M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

Verifying Safeguards Declarations with INDEPTH: A Sensitivity Study

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Abstract – *A series of Oak Ridge Isotope Generation (ORIGEN) calculations were used to simulate the irradiation and decay of a number of spent fuel assemblies. These simulations focused on variations in the irradiation history that achieved the same terminal burnup through a different set of cycle histories. Simulated nondestructive assay (NDA) measurements were generated for each test case from the ORIGEN data. These simulated measurement types included relative gammas, absolute gammas, absolute gammas plus neutrons, and concentrations of six isotopes commonly measured by NDA. The Inverse Depletion Theory (INDEPTH) code was used to reconstruct the initial enrichment, cooling time, and burnup for these assemblies using each simulated measurement type. The results were then compared to the initial ORIGEN inputs to quantify the size of the errors induced by the variations in cycle histories. Errors were compared based on the underlying changes to the cycle history as well as the data types used for the reconstructions.*

I. INTRODUCTION

As part of international safeguards protocols, inspectors may conduct nondestructive analysis (NDA) measurements of spent fuel assemblies to verify the declared initial enrichments, burnups, and cooling times. Current agreements require that these assemblies remain accessible to inspectors on demand. As some countries begin to implement plans for encapsulation and final disposal of the fuel (e.g., Sweden [1]), new procedures must be developed. One option is to make measurements of each assembly sufficient to verify the operator declarations at the time of encapsulation. The Inverse Depletion Theory (INDEPTH) code [2,3] may be useful for analyzing these measurements and verifying the operator declarations.

The INDEPTH code reconstructs design and operating history parameters like the initial enrichment, cooling time, and burnup of an assembly based on measurements. An INDEPTH analysis uses the Oak Ridge Isotope Generation (ORIGEN) code, version 6.1 [4], to simulate the irradiation and cooling of an assembly and subsequently calculate the final concentrations of isotopes and related quantities such as gamma and neutron emission rates. The ORIGEN code is part of the SCALE code system [5]. The simulated values from ORIGEN are compared to measurements to determine how well the two match. The goodness of the match is quantified using a sum of squared errors (SSE) function. A gradient-based search technique modifies the assembly parameters iteratively until the set that produces the global minimum SSE value is found.

This work quantifies how changes in the irradiation history of an assembly can affect the results of the INDEPTH reconstruction. The goal is to determine how much INDEPTH reconstruction results vary when assemblies with the same initial enrichment are irradiated to the same terminal burnup through different cycle histories. In theory, an INDEPTH analysis could be used to reconstruct the irradiation history on a cycle-by-cycle basis. Such a reconstruction would have to calculate the number of cycles plus the average power level, length, and subsequent shutdown cooling time for each cycle. As a practical matter, errors in the measurements, uncertainties in the effective nuclear data used by ORIGEN, and a lack of measureable nuclides with the required sensitivities precludes accurately reconstructing the irradiation history with this level of detail.

Previous studies have shown that these changes may result in non-unique solutions. For example, Cheatham and Francis [6] and Skutnik and Davis [7] examined how much irradiation histories could vary and still produce the same set of final isotopes to within 5% uncertainty. Both studies showed that moderately large regions of the phase space of burnup, cooling time, and initial enrichment could produce indistinguishable sets of isotopes. These non-unique areas are referred to as *degeneracy spaces*. Increasing the number of isotopes being studied reduced the size of the degeneracy space but did not eliminate it completely except in a single exceptional case studied by Skutnik and Davis [7].

Rather than devoting extensive processing time to calculating a precise but likely inaccurate cycle history, INDEPTH reconstructions assume a simple irradiation model. This model assumes a single uniform-power irradiation from birth to discharge. The optimized length and power level of this irradiation are used to calculate the burnup value reported by INDEPTH. If a degeneracy space exists, then the reported values may be non-unique. Over a group of assemblies, this non-uniqueness should result in a widening of the distribution of results around the expected values. One issue of interest is to determine how much the simplified irradiation history affects the reconstruction results. This effect has previously been assumed to be small; however, one work [8] has shown that certain isotope ratios, such as $^{134}Cs/^{137}Cs$ could be altered by as much as 30% by changes in the cycle history while maintaining the same terminal burnup.

To answer the questions posed, a large number of varied irradiation histories were modeled using ORIGEN calculations. The ORIGEN results were used to produce synthetic NDA measurement data, which were then used to perform INDEPTH reconstructions. Generating the INDEPTH inputs in this manner removes any possible errors due to measurements and effective nuclear data. Thus these results effectively test how well the search algorithm can perform when given near-ideal inputs. Each INDEPTH result was compared to the original parameter values in the ORIGEN model to assess the magnitude of the errors due to changes in the irradiation history.

II. DESCRIPTION OF THE ACTUAL WORK

ORIGEN was used to model the irradiation and cooling of a large number of (468) spent fuel assembly histories. The modeled assemblies are all variations of a base irradiation case. The base case consists of five equal-power irradiation cycles of 330 days each with 30 days of shutdown cooling between cycles. This results in a total residence time (time elapsed between start of the first irradiation cycle and end of the final cycle) of 1,770 days. This base case was split into 36 variants that include four assembly types; three initial enrichment/burnup combinations (low-enrichment/near-complete burnup, high-enrichment/partial burnup, and high-enrichment/near-complete burnup); and three different cooling times. The individual values were chosen to cover as much of the design/enrichment/burnup/cooling time phase space as possible given the necessarily limited number of simulations possible. Each variant was constructed by combining one assembly type, one initial enrichment/burnup, and one cooling time. Table I shows the characteristics of these variants.

Table I. Characteristics of the 36 modeled variants. (One value from each of the three columns forms a variant.)

Assembly Type	Initial Enrichment (%)/ Burnup (GWd/MTU)	Cooling Time (years)
15 × 15 PWR	2.0 / 20	10
17 × 17 PWR	3.5 / 20	20
8 × 8 BWR	3.5 / 45	30
10 × 10 BWR		

The 36 variants with uniform 330-day cycles and 30 days between cycles are collectively referred to as *Case 0*. They represent a nominal cycle history that might be expected during routine nuclear power plant operations. This default cycle history was modified in 12 different ways to generate Cases 1–12. Examples of these changes include longer cycles, power levels that change from one cycle to the next, longer downtimes between all cycles, a single long down time between one set of cycles, and more or fewer cycles.

One change of particular note is Case 1, which removes the cooling times between cycles completely. This case was chosen because it most closely matches the simplified irradiation pattern assumed by INDEPTH. A comparison of results between Cases 1 and 0 should quantify the error imparted by the uniform irradiation assumption. The results of the various cases should help to define when this approximation might not hold. Examples of power histories for some of the cases are shown in Figs. 1 and 2 for illustration purposes. Table II shows the variables that were changed for all 12 cases.

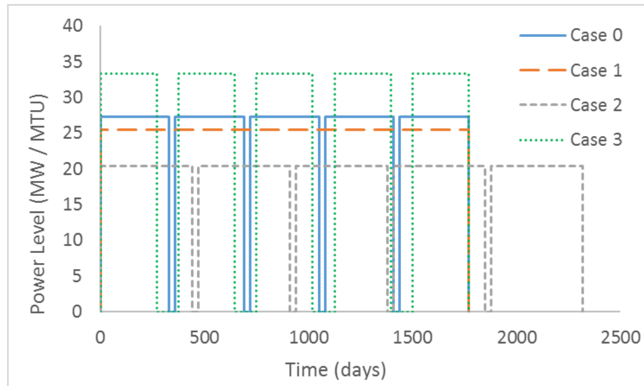

Fig. 1. Illustration of four cycle histories: Case 0 (base), Case 1 (single continuous cycle), Case 2 (longer cycles), and Case 3 (shorter cycles with longer shutdowns in between).

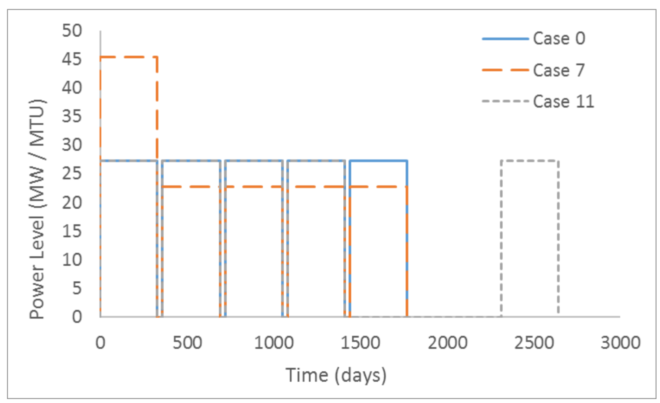

Fig. 2. Illustration of three cycle histories: Case 0 (base), Case 7 (higher power on first cycle), and Case 11 (900-day shutdown time between final pair of cycles).

Table II. Descriptions of Test Cases

Case	Description
0	Base case; five uniform 330-day cycles with 30-day shutdowns in between. Total residence time = 1770 days.
1	Single, continuous irradiation
2	Longer power cycles
3	Shorter cycles with correspondingly longer shutdowns in between; same total residence time as Case 0
4	Longer shutdowns between power cycles
5	Fewer (4), longer cycles; same total residence time as Case 0
6	More (6), shorter cycles; same total residence time as Case 0
7	Different power on cycles (first cycle higher)
8	Different powers on cycles (middle cycle higher)
9	Different powers on cycles (last cycle higher)
10	300-day decay between 4th & 5th cycles
11	900-day decay between 4th & 5th cycles
12	900-day decay between 1st & 2nd cycles

The ORIGEN simulations produced sets of isotope concentrations at the end of the final decay period. To simulate NDA measurements, gamma and neutron yield libraries were used to calculate gamma line and total neutron intensities. These quantities can be measured nondestructively using high-resolution gamma spectroscopy and a gross neutron counter such as a fission chamber.

For gamma data, lines were limited to those that would be reasonably detectable in an NDA measurement by applying a statistical uncertainty cutoff. The 1274-keV line from ^{154}Eu was assumed to have a 1% uncertainty. This uncertainty threshold was targeted in a recent set of spent fuel measurements [9] to limit the live time of measurements. The uncertainties of other lines were assumed to scale based on the inverse square roots of their intensities relative to the 1274-keV line. Only the lines with uncertainties of less than 10% were included in the simulated gamma spectra. The gamma lines passing this uncertainty threshold come primarily from ^{134}Cs, ^{137}Cs, and ^{154}Eu. In some spectra with short cooling times, lines from short-lived daughter products of ^{106}Ru and ^{144}Ce are also present.

For total neutrons, the emissions come almost entirely from the spontaneous fission of ^{244}Cm. In a real measurement, the total neutron counts would include multiplication in the assembly. The synthetic neutron data assume that the contributions from multiplication have been corrected. References 8 and 10 give examples of how such a correction could be performed on a real measurement. The total neutron inputs to INDEPTH were assumed to have a relative uncertainty of 5%. Table III shows the six isotopes that may contribute to the NDA gamma and neutron inputs used by INDEPTH.

Table III. NDA Isotopes

Isotope	Half-Life (years)
^{134}Cs	2.07
^{137}Cs	30.1
^{154}Eu	8.60
^{106}Ru	1.02
^{144}Ce	0.78
^{244}Cm	18.1

In total, four sets of synthetic measurement data were generated for the purpose of testing INDEPTH reconstructions.:

1. **Relative gammas (GREL)**: Gamma data with no absolute basis (i.e., only the relative intensity of one line to another is considered meaningful).
2. **Absolute gammas (GABS)**: Gamma data with an absolute intensity basis (i.e., gammas emitted per metric ton of uranium).
3. **Absolute gammas + total neutron (G+N)**: Combination of gamma lines and total neutrons, both with absolute intensity bases.
4. **NDA Isotopes (Isos)**: Absolute concentrations (in grams per metric ton of uranium) of the six gamma and neutron NDA isotopes.

Type #4 (Isos) is not really a measurement, but rather an idealized version of #3 (G+N) in which the concentrations of all six isotopes have been calculated. It would be extremely difficult, if not impossible, to measure some of these isotopes nondestructively for assemblies with long cooling times. This makes measurement type #4 a good bounding limit for the best set of data that could be obtained using gamma spectroscopy and neutron counting. Each isotope was assigned a relative uncertainty of 5%, giving them an equal weighting. Moving in ascending order from type #1 to type #4, each measurement adds additional data for the INDEPTH reconstruction.

For each measurement type, the synthetic data were used as inputs for INDEPTH reconstructions. The inputs included both the intensities and the uncertainties The INDEPTH optimization procedure was then used to find the minimum value of the SSE function, which is calculated using Eq. (1):

$$SSE = \sum_{i=1}^{n} \frac{\left(C_{i,INDEPTH} - C_{i,input}\right)^2}{\sigma_i^2}, \qquad (1)$$

where C_i is a specific data value (e.g., a gamma line intensity), σ_i is the uncertainty of the input value, and n is the number of data values in the input.

The uncertainties in the inputs are used as weighting terms for the SSE calculation, giving inputs with lower relative uncertainties a greater importance in the SSE formulation. In this work, no random noise was added to the data (i.e., values calculated by ORIGEN were taken directly as INDEPTH inputs), so the INDEPTH reconstructions can in theory match the ORIGEN inputs exactly.

III. RESULTS

Average Results by Measurement Type

For all combinations of cases and variants, the four synthetic measurement types were used as inputs for INDEPTH reconstructions. Tables IV, V, and VI show the average absolute error percentages for each case in the reconstructed initial enrichments, cooling times, and burnups, respectively. These results serve to show how different changes in the operating history affect the results for each input type. The shading in the tables indicates the magnitudes of the errors, with dark green representing < 2%, light green 2%–5%, yellow 5%–10%, orange 10%–25%, and red > 25%. These errors were calculated using the known values from the initial ORIGEN simulations used to generate the synthetic measurements.

Table IV. Average absolute error percentages in reconstructed initial enrichment values.

Case	1. GREL	2. GABS	3. G+N	4. Isos
0	12.82	15.86	1.58	0.41
1	3.28	7.33	0.32	0.20
2	12.83	15.84	1.10	0.20
3	25.08	1.01	10.40	1.81
4	22.84	1.19	13.69	0.30
5	9.93	15.66	1.89	0.43
6	14.05	22.24	1.89	0.42
7	19.80	22.83	2.51	0.48
8	17.32	25.12	2.05	0.55
9	42.73	22.86	1.65	1.09
10	20.61	1.65	14.58	0.99
11	39.78	3.56	23.73	4.40
12	15.54	1.63	9.48	1.24

Table V. Average absolute error percentages in reconstructed cooling time values.

Case	1. GREL	2. GABS	3. G+N	4. Isos
0	0.91	1.17	0.68	0.38
1	0.23	0.49	0.05	0.04
2	0.85	1.15	0.56	0.21
3	2.22	0.49	1.90	1.51
4	1.76	0.72	2.02	0.58
5	0.88	1.05	0.48	0.37
6	1.13	1.49	0.78	0.40
7	2.53	2.83	2.31	0.47
8	1.71	2.05	1.34	0.47
9	2.11	2.00	1.91	1.44
10	3.47	0.88	3.27	0.96
11	6.53	1.55	7.12	4.50
12	1.09	0.85	0.93	0.54

Table VI. Average absolute error percentages in reconstructed burnup values.

Case	1. GREL	2. GABS	3. G+N	4. Isos
0	4.83	1.52	0.66	0.27
1	1.20	0.75	0.13	0.06
2	5.43	1.56	0.48	0.26
3	10.07	0.64	0.72	0.26
4	9.95	0.64	0.75	0.33
5	3.94	1.93	0.68	0.35
6	5.15	2.60	0.66	0.27
7	7.25	2.90	1.40	0.19
8	5.90	3.52	0.65	0.20
9	13.77	3.38	1.07	0.50
10	10.93	0.95	0.88	0.21
11	23.88	1.91	2.42	1.92
12	6.84	1.06	1.14	0.59

From the results shown in Tables IV, V, and VI, the following observations can be made about the accuracy of the INDEPTH results:

- GREL produces the worst results in many cases. There are seven cases where GREL data produce slightly better initial enrichment and cooling time results, but worse burnup results, than GABS. These are all cases with shutdowns between cycles equal to or less than Case 0. GREL results for initial enrichment were quite poor, with almost all errors exceeding 10%, and several exceeding 25%. For cooling time, results were relatively good, with a maximum average error of

6.53% for Case 11. For burnup, results were mixed: < 5% for three cases, >10% for four cases, and between 5% and 10% for six cases.

- GABS data produced better initial enrichment and cooling time results than GREL in six cases, five of which have longer cooling times between cycles. Burnup reconstructions with GABS data are better than GREL in all 13 cases. Initial enrichment results are varied: five cases have errors of less than 10%, seven are greater than 15%, and one is in between. Cooling times are generally good, with all under 3%. All burnup results are good with values of < 4%.
- G+N data produced better results than GABS data for nine cases. For five cases (3, 4, 10, 11, and 12), G+N performed worse. These five cases all have increased cooling times between cycles relative to Case 0. Eight initial enrichment errors were less than about 2.5%, while the remaining five were 10% or greater. Most cooling time results are about 3% or less, except for Case 11, which was 7.12%. For burnup, all results were well below 2%, except for Case 11, which was 2.42%.
- The NDA isotope (Isos) data produced the lowest errors of all measurement types in almost every case. The exceptions were Cases 3 and 11, which have longer cooling times between one or more cycles. Errors were generally less than 1%, with the primary exception being Case 11, where initial enrichment and cooling time errors were over 4% and the burnup error was almost 2%. Otherwise, the Isos results were excellent.
- For all cases, the better of the GABS or G+N results were within 3.6% for initial enrichment, cooling time, and burnup at worst. Overall, the errors tend to be within 1% of the error of the idealized Isos result. This suggests that if it could be determined a priori whether or not to use the neutron data, accuracies approaching the hypothetical best case could be obtained.
- As noted in the introduction, Case 1 models the assumed INDEPTH irradiation history (single, continuous cycle). Errors for this case should represent the limits of the INDEPTH algorithm as implemented. Results for this case tend to be exceptional, with values much less than 1% in nearly every instance. The only notable exceptions are the GREL and GABS initial enrichments, which have errors of 3.28% and 7.33%, respectively. They most likely indicate areas where the gradient is essentially flat (i.e., degeneracies) with respect to initial enrichment.
- To the extent that the base case (Case 0) is a good representation of a "normal" irradiation history, the differences between the Case 1 and Case 0 results represent the bias typically induced by the INDEPTH assumption of a single, uniform irradiation cycle. The magnitude of this bias will be examined in the next section.

Case 0 (Base) Results

In this section, the individual results for Case 0 are examined. For brevity, only results for the GABS and G+N inputs are discussed. GREL results were generally much poorer, and the Isos data as presented could not be easily measured. Fig. 3 shows the relative errors of the INDEPTH results for each of the 36 Case 0 variants using GABS data. From left to right, these variants are arranged as follows:

- Four groups of nine variants for each assembly type (15 × 15 PWR, 17 × 17 PWR, 8 × 8 BWR, and 10 × 10 BWR)
- Within each assembly type, groups of three for each cooling time (10, 20, and 30 years)
- Within each cooling time, three initial enrichment/burnup combinations: 2.0%/20 GWd/MTU, 3.5%/20 GWd/MTU, and 3.5%/45 GWd/MTU.

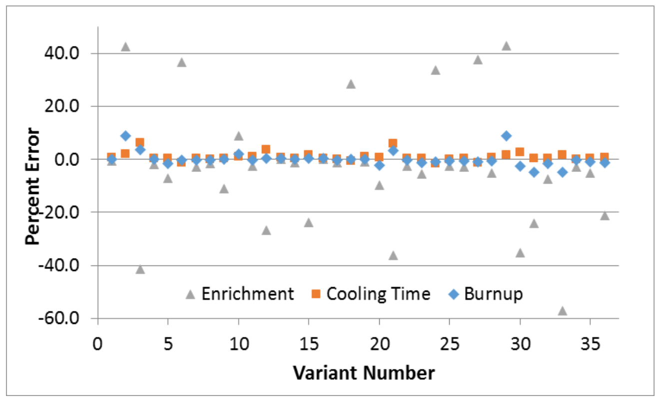

Fig. 3. Case 0 individual reconstruction results using the GABS input data.

It can be seen in Fig. 3 that the initial enrichment errors dwarf the cooling time and burnup errors. Approximately half of the initial enrichment errors are greater than 20% absolute, while the other half tend to be 10% or less. This indicates that even for near-ideal conditions (i.e., no measurement errors) the GABS data can result in large errors in the initial enrichment reconstructions. Not apparent from Fig. 3 is the fact that most of the variants with large absolute errors are the 3.5% enrichment scenarios. Variants with a 2% modeled initial enrichment have an average absolute error of 4.0%, while those with a 3.5% initial enrichment have a 20.0% average absolute error. This difference may simply be caused by the fact that the higher initial enrichment permits a much larger range of possible terminal burnup values. The direction of the initial enrichment errors appears to be essentially random. A calculation of the average error (NOTE: not absolute) does reveal a bias of −3.0%. This bias is actually somewhat smaller than the −6.1% bias for Case 1.

A closer examination (not shown) of the GABS cooling time and burnup errors does not reveal any obvious trend among the variants. The cooling time errors show a slight positive bias of +0.9%, while the burnup bias is <0.1%. Relative to Case 1, the cooling time bias is 0.5% higher, while the burnup bias is actually 0.2% lower.

In Fig. 4, there is some obvious periodicity in the G+N results. In initial enrichment, there is a trend where every third result tends to have an initial enrichment error of about +2%. These are the variants with the 2.0% modeled initial enrichment, although the three variants with initial enrichment errors in the 4% to 6% range have a 3.5% initial enrichment. For cooling time, there is a periodicity within assembly types, with a decreasing error as the cooling time decreases. This decrease likely is because the same absolute error (e.g., 0.1 years) represents a smaller error percentage as the modeled cooling time increases. Burnup tends to show this same trend, although the strength of the correlation between the error and cooling time is less obvious.

For the three parameters, the biases are +1.5% for initial enrichment, +0.7% for cooling time, and +0.5% for burnup. For G+N, the biases for Case 1 are negligible (all parameters < 0.1%), so these biases are also the difference between Cases 0 and 1.

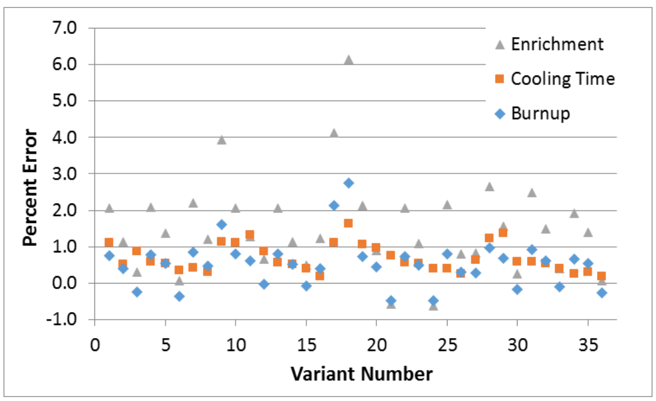

Fig. 4. Case 0 individual reconstruction results using the G+N input data.

Case 11 Results

This section examines Case 11 results examined in more detail. Case 11 was the most extreme case tested in terms of a long shutdown period before the final irradiation cycle, and it produced some of the worst INDEPTH results. The INDEPTH errors using the G+N inputs were worse for Case 11 than for any other case, and for initial enrichment and burnup, GABS produced smaller absolute errors. Fig. 5 shows the GABS results for each of the individual variants.

The most obvious trend in Fig. 5 is that the last three variants for each assembly tend to show significantly larger (negative) errors in initial enrichment and burnup. These variants represent the 30-year cooling times. All other results fall within a range of ± 5% except for two outliers in the +10% to 15% range. The most likely cause of the larger errors for the long cooling times is that the ^{134}Cs lines are either very weak or absent from the INDEPTH inputs. Without those data points, the reconstruction would be expected to produce poorer results. On average, the biases are −2.0% for initial enrichment, +0.8% for cooling time, and +1.1% for burnup.

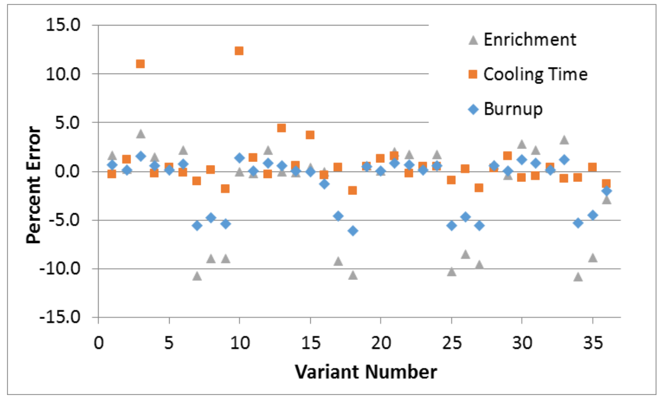

Fig. 5. Case 11 individual reconstruction results using the GABS input data.

Fig. 6 shows results for the variants using the G+N data. The most obvious feature is the number of very large negative errors in initial enrichment results. A large number of the errors are clustered around −20%; several others are even worse in the −40% to −80% range. The worst results tend to belong to variants with the higher modeled initial enrichment, although there are several exceptions. Unlike with GABS data, there is no clear trend between modeled cooling time and initial enrichment results. On average, the initial enrichment errors showed a bias of −22.6%.

The cooling time results show a clear trend between the modeled cooling time and the error, with longer cooling times resulting in smaller positive errors. With burnup, no clear trends are apparent, although they do appear to exhibit a small negative bias. The biases for cooling time and burnup were +6.7% and −1.6%, respectively.

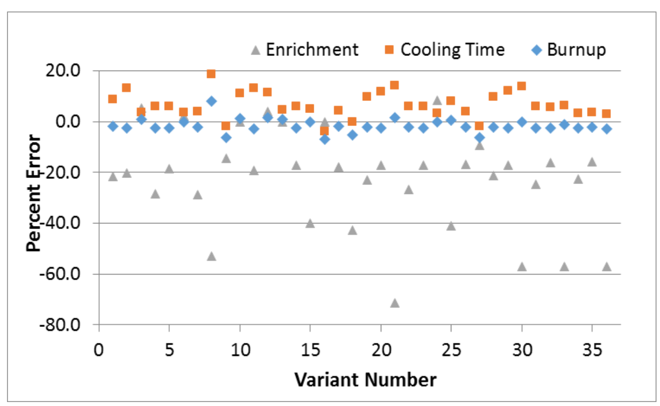

Fig. 6. Case 11 individual reconstruction results using the G+N input data.

Fig. 7 shows the individual results for each of the variants using the Isos data. The results are plotted using the same vertical scale as the GABS data for easy comparison. Except for the 30-year cooling time variants, and the two outliers at > 10% noted earlier, the GABS results show less variation in the initial enrichment and burnup. In terms of biases, reconstructions with Isos performs worse than with GABS data: +4.4% for initial enrichment, +2.8% for cooling time, and −1.8% for burnup. However, the spread (standard deviation) of results is lower with Isos than GABS for all three parameters.

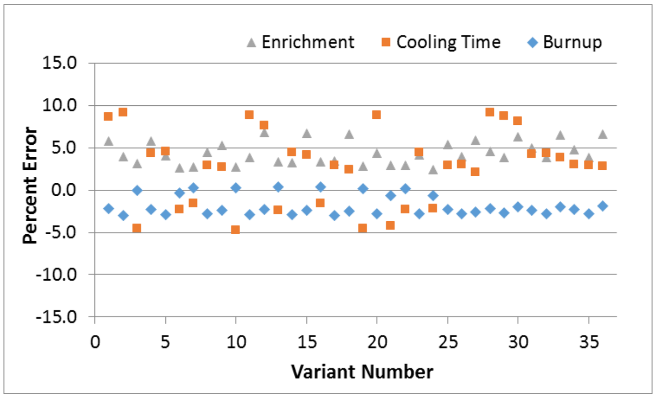

Fig. 7. Case 11 individual reconstruction results using the NDA isotopes (Isos) input data.

IV. CONCLUSIONS

The purpose of this work was to study how changes in the irradiation history of a spent fuel assembly affected INDEPTH reconstruction results for initial enrichment, cooling time, and burnup. A large number of cycle histories were simulated using the ORIGEN 6.1 code to generate synthetic gamma, neutron, and isotope measurement data. These data were used as inputs for INDEPTH reconstructions, and then the final INDEPTH results were compared to the original ORIGEN values to assess the magnitude of errors induced by the various changes.

Six isotope concentrations were modeled to simulate a best case for NDA measurements. They represent the full set of isotopes that could be measured using current NDA techniques. In many cases, all of these isotopes would not be measureable; thus the results represent a lower limit for reconstruction errors. The isotopes tended to produce average errors well under 1%, although for one case (Case 11), the initial enrichment and burnup errors were 4.5%. This case modeled a long shutdown period (900 days) between the final set of cycles, and produced some of the largest errors.

Of the gamma and neutron measurement types simulated, the relative gamma data (GREL) produced the worst results overall. In all modeled cases, either the absolute gammas (GABS) or absolute gamma plus neutrons (G+N) produced lower absolute errors. The difference was especially pronounced for burnup, where GREL underperformed all other data types for all cases. It should therefore be recommended that whenever possible, an absolute scaling should be obtained for NDA gamma measurements.

For the GABS and G+N data, the GABS results tended to be better for cases with long shutdowns between cycles. This was particularly evident when a long shutdown occurred between the final set of cycles. For other cases, the G+N results were superior. For initial enrichment, the differences were quite pronounced. The worse member of the pair produced initial enrichment errors of 10% to 25%, while the better member produced errors of 1% to 4%. This would suggest that neither data type is completely suited for determining the initial enrichment across a varied set of irradiation histories. The same trend is observed for cooling time and burnup reconstructions; however, in that case, even the worse member of the pair tends to produce average errors of less than 5%.

One particular result of note was Case 1, which simulated a single, uniform irradiation cycle. The INDEPTH code assumes this irradiation history when performing reconstructions. In order to assess the effect of this simplifying assumption, results for Case 1 were compared to the base case (Case 0), which modeled a nominal irradiation history of five uniform cycles with shutdown periods in between. With GABS data, the bias for cooling time was 0.5% worse, while the initial enrichment and burnup were actually better than the uniform case. For the G+N data types, the biases were +1.5% for initial enrichment, +0.7% for cooling time, and +0.5% for burnup.

Plans for future work include exploring the reason that adding neutron data (i.e., G+N instead of GABS) produces worse results when the irradiation history includes long shutdown periods. This will include tracking the evolution of the six NDA isotopes from the start of irradiation until the end of the cooling time. One goal of that research will be to determine if a set of metrics can be identified that will determine whether or not the neutron data should be used before the INDEPTH reconstruction is performed. If such a determination could be made a priori, then the accuracy of reconstructions with either GABS or G+N could be expected to approach the best-case Isos results.

ACKNOWLEDGMENTS

This work was performed under the support of the Spent Fuel NDA project (formerly Next Generation Safeguards Initiative – Spent Fuel, or NGSI-SF), Office of Nonproliferation and Arms Control (NPAC), National Nuclear Security Administration (NNSA).

NOMENCLATURE

BWR = boiling water reactor
G+N = (absolute) gammas plus neutrons
GABS = absolute gammas
GREL = relative gammas
GWd/MTU = gigawatt days per metric ton uranium
INDEPTH = Inverse Depletion Theory (code)
Isos = NDA isotopes
NDA = nondestructive analysis
ORIGEN = Oak Ridge Isotope Generation (code)
PWR = pressurized water reactor
SSE = sum of squared errors

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