1.00
^{146}Nd	7.624E+02	7.706E+02	7.59E+02	1.01	1.00
^{148}Nd	4.126E+02	4.088E+02	4.10E+02	0.99	0.99
^{150}Nd	1.959E+02	1.932E+02	1.93E+02	0.99	0.98
Burnup (GWd/MTU)[b]	36.69				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 14 Comparison of analyses and calculations of Takahama-3 SF95-5

	Measured[a] g/MgU				
Nuclide	SF95-5 Measured[a]	SF95-5 SAS2H	SF95-5 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.829E+02	2.634E+02	2.60E+02	0.93	0.92
^{235}U	1.544E+04	1.512E+04	1.57E+04	0.98	1.02
^{236}U	4.566E+03	4.524E+03	4.52E+03	0.99	0.99
^{238}U	9.388E+05	9.389E+05	9.39E+05	1.00	1.00
^{238}Pu	1.020E+02	9.476E+01	1.00E+02	0.93	0.98
^{239}Pu	5.635E+03	5.532E+03	5.79E+03	0.98	1.03
^{240}Pu	1.821E+03	1.862E+03	1.87E+03	1.02	1.03
^{241}Pu	1.153E+03	1.107E+03	1.18E+03	0.96	1.03
^{242}Pu	2.976E+02	3.067E+02	2.86E+02	1.03	0.96
^{241}Am	2.840E+01	3.067E+01	3.31E+01	1.08	1.16
^{242m}Am	5.687E–01	6.142E–01	6.07E–01	1.08	1.07
^{243}Am	4.400E+01	5.046E+01	4.44E+01	1.15	1.01
^{242}Cm	1.006E+01	7.787E+00	8.78E+00	0.77	0.87
^{243}Cm	2.293E–01	1.603E–01	1.77E–01	0.70	0.77
^{244}Cm	1.064E+01	1.046E+01	1.01E+01	0.98	0.95
^{245}Cm	4.839E–01	2.962E–01	4.47E–01	0.61	0.92
^{246}Cm	1.952E–02	2.724E–02	2.25E–02	1.40	1.15
^{137}Cs	1.148E+03	1.150E+03	1.11E+03	1.00	0.97
^{134}Cs	1.014E+02	8.618E+01	8.93E+01	0.85	0.88
^{154}Eu	1.817E+01	1.752E+01	1.93E+01	0.96	1.06
^{144}Ce	3.868E+02	3.829E+02	3.65E+02	0.99	0.94
^{125}Sb	3.262E+00	6.492E+00	9.21E+00	1.99	2.82
^{106}Ru	1.208E+02	1.316E+02	1.30E+02	1.09	1.07
^{142}Nd	1.371E+01	1.297E+01	N/A	0.95	N/A
^{143}Nd	8.303E+02	8.152E+02	8.13E+02	0.98	0.98
^{144}Nd	7.928E+02	7.993E+02	7.78E+02	1.01	0.98
^{145}Nd	6.518E+02	6.571E+02	6.46E+02	1.01	0.99
^{146}Nd	6.185E+02	6.290E+02	6.16E+02	1.02	1.00
^{148}Nd	3.401E+02	3.391E+02	3.37E+02	1.00	0.99
^{150}Nd	1.572E+02	1.570E+02	1.56E+02	1.00	0.99
Burnup (GWd/MTU)[b]	30.40				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

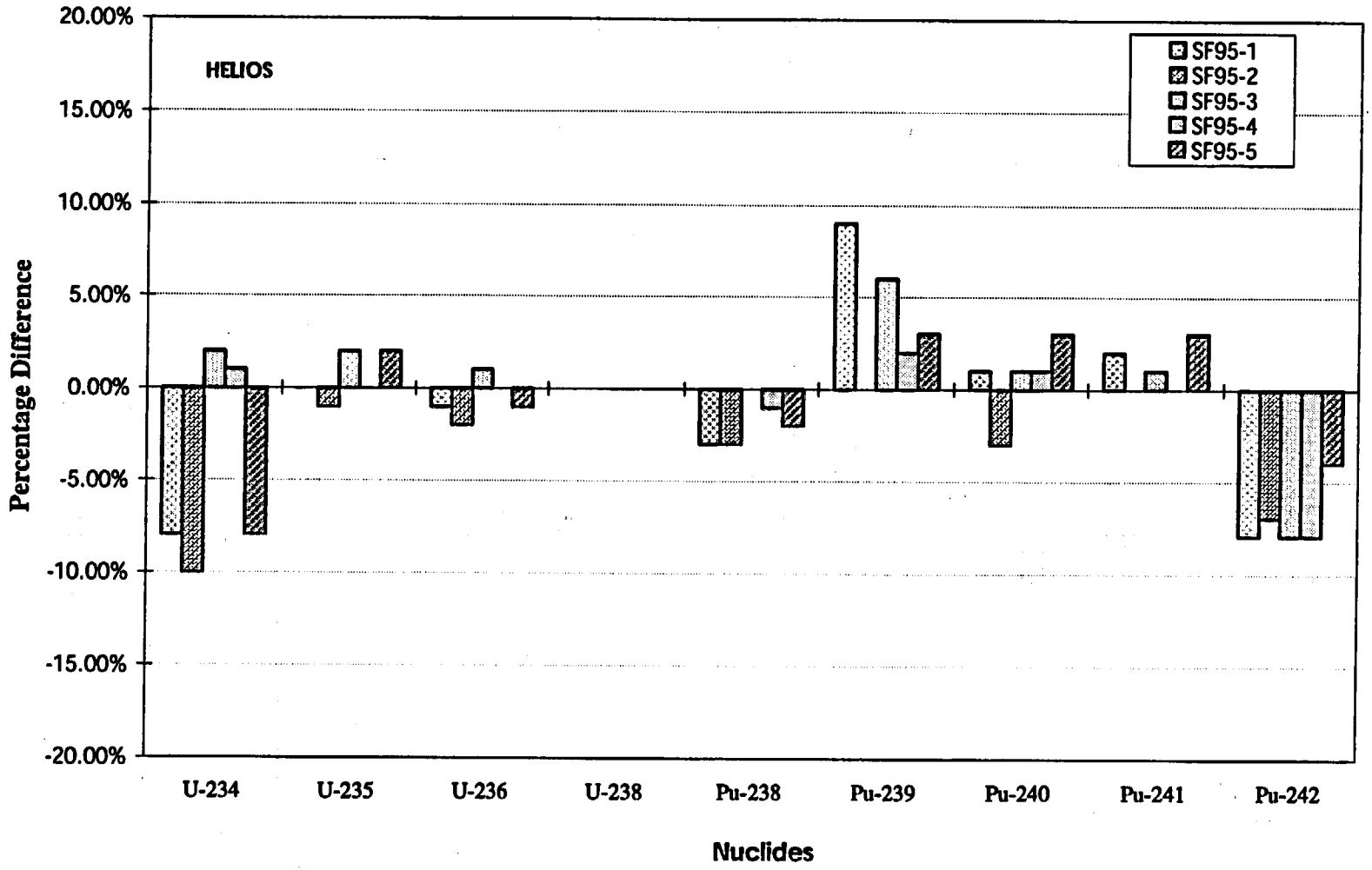

Figure 2 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for HELIOS SF95 samples 1–5 results

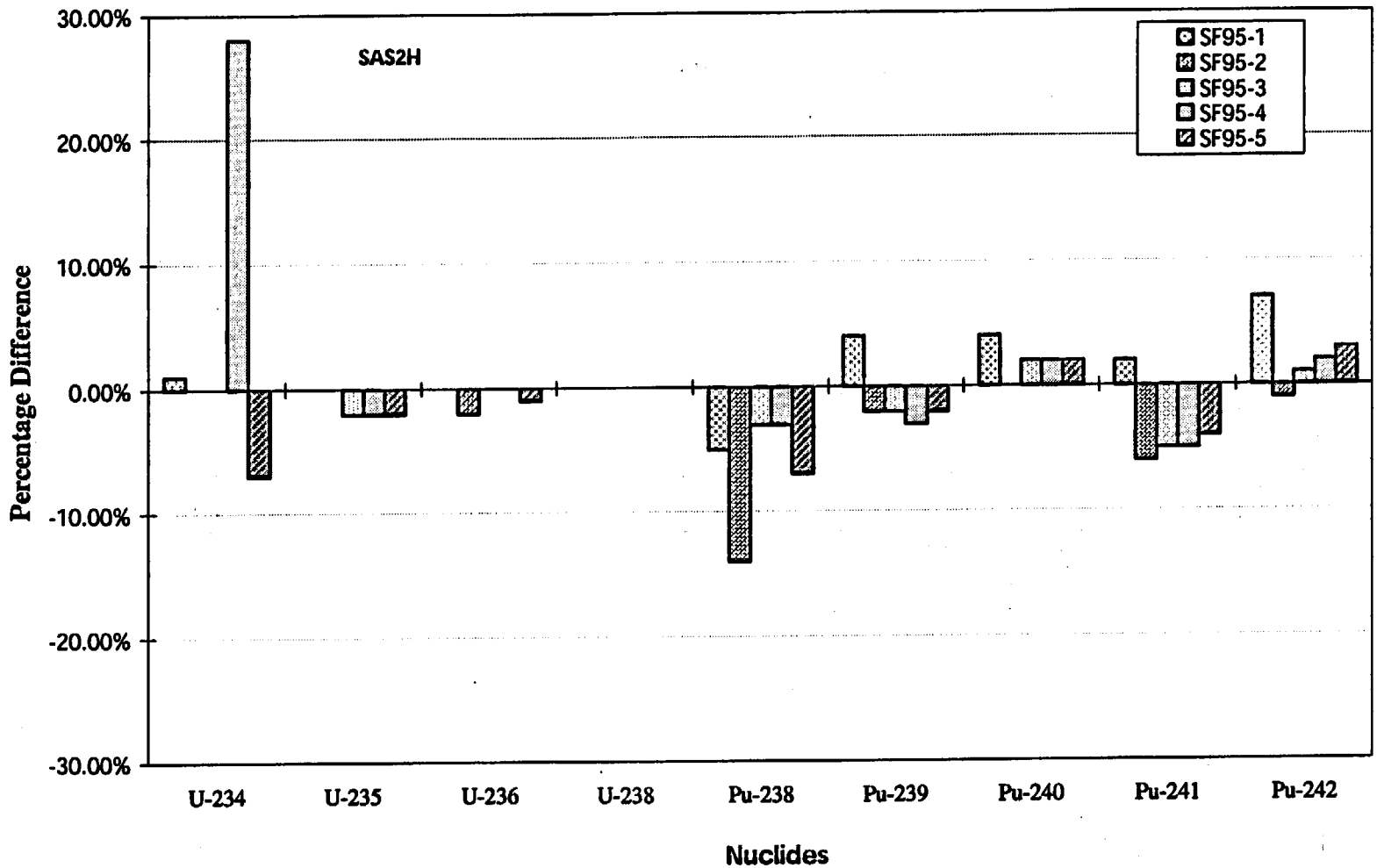

Figure 3 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for SAS2H SF95 samples 1–5 results

Table 15 Comparison of analyses and calculations of Takahama-3 SF96-1

	Measured[a] g/MgU				
Nuclide	SF96-1 Measured	SF96-1 SAS2H	SF96-1 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.805E+02	1.679E+02	1.83E+02	0.93	1.01
^{235}U	1.944E+04	1.978E+04	1.91E+04	1.02	0.98
^{236}U	1.421E+03	1.377E+03	1.46E+03	0.97	1.03
^{238}U	9.660E+05	9.652E+05	9.66E+05	1.00	1.00
^{237}Np	6.125E+01	8.218E+01	7.49E+01	1.34	1.22
^{238}Pu	8.536E+00	1.014E+01	8.58E+00	1.19	1.00
^{239}Pu	3.781E+03	4.368E+03	3.91E+03	1.16	1.04
^{240}Pu	6.764E+02	7.262E+02	6.75E+02	1.07	1.00
^{241}Pu	2.622E+02	3.059E+02	2.67E+02	1.17	1.02
^{242}Pu	2.440E+01	2.805E+01	2.24E+01	1.15	0.92
^{241}Am	5.985E+00	1.243E+01	8.80E+00	2.08	1.47
^{242m}Am	1.218E–01	1.880E–01	1.15E–01	1.54	0.94
^{243}Am	1.147E+00	1.749E+00	1.22E+00	1.52	1.06
^{242}Cm	8.502E–01	8.780E–01	7.25E–01	1.03	0.85
^{244}Cm	9.560E–02	1.303E–01	8.54E–02	1.36	0.89
^{143}Nd	2.521E+02	2.427E+02	2.41E+02	0.96	0.96
^{144}Nd	1.536E+02	1.598E+02	1.57E+02	1.04	1.02
^{145}Nd	1.800E+02	1.763E+02	1.77E+02	0.98	0.98
^{146}Nd	1.536E+02	1.499E+02	1.49E+02	0.98	0.97
^{148}Nd	8.770E+01	8.645E+01	8.61E+01	0.99	0.98
^{150}Nd	4.130E+01	4.079E+01	3.99E+01	0.99	0.97
^{137}Cs	2.813E+02	2.896E+02	2.84E+02	1.03	1.01
^{134}Cs	8.609E+00	8.186E+00	6.74E+00	0.95	0.78
^{154}Eu	2.309E+00	1.798E+00	1.77E+00	0.78	0.77
^{144}Ce	1.179E+02	9.909E+01	1.05E+02	0.84	0.89
^{125}Sb	1.433E+00	1.650E+00	2.50E+00	1.15	1.75
^{106}Ru	2.830E+01	3.034E+01	2.99E+01	1.07	1.06
Burnup (GWd/MTU)[b]	7.79				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 16 Comparison of analyses and calculations of Takahama-3 SF96-2

Nuclide	Measured[a] g/MgU				
	SF96-2 Measured	SF96-2 SAS2H	SF96-2 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.522E+02	1.437E+02	1.58E+02	0.94	1.04
^{235}U	1.408E+04	1.445E+04	1.37E+04	1.03	0.97
^{236}U	2.411E+03	2.348E+03	2.44E+03	0.97	1.01
^{238}U	9.580E+05	9.577E+05	9.58E+05	1.00	1.00
^{237}Np	1.323E+02	1.968E+02	1.75E+02	1.49	1.32
^{238}Pu	4.172E+01	4.351E+01	3.55E+01	1.04	0.85
^{239}Pu	5.459E+03	5.607E+03	4.93E+03	1.03	0.90
^{240}Pu	1.494E+03	1.554E+03	1.45E+03	1.04	0.97
^{241}Pu	8.684E+02	8.596E+02	7.77E+02	0.99	0.90
^{242}Pu	1.615E+02	1.665E+02	1.45E+02	1.03	0.90
^{241}Am	1.735E+01	3.194E+01	2.06E+01	1.84	1.19
^{242m}Am	4.579E–01	6.261E–01	3.34E–01	1.37	0.73
^{243}Am	1.728E+01	2.134E+01	1.57E+01	1.23	0.91
^{242}Cm	5.781E+00	4.986E+00	4.00E+00	0.86	0.69
^{244}Cm	3.092E+00	3.254E+00	2.23E+00	1.05	0.72
^{143}Nd	4.778E+02	4.655E+02	4.58E+02	0.97	0.96
^{144}Nd	3.588E+02	3.635E+02	3.38E+02	1.01	0.94
^{145}Nd	3.575E+02	3.529E+02	3.55E+02	0.99	0.99
^{146}Nd	3.266E+02	3.214E+02	3.19E+02	0.98	0.98
^{148}Nd	1.851E+02	1.821E+02	1.82E+02	0.98	0.98
^{150}Nd	8.972E+01	8.880E+01	8.70E+01	0.99	0.97
^{137}Cs	5.983E+02	6.147E+02	6.05E+02	1.03	1.01
^{134}Cs	3.759E+01	3.241E+01	2.76E+01	0.86	0.74
^{154}Eu	8.538E+00	7.514E+00	7.18E+00	0.88	0.84
^{144}Ce	2.250E+02	2.008E+02	2.37E+02	0.89	1.05
^{125}Sb	2.829E+00	3.893E+00	5.29E+00	1.38	1.87
^{106}Ru	6.053E+01	8.050E+01	8.64E+01	1.33	1.43
Burnup (GWd/MTU)[b]	16.44				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 17 Comparison of analyses and calculations of Takahama-3 SF96-3

Nuclide	Measured[a] g/MgU				
	SF96-3 Measured	SF96-3 SAS2H	SF96-3 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.251E+02	1.160E+02	1.27E+02	0.93	1.02
^{235}U	8.638E+03	9.331E+03	8.18E+03	1.08	0.95
^{236}U	3.244E+03	3.179E+03	3.25E+03	0.98	1.00
^{238}U	9.476E+05	9.471E+05	9.48E+05	1.00	1.00
^{237}Np	2.168E+02	3.725E+02	3.20E+02	1.72	1.48
^{238}Pu	1.206E+02	1.279E+02	1.14E+02	1.06	0.94
^{239}Pu	6.001E+03	6.249E+03	5.45E+03	1.04	0.91
^{240}Pu	2.303E+03	2.406E+03	2.23E+03	1.04	0.97
^{241}Pu	1.498E+03	1.510E+03	1.34E+03	1.01	0.89
^{242}Pu	5.103E+02	5.097E+02	4.60E+02	1.00	0.90
^{241}Am	2.845E+01	4.796E+01	2.79E+01	1.69	0.98
^{242m}Am	6.413E–01	1.050E+00	4.97E–01	1.64	0.78
^{243}Am	8.872E+01	1.074E+02	8.39E+01	1.21	0.95
^{242}Cm	1.628E+01	1.424E+01	1.09E+01	0.87	0.67
^{244}Cm	2.862E+01	2.962E+01	2.20E+01	1.03	0.77
^{143}Nd	7.158E+02	7.020E+02	6.97E+02	0.98	0.97
^{144}Nd	7.292E+02	6.791E+02	6.56E+02	0.93	0.90
^{145}Nd	5.766E+02	5.650E+02	5.64E+02	0.98	0.98
^{146}Nd	5.795E+02	5.665E+02	5.56E+02	0.98	0.96
^{148}Nd	3.201E+02	3.119E+02	3.12E+02	0.97	0.97
^{150}Nd	1.591E+02	1.574E+02	1.53E+02	0.99	0.96
^{137}Cs	1.018E+03	1.056E+03	1.03E+03	1.04	1.01
^{134}Cs	1.002E+02	8.909E+01	7.84E+01	0.89	0.78
^{154}Eu	1.973E+01	2.065E+01	1.88E+01	1.05	0.95
^{144}Ce	3.362E+02	3.298E+02	4.00E+02	0.98	1.19
^{125}Sb	3.658E+00	7.239E+00	1.00E+01	1.98	2.74
^{106}Ru	1.402E+02	1.669E+02	1.86E+02	1.19	1.33
Burnup (GWd/MTU)[b]	28.2				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 18 Comparison of analyses and calculations of Takahama-3 SF96-4

	Measured[a] g/MgU				
Nuclide	SF96-4 Measured	SF96-4 SAS2H	SF96-4 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.250E+02	1.145E+02	1.27E+02	0.92	1.02
^{235}U	8.064E+03	9.085E+03	7.91E+03	1.13	0.98
^{236}U	3.302E+03	3.215E+03	3.31E+03	0.97	1.00
^{238}U	9.475E+05	9.464E+05	9.48E+05	1.00	1.00
^{237}Np	2.252E+02	3.832E+02	3.25E+02	1.70	1.44
^{238}Pu	1.248E+02	1.344E+02	1.09E+02	1.08	0.87
^{239}Pu	5.819E+03	6.271E+03	5.32E+03	1.08	0.91
^{240}Pu	2.327E+03	2.448E+03	2.29E+03	1.05	0.99
^{241}Pu	1.480E+03	1.543E+03	1.35E+03	1.04	0.91
^{242}Pu	5.411E+02	5.345E+02	4.89E+02	0.99	0.90
^{241}Am	3.094E+01	4.852E+01	3.42E+01	1.57	1.11
^{242m}Am	6.793E–01	1.066E+00	6.09E–01	1.57	0.90
^{243}Am	9.598E+01	1.150E+02	9.06E+01	1.20	0.94
^{242}Cm	1.679E+01	1.487E+01	1.30E+01	0.89	0.77
^{244}Cm	3.128E+01	3.264E+01	2.43E+01	1.04	0.78
^{143}Nd	7.184E+02	7.142E+02	6.88E+02	0.99	0.96
^{144}Nd	7.513E+02	6.994E+02	7.03E+02	0.93	0.94
^{145}Nd	5.880E+02	5.769E+02	5.81E+02	0.98	0.99
^{146}Nd	5.948E+02	5.818E+02	5.76E+02	0.98	0.97
^{148}Nd	3.280E+02	3.197E+02	3.21E+02	0.97	0.98
^{150}Nd	1.628E+02	1.617E+02	1.58E+02	0.99	0.97
^{137}Cs	1.053E+03	1.082E+03	1.06E+03	1.03	1.01
^{134}Cs	1.047E+02	9.329E+01	8.00E+01	0.89	0.76
^{154}Eu	1.992E+01	2.156E+01	1.96E+01	1.08	0.98
^{144}Ce	3.453E+02	3.373E+02	3.57E+02	0.98	1.03
^{125}Sb	4.645E+00	7.448E+00	1.02E+01	1.60	2.19
^{106}Ru	1.291E+02	1.727E+02	1.74E+02	1.34	1.35
Burnup (GWd/MTU)[b]	28.91				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

Table 19 Comparison of analyses and calculations of Takahama-3 SF96-5

Nuclide	Measured[a] g/MgU				
	SF96-5 Measured	SF96-5 SAS2H	SF96-5 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.354E+02	1.249E+02	1.39E+02	0.92	1.02
^{235}U	9.937E+03	1.084E+04	9.61E+03	1.09	0.97
^{236}U	3.013E+03	2.948E+03	3.06E+03	0.98	1.01
^{238}U	9.522E+05	9.508E+05	9.52E+05	1.00	1.00
^{237}Np	1.875E+02	3.119E+02	2.65E+02	1.66	1.41
^{238}Pu	7.978E+01	9.427E+01	7.64E+01	1.18	0.96
^{239}Pu	5.519E+03	6.093E+03	5.18E+03	1.10	0.94
^{240}Pu	1.964E+03	2.149E+03	2.01E+03	1.09	1.02
^{241}Pu	1.203E+03	1.310E+03	1.15E+03	1.09	0.95
^{242}Pu	3.551E+02	3.771E+02	3.35E+02	1.06	0.94
^{241}Am	2.149E+01	4.394E+01	3.03E+01	2.04	1.41
^{242m}Am	5.647E–01	9.374E–01	5.25E–01	1.66	0.93
^{243}Am	5.078E+01	6.940E+01	5.28E+01	1.37	1.04
^{242}Cm	1.115E+01	1.079E+01	9.09E+00	0.97	0.82
^{244}Cm	1.280E+01	1.607E+01	1.15E+01	1.26	0.90
^{143}Nd	6.433E+02	6.290E+02	6.13E+02	0.98	0.95
^{144}Nd	5.927E+02	5.671E+02	5.67E+02	0.96	0.96
^{145}Nd	5.095E+02	4.961E+02	5.02E+02	0.97	0.99
^{146}Nd	4.910E+02	4.812E+02	4.79E+02	0.98	0.98
^{148}Nd	2.733E+02	2.677E+02	2.69E+02	0.98	0.99
^{150}Nd	1.331E+02	1.337E+02	1.31E+02	1.00	0.98
^{137}Cs	8.572E+02	9.055E+02	8.91E+02	1.06	1.04
^{134}Cs	7.146E+01	6.691E+01	5.70E+01	0.94	0.80
^{154}Eu	1.423E+01	1.564E+01	1.45E+01	1.10	1.02
^{144}Ce	3.145E+02	2.868E+02	3.08E+02	0.91	0.98
^{125}Sb	3.690E+00	6.069E+00	7.44E+00	1.64	2.01
^{106}Ru	1.344E+02	1.355E+02	1.36E+02	1.01	1.01
Burnup (GWd/MTU)[b]	24.19				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor.
[b] Burnup estimated using ^{148}Nd analysis.

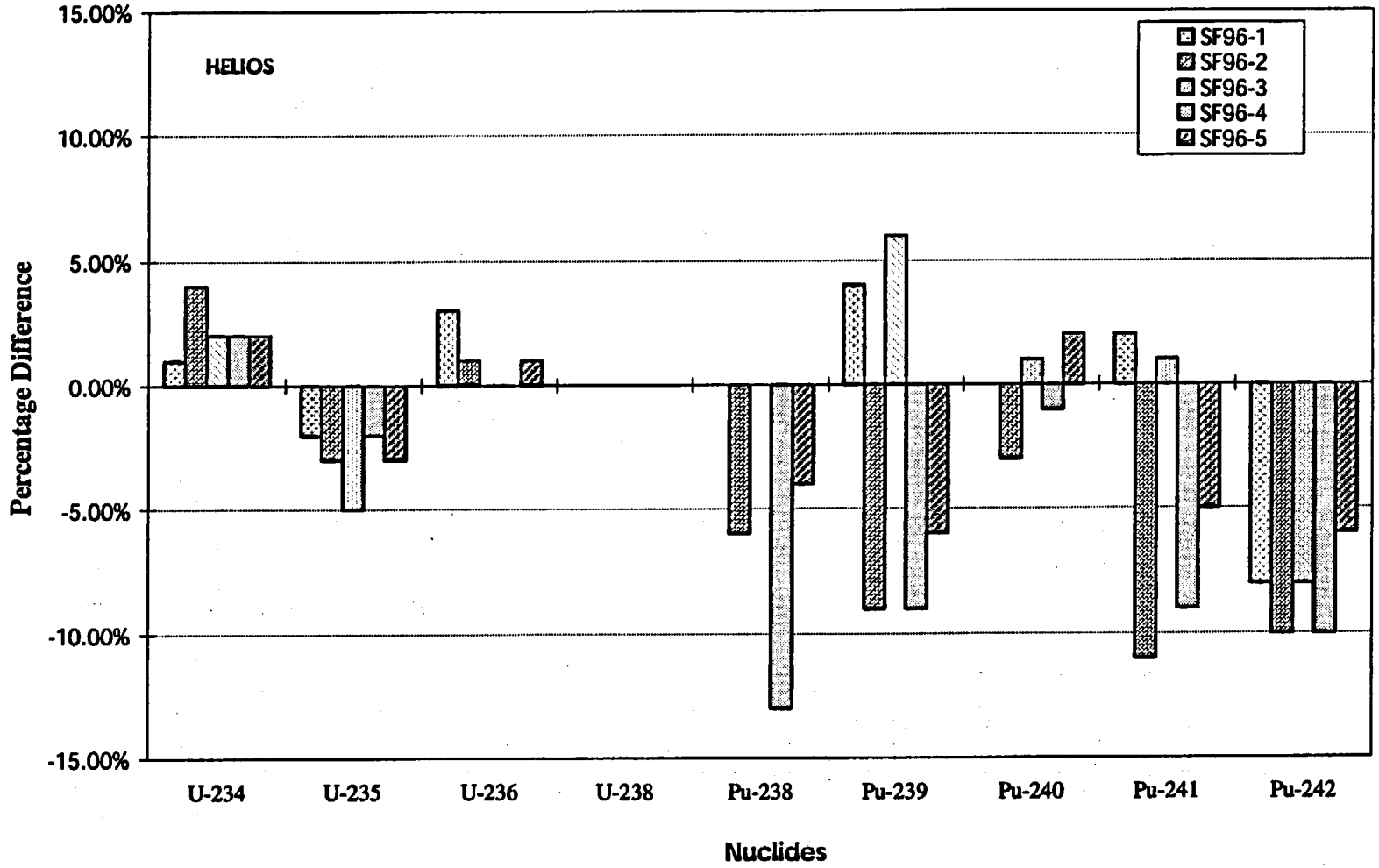

Figure 4 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for HELIOS SF96 samples 1–5 results

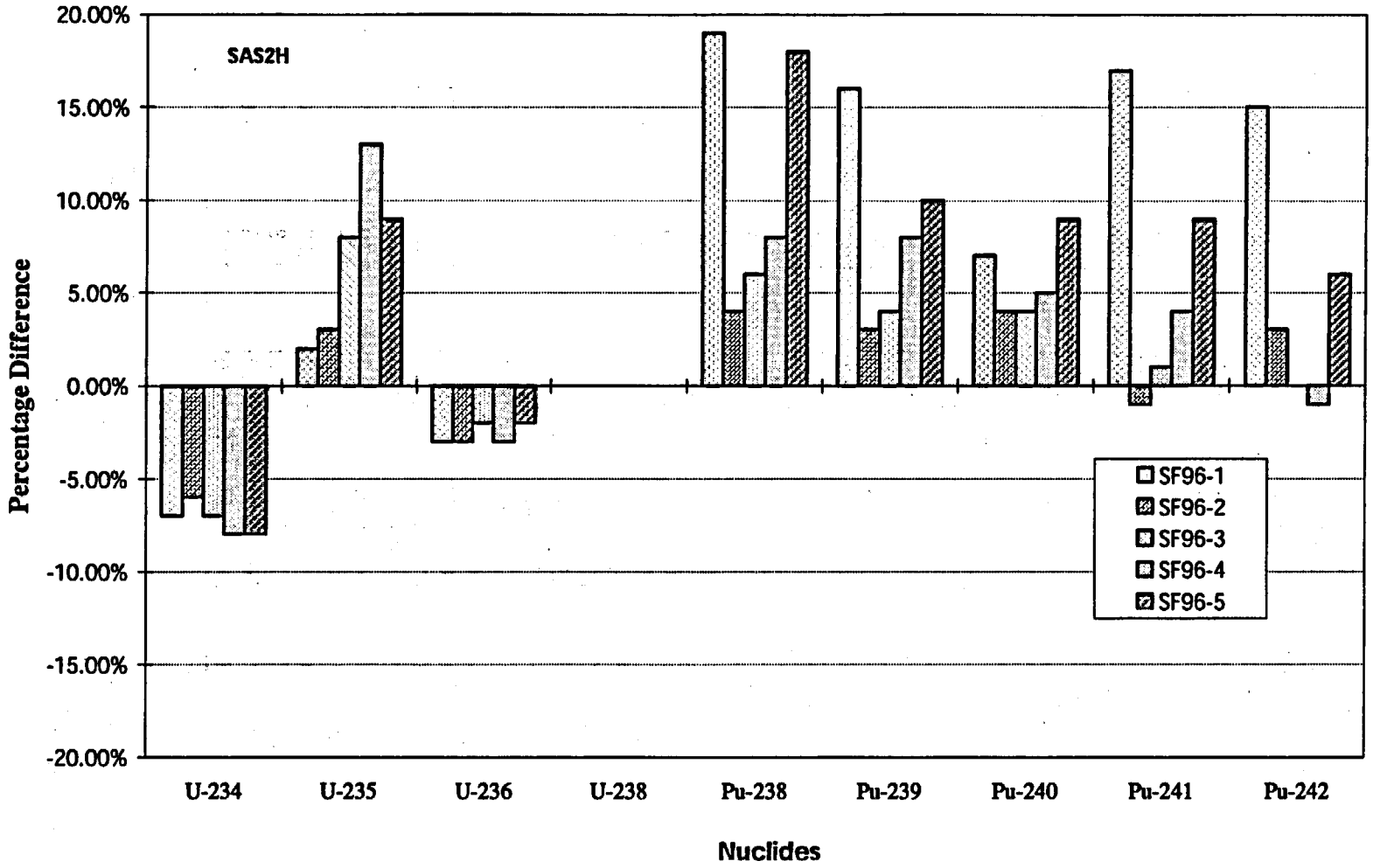

Figure 5 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for SAS2H SF96 samples 1–5 results

Table 20 Comparison of analyses and calculations of Takahama-3 SF97-1

	Measured[a] g/MgU				
Nuclide	SF97-1 Measured[a]	SF97-1 SAS2H	SF97-1 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.939E+02	3.145E+02	2.63E+02	1.07	0.89
^{235}U	2.347E+04	2.402E+04	2.42E+04	1.02	1.03
^{236}U	3.115E+03	3.148E+03	3.04E+03	1.01	0.97
^{238}U	9.493E+05	9.472E+05	9.49E+05	1.00	1.00
^{237}Np	1.521E+02	1.830E+02	1.53E+02	1.20	1.01
^{238}Pu	2.370E+01	2.909E+01	2.16E+01	1.23	0.91
^{239}Pu	3.844E+03	4.900E+03	5.24E+03	1.27	1.36
^{240}Pu	9.347E+02	1.060E+03	1.11E+03	1.13	1.18
^{241}Pu	4.237E+02	5.372E+02	5.48E+02	1.27	1.29
^{242}Pu	6.185E+01	7.487E+01	6.65E+01	1.21	1.07
^{241}Am	1.492E+01	2.483E+01	2.16E+01	1.66	1.45
^{242m}Am	2.270E–01	4.506E–01	3.22E–01	1.99	1.42
^{243}Am	4.448E+00	7.355E+00	5.14E+00	1.65	1.16
^{242}Cm	2.134E+00	2.449E+00	2.24E+00	1.15	1.05
^{243}Cm	2.483E–02	2.978E–02	1.73E–02	1.20	0.70
^{244}Cm	4.981E–01	8.356E–01	5.05E–01	1.68	1.01
^{245}Cm	1.087E–02	1.597E–02	1.10E–02	1.47	1.01
^{246}Cm	3.866E–04	6.978E–04	3.01E–04	1.80	0.78
^{247}Cm	N/A	5.292E–06	N/A	N/A	N/A
^{143}Nd	5.450E+02	5.488E+02	5.43E+02	1.01	1.00
^{144}Nd	4.661E+02	4.840E+02	4.59E+02	1.04	0.99
^{145}Nd	4.045E+02	4.065E+02	4.08E+02	1.00	1.01
^{146}Nd	3.502E+02	3.565E+02	3.52E+02	1.02	1.00
^{148}Nd	1.945E+02	1.973E+02	1.97E+02	1.01	1.01
^{150}Nd	8.570E+01	8.845E+01	8.79E+01	1.03	1.03
^{137}Cs	6.617E+02	6.586E+02	6.50E+02	1.00	0.98
^{134}Cs	2.983E+01	2.796E+01	2.52E+01	0.94	0.84
^{154}Eu	5.253E+00	6.210E+00	5.69E+00	1.18	1.08
^{144}Ce	2.026E+02	1.668E+02	1.88E+02	0.82	0.93
^{125}Sb	2.462E+00	3.009E+00	4.40E+00	1.22	1.79
^{106}Ru	5.163E+01	4.722E+01	5.18E+01	0.91	1.00
^{147}Sm	1.529E+02	1.510E+02	7.65E+01	0.99	0.50
^{148}Sm	4.092E+01	4.494E+01	3.68E+01	1.10	0.90
^{149}Sm	2.935E+00	3.037E+00	2.60E+00	1.03	0.89
^{150}Sm	1.323E+02	1.429E+02	1.36E+02	1.08	1.03
^{151}Sm	9.324E+00	1.382E+01	1.15E+01	1.48	1.23
^{152}Sm	6.526E+01	7.070E+01	7.08E+01	1.08	1.09
^{154}Sm	1.425E+01	1.472E+01	1.46E+01	1.03	1.02
Burnup (GWd/MTU)[b]	17.69				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.

[b] Burnup estimated using ^{148}Nd analysis.

Table 21 Comparison of analyses and calculations of Takahama-3 SF97-2

	Measured[a] g/MgU				
Nuclide	SF97-2 Measured[a]	SF97-2 SAS2H	SF97-2 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.348E+02	2.587E+02	2.21E+02	1.10	0.94
^{235}U	1.571E+04	1.548E+04	1.60E+04	0.99	1.02
^{236}U	4.560E+03	4.549E+03	4.35E+03	1.00	0.95
^{238}U	9.377E+05	9.375E+05	9.40E+05	1.00	1.00
^{237}Np	4.034E+02	4.062E+02	3.36E+02	1.01	0.83
^{238}Pu	1.250E+02	1.137E+02	1.08E+02	0.91	0.86
^{239}Pu	5.928E+03	5.957E+03	6.26E+03	1.00	1.06
^{240}Pu	1.871E+03	1.969E+03	1.94E+03	1.05	1.04
^{241}Pu	1.235E+03	1.191E+03	1.25E+03	0.96	1.01
^{242}Pu	3.152E+02	3.226E+02	2.94E+02	1.02	0.93
^{241}Am	4.017E+01	5.026E+01	4.75E+01	1.25	1.18
^{242m}Am	8.838E–01	1.069E+00	8.46E–01	1.21	0.96
^{243}Am	5.132E+01	5.770E+01	4.13E+01	1.12	0.80
^{242}Cm	1.049E+01	9.916E+00	9.55E+00	0.95	0.91
^{243}Cm	2.773E–01	2.166E–01	1.74E–01	0.78	0.63
^{244}Cm	1.384E+01	1.282E+01	1.05E+01	0.93	0.76
^{245}Cm	6.848E–01	4.046E–01	3.09E–01	0.59	0.45
^{246}Cm	4.222E–02	3.585E–02	1.74E–02	0.85	0.41
^{247}Cm	4.043E–04	4.982E–04	N/A	1.23	N/A
^{143}Nd	8.307E+02	8.325E+02	8.25E+02	1.00	0.99
^{144}Nd	8.843E+02	9.037E+02	8.66E+02	1.02	0.98
^{145}Nd	6.480E+02	6.576E+02	6.62E+02	1.01	1.02
^{146}Nd	6.304E+02	6.362E+02	6.20E+02	1.01	0.98
^{148}Nd	3.389E+02	3.411E+02	3.41E+02	1.01	1.01
^{150}Nd	1.582E+02	1.598E+02	1.57E+02	1.01	0.99
^{137}Cs	1.151E+03	1.144E+03	1.12E+03	0.99	0.97
^{134}Cs	1.030E+02	8.286E+01	7.45E+01	0.80	0.72
^{154}Eu	1.973E+01	1.889E+01	1.68E+01	0.96	0.85
^{144}Ce	3.061E+02	2.750E+02	3.00E+02	0.90	0.98
^{125}Sb	5.118E+00	5.929E+00	8.24E+00	1.16	1.61
^{106}Ru	1.162E+02	1.095E+02	1.14E+02	0.94	0.98
^{147}Sm	2.050E+02	2.085E+02	9.23E+01	1.02	0.45
^{148}Sm	1.194E+02	1.083E+02	8.97E+01	0.91	0.75
^{149}Sm	3.976E+00	3.698E+00	2.72E+00	0.93	0.68
^{150}Sm	2.499E+02	2.765E+02	2.51E+02	1.11	1.00
^{151}Sm	1.351E+01	1.744E+01	1.37E+01	1.29	1.01
^{152}Sm	9.546E+01	1.197E+02	1.16E+02	1.25	1.22
^{154}Sm	2.977E+01	3.012E+01	2.92E+01	1.01	0.98
Burnup (GWd/MTU)[b]	30.73				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

Table 22 Comparison of analyses and calculations of Takahama-3 SF97-3

	Measured[a] g/MgU				
Nuclide	SF97-3 Measured[a]	SF97-3 SAS2H	SF97-3 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.010E+02	2.150E+02	1.86E+02	1.07	0.93
^{235}U	1.030E+04	1.005E+04	1.05E+04	0.98	1.02
^{236}U	5.312E+03	5.288E+03	5.09E+03	1.00	0.96
^{238}U	9.282E+05	9.283E+05	9.28E+05	1.00	1.00
^{237}Np	5.845E+02	6.083E+02	5.17E+02	1.04	0.88
^{238}Pu	2.581E+02	2.343E+02	2.03E+02	0.91	0.79
^{239}Pu	6.217E+03	6.229E+03	6.50E+03	1.00	1.05
^{240}Pu	2.471E+03	2.596E+03	2.48E+03	1.05	1.00
^{241}Pu	1.689E+03	1.631E+03	1.74E+03	0.97	1.03
^{242}Pu	6.517E+02	6.625E+02	6.37E+02	1.02	0.98
^{241}Am	4.909E+01	6.057E+01	6.70E+01	1.23	1.36
^{242m}Am	1.179E+00	1.342E+00	1.26E+00	1.14	1.07
^{243}Am	1.410E+02	1.603E+02	1.26E+02	1.14	0.89
^{242}Cm	1.839E+01	1.874E+01	2.02E+01	1.02	1.10
^{243}Cm	6.921E–01	5.580E–01	3.93E–01	0.81	0.57
^{244}Cm	5.696E+01	5.372E+01	3.96E+01	0.94	0.69
^{245}Cm	3.735E+00	2.146E+00	2.21E+00	0.57	0.59
^{246}Cm	3.648E–01	3.027E–01	2.19E–01	0.83	0.61
^{247}Cm	4.974E–03	5.910E–03	N/A	1.19	N/A
^{143}Nd	1.008E+03	1.005E+03	9.94E+02	1.00	0.99
^{144}Nd	1.331E+03	1.319E+03	1.29E+03	0.99	0.97
^{145}Nd	8.387E+02	8.478E+02	8.50E+02	1.01	1.01
^{146}Nd	8.929E+02	8.972E+02	8.62E+02	1.00	0.97
^{148}Nd	4.662E+02	4.666E+02	4.63E+02	1.00	0.99
^{150}Nd	2.234E+02	2.256E+02	2.21E+02	1.01	0.99
^{137}Cs	1.582E+03	1.569E+03	1.52E+03	0.99	0.96
^{134}Cs	1.829E+02	1.525E+02	1.34E+02	0.83	0.73
^{154}Eu	3.293E+01	3.320E+01	2.95E+01	1.01	0.89
^{144}Ce	3.720E+02	3.628E+02	3.52E+02	0.98	0.95
^{125}Sb	4.966E+00	8.756E+00	9.29E+00	1.76	1.87
^{106}Ru	1.829E+02	1.783E+02	1.75E+02	0.97	0.96
^{147}Sm	2.355E+02	2.332E+02	1.30E+02	0.99	0.55
^{148}Sm	1.978E+02	1.716E+02	1.58E+02	0.87	0.80
^{149}Sm	4.259E+00	2.990E+00	3.32E+00	0.70	0.78
^{150}Sm	3.599E+02	4.068E+02	3.51E+02	1.13	0.97
^{151}Sm	1.503E+01	2.033E+01	1.59E+01	1.35	1.06
^{152}Sm	1.191E+02	1.586E+02	1.48E+02	1.33	1.24
^{154}Sm	4.536E+01	4.630E+01	4.46E+01	1.02	0.98
Burnup (GWd/MTU)[b]	42.16				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

Table 23 Comparison of analyses and calculations of Takahama-3 SF97-4

Nuclide	Measured[a] g/MgU				
	SF97-4 Measured[a]	SF97-4 SAS2H	SF97-4 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.872E+02	1.992E+02	1.853E+02	1.06	0.99
^{235}U	8.179E+03	7.893E+03	8.359E+03	0.97	1.02
^{236}U	5.528E+03	5.490E+03	5.392E+03	0.99	0.98
^{238}U	9.246E+05	9.249E+05	9.285E+05	1.00	1.00
^{237}Np	6.604E+02	6.730E+02	6.267E+02	1.02	0.95
^{238}Pu	3.199E+02	2.837E+02	2.539E+02	0.89	0.79
^{239}Pu	6.037E+03	5.981E+03	6.206E+03	0.99	1.03
^{240}Pu	2.668E+03	2.763E+03	2.662E+03	1.04	1.00
^{241}Pu	1.770E+03	1.695E+03	1.801E+03	0.96	1.02
^{242}Pu	8.246E+02	8.317E+02	8.267E+02	1.01	1.00
^{241}Am	5.311E+01	5.857E+01	5.608E+01	1.10	1.06
^{242m}Am	1.233E+00	1.261E+00	1.163E+00	1.02	0.94
^{243}Am	1.924E+02	2.157E+02	1.781E+02	1.12	0.93
^{242}Cm	2.044E+01	2.189E+01	2.247E+01	1.07	1.10
^{243}Cm	8.721E–01	7.015E–01	6.590E–01	0.80	0.76
^{244}Cm	8.810E+01	8.182E+01	7.161E+01	0.93	0.81
^{245}Cm	6.042E+00	3.315E+00	3.145E+00	0.55	0.52
^{246}Cm	7.440E–01	5.796E–01	5.729E–01	0.78	0.77
^{247}Cm	1.098E–02	1.222E–02	1.172E–02	1.11	1.07
^{143}Nd	1.048E+03	1.047E+03	1.054E+03	1.00	0.99
^{144}Nd	1.567E+03	1.529E+03	1.485E+03	0.98	0.95
^{145}Nd	9.118E+02	9.244E+02	9.176E+02	1.01	1.01
^{146}Nd	1.008E+03	1.014E+03	9.879E+02	1.01	0.98
^{148}Nd	5.204E+02	5.203E+02	5.278E+02	1.00	1.01
^{150}Nd	2.516E+02	2.540E+02	2.532E+02	1.01	1.01
^{137}Cs	1.749E+03	1.752E+03	1.734E+03	1.00	0.99
^{134}Cs	2.139E+02	1.851E+02	1.741E+02	0.87	0.81
^{154}Eu	3.739E+01	3.810E+01	3.456E+01	1.02	0.92
^{144}Ce	3.756E+02	3.997E+02	4.248E+02	1.06	1.13
^{125}Sb	6.090E+00	9.975E+00	1.162E+01	1.64	1.91
^{106}Ru	1.936E+02	2.097E+02	2.144E+02	1.08	1.11
^{147}Sm	2.468E+02	2.411E+02	2.421E+02	0.98	0.98
^{148}Sm	2.338E+02	1.983E+02	1.790E+02	0.85	0.77
^{149}Sm	3.943E+00	4.412E+00	3.568E+00	1.12	0.90
^{150}Sm	4.074E+02	4.526E+02	4.106E+02	1.11	1.01
^{151}Sm	1.491E+01	1.987E+01	1.614E+01	1.33	1.08
^{152}Sm	1.298E+02	1.750E+02	1.633E+02	1.35	1.26
^{154}Sm	5.252E+01	5.357E+01	5.278E+01	1.02	1.00
Burnup (GWd/MTU)[b]	47.03				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

Table 24 Comparison of analyses and calculations of Takahama-3 SF97-5

	Measured[a] g/MgU				
Nuclide	SF97-5 Measured[a]	SF97-5 SAS2H	SF97-5 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	1.865E+02	1.996E+02	1.75E+02	1.07	0.94
^{235}U	7.932E+03	7.530E+03	8.06E+03	0.95	1.02
^{236}U	5.532E+03	5.501E+03	5.33E+03	0.99	0.96
^{238}U	9.247E+05	9.253E+05	9.25E+05	1.00	1.00
^{237}Np	6.701E+02	6.621E+02	5.68E+02	0.99	0.85
^{238}Pu	3.188E+02	2.757E+02	2.44E+02	0.86	0.76
^{239}Pu	5.976E+03	5.786E+03	5.96E+03	0.97	1.00
^{240}Pu	2.648E+03	2.728E+03	2.61E+03	1.03	0.99
^{241}Pu	1.754E+03	1.638E+03	1.76E+03	0.93	1.00
^{242}Pu	8.341E+02	8.362E+02	8.21E+02	1.00	0.98
^{241}Am	5.327E+01	5.611E+01	6.77E+01	1.05	1.27
^{242m}Am	1.200E+00	1.171E+00	1.27E+00	0.98	1.06
^{243}Am	1.935E+02	2.130E+02	1.74E+02	1.10	0.90
^{242}Cm	1.903E+01	2.145E+01	2.36E+01	1.13	1.24
^{243}Cm	8.670E–01	6.743E–01	7.67E–01	0.78	0.88
^{244}Cm	8.823E+01	7.959E+01	7.38E+01	0.90	0.84
^{245}Cm	5.915E+00	3.082E+00	2.67E+00	0.52	0.45
^{246}Cm	7.549E–01	5.622E–01	4.22E–01	0.74	0.56
^{247}Cm	1.075E–02	1.150E–02	N/A	1.07	N/A
^{143}Nd	1.049E+03	1.037E+03	1.04E+03	0.99	0.99
^{144}Nd	1.599E+03	1.555E+03	1.55E+03	0.97	0.97
^{145}Nd	9.179E+02	9.301E+02	9.37E+02	1.01	1.02
^{146}Nd	1.014E+03	1.019E+03	9.78E+02	1.00	0.96
^{148}Nd	5.226E+02	5.226E+02	5.19E+02	1.00	0.99
^{150}Nd	2.518E+02	2.546E+02	2.50E+02	1.01	0.99
^{137}Cs	1.761E+03	1.760E+03	1.70E+03	1.00	0.96
^{134}Cs	2.144E+02	1.845E+02	1.58E+02	0.86	0.74
^{154}Eu	3.707E+01	3.726E+01	3.29E+01	1.01	0.89
^{144}Ce	3.750E+02	4.020E+02	3.55E+02	1.07	0.95
^{125}Sb	7.507E+00	9.984E+00	1.25E+01	1.33	1.66
^{106}Ru	1.162E+02	2.098E+02	1.93E+02	1.81	1.66
^{147}Sm	2.479E+02	2.435E+02	1.58E+02	0.98	0.64
^{148}Sm	2.357E+02	1.987E+02	1.87E+02	0.84	0.79
^{149}Sm	3.799E+00	4.259E+00	2.58E+00	1.12	0.68
^{150}Sm	4.113E+02	4.530E+02	3.92E+02	1.10	0.95
^{151}Sm	1.465E+01	1.872E+01	1.51E+01	1.28	1.03
^{152}Sm	1.319E+02	1.771E+02	1.65E+02	1.34	1.25
^{154}Sm	5.298E+01	5.354E+01	5.15E+01	1.01	0.97
Burnup (GWd/MTU)[b]	47.25				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

Table 25 Comparison of analyses and calculations of Takahama-3 SF97-6

	Measured[a] g/MgU				
Nuclide	SF97-6 Measured[a]	SF97-6 SAS2H	SF97-6 HELIOS	C/E SAS2H	C/E HELIOS
^{234}U	2.057E+02	2.232E+02	1.93E+02	1.09	0.94
^{235}U	1.016E+04	9.923E+03	1.04E+04	0.98	1.02
^{236}U	5.272E+03	5.232E+03	5.04E+03	0.99	0.96
^{238}U	9.310E+05	9.308E+05	9.31E+05	1.00	1.00
^{237}Np	5.570E+02	5.541E+02	4.71E+02	0.99	0.85
^{238}Pu	2.175E+02	1.986E+02	1.69E+02	0.91	0.78
^{239}Pu	5.677E+03	5.741E+03	5.93E+03	1.01	1.04
^{240}Pu	2.326E+03	2.441E+03	2.39E+03	1.05	1.03
^{241}Pu	1.494E+03	1.457E+03	1.57E+03	0.98	1.05
^{242}Pu	5.977E+02	6.086E+02	5.93E+02	1.02	0.99
^{241}Am	4.297E+01	5.451E+01	5.45E+01	1.27	1.27
^{242m}Am	9.756E-01	1.121E+00	1.05E+00	1.15	1.08
^{243}Am	1.170E+02	1.348E+02	1.09E+02	1.15	0.93
^{242}Cm	1.616E+01	1.650E+01	1.79E+01	1.02	1.11
^{243}Cm	5.600E–01	4.488E–01	3.50E–01	0.80	0.63
^{244}Cm	4.221E+01	4.089E+01	3.06E+01	0.97	0.72
^{245}Cm	2.363E+00	1.433E+00	1.30E+00	0.61	0.55
^{246}Cm	2.481E–01	2.069E–01	1.33E–01	0.83	0.53
^{247}Cm	3.139E–03	3.568E–03	N/A	1.14	N/A
^{143}Nd	9.736E+02	9.714E+02	9.65E+02	1.00	0.99
^{144}Nd	1.311E+03	1.299E+03	1.26E+03	0.99	0.96
^{145}Nd	8.247E+02	8.336E+02	8.36E+02	1.01	1.01
^{146}Nd	8.586E+02	8.655E+02	8.35E+02	1.01	0.97
^{148}Nd	4.504E+02	4.522E+02	4.50E+02	1.00	1.00
^{150}Nd	2.130E+02	2.164E+02	2.13E+02	1.02	1.00
^{137}Cs	1.531E+03	1.521E+03	1.48E+03	0.99	0.96
^{134}Cs	1.632E+02	1.386E+02	1.23E+02	0.85	0.75
^{154}Eu	2.859E+01	2.922E+01	2.59E+01	1.02	0.91
^{144}Ce	3.714E+02	3.550E+02	3.52E+02	0.96	0.95
^{125}Sb	4.546E+00	8.306E+00	9.36E+00	1.83	2.06
^{106}Ru	1.959E+02	1.662E+02	1.67E+02	0.85	0.85
^{147}Sm	2.371E+02	2.371E+02	1.41E+02	1.00	0.59
^{148}Sm	1.809E+02	1.615E+02	1.60E+02	0.89	0.89
^{149}Sm	3.843E+00	3.944E+00	2.68E+00	1.03	0.70
^{150}Sm	3.409E+02	3.837E+02	3.39E+02	1.13	0.99
^{151}Sm	1.294E+01	1.732E+01	1.43E+01	1.34	1.10
^{152}Sm	1.207E+02	1.569E+02	1.48E+02	1.30	1.23
^{154}Sm	4.231E+01	4.347E+01	4.22E+01	1.03	1.00
Burnup (GWd/MTU)[b]	40.79				

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

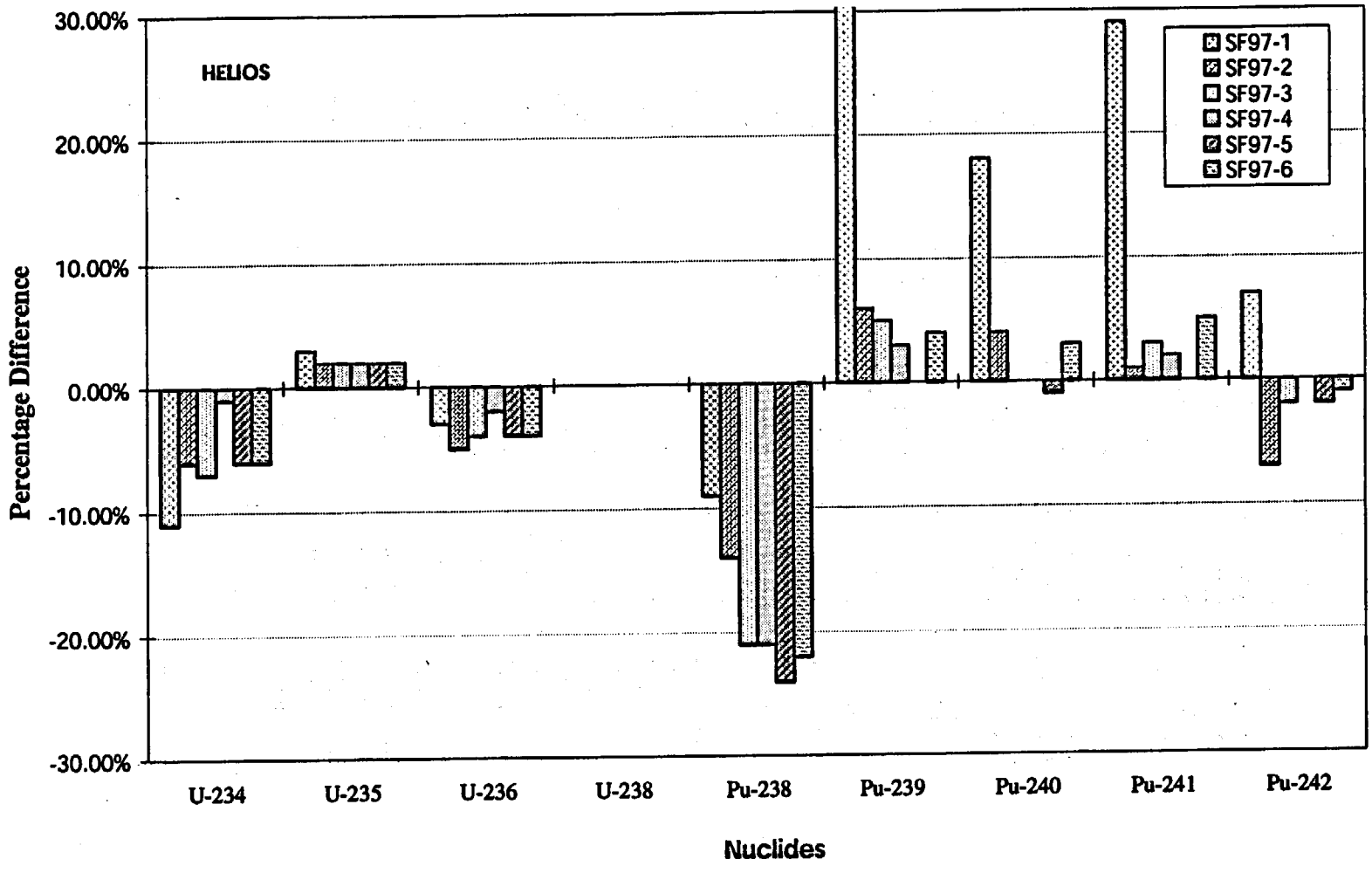

Figure 6 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for HELIOS SF97 samples 1–6 results

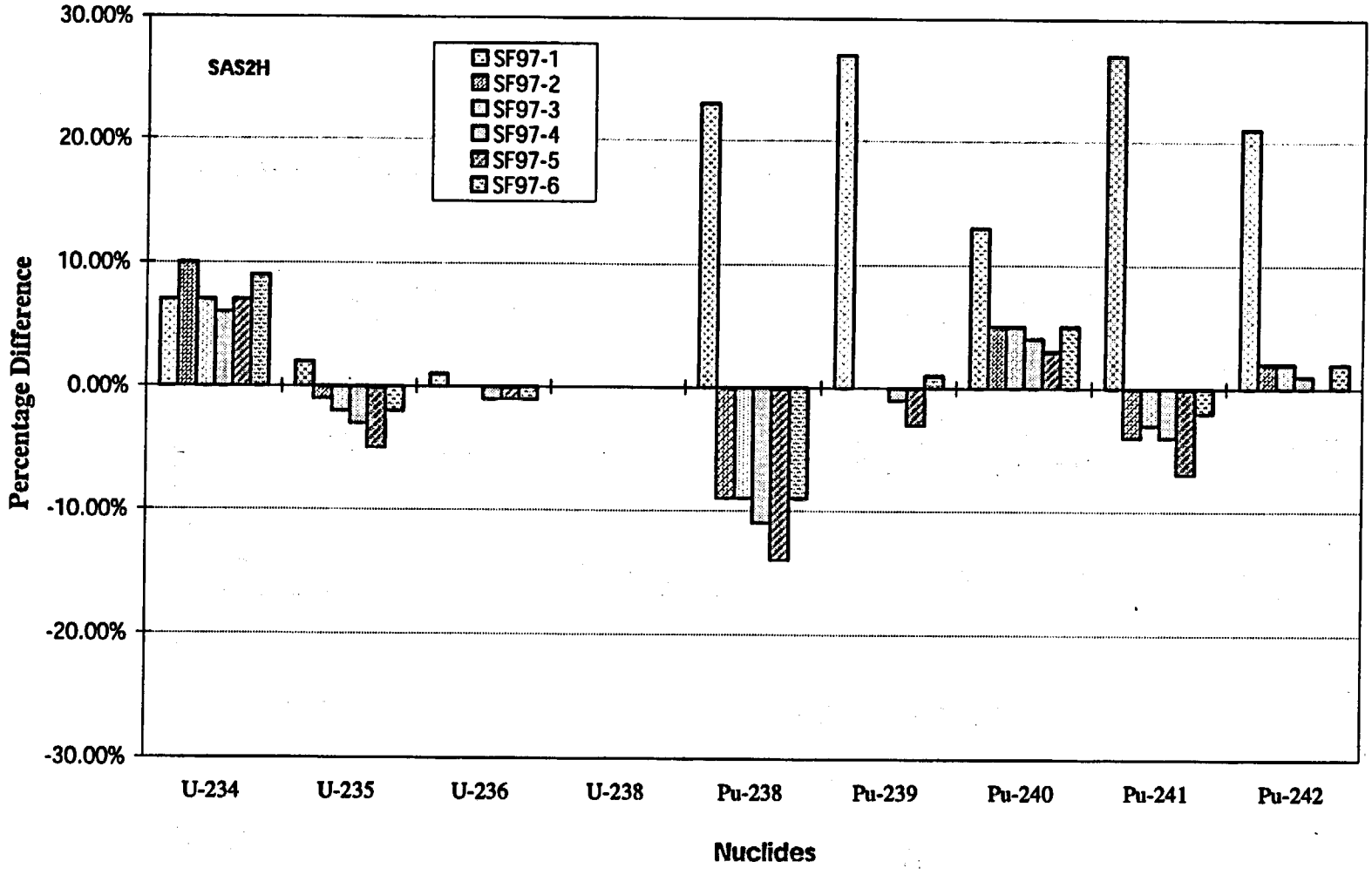

Figure 7 Percentage difference [(calculated/measured −1) × 100%] of uranium and plutonium isotopes for SAS2H SF97 samples 1–6 results

Table 26 Summary of isotopic validation results (SF95 and SF97)

Nuclide	No. of samples	HELIOS Average C/E	HELIOS σ (%)	SAS2H Average C/E	SAS2H σ (%)
^{234}U	10	0.95	4.2%	1.10	10.7%
^{235}U	10	1.01	1.0%	0.98	1.4%
^{236}U	10	0.98	2.0%	0.99	0.7%
^{238}U	10	1.00	0.1%	1.00	0.0%
^{237}Np	5	0.87	4.7%	1.01	2.1%
^{238}Pu	10	0.89	10.1%	0.92	4.0%
^{239}Pu	10	1.04	2.7%	0.99	2.1%
^{240}Pu	10	1.01	2.0%	1.03	1.7%
^{241}Pu	10	1.02	1.6%	0.96	2.5%
^{242}Pu	10	0.95	3.4%	1.02	2.1%
^{241}Am	10	1.20	15.7%	1.16	18.1%
^{242m}Am	10	1.02	5.1%	1.08	7.0%
^{243}Am	10	0.94	6.2%	1.14	2.7%
^{242}Cm	10	0.96	16.2%	0.85	21.6%
^{243}Cm	10	0.74	11.0%	0.77	4.1%
^{244}Cm	10	0.84	8.8%	0.95	5.1%
^{245}Cm	10	0.72	22.0%	0.60	7.4%
^{246}Cm	10	0.70	23.3%	0.82	26.0%
^{142}Nd	10	N/A	N/A	0.88	6.1%
^{143}Nd	10	0.98	0.8%	0.99	1.1%
^{144}Nd	10	0.97	1.6%	1.00	1.6%
^{145}Nd	10	1.00	1.1%	1.01	0.4%
^{146}Nd	10	0.98	1.5%	1.01	0.7%
^{148}Nd	10	1.00	0.7%	1.00	0.7%
^{150}Nd	5	0.99	0.9%	1.00	1.4%
^{137}Cs	10	0.97	1.0%	0.99	0.5%
^{134}Cs	10	0.77	5.5%	0.85	2.2%
^{154}Eu	10	0.97	8.8%	0.98	3.2%
^{144}Ce	10	0.97	6.1%	0.99	5.3%
^{125}Sb	10	2.23	47.9%	1.80	40.1%
^{106}Ru	10	1.12	22.7%	1.14	27.2%
^{147}Sm	5	0.64	20.3%	0.99	1.7%
^{148}Sm	5	0.80	5.5%	0.87	2.9%
^{149}Sm	5	0.75	9.4%	0.98	17.5%
^{150}Sm	5	0.98	2.1%	1.12	1.3%
^{151}Sm	5	1.06	3.0%	1.32	3.1%
^{152}Sm	5	1.24	2.1%	1.31	4.0%
^{154}Sm	5	0.99	1.5%	1.02	0.8%

SF95 (samples 1–5) and SF97 (samples 2–6).

Finally, a sensitivity study was performed for Takahama-3 samples SF97-1 and SF97-5 (assembly NT3G24, rod I-Q) to determine the potential influence of surrounding assemblies that have different burnups from that of assembly NT3G24 as may occur following fuel reloading operations. HELIO-1.6 was used to model the assemblies adjacent to NT3G24 with compositions equivalent to 1 and 2 cycles irradiation. That is, the depletion simulations of NT3G24 were repeated assuming all surrounding assemblies had a constant composition (no burnup simulation of the surrounding assemblies was performed) equivalent to 1 cycle fuel (15 GWd/MTU) and also for 2 cycle fuel (30 GWd/MTU). The results are shown in Tables 27–28. It can be seen that sample SF97-1 (low burnup) is very insensitive to the surrounding environment, while sample SF97-5 (high burnup) is affected to a greater degree by the surrounding fuel composition. However, the differences in sample SF97-5 between the various surroundings are fairly minor, generally < 2% in the predicted isotopic compositions.

Table 27 Results of HELIOS sensitivity analyses of Takahama-3 SF97-1

Nuclide (g/MgU)	SF97-1 Measured[a]	SF97-1 HELIOS	SF97-1 1 cycle	SF97-1 2 cycles	C/E	C/E 1 cycle	C/E 2 cycles
^{234}U	2.939E+02	2.63E+02	2.63E+02	2.63E+02	0.89	0.89	0.89
^{235}U	2.347E+04	2.42E+04	2.41E+04	2.42E+04	1.03	1.03	1.03
^{236}U	3.115E+03	3.04E+03	3.04E+03	3.04E+03	0.97	0.98	0.98
^{238}U	9.493E+05	9.49E+05	9.49E+05	9.49E+05	1.00	1.00	1.00
^{237}Np	1.521E+02	1.53E+02	1.54E+02	1.53E+02	1.01	1.01	1.01
^{238}Pu	2.370E+01	2.16E+01	2.18E+01	2.17E+01	0.91	0.92	0.92
^{239}Pu	3.844E+03	5.24E+03	5.25E+03	5.25E+03	1.36	1.37	1.36
^{240}Pu	9.347E+02	1.11E+03	1.11E+03	1.11E+03	1.18	1.19	1.18
^{241}Pu	4.237E+02	5.48E+02	5.51E+02	5.49E+02	1.29	1.30	1.30
^{242}Pu	6.185E+01	6.65E+01	6.72E+01	6.67E+01	1.07	1.09	1.08
^{241}Am	1.492E+01	2.16E+01	2.18E+01	2.17E+01	1.45	1.46	1.46
^{242m}Am	2.270E–01	3.22E–01	3.25E–01	3.23E–01	1.42	1.43	1.42
^{243}Am	4.448E+00	5.14E+00	5.22E+00	5.17E+00	1.16	1.17	1.16
^{242}Cm	2.134E+00	2.24E+00	2.27E+00	2.25E+00	1.05	1.06	1.05
^{243}Cm	2.483E–02	1.73E–02	1.75E–02	1.74E–02	0.70	0.71	0.70
^{244}Cm	4.981E–01	5.05E–01	5.16E–01	5.09E–01	1.01	1.04	1.02
^{245}Cm	1.087E–02	1.10E–02	1.13E–02	1.11E–02	1.01	1.04	1.02
^{246}Cm	3.866E–04	3.01E–04	3.10E–04	3.04E–04	0.78	0.80	0.79
^{247}Cm	N/A	N/A	N/A	N/A	N/A	N/A	N/A
^{143}Nd	5.450E+02	5.43E+02	5.45E+02	5.44E+02	1.00	1.00	1.00
^{144}Nd	4.661E+02	4.59E+02	4.62E+02	4.60E+02	0.99	0.99	0.99
^{145}Nd	4.045E+02	4.08E+02	4.09E+02	4.08E+02	1.01	1.01	1.01
^{146}Nd	3.502E+02	3.52E+02	3.53E+02	3.52E+02	1.00	1.01	1.01
^{148}Nd	1.945E+02	1.97E+02	1.98E+02	1.98E+02	1.01	1.02	1.02
^{150}Nd	8.570E+01	8.79E+01	8.82E+01	8.80E+01	1.03	1.03	1.03
^{137}Cs	6.617E+02	6.50E+02	6.52E+02	6.50E+02	0.98	0.99	0.98
^{134}Cs	2.983E+01	2.52E+01	2.54E+01	2.52E+01	0.84	0.85	0.85
^{154}Eu	5.253E+00	5.69E+00	5.74E+00	5.71E+00	1.08	1.09	1.09
^{144}Ce	2.026E+02	1.88E+02	1.88E+02	1.88E+02	0.93	0.93	0.93
^{125}Sb	2.462E+00	4.40E+00	4.42E+00	4.41E+00	1.79	1.79	1.79
^{106}Ru	5.163E+01	5.18E+01	5.20E+01	5.18E+01	1.00	1.01	1.00
^{147}Sm	1.529E+02	7.65E+01	6.88E+01	7.40E+01	0.50	0.45	0.48
^{148}Sm	4.092E+01	3.68E+01	3.71E+01	3.69E+01	0.90	0.91	0.90
^{149}Sm	2.935E+00	2.60E+00	2.60E+00	2.60E+00	0.89	0.89	0.89
^{150}Sm	1.323E+02	1.36E+02	1.37E+02	1.37E+02	1.03	1.04	1.03
^{151}Sm	9.324E+00	1.15E+01	1.15E+01	1.15E+01	1.23	1.23	1.23
^{152}Sm	6.526E+01	7.08E+01	7.11E+01	7.09E+01	1.09	1.09	1.09
^{154}Sm	1.425E+01	1.46E+01	1.46E+01	1.46E+01	1.02	1.03	1.02
Burnup (GWd/MTU)[b]	17.69						

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

Table 28 Results of HELIOS sensitivity analyses of Takahama-3 SF97-5

Nuclide (g/MgU)	SF97-5 Measured[a]	SF97-5 HELIOS	SF97-5 1 cycle	SF97-5 2 cycles	C/E	C/E 1 cycle	C/E 2 cycles
^{234}U	1.865E+02	1.75E+02	1.76E+02	1.73E+02	0.94	0.94	0.93
^{235}U	7.932E+03	8.06E+03	8.26E+03	7.86E+03	1.02	1.04	0.99
^{236}U	5.532E+03	5.33E+03	5.28E+03	5.33E+03	0.96	0.96	0.96
^{238}U	9.247E+05	9.25E+05	9.25E+05	9.25E+05	1.00	1.00	1.00
^{237}Np	6.701E+02	5.68E+02	5.57E+02	5.75E+02	0.85	0.83	0.86
^{238}Pu	3.188E+02	2.44E+02	2.20E+02	2.28E+02	0.76	0.69	0.72
^{239}Pu	5.976E+03	5.96E+03	5.97E+03	5.96E+03	1.00	1.00	1.00
^{240}Pu	2.648E+03	2.61E+03	2.59E+03	2.62E+03	0.99	0.98	0.99
^{241}Pu	1.754E+03	1.76E+03	1.74E+03	1.77E+03	1.00	0.99	1.01
^{242}Pu	8.341E+02	8.21E+02	7.96E+02	8.40E+02	0.98	0.95	1.01
^{241}Am	5.327E+01	6.77E+01	6.75E+01	6.78E+01	1.27	1.27	1.27
^{242m}Am	1.200E+00	1.27E+00	1.28E+00	1.29E+00	1.06	1.07	1.08
^{243}Am	1.935E+02	1.74E+02	1.66E+02	1.80E+02	0.90	0.86	0.93
^{242}Cm	1.903E+01	2.36E+01	2.38E+01	2.40E+01	1.24	1.25	1.26
^{243}Cm	8.670E–01	7.67E–01	7.01E–01	7.78E–01	0.88	0.81	0.90
^{244}Cm	8.823E+01	7.38E+01	6.60E+01	7.25E+01	0.84	0.75	0.82
^{245}Cm	5.915E+00	2.67E+00	2.46E+00	2.89E+00	0.45	0.42	0.49
^{246}Cm	7.549E–01	4.22E–01	3.32E–01	3.49E–01	0.56	0.44	0.46
^{247}Cm	1.075E–02	N/A	N/A	N/A	N/A	N/A	N/A
^{143}Nd	1.049E+03	1.04E+03	1.03E+03	1.04E+03	0.99	0.98	0.99
^{144}Nd	1.599E+03	1.55E+03	1.53E+03	1.58E+03	0.97	0.96	0.99
^{145}Nd	9.179E+02	9.37E+02	9.24E+02	9.42E+02	1.02	1.01	1.03
^{146}Nd	1.014E+03	9.78E+02	9.61E+02	9.89E+02	0.96	0.95	0.97
^{148}Nd	5.226E+02	5.19E+02	5.11E+02	5.24E+02	0.99	0.98	1.00
^{150}Nd	2.518E+02	2.50E+02	2.46E+02	2.53E+02	0.99	0.98	1.00
^{137}Cs	1.761E+03	1.70E+03	1.67E+03	1.71E+03	0.96	0.95	0.97
^{134}Cs	2.144E+02	1.58E+02	1.53E+02	1.61E+02	0.74	0.71	0.75
^{154}Eu	3.707E+01	3.29E+01	3.21E+01	3.34E+01	0.89	0.87	0.90
^{144}Ce	3.750E+02	3.55E+02	3.45E+02	3.52E+02	0.95	0.92	0.94
^{125}Sb	7.507E+00	1.25E+01	1.22E+01	1.25E+01	1.66	1.62	1.66
^{106}Ru	1.162E+02	1.93E+02	1.86E+02	1.92E+02	1.66	1.60	1.65
^{147}Sm	2.479E+02	1.58E+02	1.50E+02	1.51E+02	0.64	0.60	0.61
^{148}Sm	2.357E+02	1.87E+02	1.75E+02	1.82E+02	0.79	0.74	0.77
^{149}Sm	3.799E+00	2.58E+00	2.48E+00	2.42E+00	0.68	0.65	0.64
^{150}Sm	4.113E+02	3.92E+02	3.84E+02	3.96E+02	0.95	0.93	0.96
^{151}Sm	1.465E+01	1.51E+01	1.50E+01	1.52E+01	1.03	1.02	1.03
^{152}Sm	1.319E+02	1.65E+02	1.62E+02	1.66E+02	1.25	1.23	1.26
^{154}Sm	5.298E+01	5.15E+01	5.03E+01	5.22E+01	0.97	0.95	0.98
Burnup (GWd/MTU)[b]	47.25						

[a] At discharge, except for ^{239}Pu which includes contribution from ^{239}Np precursor, and Sm data based on 3.96 year cooling time.
[b] Burnup estimated using ^{148}Nd analysis.

4 CONCLUSIONS

The radiochemical isotopic assay data for the Takahama-3 reactor represents the highest enrichment and highest burnup spent fuel samples for commercial PWR fuel publicly available in the United States. These data have been applied to benchmark the isotopic predictions using the SCALE 4.4a and HELIOS-1.6 code systems. The large number of different nuclides measured makes these experiments highly valuable to burnup credit, decay heat, and radiation source term validation.

The analysis results for the standard fuel (4.11 wt % enrichment) rods SF95 and SF97 indicate extremely good agreement with the code predictions of both SCALE 4.4a and HELIOS. Overall the results using the two codes are comparable. An initial review of the results also suggests the concentrations are predicted with a level of accuracy that is similar to previous isotopic benchmark studies involving lower enrichment and burnup fuels. Some of the nuclide C/E ratios were improved compared to earlier results, including those for ^{134}Cs, ^{154}Eu, and many of the Sm isotopes. Note that sample SF97-1 is excluded from the statistical analysis (Table 27) because this sample was obtained very near the end of the active region of the fuel, in a neutronic environment that was not characteristic of the majority of the fuel rod. A comprehensive study integrating previous isotopic benchmark work with the present results for the high burnup Takahama-3 fuel was beyond the scope of this report. However, a comprehensive analysis of all available spent fuel assay data is in progress at ORNL.

The Takahama-3 assay data, and the results of the benchmark studies documented in this work, have potentially important implications for burnup credit in the United States. The current NRC Interim Staff Guidance on actinide-only burnup credit, ISG-8, restricts credit beyond 40 GWd/MTU and recommends a loading offset penalty for initial enrichments between 4 and 5 wt %. These restrictions were based largely on the lack of available isotopic assay date in this regime. The new Takahama-3 data extend significantly the range and quantity of previously available assay data. The benchmark results for these samples, calculated using the SCALE 4.4a and HELIOS-1.6 code systems, indicate an accuracy similar to that observed in previous studies. Therefore, these new data may help support a technical basis for extending the range of burnup credit in the United States, and for eliminating the loading offset. In addition, the large number of isotopic measurements available from these experiments greatly expands the database, reducing the uncertainty in the predictions caused by a limited sample size.

The results for the burnable poison rod SF96 indicate that 2-D depletion methods are required to accurately predict the spent fuel composition for these fuel types. The results using the 1-D SCALE methods for rod SF96 yielded substantially larger deviations than those observed for the standard fuel rods SF95 and SF97.

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APPENDIX A

SAMPLE INPUT FILES FOR SAS2H
(SF-95 Sample 4, SF-96 Sample 3, SF-97 Sample 2)

```
=sas2       parm='skipshipdata'
takahama 3 17x17 pwr, jaeri sf95-4, rod a-q, 36.69gwd/mtu
44groupndf5       latticecell
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'   mixtures of fuel-pin-unit-cell:
'
uo2  1 den=10.412 1 900 92234 0.04 92235 4.11 92238 95.85  end
zr-94  1 0 1-20 900  end
mo-94  1 0 1-20 900  end
nb-95  1 0 1-20 900  end
mo-95  1 0 1-20 900  end
tc-99  1 0 1-20 900  end
rh-103 1 0 1-20 900  end
rh-105 1 0 1-20 900  end
ru-106 1 0 1-20 900  end
sn-126 1 0 1-20 900  end
xe-131 1 0 1-20 900  end
cs-134 1 0 1-20 900  end
cs-135 1 0 1-20 900  end
cs-137 1 0 1-20 900  end
pr-143 1 0 1-20 900  end
nd-143 1 0 1-20 900  end
ce-144 1 0 1-20 900  end
nd-144 1 0 1-20 900  end
nd-145 1 0 1-20 900  end
nd-146 1 0 1-20 900  end
nd-147 1 0 1-20 900  end
pm-147 1 0 1-20 900  end
sm-147 1 0 1-20 900  end
nd-148 1 0 1-20 900  end
pm-148 1 0 1-20 900  end
sm-148 1 0 1-20 900  end
pm-149 1 0 1-20 900  end
sm-149 1 0 1-20 900  end
nd-150 1 0 1-20 900  end
sm-150 1 0 1-20 900  end
sm-151 1 0 1-20 900  end
eu-151 1 0 1-20 900  end
sm-152 1 0 1-20 900  end
eu-153 1 0 1-20 900  end
eu-154 1 0 1-20 900  end
gd-154 1 0 1-20 900  end
eu-155 1 0 1-20 900  end
gd-155 1 0 1-20 900  end
gd-157 1 0 1-20 900  end
gd-158 1 0 1-20 900  end
gd-160 1 0 1-20 900  end
'
'   zr-4 clad
arbmzirc 6.44 4 0 0 1 40000 97.91 26000 0.5 50116 0.86 50120 0.73 2 1 600  end
'
'   moderator density based on temk and 2250 psi
h2o  3 den=0.7331  1  593  end
arbm-bormod  0.7331 1 1 0 0 5000 100 3 630e-6  593  end
uo2  8 den=10.412 1 900 92234 0.04 92235 4.11 92238 95.85  end
' arbm-gd2o3  10.412 2 0 1 1 64000 2 8016 3 8 0.06 900  end
'
end comp
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'      fuel-pin-cell geometry:
'
```

```
squarepitch   1.26  0.8050 1  3  0.95   2  0.822 0   end
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'    assembly and cycle parameters:
'
npin/assm=264  fuelnght=811.13  ncycles=2  nlib/cyc=2
lightel=1  printlevel=4 inplevel=2
numz=5  end
'
'      fuel assembly geometry:
'
8 0.4025 2 0.475 3 0.7109 500 3.0870 3 3.2298
'
power=49.289   burn=385  down=88  end
power=44.057   burn=402  down=100 end
  o 134.56
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
end
```

```
=sas2       parm='skipshipdata'
takahama 3 17x17 pwr, jaeri sf96-3, gd rod c-m, 28.20gwd/mtu
44groupndf5       latticecell
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'   mixtures of fuel-pin-unit-cell:
'
uo2  1 den=10.412 1  900 92234 0.02 92235 2.63 92238 97.35  end
zr-94  1 0 1-20 900  end
mo-94  1 0 1-20 900  end
nb-95  1 0 1-20 900  end
mo-95  1 0 1-20 900  end
tc-99  1 0 1-20 900  end
rh-103 1 0 1-20 900  end
rh-105 1 0 1-20 900  end
ru-106 1 0 1-20 900  end
sn-126 1 0 1-20 900  end
xe-131 1 0 1-20 900  end
cs-134 1 0 1-20 900  end
cs-135 1 0 1-20 900  end
cs-137 1 0 1-20 900  end
pr-143 1 0 1-20 900  end
nd-143 1 0 1-20 900  end
ce-144 1 0 1-20 900  end
nd-144 1 0 1-20 900  end
nd-145 1 0 1-20 900  end
nd-146 1 0 1-20 900  end
nd-147 1 0 1-20 900  end
pm-147 1 0 1-20 900  end
sm-147 1 0 1-20 900  end
nd-148 1 0 1-20 900  end
pm-148 1 0 1-20 900  end
sm-148 1 0 1-20 900  end
pm-149 1 0 1-20 900  end
sm-149 1 0 1-20 900  end
nd-150 1 0 1-20 900  end
sm-150 1 0 1-20 900  end
sm-151 1 0 1-20 900  end
eu-151 1 0 1-20 900  end
sm-152 1 0 1-20 900  end
eu-153 1 0 1-20 900  end
eu-154 1 0 1-20 900  end
gd-154 1 0 1-20 900  end
eu-155 1 0 1-20 900  end
gd-155 1 0 1-20 900  end
gd-157 1 0 1-20 900  end
gd-158 1 0 1-20 900  end
gd-160 1 0 1-20 900  end
'
'   zr-4 clad
arbmzirc 6.44 4 0 0 1 40000 97.91 26000 0.5 50116 0.86 50120 0.73 2 1 600  end
'   moderator density based on temk and 2250 psi
h2o  3 den=0.6798  1  593  end
arbm-bormod  0.6798 1 1 0 0 5000 100 3 630e-6  593  end
'
uo2  9 den=10.412 1  900 92234 0.02 92235 2.63 92238 97.35  end
arbm-gd2o3  10.412 2 0 1 1 64000 2 8016 3  9 0.06  900 end
'
end comp
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'      fuel-pin-cell geometry:
'
```

```
squarepitch   1.26  0.8050 1  3  0.95   2  0.822 0   end
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'    assembly and cycle parameters:
'
npin/assm=264  fuelnght=811.13
ncycles=2  nlib/cyc=2 printlevel=4 lightel=1
inplevel=3  numztotal=6  end
9 0.280 9 0.4025 2 0.475 3 0.7109 500 3.087 3 3.2298
'
bon  end
nit  end
xsd
weighted cross sections in gd pin only
 i4= -2 t   end
power=37.883   burn=385  down=88  end
power=33.862   burn=402  down=100 end
  o 134.56
'
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
end
```

```
=sas2      parm='skipshipdata'
takahama 3 17x17 pwr, jaeri sf97-2, rod i-q, 30.73gwd/mtu
44groupndf5       latticecell
' - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
'
'   mixtures of fuel-pin-unit-cell:
'
uo2  1 den=10.412 1 900 92234 0.04 92235 4.11 92238 95.85  end
zr-94  1 0 1-20 900  end
mo-94  1 0 1-20 900  end
nb-95  1 0 1-20 900  end
mo-95  1 0 1-20 900  end
tc-99  1 0 1-20 900  end
rh-103 1 0 1-20 900  end
rh-105 1 0 1-20 900  end
ru-106 1 0 1-20 900  end
sn-126 1 0 1-20 900  end
xe-131 1 0 1-20 900  end
cs-134 1 0 1-20 900  end
cs-135 1 0 1-20 900  end
cs-137 1 0 1-20 900  end
pr-143 1 0 1-20 900  end
nd-143 1 0 1-20 900  end
ce-144 1 0 1-20 900  end
nd-144 1 0 1-20 900  end
nd-145 1 0 1-20 900  end
nd-146 1 0 1-20 900  end
nd-147 1 0 1-20 900  end
pm-147 1 0 1-20 900  end
sm-147 1 0 1-20 900  end
nd-148 1 0 1-20 900  end
pm-148 1 0 1-20 900  end
sm-148 1 0 1-20 900  end
pm-149 1 0 1-20 900  end
sm-149 1 0 1-20 900  end
nd-150 1 0 1-20 900  end
sm-150 1 0 1-20 900  end
sm-151 1 0 1-20 900  end
eu-151 1 0 1-20 900  end
sm-152 1 0 1-20 900  end
eu-153 1 0 1-20 900  end
eu-154 1 0 1-20 900  end
gd-154 1 0 1-20 900  end
eu-155 1 0 1-20 900  end
gd-155 1 0 1-20 900  end
gd-157 1 0 1-20 900  end
gd-158 1 0 1-20 900  end
gd-160 1 0 1-20 900  end
'
'   zr-4 clad
arbmzirc 6.44 4 0 0 1 40000 97.91 26000 0.5 50116 0.86 50120 0.73 2 1 600  end
'
'   moderator density based on temk and 2250 psi
h2o  3 den=0.6805  1  593  end
arbm-bormod  0.6805  1 1 0 0 5000 100 3 630e-6  593  end
uo2  8 den=10.412 1 900 92234 0.04 92235 4.11 92238 95.85  end
' arbm-gd2o3  10.412 2 0 1 1 64000 2 8016 3 8 0.06 900  end
'
end comp
'
' - - - - - - - - - - - - - - - - - - -
```

```
'
squarepitch   1.26  0.8050 1  3  0.95   2  0.822 0   end
'
' - - -
```

APPENDIX B

SAMPLE INPUT FILE FOR HELIOS
(SF-95 Sample 2)

(Aurora input file)

```
+THEL
!--+--1- - -+- - -2- - -+- - -3- - -+- - -4- - -+- - -5- - -+- - -6- - -+- - -7--+--!
SF95      = CASE('../LIBRARY/hy045n18g16a.dat'/'Sf95-2.hrf'/SF95)
! ---------------------------------------------------------------------------------- !
&SF95  = SET('A.SETS'/SF95;'17x17')
! ------------------------------- Geometry ------------------------------------- !
$xtot     =PAR("1.2600")                !Total width of assembly cell       [cm]  !
$ytot     =PAR("1.2600")               !Total height of assembly cell      [cm]  !
$xtub     =PAR("1.2600")               !Total width of guide tube cell     [cm]  !
$ytub     =PAR("1.2600")               !Total height of guide tube cell    [cm]  !
! ------------------------------- Temp etc ------------------------------------- !
$k        = PAR(4)                              ! Angular current discretization   !
$pw       = PAR(31.0)                           ! Power density             [W/gHM] !

$TWater   = PAR("273+ 320")                   ! Background temperature        [K] !
$Tfuel    = PAR("273+ 627")                   ! Fuel temperature              [K] !
$Tclad    = PAR("273+ 327")                   ! Zircalloy-2 temperature       [K] !
! ---------------------------------------------------------------------------------- !
SF95       = RUN(OUT:1)
```

(Aurora set file)

```
+SET
!-+-1- - -+- - -2- - -+- - -3- - -+- - -4- - -+- - -5- - -+- - -6- - -+- - -7-+-!
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;'17x17';&SF95) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 &Materials = SET('A.SETS'/IFBA)
 &Edit      = SET('A.SETS'/IFBA)

 &Wgap      = SET('A.SETS'/IFBA;Geometry)
 &Cgap      = SET('A.SETS'/IFBA;Geometry)
 &Bogap     = SET('A.SETS'/IFBA;Geometry)
 &HBogap    = SET('A.SETS'/IFBA;Geometry)
 &NORM      = SET('A.SETS'/IFBA;Geometry)
 &TUBE      = SET('A.SETS'/IFBA;Geometry)
 &HNORM     = SET('A.SETS'/IFBA;Geometry)
 &HTUBE     = SET('A.SETS'/IFBA;Geometry)
 &CTUBE     = SET('A.SETS'/IFBA;Geometry)
 &GDFU      = SET('A.SETS'/IFBA;Geometry)
 &HGDFU     = SET('A.SETS'/IFBA;Geometry)

 System   = CNX(HBogap,Bogap,Bogap,Bogap,Bogap,Bogap,Bogap,Bogap,Wgap, Cgap,
   HNORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,Wgap,   !11-20!
   HNORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,Bogap,  !21-30!
   HTUBE,NORM,NORM,TUBE,GDFU,NORM,NORM,NORM,NORM,Bogap,  !31-40!
   HGDFU,NORM,NORM,NORM,NORM,TUBE,NORM,NORM,NORM,Bogap,  !41-50!
   HNORM,NORM,NORM,NORM,NORM,NORM,GDFU,NORM,NORM,Bogap,  !51-60!
   HTUBE,NORM,NORM,TUBE,NORM,NORM,TUBE,NORM,NORM,Bogap,  !61-70!
   HNORM,NORM,GDFU,NORM,NORM,NORM,NORM,NORM,NORM,Bogap,  !71-80!
   HNORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,NORM,Bogap,  !81-90!
   CTUBE,HNORM,HNORM,HTUBE,HNORM,HNORM,HTUBE,HNORM,HNORM,HBogap/
     (1,3,4)$k(2,2,1)/(2,3,4)$k(3,2,1)/(3,3,4)$k(4,2,1)/
     (4,3,4)$k(5,2,1)/(5,3,4)$k(6,2,1)/(6,3,4)$k(7,2,1)/
     (7,3,4)$k(8,2,1)/(8,3,4)$k(9,2,1)/(9,3,4)$k(10,2,1)/
     (1,4,1)$k(11,3,2)/(11,3,4)$k(12,2,1)/(12,3,4)$k(13,2,1)/
     (13,3,4)$k(14,2,1)/(14,3,4)$k(15,2,1)/(15,3,4)$k(16,2,1)/
     (16,3,4)$k(17,2,1)/(17,3,4)$k(18,2,1)/(18,3,4)$k(19,2,1)/
     (19,3,4)$k(20,1,4)/(11,4,1)$k(21,3,2)/(21,3,4)$k(22,2,1)/
     (22,3,4)$k(23,2,1)/(23,3,4)$k(24,2,1)/(24,3,4)$k(25,2,1)/
     (25,3,4)$k(26,2,1)/(26,3,4)$k(27,2,1)/(27,3,4)$k(28,2,1)/
     (28,3,4)$k(29,2,1)/(29,3,4)$k(30,1,4)/(21,4,1)$k(31,3,2)/
     (31,3,4)$k(32,2,1)/(32,3,4)$k(33,2,1)/(33,3,4)$k(34,2,1)/
     (34,3,4)$k(35,2,1)/(35,3,4)$k(36,2,1)/(36,3,4)$k(37,2,1)/
     (37,3,4)$k(38,2,1)/(38,3,4)$k(39,2,1)/(39,3,4)$k(40,1,4)/
     (31,4,1)$k(41,3,2)/(41,3,4)$k(42,2,1)/(42,3,4)$k(43,2,1)/
     (43,3,4)$k(44,2,1)/(44,3,4)$k(45,2,1)/(45,3,4)$k(46,2,1)/
     (46,3,4)$k(47,2,1)/(47,3,4)$k(48,2,1)/(48,3,4)$k(49,2,1)/
     (49,3,4)$k(50,1,4)/(41,4,1)$k(51,3,2)/(51,3,4)$k(52,2,1)/
     (52,3,4)$k(53,2,1)/(53,3,4)$k(54,2,1)/(54,3,4)$k(55,2,1)/
     (55,3,4)$k(56,2,1)/(56,3,4)$k(57,2,1)/(57,3,4)$k(58,2,1)/
     (58,3,4)$k(59,2,1)/(59,3,4)$k(60,1,4)/(51,4,1)$k(61,3,2)/
     (61,3,4)$k(62,2,1)/(62,3,4)$k(63,2,1)/(63,3,4)$k(64,2,1)/
     (64,3,4)$k(65,2,1)/(65,3,4)$k(66,2,1)/(66,3,4)$k(67,2,1)/
     (67,3,4)$k(68,2,1)/(68,3,4)$k(69,2,1)/(69,3,4)$k(70,1,4)/
     (61,4,1)$k(71,3,2)/(71,3,4)$k(72,2,1)/(72,3,4)$k(73,2,1)/
     (73,3,4)$k(74,2,1)/(74,3,4)$k(75,2,1)/(75,3,4)$k(76,2,1)/
     (76,3,4)$k(77,2,1)/(77,3,4)$k(78,2,1)/(78,3,4)$k(79,2,1)/
     (79,3,4)$k(80,1,4)/(71,4,1)$k(81,3,2)/(81,3,4)$k(82,2,1)/
     (82,3,4)$k(83,2,1)/(83,3,4)$k(84,2,1)/(84,3,4)$k(85,2,1)/
     (85,3,4)$k(86,2,1)/(86,3,4)$k(87,2,1)/(87,3,4)$k(88,2,1)/
     (88,3,4)$k(89,2,1)/(89,3,4)$k(90,1,4)/(81,4,1)$k(91,3,2)/
     (91,3,4)$k(92,1,4)/(92,2,3)$k(93,1,4)/(93,2,3)$k(94,1,4)/
     (94,2,3)$k(95,1,4)/(95,2,3)$k(96,1,4)/(96,2,3)$k(97,1,4)/
```

```
     (97,2,3)$k(98,1,4)/(98,2,3)$k(99,1,4)/(99,2,3)$k(100,1,4))

 System    = BDRY((1,1,1)1(0))

mov        = OVLM( FuelN/*-*- (rim2,rimh2)       /
             Water  /*-0- H2O,*-*- (ri2,rih2,ric2)    /
             Uo2Gd2o3/*-*-(rin2,rinh2)        /
             Oxy/*-*-(rim3,rimh3,rin3,rinh3)        /
             Zr2 /*-*- (rim1,ri1,rih1,ric1,rimh1,rin1,rinh1))

 dov       = OVLD(1/*-**)

 tov       = OVLT($TWater/*-**/
            $Tfuel/*-*- (rim2,rimh2,rin2,rinh2)/
            $Tclad/*-*- (rim1,rimh1,ric1,rih1,ri1,rin1,rinh1))

 mos       = OVSM(mov)
 dos       = OVSD(dov)
 tos       = OVST(tov)

 st        = STAT(mos,dos,tos,$pw)

 BU        = PATH(/NC,(st),5000,10000,12594,(88),15000,26425,(100))

! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;&Materials) ! >>>>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 Zr2       = MAT( 6.44 / 40002,100)
 FuelN     = MAT(10.412 / 92238,95.85; 92235,4.11; 92234,0.04;8001,0)
 Uo2Gd2o3 = MAT (/ 92238,2.1308E-02; 92235,5.7627E-04 ; 92236,2.6396E-06;
    92234,4.8468E-06; 64152,3.0581E-06;64154,3.2900E-05; 64155,2.2191E-04;
    64156,3.0496E-04; 64157,2.3166E-04;64158,3.6537E-04; 64160,3.1751E-04;
    8001, 4.5988E-02)
 Oxy       = MAT(NB  /0.001/ 8016,100  )
!630ppm B in moderator  !
 Water     = MAT(NB/.6806/1001,11.188; 8016,88.749; 5010,0.0116; 5011,0.0514)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&Wgap) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 Wgap        = STR(("-$xtot/2","-0.04352/2") ("-$xtot/2"," 0.04352/2")  !  1-2  !
             ("$xtot/2"," 0.04352/2") ("$xtot/2 ","-0.04352/2")         !  3-4  !
              /4,H2O//)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&Bogap) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 Bogap       = STR(("-$xtot/2","-0.04352/2") ("-$xtot/2"," 0.04352/2")  !  1-2  !
             ("$xtot/2"," 0.04352/2") ("$xtot/2 ","-0.04352/2")         !  3-4  !
              /4,H2O//)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&HBogap) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 HBogap      = STR(("-$xtot/4","-0.04352/2") ("-$xtot/4"," 0.04352/2")  !  1-2  !
             ("$xtot/4"," 0.04352/2") ("$xtot/4 ","-0.04352/2")         !  3-4  !
              /4,H2O//)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&Cgap) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 Cgap = STR(("-0.04352/2","-0.04352/2") ("-0.04352/2","0.04352/2 ")    !  1-2  !
      ("0.04352/2 ","0.04352/2 ")  ("0.04352/2 ","-0.04352/2")         !  3-4  !
       /4,H2O//)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&NORM) ! >>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 $rim1       = PAR("0.40250")
 $rim3       = PAR("0.41100")
 $rim2       = PAR("0.47500")
```

```
 $rimi1      = PAR("0.550*$rim1")
 $rimi2      = PAR("0.820*$rim1")

 ZrRingaa    = CCS($rimi1,$rimi2,$rim1,$rim3,$rim2 // rim2,rim2,rim2,rim3,rim1)

NORM        = STR(("-$xtot/2","-$ytot/2")   ("-$xtot/2"," $ytot/2")    !  1-2  !
            (" $xtot/2"," $ytot/2")   (" $xtot/2","-$ytot/2")          !  3-4  !
                                                   ! Nodes for H2O mesh     !
            ("-$xtot/2" ,  0      )   (   0      , " $ytot/2")         !  5-6  !
            ("$xtot/2"  ,  0      )   (   0      ," -$ytot/2")         !  7-8  !
            ("-$rim2",0)(0,"$rim2")("$rim2",0)(0,"-$rim2")              !  9-12 !

             /4,H2O/ZrRingaa(0,0)/
             1, 5, 9,12, 8,H2O;    2, 6,10, 9, 5,H2O;            ! 3-4 !
             3, 7,11,10, 6,H2O)                                  ! 5-5 !
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&HNORM) ! >>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 $rimh1      = PAR("0.40250/2")          ! Outer radius of 2nd ring (MOX) [cm] !
 $rimh3      = PAR("0.41100/2")
 $rimh2      = PAR("0.47500/2")          ! Outer radius of 1st ring (Zr)  [cm] !

 ZrRingah    = CCS($rimh1,$rimh3,$rimh2 //rimh2,rimh3,rimh1)
 HNORM       = STR(("-$xtot/4","-$ytot/2")   ("-$xtot/4"," $ytot/2")    !  1-2  !
                  (" $xtot/4"," $ytot/2")   (" $xtot/4","-$ytot/2")     !  3-4  !
                                                   ! Nodes for H2O mesh     !
                  ("-$xtot/4" ,  0      )   (   0      , " $ytot/2")    !  5-6  !
                  ("$xtot/4"  ,  0      )   (   0      ," -$ytot/2")    !  7-8  !
            ("-$rimh2",0)(0,"$rimh2")("$rimh2",0)(0,"-$rimh2")          !  9-12 !

                     /4,H2O/ZrRingah(0,0)/
                     1, 5, 9,12, 8,H2O;    2, 6,10, 9, 5,H2O;           !  3-4  !
                     3, 7,11,10, 6,H2O)
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&GDFU) ! >>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 $rin1       = PAR("0.40250")
 $rin3       = PAR("0.41100")
 $rin2       = PAR("0.47500")
 $rini1      = PAR("0.550*$rim1")
 $rini2      = PAR("0.820*$rim1")

 ZrRinnaa    = CCS($rini1,$rini2,$rin1,$rin3,$rin2 // rin2,rin2,rin2,rin3,rin1)
 GDFU        = STR(("-$xtot/2","-$ytot/2")   ("-$xtot/2"," $ytot/2")    !  1-2  !
            (" $xtot/2"," $ytot/2")   (" $xtot/2","-$ytot/2")     !  3-4  !
                                          ! Nodes for H2O mesh    !
            ("-$xtot/2" ,  0      )   (   0      , " $ytot/2")    !  5-6  !
            ("$xtot/2"  ,  0      )   (   0      ," -$ytot/2")    !  7-8  !
            ("-$rin2",0)(0,"$rin2")("$rin2",0)(0,"-$rin2")         !  9-12 !

             /4,H2O/ZrRinnaa(0,0)/
             1, 5, 9,12, 8,H2O;    2, 6,10, 9, 5,H2O;            ! 3-4 !
             3, 7,11,10, 6,H2O)                                  ! 5-5 !
! ------------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&HGDFU) ! >>>>>>>>>>>>>> !
! ------------------------------------------------------------------------- !
 $rinh1      = PAR("0.40250/2")          ! Outer radius of 2nd ring (MOX) [cm] !
 $rinh3      = PAR("0.41100/2")
 $rinh2      = PAR("0.47500/2")          ! Outer radius of 1st ring (Zr)  [cm] !

 ZrRinnh     = CCS($rinh1,$rinh3,$rinh2 //rinh2,rinh3,rinh1)
 HGDFU       = STR(("-$xtot/4","-$ytot/2")   ("-$xtot/4"," $ytot/2")    !  1-2  !
            (" $xtot/4"," $ytot/2")   (" $xtot/4","-$ytot/2")          !  3-4  !
                                                   ! Nodes for H2O mesh     !
            ("-$xtot/4" ,  0      )   (   0      , " $ytot/2")         !  5-6  !
            ("$xtot/4"  ,  0      )   (   0      ," -$ytot/2")         !  7-8  !
```

```
          ("-$rinh2",0)(0,"$rinh2")("$rinh2",0)(0,"-$rinh2")          !  9-12 !

           /4,H2O/ZrRinnh(0,0)/
           1, 5, 9,12, 8,H2O;    2, 6,10, 9, 5,H2O;                   !  3-4 !
           3, 7,11,10, 6,H2O)
! ---------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&TUBE) ! >>>>>>>>>>>>>> !
! ----------------------------------------------------------------------!
 $ri1      = PAR("0.56200")            ! Outer radius of 2nd ring (H2O) [cm] !
 $ri2      = PAR("0.60200")            ! Outer radius of 1st ring (Zr)  [cm] !
 $rii1     = PAR("0.550*$ri1")
 $rii2     = PAR("0.820*$ri1")

 TRing     = CCS($rii1,$rii2,$ri1,$ri2 // ri2,ri2,ri2,ri1)
 TUBE      = STR(("-$xtub/2","-$ytub/2")   ("-$xtub/2"," $ytub/2")    !  1-2  !
           (" $xtub/2"," $ytub/2")   (" $xtub/2","-$ytub/2")          !  3-4  !
                                                   ! Nodes for H2O mesh    !
           ("-$xtub/2" ,  0      )   (   0      , " $ytub/2")         !  5-6  !
           ("$xtub/2"  ,  0      )   (   0      ," -$ytub/2")         !  7-8  !
           ("-$ri2",0)(0,"$ri2")("$ri2",0)(0,"-$ri2")                  !  9-12 !

           /4,H2O/TRing(0,0)/
           1, 5, 9,12, 8,H2O;    2, 6,10,9, 5,H2O;                    ! 3-4 !
           3, 7,11,10, 6,H2O)                                         ! 5-5 !
! ---------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&HTUBE) ! >>>>>>>>>>>>>> !
! ---------------------------------------------------------------------- !
 $rih1      = PAR("0.56200/2")          ! Outer radius of 2nd ring (H2O) [cm] !
 $rih2      = PAR("0.60200/2")          ! Outer radius of 1st ring (Zr)  [cm] !

 HTRing     = CCS($rih1,$rih2 //rih2,rih1)
 HTUBE      = STR(("-$xtub/4","-$ytub/2")   ("-$xtub/4"," $ytub/2")    !  1-2  !
            (" $xtub/4"," $ytub/2")   (" $xtub/4","-$ytub/2")          !  3-4  !
                                                   ! Nodes for H2O mesh    !
            ("-$xtub/4" ,  0      )   (   0      , " $ytub/2")         !  5-6  !
            ("$xtub/4"  ,  0      )   (   0      ," -$ytub/2")         !  7-8  !
            ("-$rih2",0)(0,"$rih2")("$rih2",0)(0,"-$rih2")              !  9-12 !

             /4,H2O/HTRing(0,0)/
             1, 5, 9,12, 8,H2O;    2, 6,10,9, 5,H2O;                   !  3-4  !
             3, 7,11,10, 6,H2O)                                        !  5-5  !
! ---------------------------------------------------------------------- !
! <<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;Geometry;&CTUBE) ! >>>>>>>>>>>>>> !
! ----------------------------------------------------------------------------
   ------------------------------------- !
 $ric1      = PAR("0.56200/4")          ! Outer radius of 2nd ring (H2O) [cm] !
 $ric2      = PAR("0.60200/4")          ! Outer radius of 1st ring (Zr)  [cm] !

 CTRing     = CCS($ric1,$ric2 // ric2,ric1)
 CTUBE      = STR(("-$xtub/4","-$ytub/4")   ("-$xtub/4"," $ytub/4")    !  1-2  !
                 (" $xtub/4"," $ytub/4")   (" $xtub/4","-$ytub/4")     !  3-4  !
                                                   ! Nodes for H2O mesh    !
                 ("-$xtub/4" ,  0      )   (   0      , " $ytub/4")   !  5-6  !
                 ("$xtub/4"  ,  0      )   (   0      ," -$ytub/4")   !  7-8  !
            ("-$ric2",0)(0,"$ric2")("$ric2",0)(0,"-$ric2")              !  9-12 !

                  /4,H2O/CTRing(0,0)/
                  1, 5, 9,12, 8,H2O;    2, 6,10,9, 5,H2O;              !  3-4  !
                  3, 7,11,10, 6,H2O)                                   !  5-5  !
! ---------------------------------------------------------------------- !
! <<<<<<<<<<<<<<<<<<< ! &ADD = SET('A.SETS'/SF95;&Edit) ! >>>>>>>>>>>>>>>>>>> !
! ---------------------------------------------------------------------- !
 ng1        = GROUP(N/0)
 ngx        = GROUP(N/0)
 gg1        = GROUP(G/0)
```

```
all         = AREA(*-*-<rim2>)
all1        = AREA(*-*-<rimh2>)
all2        = AREA(*-*-<rin2>)
all3        = AREA(*-*-<rinh2>)
alh         = AREA(19-*-<rim2>)

Nalm2       = MACRO(ngx,all/ab,fi,nf,kf,tr,p0,ch)
nalm2       = MICRO(ngx,all//ab,fi,nf,kf,tr,p0)
Nalmh2      = MACRO(ngx,all1/ab,fi,nf,kf,tr,p0,ch)
nalmh2      = MICRO(ngx,all1//ab,fi,nf,kf,tr,p0)
Naln2       = MACRO(ngx,all2/ab,fi,nf,kf,tr,p0,ch)
naln2       = MICRO(ngx,all2//ab,fi,nf,kf,tr,p0)
Nalnh2      = MACRO(ngx,all3/ab,fi,nf,kf,tr,p0,ch)
nalnh2      = MICRO(ngx,all3//ab,fi,nf,kf,tr,p0)
Nallh       = MACRO(ngx,alh/ab,fi,nf,kf,tr,p0,ch)
nallh       = MICRO(ngx,alh//ab,fi,nf,kf,tr,p0)
LOCBU       = MACRO(ngx,all/bu)
LOCBUH      = MACRO(ngx,alh/bu)
! ------------------------------------------------------------------------------ !
! <<<<<<<<<<<<<<<<  E n d   o f   A u r o r a   s e t s   >>>>>>>>>>>>>>>>>> !
! ------------------------------------------------------------------------------ !
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(2-89)
NRCM 1102
3201, 3202

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BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR- 6798
ORNL/TM-2001/259

2. TITLE AND SUBTITLE

Isotopic Analysis of High-Burnup PWR Spent Fuel Samples From the Takahama-3 Reactor

3. DATE REPORT PUBLISHED

MONTH	YEAR
January	2003

4. FIN OR GRANT NUMBER

W6479

5. AUTHOR(S)

C. E. Sanders and I. C. Gauld

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION — NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Oak Ridge National Laboratory
Managed by UT-Battelle, LLC
Oak Ridge, TN 37831-6370

9. SPONSORING ORGANIZATION — NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Regulatory Commission, and mailing address.)*

Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

R. Y. Lee, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This report presents the results of computer code benchmark simulations against spent fuel radiochemical assay measurements from the Kansai Electric Ltd. Takahama-3 reactor published by the Japan Atomic Energy Research Institute. Takahama-3 is a pressurized-water reactor that operates with a 17 × 17 fuel-assembly design. Spent fuel samples were obtained from assemblies operated for 2 and 3 cycles and achieved a maximum burnup of 47 GWd/MTU. Radiochemical analyses were performed on two rods having an initial enrichment of 4.11 wt %, and one integral burnable absorber rod containing Gd_2O_3. These measurements represent the highest enrichment and highest burnup samples currently available in the United States. The benchmark results are important to burnup credit initiatives in the United States since the lack of available benchmark data has led to restrictions on the allowable credit beyond 4.0 wt % and 40 GWd/MTU. Although the primary objective of the measurements was support of burnup credit, radiochemical analyses were also available for a number of actinide and fission product nuclides important to decay heat and radiation source term analysis. Isotopic predictions from both the SCALE 4.4a and HELIOS-1.6 code systems were used in this benchmark study. The results indicate that the level of agreement between predictions and measurements is very good. The results, for the most part, are consistent with the findings of earlier studies for lower enrichment and lower burnup samples and yield similar biases and levels of uncertainty.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

spent fuel, isotopic analysis, pressurized water reactor, high burnup, code validation

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

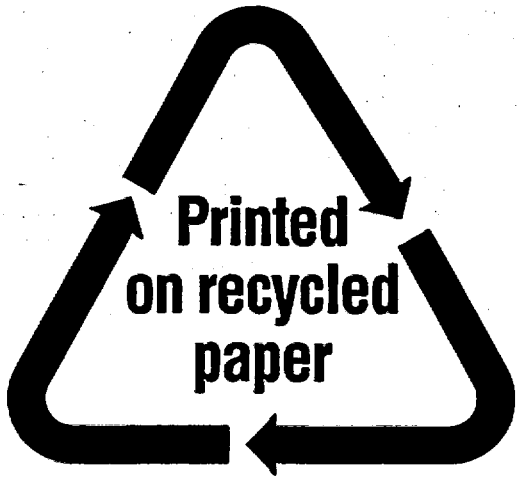
(This Page) unclassified

(This Report) unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)



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