Draft Report

NATIONAL INSTITUTE FOR
OCCUPATIONAL SAFETY AND HEALTH

ADVISORY BOARD ON RADIATION AND WORKER HEALTH

SC&A REVIEW OF NIOSH RESPONSES TO SC&A REVIEW OF ORAUT-OTIB-0054, FINDINGS 1–4:

FISSION AND ACTIVATION PRODUCT ASSIGNMENT FOR INTERNAL DOSE-RELATED GROSS BETA AND GROSS GAMMA ANALYSES

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SC&A Review of NIOSH Responses to SC&A Review of ORAUT-OTIB-0054, Findings 1–4: ***Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses***	Supersedes: N/A
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REVISION LOG

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ABBREVIATIONS AND ACRONYMS

ABRWH	Advisory Board on Radiation and Worker Health
Al	Aluminum
ATR	Advanced Test Reactor
BRS	Board Review System
CANDU	CANada Deuterium Uranium (reactor)
DOE	U.S. Department of Energy
FFTF	Fast Flux Test Facility
g	gram
GA	General Atomics
INL	Idaho National Laboratory
kg	kilograms
kW	kilowatt
lb	pound
MW	Megawatt
MW_{th}	Megawatt thermal
MWd	Megawatt Day
MTHM	Metric Tons of Heavy Metal
MTU	Metric Tons of Uranium
$n/(cm^2$-sec)	neutrons per centimeter squared per second
NIOSH	National Institute for Occupational Safety and Health
ORAUT	Oak Ridge Associated Universities Team
ORIGEN	Oak Ridge Isotope Generator
ORNL	Oak Ridge National Laboratory
OTIB	ORAUT Technical Information Bulletin
PWR	Pressurized Water Reactor
SC&A	S. Cohen and Associates (SC&A, Inc.)
sec	second
SS	Stainless Steel
TRIGA	Training, Research, Isotopes, General Atomic
U	uranium
U.S.	United States
UZrH	uranium zirconium hydride
wt%	Weight Percent

1.0 INTRODUCTION

1.1 BACKGROUND

Frequently, air-sampling or urinalysis data on worker exposure to mixed fission and activation products associated with nuclear reactors or nuclear fuel are available only in the form of gross beta or gross gamma activity unattributed to specific radionuclides. This is particularly true for exposures during the early decades of the U.S. nuclear program. For those cases, ORAUT-OTIB-0054, *Fission and Activation Product Assignment for Internal Dose-Related Gross Beta and Gross Gamma Analyses* (hereafter referred to as "the OTIB" or "OTIB-0054") provides guidance and a standard approach to the dose reconstructor on how to assign radionuclide-specific intakes to exposed workers.

SC&A reviewed Rev. 0 of the Oak Ridge Associated Universities technical information bulletin (OTIB) (ORAUT 2007) in 2008 (SC&A 2008) and identified 26 issues, some of which were subsequently resolved through work of the Advisory Board on Radiation and Worker Health (ABRWH) Subcommittee on Procedures Review, the National Institute for Occupational Safety and Health (NIOSH), and SC&A. The technical basis of the OTIB was substantially revised from Rev. 0 to Rev. 1 (ORAUT 2013), leading the Subcommittee at its July 18, 2013, meeting to authorize SC&A to perform a full *de novo* review of Rev.1. SC&A presented its comprehensive technical review of Rev. 1 of the OTIB in its November 2013 report (SC&A 2013). That review produced 10 findings, which NIOSH responded to on February 4, 2014, via entries to the online Board Review System (BRS). Those 10 findings were labelled 27–36, but were also numbered 1–10 for convenience, as they replaced the original group of 26 following SC&A's *de novo* review; the latter numbering will be used throughout this report.

While SC&A comments were made on Rev. 1 of the OTIB (ORAUT 2013), they apply equally to Rev. 2, issued on March 6, 2014 (ORAUT 2014a). The Publication Record for Rev. 2 states:

> *Revision initiated to correct an error with the Pm-147 intake fractions in Tables 7-3b and 7-3c. The values had mistakenly been entered as zeros. No changes occurred as a result of formal internal review.*

SC&A checked that NIOSH did indeed make that correction in Rev. 2 of those two tables, for the ATR (Advanced Test Reactor) 2 and ATR 3, respectively. Based on a cursory comparison of Rev. 1 and Rev. 2, SC&A did not notice any other changes to the documents. In addition, the changes from Rev. 1 to Rev. 2 do not affect Findings 1–4.

Subsequent to SC&A's review of the OTIB in SC&A 2013, the Subcommittee on Procedures Review teleconferences that discussed the OTIB were held on November 7, 2013; February 13, 2014; April 16, 2014; August 28, 2014; and November 25, 2014. In addition, SC&A, NIOSH, and ORAUT (NIOSH's subcontractor) participated in technical calls to obtain clarification on specific items on May 13, 2014, and October 2, 2014. SC&A issued Rev. 0 of this report on

April 10, 2014 (SC&A 2014), and has now revised it following receipt of ORAUT 2014b, the so-called Reactor Modeling Report,[1] which responds to Findings 1–4.

1.2 SUMMARY OF STATUS OF FINDINGS

The status of, and information about, the 10 findings can be found in the BRS system. The current entries for Findings 1–4, the subject of this evaluation, are shown in Table 1.

Table 1. Status of Findings 1–4 on ORAUT-OTIB-0054 [(a),(b)]

Finding	Board Review System (BRS) Entries	Status
1	Ostrow, Stephen (SC&A), 11/5/2013: SC&A is not able to evaluate the appropriateness of the input parameters used for the ORIGEN2 runs since they are not specified, or references cited in the OTIB. For more discussion on this finding see the attached SC&A report SCA-TR-PR-2013-0084 [SC&A 2013]. Burns, Bob (ORAUT), 2/4/2014: The ORIGEN2 runs and the process of down-selecting to four representative reactors were not affected by the revision. A separate report is planned that will document the reactor modeling process in detail. Munn, Wanda (Chair, Procedures Subcom.), 2/13/2014: Since NIOSH has provided a response to the finding, the status has been changed to In Progress and SC&A has been asked to review the NIOSH response. Ostrow, Stephen (SC&A), 4/10/2014: SC&A will review the NIOSH reactor modeling report when it is available and recommends that the status of this finding remain In Progress pending that review. Ostrow, Stephen (SC&A), 4/16/2014: This finding on OTIB-0054, Revision 01 also applies to Revision 02 (03/06/2014).	In Progress

[1] This report will usually refer to ORAUT 2014b by its unofficial name, the Reactor Modeling Report.

Table 1. Status of Findings 1–4 on ORAUT-OTIB-0054 (a),(b)

Finding	Board Review System (BRS) Entries	Status
2	Ostrow, Stephen (SC&A), 11/5/2013: The OTIB does not provide sufficient information to allow evaluation of its down-select from the initial seven to the final four representative reactors chosen. For more discussion on this finding, see SC&A report SCA-TR-PR-2013-0084, attached to Finding OTIB-0054-027 [i.e., Finding 1]. Burns, Bob (ORAUT), 2/4/2014: See response to Rev. 1, Finding 1. Munn, Wanda (Chair, Procedures Subcom.), 2/13/2014: Since NIOSH has provided a response to the finding, the status has been changed to In Progress and SC&A has been asked to review the NIOSH response. Ostrow, Stephen (SC&A), 4/10/2014: SC&A will review the NIOSH reactor modeling report when it is available and recommends that the status of this finding remain In Progress pending that review. Ostrow, Stephen (SC&A), 4/16/2014: This finding on OTIB-0054, Revision 01, also applies to Revision 02 (03/06/2014).	In Progress
3	Ostrow, Stephen (SC&A), 11/5/2013: While Rev. 0 of the OTIB (Section 5.2) provides extensive discussions of the ORIGEN2 runs for each reactor, Rev. 1 does not for the ORIGEN-S runs. For each of the nine representative reactor cases, the OTIB (Table 5-2) specifies the specific power, irradiation time, and burnup, and includes a basis (e.g., "maximum burnup at nominal power" for ATR 1), but does not say how the values were selected or cite any reference; Rev. 0 made extensive use, for example, of the DOE report, *Source Term Estimates for DOE Spent Nuclear Fuels*, DOE/SNF/REP-078, Rev. 0, March 2003 [DOE 2003]. SC&A cannot fully evaluate the appropriateness of the values chosen for each case without such information. For more discussion on this finding, see SC&A report SCA-TR-PR-2013-0084, attached to Finding OTIB-0054-027 [i.e., Finding 1]. Burns, Bob (ORAUT), 2/4/2014: See response to Rev. 1, Finding 1. Munn, Wanda (Chair, Procedures Subcom.), 2/13/2014: Since NIOSH has provided a response to the finding, the status has been changed to In Progress and SC&A has been asked to review the NIOSH response. Ostrow, Stephen (SC&A), 4/10/2014: SC&A will review the NIOSH reactor modeling report when it is available and recommends that the status of this finding remain In Progress pending that review. Ostrow, Stephen (SC&A), 4/16/2014: This finding on OTIB-0054, Revision 01, also applies to Revision 02 (03/06/2014).	In Progress

Table 1. Status of Findings 1–4 on ORAUT-OTIB-0054 [(a),(b)]

Finding	Board Review System (BRS) Entries	Status
4	Ostrow, Stephen (SC&A), 11/5/2013: SC&A notes that Table 5-1 of the OTIB lists both aluminum and stainless steel-clad TRIGA reactors as belonging to the initial set of seven reactors. However, Table 5-2, which lists the four reactors chosen as references, as well as the accompanying text, do not indicate which cladding was assumed for the TRIGA reactor. The OTIB also does not indicate what fuel enrichment was chosen, give a source for the specific power or the chosen burnups, or provide justification for its assumptions. For more discussion on this finding, see SC&A report SCA-TR-PR-2013-0084, attached to Finding OTIB-0054-027 [i.e., Finding 1]. Burns, Bob (ORAUT), 2/4/2014: The cladding type (stainless steel) can be specified in Table 5-2. See response to Rev. 1, Finding 1. Munn, Wanda (Chair, Procedures Subcom.), 2/13/2014: Since NIOSH has provided a response to the finding, the status has been changed to In Progress and SC&A has been asked to review the NIOSH response. Ostrow, Stephen (SC&A), 4/10/2014: SC&A will review the NIOSH reactor modeling report when it is available and recommends that the status of this finding remain In Progress pending that review. Ostrow, Stephen (SC&A), 4/16/2014: This finding on OTIB-0054, Revision 01, also applies to Revision 02 (03/06/2014).	In Progress

Notes:

(a) BRS entries are current as of January 7, 2015.
(b) The findings apply equally to Rev. 1 and Rev. 2 of the OTIB

1.3 SUMMARY OF SC&A'S RECOMMENDATIONS

Sections 2.2 through 2.5 present SC&A's review of NIOSH's response in the Reactor Modeling Report to Findings 1–4, respectively. SC&A's recommendations for the disposition of those findings are shown in Table 2.

Table 2. Summary of Recommendations on the Status of Findings 1–4

Finding	Current Status	Recommended Status
1	In Progress	Closed
2	In Progress	In Progress
3	In Progress	Closed
4	In Progress	Closed

2.0 EVALUATION OF NIOSH RESPONSES TO FINDINGS 1–4

As seen in Table 1, Findings 1–4 were designed in the BRS as In Progress pending receipt and evaluation of the so-called NIOSH Reactor Modeling Report (ORAUT 2014b). This report, entitled, *Supporting Calculations for ORAUT-OTIB-0054 and ORAUT-RPRT-0047*:

> *…summarizes the modeling of the reactor fuel and core configurations for the development of the following Oak Ridge Associated Universities (ORAU) Team work products:*
>
> - *ORAUT-OTIB-0054, "Fission and Activation Product Assignments for Internal Dose-Related Gross Beta and Gross Gamma Analyses," Revision 2…*
> - *ORAUT-RPRT-0047, Assignment of Fission and Activation Product Radionuclides for Non-Specific Bioassays at Savannah River Site – Comparison of Methods, Revision 00…*

The current SC&A evaluation reviews only those portions of the Reactor Modeling Report pertinent to OTIB-0054 (i.e., it doesn't examine the Savannah River portions).

2.1 REACTOR MODELING REPORT (ORAUT 2014b)

The Reactor Modeling Report (ORAUT 2014b) is a very detailed and technical description of how ORAUT modeled fuel in a number of representative nuclear reactors, and developed accompanying cross section and other datasets in order to determine isotopic compositions under a variety of conditions and assumptions. It is not the intention of this report to repeat what is presented in the very detailed Reactor Modeling Report or elsewhere, but a brief summary would be instructive.[2]

Although modern nuclear power reactor and fuel designs in the United States have been reduced to primarily a few different types since their first appearance in the late 1940s and early 1950s, many different experimental, training, and special purpose reactors (e.g., plutonium production, tritium production, or materials testing reactors) were developed and operated, especially at the weapons complex laboratories, such as Idaho National Laboratory, Savannah River Site, and Hanford. Recognizing that, out of practical considerations, a dose reconstructor would not be able to model every reactor and fuel type and operating history that a claimant might have encountered, it would be highly desirable to reduce the large number of possible combinations to a more manageable, representative few that would encompass most cases.

The primary goal of the modeling in the Reactor Modeling Report, which is an essential part of OTIB-0054, is to reduce a large amount of representative reactor fuel isotopic data into a form easily usable by a dose reconstructor looking at actual claimant cases. The starting point is the radionuclide mix in spent fuel for a number of different reactor types and fuel designs operated under a variety of different conditions (e.g., specific power, irradiation time, and burnup) calculated at several different decay times following removal from the reactor. It is assumed that an actual claimant case condition will fit somewhere within the parameters defined by the

[2] Parts of the following description are adapted from SC&A 2013 and ORAUT 2014b.

selected representative reactor types. As stated in the introduction of the Reactor Modeling Report:

> *The first step served to narrow the reactor and fuel designs under consideration to a manageable number. Once the representative reactor systems were selected, depletion modeling was performed to develop case-specific cross-section sets for each system over a range of operating conditions. Last, the case-specific cross-section sets were used in radioisotope generation and depletion calculations to obtain the fission and activation product inventories (by activity) for each reactor system as a function of time after reactor shutdown. Multiple inventory calculations were performed for the representative reactor systems to encompass a range of operating conditions.*

Section 5 of the OTIB and Section 3 of the Reactor Modeling Report begin by choosing seven actual reactors to represent five different general categories. Table 3 summarizes the reactors and cases:

Table 3. Reactor Categories and Representative Reactors

Reactor	Category
Plutonium Production Reactors	Hanford N-Reactor Hanford Single-Pass Reactors
Sodium-Cooled Fast Reactors	Fast Flux Test Facility (FFTF)
High-flux Reactors	Advanced Test Reactor (ATR)
Research Reactors	TRIGA® Reactor (Al-clad fuel) TRIGA® Reactor (SS-clad fuel)
Generic Reactor	Pressurized Water Reactor (PWR)

Source: ORAUT 2014a, Table 5-1 and ORAUT 2014b Table 3-1.

The ORIGEN2 Version 2.1 isotope generation and depletion code (Croff 1980) was then used to calculate isotopic inventories for the seven representative reactors in Table 3 in 11 runs, decayed for 7 decay times after irradiation had ceased: 10, 40, 60, 90, and 180 days, and 1 and 3 years. The code contains nuclear data libraries for the FFTF, ATR, and PWR, but not for the two Hanford production reactors and the two TRIGA reactors. For each of those cases lacking an ORIGEN2 library, ORAUT ran the code twice with different available cross-section and fission product yield libraries chosen to attempt to bound the irradiation results.

ORIGEN2 is a widely-used, one energy group, industry-standard code, developed by Oak Ridge National Laboratory (ORNL), to calculate the isotopic inventory after buildup and decay of isotopes in a nuclear reactor under conditions specified by the user. The code uses a matrix exponential method to solve coupled linear, first-order differential equations with constant coefficients. The code contains data libraries, including cross sections, fission product yields, decay data, and decay photon data. SC&A believes that the use of ORIGEN2 is appropriate and consistent with common practice in the nuclear community.

The 11 ORIGEN2 runs produced activity data for 879 fission product nuclides and 688 activation product nuclides, with a large overlap of nuclides between the two categories, and including some stable nuclides in addition to the radioactive ones. The activities in each dataset were normalized to that of Cs-137 at 10 days of decay.

The Reactor Modeling Report states:

> *Based on comparison of the fission and activation product relative activity data for the 11 ORIGEN2 runs, four cases were selected as having isotopic inventories that would be representative for the variety of reactors and fuel combinations: the ATR, the FFTF, the N-Reactor (run with a PWR cross-section library), and the TRIGA reactor (run with stainless-steel (SS) cladding and a PWR cross-section library).*

The fission and activation product relative inventory data were summed to produce tables of relative activity (normalized to Cs-137 at 10 days of decay) for 1,192 nuclides for the 7 decay times.

ORAUT then switched from the ORIGEN2 to the ORIGEN-S code for further fission and activation product inventory calculations for the four representative reactors remaining. ORIGEN-S (which uses three neutron energy groups: thermal, resonance, and fast) is a more modern and capable version of ORIGEN2 and is part of the SCALE code system (ORNL 2015) for nuclear safety analysis and design, developed and maintained by ORNL. The ORIGEN-ARP preprocessor prepared data and the TRITON code created case-specific cross-section libraries for ORIGEN-S; both codes are modules in the SCALE system. Multiple sets of irradiation parameters were defined for each of the four representative reactors. SC&A believes that use of these SCALE system modules is appropriate.

2.2 FINDING 1

The BRS entry associated with this finding is shown in Table 1, and the background for that finding is found in Section 1.1 of SC&A 2013. To repeat the finding here for convenience: "SC&A is not able to evaluate the appropriateness of the input parameters used for the ORIGEN2 runs, since they are not specified, or references cited in the OTIB."

Section 2.1 of the Reactor Modeling Report discusses the use of ORIGEN2:

> *…used to perform the fission and activation product inventory calculations used to narrow down the broad set of reactor systems initially selected for OTIB-0054 to the four ultimately considered* (ORAUT 2014b).

Subsections of Section 3.2 of the Reactor Modeling Report presents, in turn, the parameters used for each of the 7 reactors considered in the 11 ORIGEN2 runs. SC&A reviewed the chosen parameters and examined some of the copious technical literature available on each of the reactors to inform an opinion on the appropriateness of ORAUT's parameter choices. The different reactors will be examined below.

Advanced Test Reactor (ATR)

The ATR is a materials testing reactor that has operated at Idaho National Laboratory (INL) for over 40 years (it is still in operation). Its high-flux capability allows simulation of long-term irradiation in less than real time. An INL website states the following:

> *The ATR is a water-cooled, high-flux test reactor, with a unique serpentine design that allows large power variations among its flux traps. The reactor's curved fuel arrangement places fuel closer on all sides of the flux trap positions than is possible in a rectangular grid. The reactor has nine of these high-intensity neutron flux traps and 68 additional irradiation positions inside the reactor core reflector tank, each of which can contain multiple experiments. Experiment positions vary in size from 0.5" to 5.0" in diameter and all are 48" long. The peak thermal flux is 1×10^{15} n/cm^2-sec and fast flux is 5×10^{14} n/cm^2-sec when operating at full power of 250 MW. There is a hydraulic shuttle irradiation system, which allows experiments to be inserted and removed during reactor operation, and pressurized water reactor (PWR) loops, which enable tests to be performed at prototypical PWR operating conditions. Learn more by viewing the ATR User's Guide* (INL 2015).

The ATR User's Guide (INL 2008), referenced above, contains much detailed information about the ATR; considerably more than is required for the ORIGEN2 modeling.

Section 3.2.1 of the Reactor Modeling Report summarizes the important features of the ATR model developed by ORAUT. The section contains data, including the uranium isotopic masses and aluminum and impurity masses of a single fuel element, and the assumed fuel burnup. Most of the data is taken from *Source Term Estimates for DOE Spent Nuclear Fuels* (DOE 2003). This data source was prepared by the Department of Energy (DOE) to support Yucca Mountain safety analysis studies by characterizing source terms for a wide range of spent nuclear fuel held by DOE at its various facilities. The DOE report was examined by SC&A, which found that the assumptions made and the methodologies used appear reasonable and should produce conservative (i.e., high) radioactivity estimates. DOE 2003 explicitly estimates the ATR spent fuel source terms as Template 12.

SC&A examined whether the DOE report data were correctly transferred to the Reactor Modeling Report.

Table 4. ATR Fuel Loading Comparison (93.2 wt% enrichment)

	Fuel Loading, g/fuel element	
Isotope	**DOE 2003** (p. A-103)	**ORAUT 2014b** (Section 3.2.1)
U-235	1,075.0	1,073.0
U-238	69.93	63.64
U-234	13.87	12.29
U-236	8.09	2.40
Total	1,166.89	1,151.33

While not an exact match, the differences are not significant for nuclear fuel modeling.

The Reactor Modeling Report uses the DOE report's upper-end burnup of 314,683 MWd/ MTHM, which corresponds to 362.3 MWd for the assumed fuel element, and states, "The composition was therefore assumed to be irradiated for 36.23 days at a constant power of 10 MW in increments of 10 days" (ORAUT 2014b). DOE 2003 (p. A-104) gives 10 MW_{th} as the maximum power level for a fuel element. Finally, the Reactor Modeling Report notes that, "the cross-section and fission product yield library was developed specifically for the ATR by the Idaho National Laboratory," but since the INL data do not include ATR-specific activation product cross sections, the Reactor Modeling Report took them from the standard-burnup PWR library accompanying ORIGEN2. Actinide and fission product cross sections are ATR-specific, however. SC&A believes that the process employed in the Reactor Modeling Report is valid.

Fast Flux Test Facility (FFTF)

The FFTF was a 400 MW_{th}, liquid sodium-cooled, fast-flux test reactor located at the DOE Hanford site that operated from April 1982 to April 1992 (DOE 2014). The Reactor Modeling Report draws most of its information on this reactor from DOE 2003, where it is modeled explicitly as Template 3. DOE 2003 states that the fuel was mixed oxide with plutonium (86 wt% Pu-239) amounting to 29 wt% of the heavy metal (uranium plus plutonium); the driver assemblies were clad with 316 SS; and the assemblies were subjected to high burnups. The Reactor Modeling Report lists the heavy metal (uranium, plutonium, and americium) contents of a driver assembly in Table 3-3 and the elemental content of the 316 SS of a driver assembly in Table 3-4. The ORAUT reactor model specifies that:

> *…a representative burnup of 80,000 MWd/ MTHM was selected, which equates to 2,633.4 MWd for the fuel assembly defined above. The composition was therefore assumed to be irradiated for 487.7 days at a constant power of 5.4 MW in increments of 50 days* (ORAUT 2014b).

SC&A verified that the material contents listed in Tables 3-3 and 3-4 correspond to the values in Tables 1 and 2, respectively, of DOE 2003. In addition, DOE 2003 (Table 3 and p. A-6) gives the average power for a standard fuel assembly as 5.4 MW, which corresponds to the assumption in the Reactor Modeling Report.

DOE 2003 (p. A-6) notes that the highest burnup was 152,230 MWd/MTHM, with most in the range of 70,000–90,000. Therefore, SC&A believes that the Reactor Modeling Report's choice of 80,000 MWd/MTHM appears representative. In addition, ORIGEN2 already contains cross-section and fission product yield libraries created specifically for the FFTF.

Hanford N Reactor

The features of the Hanford N Reactor, which operated from 1963 to 1987, are summarized in DOE 2003 (Template 7, p. A-45), which, as noted in that document, was largely taken from Bergsman (1994); the former characterizes and inventories the spent fuel stored at the Hanford site.

> *The … N-Reactor is a graphite-moderated, [slightly enriched] pressurized water-cooled reactor … initially designed for plutonium production for national defense [and, later] modified to produce steam to be used by the Washington Public Power Supply System to generate electricity. N-Reactor was the only dual-*

> *purpose reactor in the United States. The core of the N-Reactor was a 1800-ton graphite block, 33 feet (10 meters) high by 33 feet (10 meters) wide by 39 feet (12 meters) long* (DOE 2003, p. A-46).

Bergsman notes that the N Reactor primarily used two different types of fuel elements, the Mark IV and the Mark IA, both clad with Zircaloy-2. The Mark IV elements had a pre-operations enrichment of 0.947% U-235 in both of its concentric tubes, while the Mark IA elements had a pre-operations enrichment of 1.25% U-235 in the outer tube and 0.947% in the inner tube. The Mark IV elements, though, contained a greater uranium weight than the Mark IA elements—50.0 lb (22.7 kg) vs. 35.9 lb (16.3 kg) (Bergsman 1994, p. 3). DOE 2003 based its radioactive inventory determination on the Mark IV elements, as does the Reactor Modeling Report. The Reactor Modeling Report lists the uranium composition per metric ton of fuel in Section 3.2.3. The values can be obtained from DOE 2003 by dividing by 11.6 MTU (DOE 2003, p. A-53). Table 3-5 lists the elemental composition of the Zircaloy 2 cladding and trace elements.

ORAUT selected a representative burnup of 1,188 MWd/MTHM (Schwarz 1997), which is characteristic of the outer fuel elements (and a higher burnup than experienced by the inner elements) and, in its reactor model, irradiates the fuel for 100 days at 11.88 MW in increments of 20 days. The Reactor Modeling Report notes that "a cross section and fission product yield library specifically for the N Reactor exists, but it was not readily available" (ORAUT 2014b). Instead, ORAUT ran two sets of ORIGEN2 cases, using data from a slightly enriched CANDU reactor and a typical, more highly enriched, U.S. PWR.

SC&A believes that the Reactor Modeling Report appears to have taken all its data for the N Reactor from authoritative sources and reasonably simulated the actual isotopic composition after irradiation by considering two different data sets.

<u>Hanford Single-Pass Reactors</u>

Nine light water-cooled, graphite-moderated reactors to produce plutonium for nuclear weapons were built along the Columbia River on the Hanford reservation over a 20-year period beginning in 1943. They were designated 100-B, C, D, DR, F, H, KW, KE, and N. The first eight were "single pass," in that the cooling water for the core was taken from the river and not recirculated, while the last, the N Reactor, recirculated the primary coolant water in a closed loop. The cylindrical metallic uranium fuel "slugs" were clad with aluminum. The single-pass reactors were shut down between 1964 and 1971 (Gerber 1995).

The Reactor Modeling Report presents data on the single-pass reactors in Section 3.2.4, including typical fuel (uranium and aluminum) dimensions and densities for the fuel slugs used during the Manhattan Project era. Scaling up the amount of uranium and aluminum in a single slug to 1 metric ton of metal results in the aluminum composition in Table 3-6 and the uranium loading just above it: U-234 - 55.3 g, U-235 - 7,110 g, and U-238 - 992,834.7 g.

The Reactor Modeling Report adopts a representative burnup of 220 MWd/MTHM for those slugs, and the ORIGEN2 runs irradiated the fuel for 200 days at a constant power of 1.1 MW. Since ORIGEN2 cross-section and fission product yield libraries specific to the single-pass reactors were not available, ORAUT ran cases using a natural uranium oxide fuel CANDU reactor library and a U.S. 3.2 wt% enrichment PWR library. The Reactor Modeling Report provides several references (Kelly 1945; Gawthrop and Jones 1945; and Heeb 1993) as data sources.

SC&A believes that ORAUT has adequately documented its data sources for the Hanford Single-Pass Reactor modeling.

Pressurized Water Reactor (PWR)

Section 3.2.5 of the Reactor Modeling Report describes features of the standard burnup U.S. PWR from an ORNL report (Ludwig and Reiner 1989). The Reactor Modeling Report states that this ORIGEN2 model "was included to see how the results from the other models compared with those for a system with such well-known behavior" (ORAUT 2014b). The UO_2 PWR fuel is enriched to 3.2% and clad with Zircaloy 4. Table 3-7 and an unlabeled table give the isotopic composition of the fuel and the elemental composition of the fuel and cladding normalized to 1 metric ton of uranium. SC&A checked that the values correspond to those of Ludwig and Reiner 1989. The fuel loading is U-234 - 290.0 g, U-235 - 32,000 g, and U-238 - 967,710.0 g. A total fuel burnup of 33,000 MWd/MTHM and an irradiation period of 880 days at a constant power of 37.5 MW in increments of 60 days are assumed. The ORIGEN2 code package contains standard burnup PWR cross-section and fission product datasets. SC&A finds the NIOSH procedure reasonable and data sources adequately referenced.

TRIGA Reactors

Section 3.2.6 of the Reactor Modeling Report considers Al-clad and SS-clad TRIGA reactors. The low-power, water-cooled, pool-type, uranium zirconium hydride (UZrH)-fueled reactors are manufactured by General Atomics (GA) primarily for research and educational purposes, and are considered inherently safe due to their very large prompt negative temperature coefficient of reactivity that quickly drops the reactor subcritical in response to any power excursions (which raises the water coolant temperature). This feature also allows the TRIGA to be pulsed to a high power level, followed by a quick automatic self-shutdown. GA has supplied over 65 reactors throughout the world over the past 45 years, ranging in (thermal) power from 20 kW to 16 MW and containing 60–100 fuel elements (GA 2015). The models progressed from Mark I through Mark III, with a number of specially modified units also produced. The early models used highly enriched uranium (70%), but the later models greatly reduced the enrichment (to 20%) in response to U.S. government proliferation concerns, and the earlier models were converted to the lower fuel enrichment as well.

The Reactor Modeling Report relies on information on the TRIGA from the INL report Sterbentz (1997) and the Westinghouse Hanford report Schmittroth and Lessor (1996) for constructing its ORIGEN2 model for one fuel rod, distinguishing between Al-clad and SS-clad cases. The Reactor Modeling Report notes that:

> *The compositions and burnup for the ORIGEN2 modeling for TRIGA reactors were selected to represent TRIGA reactors in the DOE complex. These reactors were primarily used for radiography applications. It was not intended to represent the entire gamut of TRIGA reactor varieties at universities and other research-oriented facilities.* (ORAUT 2014b)

The Al-clad case considers a single fuel element containing 180 g of uranium, and assumes 20% enriched U-235 at 8 wt% of the UZrH, with a Zr:H ratio of 1.0. Table 3-8 presents the composition of the Al cladding, and the information before the table lists the uranium isotopic composition: U-234 - 0.299 g, U-235 - 35.508 g, U-236 - 0.177 g, and U-238 - 144.014 g. The constituent and impurity compositions for the ZrH matrix are presented in Table 3-9, taken from DOE 2003. The Reactor Modeling Report states, "A midrange burnup of 21,116 MWd/MTHM was used, which equates to 5.9 MWd for the fuel element" (ORAUT 2014b). The ORIGEN2 run assumed irradiation for 5.384 years at a constant power of 3.0 kW per fuel element in increments of 0.25 years.

The SS-clad case for a single fuel element specified 20% enrichment of U-235 at 8.5 wt% of the UZrH matrix, with a Zr:H atom ratio of 1:7. Each fuel element contained 195 g of uranium and 819.4 g of 304 SS. The uranium isotopic composition is U-234 - 0.324 g, U-235 - 38.467 g, U-236 - 0.192 g, and U-238 - 156.015 g. Table 3-10 lists the 304 SS composition, and Table 3-11 lists the constituent and impurity composition of the ZrH matrix. A midrange burnup of 19,462 MWd/MTHM was assumed, which is equivalent to 3.8 MWd for one fuel element. The element was irradiated in ORIGEN2 for 3.469 years at a constant power of 3.0 kW in increments of 0.25 years.

ORAUT could not locate a TRIGA-specific ORIGEN2 model, so for both Al-clad and SS-clad cases, ORAUT used available ATR and standard burnup PWR cross-section and fission product yield libraries.

SC&A believes that the Reactor Modeling Report adequately references the data sources and assumptions underlying the ORIGEN2 runs.

> ***SC&A's Assessment for Finding 1:*** After review of the data sources and input parameters presented in the ORAUT Reactor Modeling Report (ORAUT-RPRT-0067, Rev. 0, August 26, 2014) as well as an examination of the literature, SC&A is satisfied that the report adequately specifies and references the pertinent input parameters and assumptions associated with the ORIGEN2 runs and finds them appropriate. SC&A, therefore, recommends that this finding be Closed.

2.3 FINDING 2

The BRS entry associated with this finding is shown in Table 1 and the background for that finding is found in Section 1.1 of SC&A 2013. To repeat the finding here for convenience: "The OTIB does not provide sufficient information to allow evaluation of its down-select from the initial seven to the final four representative reactors chosen."

Section 3.3 of the Reactor Modeling Report discusses the process that ORAUT used, subsequent to its 11 ORIGEN2 runs on the initial set of reactor cases, to reduce that set to the final 4 chosen for further analysis. That section, copied in its entirety, explains:

> *The results from the 11 ORIGEN2 runs were compared on the basis of relative activity (to ^{137}Cs) at 10 days of decay. Fission and activation product inventories*

from the 11 runs were compared separately so potential dependence on the choice of cross-section libraries could be evaluated independently for these different modes of production. Each ORIGEN2 run gave activity (in curies) for 879 fission product nuclides and 688 activation product nuclides. These include some stable species, and many nuclides appear in both categories (i.e., they are produced by both fission and activation).

Based on comparison of the fission and activation product relative activity data for the 11 ORIGEN2 runs, four reactors were selected as having isotopic inventories and ratios that would be representative of the variety of reactors and fuel combinations under consideration:

- *The ATR*
- *The FFTF*
- *The N Reactor*
- *The TRIGA reactor (with SS-clad fuel)*

Section 3.3 of the Reactor Modeling Report, reproduced above, appears identical to Section 5.2 of the OTIB (ORAUT 2014a), with only the addition of the parenthetical text in the last bullet of the former (which answers the question of which TRIGA reactor was chosen). While the section of the Reactor Modeling Report explains the procedure that ORAUT used, which appears reasonable, it does not provide sufficient detail, such as comparative data in tables, to allow assessment of the down-selection from the initial seven to the final four representative reactors. The selected reactors should both capture the full range of possible isotopic mixtures to which workers might have been exposed, as well as represent the most commonly encountered types of reactors.

SC&A Assessment for Finding 2: Section 3.3 of the Reactor Modeling Report discusses the down-selection process. However, it is virtually identical to Section 5.2 of the OTIB (Rev. 1 or 2) on which SC&A originally made the finding. While the explanation of the procedure followed to reduce the number of reactors considered from the initial seven to the final four representative ones appears reasonable, the section does not provide sufficient detail, such as comparative data in tables, to allow assessment of the final choices; i.e., whether they capture the full range of isotopic mixtures that might have been encountered by workers, and whether they represent the most commonly encountered types of reactors. SC&A, therefore, recommends that this finding remain In Progress until such time that NIOSH provides additional information that can be evaluated.

2.4 FINDING 3

The BRS entry associated with this finding is shown in Table 1 and the background for that finding is found in Section 1.1 of SC&A 2013. To repeat the finding here for convenience:

While Rev. 0 of the OTIB (Section 5.2) provides extensive discussions of the ORIGEN2 runs for each reactor, Rev. 1 does not for the ORIGEN-S runs. For each of the nine representative reactor cases, the OTIB (Table 5-2) specifies the *specific power, irradiation time, and burnup, and includes a basis (e.g., "maximum burnup at nominal power" for ATR 1), but does not say how the values were selected or cite any reference; Rev. 0 made extensive use, for example, of the DOE report, Source Term Estimates for DOE Spent Nuclear Fuels, DOE/SNF/REP-078, Rev. 0, March 2003 [DOE 2003]. SC&A cannot fully evaluate the appropriateness of the values chosen for each case without such information.*

Section 5 of the Reactor Modeling Report provides extensive information on the ORIGEN-S cases for each of the representative reactors: the ATR, the FFTF, the Hanford N Reactor, and the TRIGA Mark I (SS cladding). In addition, Section 6 provides detailed information on the TRITON depletion modeling portion (required to generate case-specific cross-section sets) of the overall analysis for each reactor.

The OTIB (ORAUT 2014a) summarizes the important modeling parameters of the Reactor Modeling Report in Table 5-2, which is reproduced here in Table 5.

Table 5. ORIGEN-S Irradiation Parameters for the Representative Reactor Cases

Case	Parameters	Basis
ATR 1	Specific power = 2,379.1 MW/MTU Irradiation time = 132.27 days Burnup = 314,684 MWd/MTU	Maximum burnup at nominal power
ATR 2	Specific power = 8,651.2 MW/MTU Irradiation time = 36.4 days Burnup = 314,904 MWd/MTU	Maximum burnup at maximum assembly power
ATR 3	Specific power = 2,379.1 MW/MTU Irradiation time = 56 days Burnup = 133,230 MWd/MTU	Nominal burnup at nominal power
FFTF 1	Specific power = 163.8 MW/MTHM Irradiation time = 929.4 days Burnup = 152,230 MWd/MTHM	Maximum burnup at nominal power
FFTF 2	Specific power = 163.8 MW/MTHM Irradiation time = 488.3 days Burnup = 79,984 MWd/MTHM	Nominal burnup at nominal power
N-Reactor 1	Specific power = 10.4 MW/MTU Irradiation time = 114.2 days Burnup = 1,188 MWd/MTU	Production of weapons-grade plutonium (nominal 6% Pu-240 content) at nominal power
N-Reactor 2	Specific power = 10.4 MW/MTU Irradiation time = 285.6 days Burnup = 2,970 MWd/MTU	Production of fuel-grade plutonium (nominal 12% Pu-240 content) at nominal power
TRIGA 1	Specific power = 15.57 MW/MTU [(a)] Irradiation time = 730.1 days Burnup = 11,368 MWd/MTU	Maximum burnup at nominal power
TRIGA 2	Specific power = 15.57 MW/MTU Irradiation time = 115.2 days Burnup = 1,994 MWd/MTU	Nominal burnup at nominal power

(a) OTIB Table 5-2 typo misstates "MWd" rather than the correct "MW," which is used here.
Source: ORAUT-OTIB-0054, Rev. 2, Table 5-2 (ORAUT 2014a)

SC&A made a quick check by comparing the tabulated values to those in the Reactor Modeling Report, and by multiplying the specific power by the irradiation time for each case, which should then produce the last entry, the burnup. The "arithmetic" is essentially correct, except for the TRIGA 2 case, where (15.57 MW/MTU) × (115.2 days) = 1,794 MWd/MTU. The table lists 1,994 MWd/MTU, however, which might just be a typo, since it is off in only one digit; this is not seen as an important difference in any event.

> ***SC&A Assessment for Finding 3:*** SC&A believes that the Reactor Modeling Report contains sufficient information on the parameters selected for the ORIGEN-S runs for each of the representative reactors to inform an assessment that the values chosen are appropriate. SC&A, therefore, recommends that this finding be Closed.

2.5 FINDING 4

The BRS entry associated with this finding is shown in Table 1 and the background for that finding is found in Section 1.1 of SC&A 2013. To repeat the finding here for convenience:

> *SC&A notes that Table 5-1 of the OTIB lists both aluminum and stainless steel-clad TRIGA reactors as belonging to the initial set of seven reactors. However, Table 5-2, which lists the four reactors chosen as references, as well as the accompanying text, do not indicate which cladding was assumed for the TRIGA reactor. The OTIB also does not indicate what fuel enrichment was chosen, give a source for the specific power or the chosen burnups, or provide justification for its assumptions.*

Section 3.2.6 of the Reactor Modeling Report provides information and references pertaining to the TRIGA reactors, and, in particular, the SS-clad one, which was chosen as the TRIGA reference reactor. The report states, "The SS-clad TRIGA fuel that was modeled was 20%-enriched ^{235}U at 8.5 wt% of the UZrH matrix." The uranium and cladding compositions per fuel rod are given in the tables in that section. Section 5.4 of the Reactor Modeling Report, as discussed above, gives the specific powers and burnups assumed for the TRIGA reactor cases, and Section 7.4 contains the composition of the UZrH fuel and the 304 SS cladding for the entire core.

> ***SC&A Assessment for Finding 4:*** The Reactor Modeling Report contains the information on the TRIGA reactor cases found lacking in the OTIB, which is consistent with the literature. SC&A, therefore, recommends that this finding be Closed.

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