**Non-Fuel Assembly Components:
10 CFR 61.55 Classification for Waste Disposal**

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Abstract

This document reports the results of laboratory radionuclide measurements on a representative group of non-fuel assembly (NFA) components for the purposes of waste classification. This document also provides a methodology to estimate the radionuclide inventory of NFA components, including those located outside the fueled region of a nuclear reactor. These radionuclide estimates can then be used to determine the waste classification of NFA components for which there are no physical measurements.

Previously, few radionuclide inventory measurements had been performed on NFA components. For this project, recommended scaling factors were selected for the ORIGEN2 computer code that result in conservative estimates of radionuclide concentrations in NFA components. These scaling factors were based upon experimental data obtained from the following NFA components: 1) a pressurized water reactor (PWR) burnable poison rod assembly, 2) a PWR rod cluster control assembly, and 3) a boiling water reactor cruciform control rod blade. As a whole, these components were found to be within Class C limits. Laboratory radionuclide measurements for these components are provided in detail.

Summary

The radionuclide inventory of materials that have been irradiated in a reactor is dependent upon several parameters. The major variables are initial material composition, irradiation history, and location of materials in the reactor. In the case of non-fuel assembly (NFA) components, the structural materials are composed of various alloys of stainless steel, inconel, and zircaloy. The irradiation histories of these components are often rather complex, since some of these components are irradiated over several cycles in various reactor locations.

The ORIGEN2 computer code (Croff 1980) can be used to estimate the radionuclide inventory of materials irradiated in the fueled region of the reactor. Input parameters include the composition of the material to be irradiated and the irradiation history. Outside the fueled region, ORIGEN2 estimates are not applicable because of changes in the absolute magnitude of the neutron flux and shifts in the neutron spectrum. For many NFA components, much of the material of interest is located outside of the fueled region. To provide conservative estimates of the radionuclide inventory in these components, the Pacific Northwest Laboratory (PNL) selected scaling factors that can be applied to ORIGEN2 calculations to partially compensate for the changed neutron flux.

Determining these scaling factors requires comparing ORIGEN2 results with actual measurements. To obtain these radionuclide measurements, samples were cut from three irradiated NFA components. The components obtained were a pressurized water reactor rod cluster control assembly (RCCA) and burnable poison rod assembly (BPRA) and a boiling water reactor cruciform control rod blade (CRB). Each sample was individually analyzed for both elemental composition and 10 CFR 61.55 radionuclide content.

Because the amount of experimental data was limited, PNL developed a model for the BPRA and RCCA using the Monte Carlo Neutron/Photon (MCNP) code. MCNP is a general purpose Monte Carlo code that can be used to study neutron, photon, or coupled neutron/photon transport problems. Extensive run times were often necessary to reduce statistical uncertainties to within acceptable levels.

The goal of developing the MCNP model was to match the measured data where they were available and then extrapolate to other locations where there were no measured data. This methodology would enable ORIGEN2 scaling factors to be developed for any arbitrary location along the BPRA and RCCA. The MCNP results were able to match only the trends, and not the magnitude, of the activity profiles. Therefore, the scaling factors were based upon the laboratory measurements alone.

General scaling factors (see Table S.1) were developed that relate the activation rate in the reactor's fueled region to rates outside the core. These factors are applied to ORIGEN2 results by multiplying the fueled region radionuclide inventories, as calculated by ORIGEN2, by the appropriate scaling factor for the region in which the material is located. For the purposes of this approximation, it is assumed that the same scaling factors may be used for each nuclide. The scaling factors were chosen to be conservative, but they are not necessarily bounding.

Table S.1. ORIGEN2 Scaling Factors

Component Region	Typical NFA Components	Approximate Scaling Factors
In-core	BPRA clad	1.0
	CRB handle and tip	
Within 12 inches of core periphery	BPRA hold-down assembly	0.1
	RCCA end caps	
More than 12 inches outside core	RCCA spider assembly and clad	1.0E-5
	CRB velocity limiter	

These scaling factors are only useful for average radionuclide inventory estimates and should be applied to general regions. They should not be applied to small sections because of the significant variations in the neutron flux that occur with respect to position.

Based upon the analytical measurements, waste classifications were determined for the CRB, RCCA, and BPRA. The classifications can vary, depending upon how the components are sectioned. For this report, it was assumed that each component was cut into four pieces. In actuality, the manner in which NFA components are cut is at the discretion of the waste packager. All of the components in this report were found to be within the Nuclear Regulatory Commission's Class C limits if concentrations were averaged over the entire component. In fact, some sections of the CRB and RCCA were Class A or B. Only one section, the BPRA hold-down assembly, was individually found to be Greater-Than-Class C.

From the results of the three NFA components studied, general observations can be made concerning classification of similar NFA components. The RCCA studied was within Class C limits. It is not anticipated that stainless steel RCCAs from other reactors would be GTCC since these components are not usually fully inserted into the core during power operation for any appreciable length of time. However, the same cannot be said for CRBs and BPRAs. While the CRB and BPRA studied in this report were within Class C limits, longer irradiation times may cause these types of NFA components to be GTCC. For example, if the BPRA classified as Class C in this report had been irradiated for an additional cycle, it would have been classified as GTCC.

Acronyms

BOC	Beginning Of Cycle
BPRA	Burnable Poison Rod Assembly
BWR	Boiling Water Reactor
CRB	Control Rod Blade
DMG	Dimethylglyoxime
EOC	End Of Cycle
GTCC	Greater-Than-Class C
ICP/MS	Inductively Coupled Plasma Mass Spectrometer
LSC	Liquid Scintillation Counting
LEPS	Low Energy Photon Spectroscopy
MCNP	Monte Carlo Neutron Photon
NFA	Non-Fuel Assembly
NIST	National Institute for Standards Technology
NRC	Nuclear Regulatory Commission
PNL	Pacific Northwest Laboratory
PWR	Pressurized Water Reactor
RCCA	Rod Cluster Control Assembly
RPD	Relative Percent Difference
SAL	Shielded Analytical Laboratory

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1.0 Introduction

This section identifies the purpose and objectives for this report. The background and nuclides of interest for this study also are identified. Finally, the approach for this study is outlined.

1.1 Purpose

The principal purpose of this report is to provide the results of laboratory measurements of NFA components. In addition, this report provides a method with which to estimate radionuclide concentrations in NFA waste for the purpose of waste classification. This methodology should be more inexpensive to perform than current techniques that require radioassays.

1.2 Background

The Nuclear Regulatory Commission (NRC) has established radiological limits (10 CFR 61.55) for radioactive waste disposal in shallow, land burial sites. Low-level waste classified as Class A, B, or C can be disposed of in a shallow, land burial site, and it is the responsibility of the states to provide these sites. If the radionuclide inventory exceeds the Class C limits, it is referred to as Greater-Than-Class C (GTCC) low-level radioactive waste. The Nuclear Waste Policy Act of 1982 stipulates that the Department of Energy has responsibility for the disposal of GTCC waste.

Commercial nuclear power reactors contain many core components that are not an integral part of the fuel assembly (e.g., in-core instrumentation, control rods, burnable poison assemblies, fission chambers, primary and secondary neutron sources). Hawkes (1994) presents an extensive list of NFA components. Previously, few radionuclide inventory measurements had been performed on NFA components. Thus, there were large uncertainties in the classification of NFA components. To compound this classification problem, there are many different types of NFA components currently in use in domestic power reactors. Of these, the Pacific Northwest Laboratory (PNL) selected three common NFA components on which to perform radionuclide measurements: a PWR burnable poison rod assembly, a PWR rod cluster control assembly, and a BWR cruciform control rod blade.

Currently, radionuclide concentrations are typically estimated by first measuring the gamma activity of a strong gamma emitting isotope, such as cobalt-60, with a detector along the length of the component. From these doses, rough concentrations of other radioisotopes of interest are estimated based upon the relative fraction of alloying constituents and their nuclear cross sections. Classification of NFA components is then performed despite the large uncertainties in the radionuclide concentrations.

This report presents a methodology for determining the classification of NFA component waste based on the use of the ORIGEN2 code. ORIGEN2 can be used to predict the activity of the materials

irradiated in the reactor's fueled region based on the reactor power history; however, the fueled region of the reactor core is the only region where ORIGEN2 results are directly applicable.

Many NFA components are not located within the fueled region. Hence, ORIGEN2 cannot be used to determine the extent of NFA activation unless a "scaling factor" is introduced. These scaling factors adjust core-average ORIGEN2 calculations to conservatively account for changes in the neutron flux and energy spectrum outside the fueled region. Thus, the problem of classifying the different types of NFA components has been reduced to finding the appropriate scaling factors for the different components.

It should be recognized that the ORIGEN2 scaling factors proposed in this report are significant approximations. The scaling factors were selected to produce conservative results, but will not necessarily bound the true value in all cases.

1.3 NFA Nuclides of Interest

Six of the radioactive isotopes listed in 10 CFR 61.55 are present in NFA components. They are: carbon-14, nickel-59, niobium-94, nickel-63, technetium-99, and cobalt-60. These isotopes are created when non-radioactive parent isotopes are bombarded with neutrons. After absorbing a neutron, the parent isotope will emit either a proton, beta particle, or gamma ray, thus forming a radioactive daughter.

10 CFR 61.55 limits the quantity of cobalt-60 that may be present in radioactive waste. This limit defines, in part, the threshold for Class A waste. Note, however, that there is no Class C limit for this isotope. For this reason, it was not mandatory to perform cobalt-60 measurements to determine if the NFA components were GTCC. Cobalt-60 concentrations were measured to facilitate comparison between the analytical and computational results since cobalt-60 concentrations are easily and accurately measured. Cobalt-60 activation measurements are very accurate because readily detectable, high-energy gammas are released during its decay.

Four of the six activation products have two parent isotopes. Note that while some of the parent isotopes are present only in trace quantities (e.g., nitrogen-14, molybdenum-98), nickel is a primary constituent of stainless steel and is present in much higher concentrations. Table 1.1 provides a listing of the 10 parent isotopes and the reactions of interest.

For activation products that have two parents, the "dominant parent" is the parent isotope from which most of the activation products arise. In the list, the dominant parent has been listed first. The concentrations and/or cross sections of the less significant parent isotopes are so small that their contributions were at times insignificant relative to the dominant parents. However, if the parent concentrations change appreciably, it is possible that the less significant parent contribution would become

Table 1.1. NFA Reactions of Interest

$^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}$
$^{98}\text{Mo}(n,\gamma)^{99}\text{Mo}\beta^- \rightarrow ^{99}\text{Tc}$
$^{93}\text{Nb}(n,\gamma)^{94}\text{Nb}$ and $^{94}\text{Mo}(n,p)^{94}\text{Nb}$
$^{14}\text{N}(n,p)^{14}\text{C}$ and $^{13}\text{C}(n,\gamma)^{14}\text{C}$
$^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$ and $^{63}\text{Cu}(n,p)^{63}\text{Ni}$
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ and $^{60}\text{Ni}(n,p)^{60}\text{Co}$

more significant. Therefore, it is essential to have a good estimate of the concentration of the parent nuclides because the parent isotope concentrations have a one-to-one effect on the amount of activation products produced.

1.4 Approach

Three distinct NFA components were obtained by PNL from electric power utilities. Iowa Electric Light and Power Co., Duane Arnold plant, contributed a control rod blade (CRB) from a General Electric boiling water reactor (BWR). Wisconsin Electric, Point Beach 1, contributed two components from a Westinghouse pressurized water reactor (PWR): a rod cluster control assembly (RCCA) and burnable poison rod assembly (BPRA).

Pieces were cut from these components and analyzed by the Analytical Chemistry Laboratory at PNL. The analysis had two purposes: first, the concentrations of parent nuclides in each sample were determined. Second, the activity due to each of the six 10 CFR 61.55 isotopes was individually measured. Activities were reported in units of Ci/g of activated metal. Sections 2.0 and 3.0 detail the sample description and laboratory analysis, respectively.

A Monte Carlo Neutron-Photon (MCNP) code model was developed for the BPRA and RCCA to bridge the gaps in the measured data. The MCNP model was created because analytical laboratory data were available only at discrete points, which were usually 2 feet apart or more. It was expected that the MCNP model would allow ORIGEN2 scaling factors to be generated at arbitrary locations outside the fueled region of the core. In addition to the MCNP model, ORIGEN2 models were developed for the components.

The MCNP results were compared with the experimental results. The trend in the activation data was reproduced by the MCNP calculations, although the MCNP results were not sufficiently representative to justify their use in the scaling factor development. Section 4.0 discusses the MCNP model

and compares the results with the ORIGEN2 results and laboratory measurements. Section 5.0 discusses the waste classification of the components and presents ORIGEN2 scaling factors which can be applied to other NFA components. Finally, Section 6.0 provides the references for this document, and Section 7.0 gives the bibliography list.

2.0 Sample Descriptions

This section provides details on the three NFA components, their geometry, and their preparation for the laboratory analysis.

2.1 Control Rod Blade Description and Irradiation History

The General Electric BWR CRB was obtained from Iowa Electric Light and Power Company, Duane Arnold Plant. The CRB is approximately 14 feet long and is primarily constructed out of stainless steel. Inside the blade are stainless steel tubes filled with boron carbide (B_4C) powder, which is the neutron absorber material. The absorbing section of the blade is shaped like an "X". At the bottom of the blade is a circular velocity limiter.

Figure 2.1 shows the Duane Arnold core layout. The CRB was located in position 26 x 27 from June 1978 to April 1987 and in position 34 x 39 until its discharge in October 1988. It was exposed to 10 operating cycles. The CRB was inserted to various levels in the core during its exposure. Upon discharge, the absorber depletion was as shown in Table 2.1.

Figures 2.2 through 2.11 present the exposure history of the CRB. The time at full power is indicated for each level of insertion. The neutron exposure of the blade is determined by relating neutron exposure to total exposure time in the core. This exposure was calculated by taking the ratio of the reactor power level to full power over each 24-hour period. The neutron exposure of the blade during full insertion is, therefore, extremely low since the reactor was either coasting down or at a zero power level.

2.2 RCCA Description and Irradiation History

The RCCA was obtained from a Westinghouse PWR, Wisconsin Electric Point Beach 1. The RCCA is approximately 14 feet long and is constructed out of stainless steel. The top of the component is called the spider assembly because of its spider-like appearance. Sixteen rods are attached to the spider assembly. The rods are filled with Ag-In-Cd, which is the neutron absorber material. The RCCA is designed to fit into a 14 x 14 fuel lattice.

The RCCA had been discharged in April 1985 after 12 cycles and 102,767 hours of critical reactor service. The best information available indicated that the RCCA was fully withdrawn at all times during full power operations. The output of the reactor was 1500 MWt. Table 2.2 presents the core location, host assembly identification, and assembly burnup for each cycle. Figure 2.12 shows the physical core locations.

1 June 1978 to April 1987
 2 April 1987 to October 1988

Figure 2.1. Location of CRB in Core

2.3 BPRA Description and Irradiation History

The Westinghouse BPRA was also obtained from Wisconsin Electric Point Beach 1. The BPRA is approximately 14 feet long and is constructed principally out of stainless steel. The top of the BPRA is called the hold-down assembly. Inconel springs are part of the hold-down assembly. These springs

Table 2.1. Depletion of Boron-10 in Control Rod Blade

Quarter	Snvts ^(a)	% Depletion
1 (top)	1.85	30.73
2	1.91	31.69
3	1.46	21.16
4 (bottom)	0.48	7.98
(a) The units "snvts" is a term used to denote 10^{21} n/cm ² . It is a measure of the total irradiation the CRB has experienced and is correlated to the percent depletion of boron-10.		

will activate differently than the stainless steel. Attached to the hold-down assembly are four burnable poison rods and 12 thimble plugs. The thimble plugs are constructed of solid stainless steel, while the poison rods are filled with borosilicate glass, a neutron burnable absorber.

The BPRA had been irradiated during Cycle 3 (May 23, 1974, through November 16, 1975) in location E22. Table 2.3 provides the BPRA irradiation history, along with its eight nearest neighbors. The data presented consist of the following: assembly identification, initial uranium-235 enrichment, beginning of cycle 3 (BOC3) burnup, and end of cycle 3 burnup (EOC3). Figure 2.13 shows the BPRA core location.

2.4 Sample Preparation

The NFA components were shipped to hot cells at PNL in modified fuel casks. Once at PNL, samples were prepared for the laboratory analysis. Since whole components had been shipped, samples were cut from sections of the NFA components. Twenty-eight samples were cut in hot cells at PNL. Eleven samples were cut from the CRB, 8 samples from the RCCA, and 9 samples from the BPRA; Figures 2.14, 2.15, and 2.16 show the approximate sample locations for each of the listed components.

Originally, samples from the CRB were to be taken from the center (axial) structure by using a core drill at the intersection between two adjacent cruciform blades. This type of sample was desired because penetration of the actual blade would allow the escape of the "ball bearing" form of neutron absorber materials contained in the rods of the blades. It was difficult to remove samples from the axis of the structure without shearing the drill bit. Photographs of the samples are reproduced in

Figure 2.2. CRB Exposure - Cycle 1

Figure 2.3. CRB Exposure - Cycle 2

Figure 2.4. CRB Exposure - Cycle 3

Figure 2.5. CRB Exposure - Cycle 4

Figure 2.6. CRB Exposure - Cycle 5

Figure 2.7. CRB Exposure - Cycle 6

Figure 2.8. CRB Exposure - Cycle 7

Figure 2.9. CRB Exposure - Cycle 8

Figure 2.10. CRB Exposure - Cycle 9

Figure 2.11. CRB Exposure - Cycle 10

Table 2.2. RCCA Irradiation History

Cycle	Core Location	Host Assembly	Host Assembly Burnup (MWd/MTU)
1	L-6	B24	18,770
2	I-5	B24	10,721
3	L-6	E33	13,932
4	L-6	F02	8,225
5	L-6	G24	10,141
6	H-2	G24	8,830
7	H-2	H15	9,351
8	H-2	L01	8,417
9	H-2	L16	7,313
10	I-3	L16	8,180
11	H-2	M09	7,916
12	K-5	N25	13,793
Total			125,589

Appendix A. Figure A.1 shows a damaged drill bit. Therefore, it was decided that the samples would have to be taken from the sheath material of the cruciform blade by a small grinder or cutting tool. The desired sample sizes were approximately 1/2 by 1/2 inch. Figure A.2 shows a portion of the cut CRB with the absorber material intact. Figures A.3 through A.13 illustrate the actual samples.

Samples of the cladding tube portions of the RCCA and BPRA were cut approximately 1/2 inch in length. It was necessary to axially split the sides of these samples to remove the absorber because it was tightly bonded to the clad. At non-tubing locations, an equivalent size (1/2 by 1/2 inch) of solid sample was taken. Figures A.14 through A.30 illustrate the samples for the BPRA and RCCA.

It was assumed that the neutron absorber material within the three components would not activate appreciably. Activation measurements were separately performed for these absorber materials, but not under stringent quality assurance guidelines. Hence, the results are not presented here. These measurements confirm the assumption that the absorber material may be neglected for classification determinations. It is interesting that these measurements showed pico-Curie per gram concentrations of transuranics in the CRB boron carbide, which were likely a result of uranium impurities present prior to irradiation. These concentrations were not high enough to affect component classification.

Figure 2.12. Location of RCCA by Cycle

The CRB, RCCA, and BPRA samples were further sub-sectioned in the shielded analytical laboratory (SAL) hot cells. The hot cell facilities where these samples were sub-sectioned are highly contaminated because a wide variety of radioactive samples have been processed through them. In an effort to evaluate the extent of radionuclide contamination from the SAL processing and the accuracy of the overall process, National Institute for Standards Technology (NIST) stainless steel standards were prepared identically to the samples. One standard was cut and prepared for each sample batch. The samples were divided into four batches: two batches for the CRB samples and one batch each for the RCCA and BPRA samples.

Table 2.3. BPRA Irradiation History

	Position in Core		
Assembly ID	E18	D01	E26
Enrichment	2.595	3.038	2.595
BOC3 burnup	0	12,426	0
EOC3 burnup	16,019	16,211	15,953
Assembly ID	D26	E22	A02
Enrichment	3.038	2.695	2.265
BOC3 burnup	10,455	0	12,251
EOC3 burnup	16,456	16,424	14,199
Assembly ID	E12	D08	E32
Enrichment	2.595	3.038	2.595
BOC3 burnup	0	12,223	0
EOC3 burnup	15,724	16,275	16,337

Figure 2.13. Location of BPRA During Cycle 3

Figure 2.14. CRB Sample Locations

Figure 2.15. RCCA Sample Locations

The standards and samples were sub-sectioned in the SAL using a circular saw and a vise grip. Because of the inherent limitations of the hot cell manipulators and cutting tools and grips available, little control could be exercised over the actual sample section size/mass. Targeted masses were 3.0 g: 1.5 g for dissolution and two 0.75 g samples for carbon-14 analysis. Several samples were smaller than the target mass after the cladding interior was removed because the cladding was thinner than previously anticipated. This was not a concern at non-tubing locations.

After sub-sectioning, the exterior surfaces of the samples were cleaned to remove both corrosion film and any contamination resulting from the cutting procedure. (Thomas 1992) The cleaning steps entail the use of a hot 6 M HCl dip, a hot 8 M HNO₃ dip, and sonication in a bath of Micro™ cleaning solution. These steps were repeated at least once on each sample with a low surface-area-to-volume ratio. For the samples with a high surface-area-to-volume ratio, care had to be taken to ensure the sample did not completely dissolve in the cleaning process.

Figure 2.16. BPRA Sample Locations

The stainless steel samples were then dissolved in 6 M HCl. The inconel sample (BPRA-2, outer spring) was dissolved in a combination of HF, HNO₃, and HCl. The samples were brought to a known volume, and aliquots were distributed for the various analyses.

3.0 Laboratory Analysis

The samples were analyzed to determine the exact proportions of the constituent elements. They were also analyzed for activation product concentrations.

3.1 Elemental Analysis

After activation, the concentration of radioactive activation products in the metal samples is directly related to the concentration of the parent isotopes. For example, two locations exposed to identical flux profiles could have dissimilar activities if the concentration of parent isotopes is dissimilar. To obtain meaningful activation results, it is necessary to know the concentrations of the parent isotopes within known and reasonable accuracies.

An inductively coupled plasma/mass spectrometer (ICP/MS), modified to accommodate radioactive material, was used for the elemental analysis (Wyse 1993). The ICP/MS is operated as follows: the liquid sample is aspirated through a pneumatic nebulizer and mixed with argon to form an aerosol. This aerosol then is introduced into an inductively coupled plasma. The plasma atomizes and ionizes the aerosol. This ion beam is then focused and sent through a quadrupole mass spectrometer, which separates the ions according to mass per unit charge (m/z). Ions are detected with an electron multiplier. By varying the radio frequency/magnetic fields of the quadrupole, the masses of interest can be scanned.

The samples were composed primarily of chromium, iron, and nickel. In addition, trace quantities of the parent elements cobalt, niobium, and molybdenum were also measured. The copper concentration was below the instrument detection limit. Parent elements nitrogen and carbon cannot be measured by the ICP/MS. An assessment of elemental nitrogen and carbon concentrations was not possible without installing prohibitively expensive equipment and was not performed.

Table 3.1 shows the results of the elemental analysis. The data indicate that parent isotope concentrations are not necessarily uniform along the components. The primary constituents and the parent elements of interest are listed. The results are tabulated in $\mu\text{g/g}$ of metal. The mass balance shown in the far right column is the sum of all the concentrations.

3.2 Radionuclide Analysis

There were six radioactive isotopes of interest in this study: cobalt-60, niobium-94, nickel-63, nickel-59, carbon-14, and technetium-99. Except for cobalt-60, all of these isotopes required extensive chemical separations for accurate analysis. Trends in the data were very similar for each of the radioisotopes measured. This phenomenon is expected based upon the approximate $1/v$ nature of the parent nuclide cross sections.

Table 3.1. Elemental Analytical Results

Sample	Cr $\mu\text{g/g}$	Fe $\mu\text{g/g}$	Co $\mu\text{g/g}$	Ni $\mu\text{g/g}$	Nb $\mu\text{g/g}$	Mo $\mu\text{g/g}$	Mass Balance %
RCCA-1	168,000	695,000	934	88,200	199	3,360	96
RCCA-2	300,000	620,000	1,060	89,500	134 $\pm$ 18	2,200	101
RCCA-3	169,000	690,000	286	94,000	92 $\pm$ 16	2,660	96
RCCA-4	172,000	690,000	297	91,500	90 $\pm$ 20	2,580	96
RCCA-5	170,000	675,000	320	93,500	134 $\pm$ 17	2,940	94
RCCA-6	190,000	757,000	359	98,500	122	2,610	105
RCCA-7	186,000	720,000	303	94,500	110	2,620	100
RCCA-8	210,000	735,000	1,100	107,000	21.5	136 $\pm$ 18	105
BPRA-1	188,000	743,000	1,360	93,000	123 $\pm$ 17	4,480	103
BPRA-1 Duplicate	176,000	719,000	1,340	93,500	113	3,880	99.4
BPRA-2	163,000	80,200	554	829,000	12300	712	109
BPRA-3	159,000	621,000	975	76,800	110 $\pm$ 27	3,060	86.1
BPRA-4	131,000	580,000	504	72,400	26.8	717	78.5
BPRA-5	169,000	760,000	704	94,600	42.8	910	103
BPRA-6	65,000	734,000	664	92,500	47.0	860	99.3
BPRA-7	156,000	702,000	637	91,300	41.9	827	95.1
BPRA-8	168,000	755,000	692	93,500	78.4	950	102
BPRA-9	148,000	562,000	631	77,800	70 $\pm$ 13	616	78.9
Note: Unless otherwise indicated, errors are estimated to be $\pm$ 10%.							

Table 3.1. (contd)

Sample	Cr $\mu\text{g/g}$	Fe $\mu\text{g/g}$	Co $\mu\text{g/g}$	Ni $\mu\text{g/g}$	Nb $\mu\text{g/g}$	Mo $\mu\text{g/g}$	Mass Balance %
C-1	184,000	741,000	1,790	88,400	123	1,890	102
C-2	204,000	773,000	2,150	95,300	159	3,390	108
C-3	187,000	796,000	1,230	93,500	111 $\pm$ 16	2,570	108
C-4	197,000	820,000	1,260	98,900	96.9	2,600	112
C-5	189,000	793,000	1,170	95,800	107	3,540	108
C-6	185,000	753,000	1,120	94,200	91 $\pm$ 10	3,600	104
C-7	187,000	744,000	1,180	94,900	110	2,470	103
C-8	193,000	753,000	1,110	98,100	85.9	3,650	105
C-9	188,000	735,000	1,170	95,500	81.2	2,440	102
C-9 Duplicate	201,000	794,000	1,230	102,000	116	2,620	110
C-10	206,000	745,000	207	87,500	56.4	15 $\pm$ 10	104
C-11	216,000	774,000	214	92,900	37.2	20.2	108

The results are presented in Tables 3.2 through 3.7. These tables present the activities in both Ci/g metal and Ci/m³. Percent error and relative percent difference (RPD) are also provided. RPD is a measure of the accuracy between a duplicate and sample. Small RPDs are desired. Graphs of these data are presented in Section 4.0, where comparisons are made to computational results. Unless otherwise indicated, cited errors are based on the propagated measurement errors.

Appendix B presents similar information with arrows pointing to NFA component diagrams. Results shown are Ci/g metal, parent isotope concentration, and Ci/g dominant parent.

The measured data appear reasonable based upon the known irradiation histories. Figure 3.1 shows a typical PWR power profile. The BPRA concentrations peaked around the middle of the core since the power level and neutron flux were highest in this region. All of the BPRA samples were stainless steel except BPRA-2, which was inconel. Since the parent isotope concentrations of these two metals are different, BPRA-2 activated differently than the stainless steel samples. Because the inconel activations are plotted on the same graph as the steel activations, the plot often appears to "dip" or "spike" in relation to the neighboring stainless steel samples.

Table 3.2. Cobalt-60 Analytical Results

Sample ID	Ci/g	Ci/m ³	Error (%)	RPD (%)
C-1	4.68E-02	3.74E+05	1.1	
C-2	5.33E-02	4.26E+05	1.1	
C-3	1.02E-02	8.16E+04	1.1	
C-6	5.55E-03	4.44E+04	1.1	
C-9	1.45E-04	1.16E+03	1.1	
C-9 Duplicate	1.39E-04	1.11E+03	1.1	4.1
C-10	1.97E-06	1.58E+01	1.3	
C-11	1.33E-07	1.06E+00	1.3	
RCCA-1	7.20E-08	5.76E-01	1.5	
RCCA-2	1.71E-07	1.37E+00	1.2	
RCCA-3	6.35E-07	5.08E+00	1.1	
RCCA-5	1.97E-07	1.58E+00	1.2	
RCCA-8	6.49E-03	5.19E+04	1.1	
BPRA-1	1.55E-04	1.24E+03	1.1	
BPRA-1 Duplicate	1.51E-04	1.21E+03	1.1	2.6
BPRA-2	8.45E-05	6.97E+02	1.1	
BPRA-3	4.09E-04	3.27E+03	1.1	
BPRA-6	2.99E-03	2.39E+04	1.1	
BPRA-9	1.69E-03	1.35E+04	1.1	

Table 3.3. Niobium-94 Analytical Results

Sample ID	Ci/g	Ci/m ³	Error (%)	RPD (%)
C-1	2.21E-07	1.77E+00	3.4	
C-2	1.33E-07	1.06E+00	3.7	
C-2 Lab dup.	1.18E-07	9.00E-01	4.8	12
C-3	2.81E-08	2.25E-01	3.5	
C-6	1.09E-08	8.72E-02	6.1	
C-9	1.29E-10	1.03E-03	4.9	
C-9 Hot cell dup.	2.85E-10	2.30E-03	6.2	76
C-11	<1.62E-11	<1.30E-04	*	
RCCA-5	<1.25E-10	<1.00E-03	*	
RCCA-8	7.83E-09	6.26E-02	3.2	
BPRA-1	1.84E-10	1.47E-03	6.3	
BPRA-1 Hot cell dup.	2.82E-10	2.30E-03	5.8	42
BPRA-2	1.47E-07	1.21E+00	2.5	
BPRA-3	8.53E-10	6.82E-03	2.9	
BPRA-6	1.13E-08	9.04E-02	2.9	
BPRA-9	1.28E-08	1.02E-01	2.2	
Note: Less than (<) values invalidate error determination.				

Table 3.4. Nickel-63 Analytical Results

Sample ID	Ci/g	Ci/m ³	Error (%)	RPD (%)
C-1	1.81E-02	1.45E+05	8.3	
C-2	8.42E-03	6.74E+04	8.3	
C-3	1.59E-03	1.27E+04	8.2	
C-6	9.76E-04	7.81E+03	8.3	
C-6 Bench duplicate	9.74E-04	7.79E+02	8.3	0.20
C-9	2.64E-05	2.11E+02	8.3	
C-9 Hot cell duplicate	3.90E-05	3.12E+02	8.2	38.5
C-11	2.44E-06	1.95E+01	8.2	
RCCA-1	2.27E-08	1.82E-01	14.1	
RCCA-2	1.26E-08	1.01E-01	15.9	
RCCA-3	1.07E-07	8.56E-01	15.9	
RCCA-5	4.81E-08	3.85E-01	14.3	
RCCA-8	1.02E-02	8.16E+04	9.0	
RCCA-8 Bench duplicate	9.76E-03	7.81E+04	9.0	4.4
BPRA-1	7.23E-05	5.78E+02	8.6	
BPRA-1 Hot cell duplicate	6.96E-05	5.57E+02	8.5	3.8
BPRA-2	8.65E-04	7.14E+03	8.3	
BPRA-3	2.22E-04	1.78E+03	8.6	
BPRA-3 Bench duplicate	2.19E-04	1.75E+03	8.7	1.4
BPRA-6	2.93E-03	2.34E+04	8.2	
BPRA-9	1.31E-03	1.05E+04	8.4	

Table 3.5. Nickel-59 Analytical Results

Sample ID	Ci/g	Ci/m ³	Error (%)	RPD (%)
C-1	1.14E-04	9.12E+02	13.2	
C-2	6.50E-05	5.20E+02	12.8	
C-3	1.28E-05	1.02E+02	12.5	
C-6	8.09E-06	6.47E+01	12.4	
C-6 Bench duplicate	7.76E-06	62.1E+01	12.8	4.2
C-9	1.97E-07	1.58E+00	13.7	
C-9 Hot cell duplicate	2.90E-07	2.32E+00	12.8	38.2
C-11	1.40E-08	1.12E-01	85.7	
RCCA-1	1.89E-10	1.51E-03	23.8	
RCCA-2	5.06E-11	4.05E-04	45.5	
RCCA-3	8.75E-10	7.00E-03	19.4	
RCCA-5	3.15E-10	2.52E-03	20.3	
RCCA-8	8.24E-05	6.59E+02	13.3	
RCCA-8 Bench duplicate	7.95E-05	6.36E+02	12.6	3.6
BPRA-1	6.60E-07	5.28E+00	13.0	
BPRA-1 Hot cell duplicate	6.33E-07	5.1E+00	13.0	4.2
BPRA-2	8.27E-06	6.82E+01	13.3	
BPRA-3	2.08E-06	1.66E+01	13.0	
BPRA-3 Bench duplicate	2.15E-06	1.72E+01	13.0	3.3
BPRA-6	2.61E-05	2.09E+02	12.6	
BPRA-9	1.23E-05	9.84E+01	13.0	

Table 3.6. Carbon-14 Analytical Results (Average)

Sample ID	Ci/g	Ci/m ³	RPD (%)
C-1	3.3E-05	2.60E+02	72
C-2	8.3E-06	6.64E+01	66
C-3	<1.4E-06	<1.12E+01	*
C-4	7.1E-07	5.68E+00	37
C-5	1.2E-06	9.56E+00	120
C-6	1.5E-06	1.20E+01	12
C-7	5.6E-07	4.44E+00	12
C-8	1.2E-07	9.60E-01	(1)
C-9	2.7E-08	2.12E-01	12
C-10	4.5E-09	3.60E-02	64
C-11	3.9E-10	3.08E-03	81
RCCA-1	<3.5E-07	<2.72E+00	*
RCCA-2	<5.2E-07	<4.12E+00	*
RCCA-3	<5.8E-07	<4.64E+00	*
RCCA-4	<6.0E-07	<4.80E+00	*
RCCA-5	<4.5E-07	<3.60E+00	*
RCCA-6	<3.2E-07	<2.56E+00	*
RCCA-7	<3.9E-07	<3.12E+00	*
RCCA-8	1.1E-05	8.80E+01	12
BPRA-1	1.2E-07	9.60E-01	2.9
BPRA-2	3.7E-08	3.05E-01	5.0
BPRA-3	2.3E-07	1.80E+00	38
BPRA-4	6.6E-06	5.28E+01	(1)
BPRA-5	8.6E-06	6.88E+01	(1)
BPRA-6	7.8E-06	6.24E+01	(1)
BPRA-7	8.0E-06	6.40E+01	(1)
BPRA-8	8.03E-06	6.40E+01	(1)
BPRA-9	2.8E-06	2.24E+01	5.3
<p>Note: The results reported in this table are average results when there was enough metal for two samples per sample location. In such cases, RPD values are reported. When there was enough metal for only 1 sample, an RPD cannot be calculated and the RPD column is marked with a (1). RPDs also cannot be reported when the reported values are less than (<) values and the RPD column is marked with an asterisk (*).</p>			

Table 3.7. Technetium-99 Analytical Results

Sample ID	Ci/g	Ci/m ³	Error (%)	RPD (%)
C-1	3.57E-08	3.00E-01	12.0	
C-2	7.03E-08	5.62E-01	12.9	
C-2 Bench dup.	6.16E-08	4.90E-01	7.8	13.1
C-3	1.62E-08	1.30E-01	5.7	
C-6	1.11E-08	8.88E-02	10.8	
C-9	9.15E-11	1.61E-03	15.3	
C-9 Hot cell dup.	2.01E-10	1.60E-03	28.9	74.7
C-11	6.70E-11	5.36E-04	14.9	
RCCA-5	1.10E-12	9.35E-06	25.5	
RCCA-8	1.57E-09	1.30E-02	15.3	
BPRA-1	2.63E-10	2.10E-03	14.8	
BPRA-1 Hot cell dup.	2.71E-10	2.17E-03	15.1	3.0
BPRA-2	1.07E-10	8.83E-04	15.0	
BPRA-3	8.14E-10	6.51E-03	14.7	
BPRA-6	4.88E-09	3.90E-02	15.0	
BPRA-6 Bench dup.	5.92E-09	4.70E-02	15.0	19.3
BPRA-9	2.06E-09	1.65E-02	15.0

Figure 3.1. Typical PWR Power Profile

The RCCA radionuclide concentrations did not follow the PWR power profile because the RCCA was not inserted into the core. The tip (RCCA-8), which was closest to the core, was highly activated. The activation dropped off quickly to negligible levels a short distance (less than 2 feet) from the core.

Unlike the other two components, the BWR CRB was inserted at variable depths throughout its life. It was difficult, therefore, to accurately predict the activation profile of this component. Since the CRB was inserted from the bottom of the core, the tip was in the core much of the time, while the bottom of the blade was outside the core much of the time. Reflecting this exposure history, the blade was most activated at the tip, with activation decreasing further from the tip.

Following is a discussion of the analytical techniques used to measure radionuclide concentrations.

3.2.1 Cobalt-60

The cobalt-60 concentration is measured directly by gamma energy analysis of the dissolved and diluted samples. This analysis is very straightforward because cobalt-60 always emits two gammas (1173 and 1332 keV) in sequence when it decays. It is relatively easy to measure this gamma activity. In fact, cobalt-60 is often used as a standard for radiation measurements because of its readily discernable gamma peaks.

Table 3.2 shows the results in tabular form.

3.2.2 Niobium-94

Thirteen samples were analyzed for niobium-94 activity. As with the nickel, the niobium was first chemically separated from the original solution because the activity of the other radioisotopes, principally cobalt, was high enough to interfere with the measurement.

The separation procedure (Wynhoff 1991; Fadeff 1993) is as follows. Niobium is first precipitated as niobium hydroxide and then as niobic acid. Niobium-95 is added to each sample before the separations to serve as a yield monitor. Both niobium-95 and niobium-94 are measured in the final sample by gamma spectroscopy. Germanium solid state detectors are used for the measurements. An analysis of the gamma spectra for these samples indicates a good separation was achieved for niobium from other gamma emitters.

The niobium analysis was performed after the carbon and cobalt analyses, at which time it was clear that only the tip of the RCCA had received considerable exposure. Therefore, only two RCCA samples were analyzed for this isotope. RCCA-8 showed an order of magnitude greater activity than RCCA-5 since it was closer to the core.

Table 3.3 shows the results in tabular form.

3.2.3 Nickel-63 and Nickel-59

Nickel-63 is a low energy beta emitter and is best quantified using liquid scintillation counting. Nickel-59, however, decays by electron capture to cobalt-59 and is best measured by counting the 6.9 KeV cobalt x-ray emitted in this process. To minimize interference for both counting techniques, the analytes must be separated from other radioactive contaminants (Strebin 1993; Kaye 1992).

The nickel purification procedure is as follows. A sample is equilibrated with a stable nickel carrier and prepared for loading onto a dimethylglyoxime (DMG) precipitation column. The sample is then loaded on the DMG column where the nickel forms a NiDMG complex. Other cations and anions are effectively eluted off with the load and wash solutions. Next, nickel is stripped off the column with 3 M HNO₃. It is again precipitated as the NiDMG complex, filtered onto a 1-inch filter paper, and washed. Afterward, the filter paper NiDMG complex is mounted for low energy photon spectroscopy

(LEPS) counting where nickel-59 activity is determined. The NiDMG is then oxidized in a muffle furnace leaving NiO, which is then dissolved. An aliquot of the nickel solution is then counted on a liquid scintillation counter (LSC) for nickel-63 activity, and another aliquot is analyzed for total nickel to determine radiochemical yield.

Tables 3.4 and 3.5 show the results in tabular form for nickel-63 and nickel-59, respectively.

3.2.4 Carbon-14

The analytical procedure involves total combustion in oxygen of a metal sample in an induction furnace (Baldwin 1992). All forms of carbon, including carbon-14, are oxidized and collected. Next, the oxygen gas stream from the furnace is passed through a catalytic heater for conversion of any CO to CO₂, as well as H₂ to H₂O, then passed through a drying column for removal of interfering tritiated water, HTO. The gas is sparged through a NaOH collection bubbler for quantitative collection of ¹⁴CO₂ and measured by liquid scintillation counting. The carbon recovery is then evaluated relative to NIST-traceable stainless steel carbon standards using a calometric carbon analyzer. Finally, the liquid scintillation counter is calibrated by NIST-traceable carbon-14 standards.

Optimally, samples of similar carbon-14 concentrations are run together, and lower activity samples are run prior to higher activity samples. This method minimizes the effects of potential cross contamination of high activity samples into lower-activity samples. This carbon-14 determination was complicated by the fact that carbon-14 concentrations were not known *a priori*. Samples were analyzed sequentially (BPRA-1, 2, etc.) and not in the order of increasing activity. In some cases, residual carbon-14 (e.g., on walls of transport tubing) caused by the high concentration samples was larger than the activity of the samples that followed. The degree of cross-contamination was monitored by blank sample runs. In such cases only "less than" values, as a function of the instrument blank measurement, could be reported. This cross contamination did not compromise classification determination because wherever cross contamination was a concern, the carbon-14 concentrations were well below Class C limits. The degree of precision varied widely with these samples, indicating inhomogeneity on a local scale was occurring for many samples.

Table 3.6 shows the results in tabular form.

3.2.5 Technetium-99

The technetium-99 activity was measured for 13 selected samples (6 CRB, 5 BPRA, and 2 RCCA). Technetium-99 is a low energy, beta emitter and can be quantified either by liquid scintillation counting or ICP/MS. The samples were analyzed using both techniques since the activities were rather small. It was hoped that the measured activities using the two methods would be the same. As with the nickel and niobium, the technetium must first be separated prior to analysis to minimize interference from other radioisotopes.

The separation procedure (Strebin 1993) is as follows. A radiochemical tracer with a short half life (6.01 h), technetium-99m, is added to each sample. The sample matrix is converted to dilute HNO_3 , and technetium is oxidized to pertechnetate with H_2O_2 . The sample is then loaded onto a cation exchange column. Next, the pertechnetate is eluted through the cation exchange column (Dowex 50 x 4, 100-200 mesh) and most of the cations (including transition metals) are retained on the column. The technetium fraction is then passed through a TEVA-Spec[®] (Eichrom Ind., Darien, Illinois) column, where the technetium is retained and most impurities are washed through the column. The technetium is eluted from the TEVA-Spec[®] column with 8M HNO_3 , evaporated to near dryness, and brought to a 2 mL volume; 1 mL is aliquoted for LSC analysis and 1 mL remains for ICP/MS analysis. The chemical yield is determined by gamma counting the radiochemical tracer and comparing the sample count rate to that of a 100% yield comparator standard. Finally, after a suitable decay period for the technetium-99m tracer, one aliquot is counted by LSC for technetium-99 activity and the second aliquot analyzed by ICP/MS for technetium-99 concentration.

Table 3.7 shows the results in tabular form.

4.0 Computer Calculations

Both the ORIGEN2 and MCNP computer codes were used as part of the methodology described in this report. The codes are described below. Comparisons are also made between the results generated by ORIGEN2, MCNP, and the laboratory.

4.1 ORIGEN2 Calculations

ORIGEN2 models were developed for the three NFA components. ORIGEN2 is a computer code developed at Oak Ridge National Laboratory to calculate burnup and depletion of nuclides during irradiation and decay in a nuclear reactor. It is relatively simple to execute, as it requires only zero-dimensional geometry. The code uses one group cross sections that are present in multiple cross section libraries. The library chosen for a particular case is dependent upon the type of reactor being studied.

The purpose of these ORIGEN2 calculations was not to reproduce the laboratory results, as was the goal of the MCNP model. Except for the BPRA rods, ORIGEN2 results will not match the laboratory data because the components were not always located in the fueled region of the core. Comparison of these ORIGEN2 results with the laboratory data facilitated the selection of scaling factors.

4.1.1 Control Rod Blade

The CRB was inserted into the core at variable penetration depths over its irradiation history. If the blade exposure history is known in sufficient detail, ORIGEN2 and appropriate scaling factors may be used *with caution*. Since a point on the blade is subjected to multiple reactor locations and neutron spectrums, the results will not be as accurate as for the BPRA rods, which are stationary and located in-core. Boron-10 depletion data, as indicated in Table 2.1, were available for each quarter of the CRB. ORIGEN2 was run until the boron-10 depletion in each quarter of the blade matched the known depletion.

ORIGEN2 was run separately for the handle, assuming that the handle had been in the reactor for all 10 cycles at a "core average" location. Since the handle was always within the fueled region of the core, ORIGEN2 was applied directly. Scaling factors will not be needed for the handle.

Since the measured parent element concentrations varied along the length of the blade, an average of the measured concentrations was assumed for the entire blade. The following assumptions were used in the development of the ORIGEN2 model. The assumptions were chosen to model the CRB irradiation history as accurately as possible using the best possible information. Some assumptions reflect typical BWR conditions.

Blade

- flux irradiation with $\phi = 5 \times 10^{12}$ n/cm²/s to match the boron-10 depletion

Handle and Tip

- power irradiation with power density = 13.37 MW/MTU
- enrichment = 2.5 w/o uranium-235
- irradiation time = 5235 days
- no imbedded decay periods
- The CRB handle had seen ten operating cycles. Some of these cycles were with fresh fuel and other cycles were with burned fuel. In an attempt to model these different environments, ORIGEN2 was run to a burnup of 23,000 MWd/MTU. The burned fuel was replaced with fresh fuel and the burnup continued to 47,000 MWd/MTU. Finally, the burned fuel was again replaced with fresh fuel and the burnup continued to 70,000 MWd/MTU.

4.1.2 Rod Cluster Control Assembly

The RCCA was out of the core while the reactor was operating. A core-average ORIGEN2 calculation was performed for the entire RCCA. Consequently, without scaling factors the ORIGEN2 results for the RCCA will not be expected to correspond with any of the laboratory data points because the RCCA was not in the fueled region of the core.

Although the parent element concentrations varied along the length of the RCCA, the measured concentrations for sample RCCA-8 (rod tip) were assumed in the ORIGEN2 calculation since this sample was closest to the core and received the most activation. The following data were used in the ORIGEN2 model:

- burnup of host assemblies = 125,589 MWd/MTU
- power density = 25 MW/MTU
- initial enrichment = 3.2 w/o uranium-235
- As with the CRB handle, the RCCA was exposed to many different host assembly burnups. To simulate this environment, the burned fuel was replaced with fresh fuel after 1/4, 1/2, and 3/4 of the total burnup.

4.1.3 Burnable Poison Rod Assembly

Of the three NFA components studied, the ORIGEN2 model for the BPRA was the most complete. Since the BPRA rods were in the core, ORIGEN2 was run directly for several different sample locations. One clad-average case was also run using the average parent isotope concentrations. The enrichment and power density were the same as for the RCCA model.

The burnup at each location was assumed to be the assembly-average burnup multiplied by the relative power based on a typical PWR power profile (Figure 3.1). Power was assumed to be radially uniform across the BPRA. The values are given in Table 4.1.

4.1.4 ORIGEN2 Results

The results for the ORIGEN2 runs are shown in Table 4.2. Since the BPRA was inserted into the core, it is anticipated that the computed values will be similar to the laboratory values. The CRB values should bear some resemblance to the laboratory values because an attempt was made to model the irradiation history of the blade. The CRB tip results should compare well with the laboratory data because the tip was always in the fueled region of the core. The RCCA values calculated by ORIGEN2 will be much higher than the experimental values because ORIGEN2 modeled the RCCA as if it were in the core. Detailed comparisons of these results with laboratory data are made in Section 4.3.

Table 4.1. ORIGEN2 Assumptions for the BPRA

Power and Burnup Assumptions	BPRA Average	BPRA-4	BPRA-5	BPRA-6	BPRA-7	BPRA-8	BPRA-9
Relative Power Fraction	1.00	0.75	1.08	1.11	1.16	1.23	0.34
Power, MW/MTU	37.9	28.4	40.9	42.2	44.1	46.6	13.1
Burnup, MWd/MTU	16,400	12,300	17,700	18,300	19,100	20,200	5,700

Table 4.2. ORIGEN2 Results

Sample	^{60}Co (Ci/m ³)	^{94}Nb (Ci/m ³)	^{63}Ni (Ci/m ³)	^{59}Ni (Ci/m ³)	^{14}C (Ci/m ³)	^{99}Tc (Ci/m ³)
CRB Handle (C-1)	6.25E+05	3.26	1.18E+05	7.21E+02	3.73E+02	6.08E-01
CRB Top 1/4	1.95E+04	6.59E-02	2.37E+03	1.79E+01	6.63	1.41E-02
CRB 2nd 1/4	2.00E+04	6.84E-02	2.45E+03	1.86E+01	6.88	1.46E-02
CRB 3rd 1/4	1.61E+04	4.97E-02	1.80E+03	1.35E+01	5.00	1.07E-02
CRB Bottom 1/4	5.97E+03	1.50E-02	5.48E+02	4.08	1.50	3.22E-03
RCCA	5.84E+05	9.98E-01	1.91E+05	1.18E+03	5.92E+02	8.56E-03
BPRA-4	2.03E+04	1.58E-01	1.51E+04	1.34E+02	6.25E+01	6.65E-03
BPRA-5	4.11E+04	3.65E-01	2.86E+04	2.49E+02	9.10E+01	1.21E-02
BPRA-6	4.00E+04	4.14E-01	2.89E+04	2.51E+02	9.41E+01	1.18E-02
BPRA-7	4.02E+04	3.86E-01	2.99E+04	2.58E+02	9.86E+01	1.18E-02
BPRA-8	4.63E+04	7.64E-01	3.24E+04	2.79E+01	1.05E+02	1.43E-02
BPRA-9	1.18E+04	1.93E-01	7.56E+03	6.85E+01	2.88E+01	2.69E-03

4.2 MCNP Calculations

The model discussed in this section employs the MCNP code (LANL 1990) to calculate neutron activation of NFA components.^(a) Specifically, MCNP is used to directly calculate the concentrations of 10 CFR 61.55 radionuclides in the waste components of interest. The input consists of geometry, irradiation history and cooling time, and material composition.

The primary objective of the MCNP analysis was to calculate the activation as a function of axial position for both the BPRA and RCCA. This information could then be used to develop ORIGEN2 scaling factors to be used in NFA activation calculations outside the fueled region of the core.

The dimensions, materials, and operational history were obtained for the RCCA and BPRA from Wisconsin Electric to support the modelling effort. Data were gathered for the following components: reactor fuel, grid spacers, upper and lower nozzles, guide tubes, poison rods, thimble plugs, control rods, upper and lower core support plates, and upper core plate. Operational data encompassed fuel cycle information, including: axial and radial power profiles, control rod positions, assembly load patterns, fuel assembly types and enrichments, and soluble boron concentrations.

4.2.1 Model Development

The principal components of interest in this study were the BPRA and the RCCA. An MCNP model was not developed for the CRB because of its complex irradiation history.

Since the loading patterns were relatively uniform throughout the life of the core, the fuel model (which provides the source neutrons for activation) could be considerably simplified. For the RCCA, a single fuel-loading pattern averaged over all 12 cycles was used as a representation of the active core throughout the reactor life.

Fuel isotopics at various burnups were not readily available. Therefore, the ORIGEN2 code (Coff 1980) was used to calculate fuel isotopics at burned conditions. The average fuel enrichment and burnup data were used for typical PWR conditions. These conditions are incorporated in the PWR nuclear data library, which is a library input for the ORIGEN2 model.

The fuel elements were modelled explicitly in three dimensions. The dimensions and materials used for the fuel element model are summarized in Table 4.3.

(a) Love, E. F., et. al. 1993. Use of MCNP for Characterization of Reactor Vessel Internals Waste from Decommissioned Nuclear Reactors (Draft). Pacific Northwest Laboratory, Richland, Washington.

Table 4.3. Fuel Element Physical Characteristics

Component	Material	Inner Radius (cm)	Outer Radius (cm)	Length (cm)
Active Fuel	UO ₂	Not Applicable	0.4788	367.51
Cladding	Zircaloy-4	0.4788	0.5359	367.51
Upper Plenum	Zircaloy-4	0.4788	0.5359	16.44
End cap	Zircaloy-4	Not Applicable	0.5359	1.73

The geometric information for each component was obtained from drawings and correspondence from the Wisconsin Electric Power Company. The geometric model consisted of a 1/8 assembly containing a BPRA and a 1/8 assembly containing an RCCA. These two 1/8 assemblies were modeled side by side. Figure 4.1 shows a typical cross section of the model. Such simplifications (using 1/8- or 1/4-assembly models) are common in reactor physics because of the symmetry generally available in reactor assemblies.

The elemental composition of the materials in the components of interest was measured. The measurements taken at individual locations were used in the MCNP model. These results were presented in Table 3.1. However, as was noted in Section 3.1, the concentrations of three trace elements of interest (nitrogen-14, carbon-13, and copper-63) were unable to be measured either because of cost constraints or method detection limits. The concentrations of these elements were estimated using values reported in industrial literature.

Two different types of tallies were utilized in the Point Beach MCNP model. These included volume-averaged (n,γ) reaction rates and volume-averaged (n,p) reaction rates. The volume averaged (n,γ) and (n,p) reaction rates were used to compute the concentrations of the radionuclides of interest in waste classification.

4.2.2 MCNP Results

The results of the MCNP calculations are presented in Table 4.4. The results appeared to be approximately an order of magnitude less than the laboratory measurements, but closely matched the activation trends seen in the laboratory measurements, both in the fueled and nonfueled regions of the core. Section 4.3 will compare and plot the experimental, ORIGEN2, and MCNP results.

Figure 4.1. MCNP Model at an Axial Height of 8.2 ft

4.3 Comparison of Laboratory and Computational Results

This section compares the laboratory results with the computational results. Note that in Figures 4.2 through 4.19, straight lines connecting the data points are to be interpreted as visual aids not possessing physical significance. No scaling factors were used to generate the plots.

4.3.1 Control Rod Blade

Figures 4.2 through 4.7 show the laboratory and ORIGEN2 results for the CRB. It is difficult to compare the measurements with the calculations because of the inherent limitations of the ORIGEN2 model. Horizontal lines on the figures indicate that the results represent a quarter of the blade, since the depletion data were only available for each quarter. ORIGEN2 users may be able to obtain better results if available blade depletion data are more discrete. ORIGEN2 predicts the activation of the tip very well. This is an important result, since the tip will usually be the most activated part of the blade.

Table 4.4. MCNP Results

Sample	^{60}Co (Ci/m ³)	^{94}Nb (Ci/m ³)	^{63}Ni (Ci/m ³)	^{59}Ni (Ci/m ³)	^{14}C (Ci/m ³)	^{99}Tc (Ci/m ³)
RCCA-4	2.36	3.17E-05	2.38	2.06E-02	2.06E-04	4.29E-06
RCCA-6	1.91E+02	3.70E-03	1.88E+02	1.64	1.51E-02	5.81E-04
RCCA-8	1.43E+04	1.46E-02	5.20E+03	4.52E+01	3.82E-01	6.39E-04
BPRA-1	7.50E+01	4.15E-04	3.14E+01	2.77E-01	2.70E-03	6.76E-05
BPRA-2	5.07E+01	7.42E-03	8.83E+01	7.83E-01	4.27E-03	5.85E-05
BPRA-3	1.08E+02	8.39E-04	5.12E+01	4.53E-01	5.34E-03	9.59E-05
BPRA-4	3.60E+03	1.74E-02	1.32E+03	1.19E+01	1.56E-01	6.50E-03
BPRA-5	7.24E+03	3.99E-02	2.49E+03	2.24E+01	2.24E-01	1.19E-02
BPRA-6	7.06E+03	4.53E-02	2.52E+03	2.27E+01	2.32E-01	1.16E-02
BPRA-7	7.07E+03	4.22E-02	2.60E+03	2.34E+01	2.42E-01	1.17E-02
BPRA-8	8.13E+03	8.35E-02	2.81E+03	2.53E+01	2.56E-01	1.42E-02
BPRA-9	2.09E+03	3.53E-02	1.15E+03	1.03E+01	1.24E-01	5.99E-03

Figure 4.2. Comparison of CRB Laboratory and ORIGEN2 Results, ^{60}Co

Figure 4.3. Comparison of CRB Laboratory and ORIGEN2 Results, ^{94}Nb

Figure 4.4. Comparison of CRB Laboratory and ORIGEN2 Results, ^{63}Ni

Figure 4.5. Comparison of CRB Laboratory and ORIGEN2 Results, ^{59}Ni

Figure 4.6. Comparison of CRB Laboratory and ORIGEN2 Results, ^{14}C

Figure 4.7. Comparison of CRB Laboratory and ORIGEN2 Results, ^{99}Tc

Figure 4.8. Comparison of RCCA Laboratory and MCNP Results, ^{60}Co

Figure 4.9. Comparison of RCCA Laboratory and MCNP Results, ^{94}Nb

Figure 4.10. Comparison of RCCA Laboratory and MCNP Results, ^{63}Ni

Figure 4.11. Comparison of RCCA Laboratory and MCNP Results, ^{59}Ni

Figure 4.12. Comparison of RCCA Laboratory and MCNP Results, ^{14}C

Figure 4.13. Comparison of RCCA Laboratory and MCNP Results, ^{99}Tc

Figure 4.14. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{60}Co

Figure 4.15. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{94}Nb

Figure 4.16. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{63}Ni

Figure 4.17. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{59}Ni

Figure 4.18. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{14}C

Figure 4.19. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{99}Tc

4.3.2 Rod Cluster Control Assembly

Figures 4.8 through 4.13 show the laboratory and MCNP results for the RCCA. The ORIGEN2 results are not included on the plots because the results would not be expected to represent the RCCA conditions without scaling factors. MCNP was able to predict the trend in the data. MCNP consistently underpredicted the laboratory results for the section of the RCCA that was closest to the core (RCCA-8). This underprediction was present for all of the MCNP cases.

Note that for carbon-14 the results do not appear to correlate (Figure 4.12). This finding is to be expected, since most of the laboratory results were "less than" values, as explained in Section 3.2.4, causing the carbon-14 concentration to appear "flat." In addition, the MCNP results for carbon-14 may be poor because the parent element concentrations were not measured, but estimated from the literature.

4.3.3 Burnable Poison Rod Assembly

Figures 4.14 through 4.19 show the laboratory, MCNP, and ORIGEN2 results for the BPRA. The BPRA was studied in more computational detail than the other two components. MCNP results are available at all laboratory data points. In addition, ORIGEN2 results are available at all data points that were within the active region of the core. The MCNP results in the core region (BPRA-4 through 8) were derived by applying the PWR power profile to the average MCNP activation in the clad. Since MCNP and ORIGEN2 utilized the same power profile, the curves were very similar.

As can be seen from the BPRA figures, ORIGEN2 was able to predict the measured activation reasonably well. However, it overpredicted the niobium-94 activation and underpredicted the technetium-99 activation. This is not a problem for technetium-99, since the activity of this isotope is not near the 10 CFR 61.55 limit. Overpredicting the niobium-94 activation could cause difficulties with waste classification efforts because the 10 CFR 61.55 limit on niobium-94 is relatively low. As with the RCCA, the carbon-14 measurements do not compare as well as the other isotopes because the parent element concentrations were not measured.

MCNP matched the trend in the laboratory data reasonably well, even in the far core regions. However, the values consistently underpredicted experimental values by an order of magnitude or more.

Appendix C presents the same information provided on the plots in a different form, utilizing diagrams of the components.

4.3.4 Activity Ratios

Dose profiling is often used to estimate radionuclide concentrations in NFA component hardware. Cobalt-60 concentrations are determined from gamma scan measurements along the length of a component. From these doses, rough concentrations of other radioisotopes of interest are estimated based upon the relative fraction of alloying constituents and their nuclear cross sections.

The laboratory data allow a direct comparison between cobalt-60 concentrations and the concentrations of other 10 CFR 61.55 nuclides. Tables 4.5 through 4.7 present activity ratios between selected nuclides using the different experimental and computational techniques for each of the three NFA components. The laboratory ratios will allow dose profiling methods to achieve a greater level of accuracy. Once cobalt-60 concentrations are estimated, the laboratory ratios can be used to estimate 10 CFR 61.55 radionuclide concentrations in other NFA components that have experienced similar neutron spectra.

The ratios were calculated at the time each component was discharged from the reactor. They were also normalized for the parent isotope concentration at each location. Carbon-14 is not present in the ratio tables because the parent isotope concentration for this isotope was not measured. *To properly apply these ratios to other NFA components, estimates of the parent isotope concentrations must first be made, as well as the time from component discharge.* The ratios were calculated from the following equation:

$$\text{Ratio} = \left[\frac{\text{Activity isotope A/parent isotope concentration for isotope A}}{\text{Activity isotope B/parent isotope concentration for isotope B}} \right] \times \text{decay correction}$$

Since cobalt-60 has a relatively short half-life, it will usually decay one or more half-lives before the component is prepared for final waste disposal. The "decay correction" simply builds-up the cobalt-60 concentration to its discharge value, using the standard radioactive decay equation. It may be assumed that the other radionuclide concentrations remain approximately constant with time due to their relatively long half-lives.

The activity ratios also serve as a check to determine if the codes were treating cross sections properly, which is the reason they are addressed in this section. For example, the MCNP results were much lower than the experimental results. However, if the activity ratio between two nuclides is the same for both MCNP and the experimental values, MCNP was treating cross sections properly. In most cases the ratios agree reasonably well, providing confidence in the cross-section treatment for both MCNP and ORIGEN2.

It is expected that the laboratory ratios will differ somewhat between sample locations because each sample was exposed to a different neutron spectrum. The neutron spectrum can be loosely defined as the proportion of both fast and thermal neutrons in the total neutron flux. While the magnitude of the total flux may change significantly throughout the core, the spectrum often will not change greatly

Table 4.5. CRB Radionuclide Activity Ratios

Laboratory Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
C-1	2.47E+04	9	2.63E+04	5.86E+05	2825
C-2	4.43E+04	19	5.36E+04	5.32E+05	2305
C-3	7.38E+04	33	5.92E+04	5.85E+05	2210
C-6	7.03E+04	33	7.48E+04	7.15E+05	2146
C-9	7.32E+04	31	1.41E+05	7.19E+05	2384
C-11	5.02E+03	2	2.58E+03	8.34E+01	3101
ORIGEN2 Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
Handle (C-1)	9.13E+04	31	3.09E+04	1.22E+06	2919
Top 1/4 (~ C-3)	1.15E+05	49	4.77E+04	1.64E+06	2355
Second 1/4 (~ C-5)	1.13E+05	48	4.70E+04	1.62E+06	2353
Third 1/4 (~ C-6)	1.26E+05	53	5.22E+04	1.80E+06	2365
Bottom 1/4 (~ C-8)	1.54E+05	64	6.42E+04	2.21E+06	2390
Note: Propagated errors for the laboratory values are approximately +/- 20%					

Table 4.6. RCCA Radionuclide Activity Ratios

Laboratory Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
RCCA-1	6.94E+04	32	NA ^(a)	NA ^(a)	2137
RCCA-2	5.51E+05	124	NA ^(a)	NA ^(a)	4430
RCCA-3	4.60E+05	212	NA ^(a)	NA ^(a)	2176
RCCA-5	3.53E+05	130	1.89E+03	1.16E+06	2717
RCCA-8	1.48E+04	7	4.64E+04	3.60E+05	2202
ORIGEN2 Result	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
Core Avg.	9.28E+04	32	3.28E+04	6.00E+06	2873
MCNP Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
RCCA-4	6.82E+04	33	6.47E+04	3.38E+06	2051
RCCA-6	6.17E+04	30	5.02E+04	1.68E+06	2045
RCCA-8	5.93E+04	29	5.48E+04	1.95E+06	2046
Note: Propagated errors for the laboratory values are approximately +/- 25%					
(a) Not available					

Table 4.7. BPRA Radionuclide Activity Ratios

Laboratory Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
BPRA-1	1.07E+05	55	7.52E+05	4.72E+06	1949
BPRA-2	1.02E+05	55	1.26E+05	2.47E+06	1861
BPRA-3	1.03E+05	54	5.34E+05	3.84E+06	1899
BPRA-6	1.06E+05	53	1.85E+05	1.93E+06	1997
BPRA-9	1.13E+05	60	1.45E+05	1.95E+06	1895
ORIGEN2 Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
BPRA-4	1.45E+05	72	6.74E+04	1.06E+07	2008
BPRA-5	1.48E+05	72	6.76E+04	1.07E+07	2049
BPRA-6	1.48E+05	72	6.77E+04	1.07E+07	2053
BPRA-7	1.49E+05	72	6.77E+04	1.07E+07	2059
BPRA-8	1.49E+05	72	6.77E+04	1.08E+07	2068
BPRA-9	1.42E+05	72	6.72E+04	1.04E+07	1961
MCNP Results	$^{60}\text{Co}/^{59}\text{Ni}$	$^{60}\text{Co}/^{63}\text{Ni}$	$^{60}\text{Co}/^{94}\text{Nb}$	$^{60}\text{Co}/^{99}\text{Tc}$	$^{63}\text{Ni}/^{59}\text{Ni}$
BPRA-1	1.15E+05	57	1.52E+05	8.33E+06	2017
BPRA-2	6.04E+05	302	1.40E+06	2.54E+06	2005
BPRA-3	1.17E+05	59	1.35E+05	8.07E+06	2011
BPRA-4	1.68E+05	85	6.34E+04	1.12E+06	1970
BPRA-5	1.68E+05	85	6.34E+04	1.12E+06	1970
BPRA-6	1.68E+05	85	6.34E+04	1.12E+06	1970
BPRA-7	1.68E+05	85	6.34E+04	1.12E+06	1970
BPRA-8	1.68E+05	85	6.34E+04	1.12E+06	1970
BPRA-9	1.57E+05	79	6.08E+04	7.77E+05	1993
Note: Propagated errors for the laboratory values are approximately +/- 20 %					

between locations in the fueled region of the core. The neutron spectrum outside the fueled region of the core is, however, much different than the core average spectrum. For this reason, differences were minimal between the activity ratios at different locations, with somewhat larger differences seen at locations out of the core.

The activity ratios derived from laboratory data were subject to uncertainty inherent in the laboratory measurements. The uncertainty in the laboratory ratios is approximately 20% to 25%.

It is most instructive to compare the nickel ratios because both nickel-63 and nickel-59 have parents that are present in natural nickel. In this case, the ratio of parent isotopes will always be constant at any location. The nickel-63/nickel-59 ratio should then be more constant than the other isotope ratios since one element of uncertainty has canceled out. The nickel ratios for ORIGEN2 and MCNP are very close to those of the laboratory measurements, providing confidence that the codes were handling the cross sections reasonably well.

4.3.5 Conclusions from Computer Calculations

MCNP was very successful, in many respects, in calculating radioisotope concentrations. The MCNP results, when plotted, displayed a shape very similar to the laboratory measurements. This finding is especially true for the BPRA, which was modeled in more depth using MCNP than the RCCA. The success in predicting the axial radioisotope distribution indicates that MCNP is properly treating both the cross sections and the neutron spectrum.

The results, though, did not compare closely in absolute magnitude. MCNP tended to underpredict the measured values by an order of magnitude or more. MCNP was able to provide only crude estimates of the absolute level of NFA activation. This information, while self consistent, was not sufficiently accurate to allow its use in the ORIGEN2 scaling factor development. Consequently, it was decided to develop the ORIGEN2 scaling factors based upon the measured data alone.

ORIGEN2 computed the in-core activation reasonably well, as shown in the BPRA plots. The RCCA and CRB results did not compare as well, but this behavior was anticipated because ORIGEN2 was not coded to directly solve problems such as these. Scaling factors will be selected based upon the ORIGEN2 models discussed in this section to provide conservative estimates of radionuclide content in NFA components located out of the fueled region of the core. These scaling factors will be presented in Section 5.3.

5.0 10 CFR Part 61.55 Classification

This section provides a detailed summary of the federal regulation and classification of the examined NFA components based on the test results. Finally, an extrapolation to other NFA components is provided.

5.1 Description of Regulation

10 CFR 61.55 defines radiological limits for the classification of low-level radioactive waste. Low-level waste is divided into four categories: Class A, B, C, and GTCC. Table 5.1 is a concise summary of the regulation.

Radionuclides identified in 10 CFR 61.55 have set limits for each waste class. The limits are different for each isotope. While many factors were considered in the development of these limits, the two main factors were 1) concern over groundwater contamination and 2) the protection of inadvertent intruders. Several of the short-lived isotopes have no Class C limit because it is assumed that they will decay to insignificant levels in a relatively short period of time.

Most NFA components will contain more than one radioisotope. When multiple radioisotopes are present, the total allowable radionuclide concentration is determined using the sum of fractions rule, as defined in 10 CFR 61.55. For a particular component, the sum of the fractions of the activity levels is determined by dividing each nuclide's concentration by the appropriate limit for that isotope. A separate calculation is performed for long and short-lived isotopes. That is,

$$\text{sum of the fractions} = \sum_i \frac{A_i}{A_{Li}} \leq 1$$

where A_i is the activity level for isotope i in Ci/m^3 and A_{Li} is the Class C limit for isotope i . If the value calculated for either the long- or short-lived nuclides is greater than 1, then the component in question is GTCC.

There are additional guidelines for mixtures of short- and long-lived radionuclides. If the sum of the fractions for the long-lived nuclides is less than 0.1 (less than 10% of Class C limits), classification will be determined by the short-lived nuclides only. If the concentration of any long-lived nuclide lies between the Class A and C limits, the waste is Class C, provided that the short-lived radionuclides are within Class C limits as well.

Table 5.1. Title 10 Code of Federal Regulation Part 61.55

Radionuclide	Concentration (Ci/m ³)		
	Class A limit	Class B limit	Class C limit
Carbon-14	.8	(1)	8
Carbon-14 in activated metal	8	(1)	80
Nickel-59 in activated metal	22	(1)	220
Niobium-94 in activated metal	0.02	(1)	0.2
Technetium-99	0.3	(1)	3
Iodine-129	0.008	(1)	0.08
Alpha emitting transuranic nuclides with half-life greater than five years	10(nCi/g)	(1)	100(nCi/g)
Plutonium-241	350(nCi/g)	(1)	3,500(nCi/g)
Californium-242	2,000(nCi/g)	(1)	20,000(nCi/g)
Short half-life			
Total of all nuclides with less than five year half-life	700	(2)	(2)
Helium-3	40	(2)	(2)
Cobalt-60	700	(2)	(2)
Nickel-63	3.5	70	700
Nickel-63 in activated metal	35	700	7,000
Strontium-90	0.04	50	7,000
Cesium-137	1	44	4,600
Notes: 1. Long half-life nuclides, in excess of Class A limits, are considered Class C or GTCC. 2. There are no Class B or C limits for these isotopes.			

All limits are defined in units of Ci/m³. This unit introduces a great deal of both flexibility and ambiguity when determining waste classification. For instance, if a piece of GTCC irradiated metal were mixed with Class C waste and placed in a container, the activity averaged over the volume of all the components within the container would likely classify the container as Class C.

Such volume averaging is acceptable, even preferable, since the amount of GTCC waste will be reduced. However, mixing with the sole intent of diluting radionuclide concentrations to lower a waste's classification is not permitted. Specific rules governing concentration averaging have not yet been adopted. The NRC has developed a draft technical position with proposed guidelines for the volume averaging of low level waste.^(a) It must be stressed, however, that at the present time the proposed guidelines are still in the draft stage and may be changed before final ratification. A discussion of the proposed guidelines follows.

5.1.1 Proposed Guidelines for Volume Averaging of Low-Level Waste

As most NFA components are rather large, it will be practical to cut them into smaller pieces prior to disposal. How a component is sectioned may significantly affect the subsequent volume averaging. This sectioning will be at the discretion of the persons packaging the waste for disposal. For volume averaging purposes, a cut piece may or may not be considered separate from the original component from which it was cut. There are several proposed criteria to determine when a piece of a cut component is to be treated as a discrete item. The proposed criteria are discussed in the following paragraphs.

The determination of whether a sectioned piece is to be treated as a discrete item is very important, since many NFA components are only partially inserted into the core. Consequently, when a component is cut into smaller pieces, one piece may be much more activated than another. Because of proposed restrictions on the volume averaging of radionuclides within a disposal container, it is beneficial to consider each cut piece as a member of a larger component, rather than as a discrete entity. *It is always permissible to volume average radionuclide concentrations over a component before it is cut, regardless of the variation of the radioisotope concentration within the component.*

A cut piece should be considered discrete if

- a. the volume of the piece is less than 0.01 ft³ (or 280 cm³) *and*
- b. the specific nuclide activity in the piece is greater than the respective value shown in Table 5.2.

In addition, cut pieces will be considered discrete if the specific nuclide activity in the piece is greater than the respective value shown in Table 5.3.

(a) "Draft NRC report dated September 1993 titled "Branch Technical Position on Concentration Averaging and Encapsulation."

Table 5.2. Activity Levels in Individual Pieces of Larger Components *Potentially* Requiring Their Piecemeal Consideration in Classification Determinations (for Predominantly Gamma-Emitting Nuclides)

Nuclide	For Waste Classified as Class A or B	For Waste Classified as Class C
Co-60	> 700 Ci	No Class C limit
Nb-94	> 10^{-3} Ci	> 10^{-3} Ci
Cs-137/Ba-137 (provided for completeness)	> 3×10^{-3} Ci	> 30 Ci

Table 5.3. Activity Levels in Individual Pieces of Larger Components Requiring Their Piecemeal Consideration in Classification Determinations (for Predominantly Beta-Emitting Nuclides)

Nuclide	For Waste Classified as Class A or B	For Waste Classified as Class C
C-14	> 1 Ci	> 10 Ci
Ni-59	> 4 Ci	> 40 Ci
Ni-63	> 7 Ci	> 1500 Ci
H-3 (provided for completeness)	> 8 Ci	No Class C limit
Alpha emitting transuranics with half-life greater than 5 years (excl. Pu-241 and Cm-242) (provided for completeness)	> 3×10^{-3} Ci	> 3×10^{-2} Ci

For completeness, limits are provided in Tables 5.2 and 5.3 for isotopes not of direct interest in this report. Note that the NRC has not provided limits for technetium-99, presumably because this isotope is present in trace quantities.

Pieces with similar radionuclide concentrations would be required to be placed into an appropriate storage container. All cut pieces considered to be part of a larger component would be required to be

placed in the *same* disposal container. *If all pieces of the component are not placed in the same disposal container, regardless of their volume or activity, they would be considered as discrete items in classification determinations.*

Containers are classified as Class A, B, or C, not the individual pieces or components. The classification of the waste filled container should be based on the volume-averaged concentration of the combined pieces and components. The volume used for averaging is the total displaced water volume of the activated metal, not the container volume. It is very important to note that an individual piece of activated metal may be GTCC, but once it is placed into a container filled with other activated metal, the container may be within Class C limits. This method is acceptable for volume averaging, as long as it is not for the sole purpose of diluting.

Unlimited diluting of waste would not be allowed. The NRC has proposed that for the predominantly gamma-emitting nuclides listed in Table 5.2, the radionuclide concentration of the most activated piece (or component) must be within a factor of 1.5 of the container averaged concentration. In addition, for the predominantly beta-emitting nuclides of Table 5.3, the radionuclide concentration of the hottest piece (or component) must be within a factor of 10 of the container averaged concentration.

Note that volume reduction may entail "double" volume averaging if radionuclide concentrations are not uniform over a contiguous piece of metal. The following packaging steps should clarify this point:

1. The radionuclide concentrations within a cut piece (or entire component) with a non-uniform radionuclide concentration are first averaged over the volume of the piece. There are no restrictions on concentration averaging within a contiguous piece of metal.
2. For each piece cut from a larger component, it should be decided (with the aid of Tables 5.2 and 5.3) if the piece is an "independent" piece, or simply part of a larger component. Note that for the predominantly gamma emitting isotopes, Table 5.2 can be avoided altogether if the piece is larger than 0.01 ft³. However, a piece larger than 0.01 ft³ may still fail the criteria in Table 5.3 if there is significant beta activity.
3. "Independent" pieces (or entire components) are combined and volume-averaged within a container. It is the average concentration of each "independent" piece (or entire component) that must obey the "10 times average" and "1.5 times average" rules when compared with the *container* average. This distinction will be clarified by the following example.

Example: The cruciform section of a CRB (0.169 m³) contains a niobium-94 concentration of 0.16 Ci/m³, a nickel-59 concentration of 22 Ci/m³, and a nickel-63 concentration of 5000 Ci/m³. The blade, as a whole, would be classified as Class C waste (i.e., niobium-94 fraction (0.8) + nickel-59 fraction (0.1) = 0.9; the nickel-63 concentration is within Class C limits). The blade, however, is sectioned into four equal pieces to facilitate shipment. The "hottest" piece contains 80% of the blade's activity. This piece would contain a niobium-94 concentration above the Class C limit. However, *if all pieces*

of the blade are contained in the same disposal container, the container could be classified as Class C waste, based on the blade as a whole, because the volume of each piece exceeds 280 cm³ (Table 5.2). It does not matter if the niobium-94 concentration in the hottest piece is more than 1.5 times the blade average because the blade is still *considered to be* a contiguous piece of metal.

Note that some NFA components may not need to be classified. Many NFA components, such as the BPRA and RCCA, fit into a fuel assembly. If a host assembly is available, it would likely be most effective to dispose of them together, since spent fuel assemblies are considered high-level waste and will have their own repository. However, there will not always be a host assembly for every NFA component requiring disposal. In addition, many NFA components, such as the CRB, do not fit within an assembly. In these cases, it is necessary to perform the proper classification.

5.2 Classification of BPRA, RCCA, and CRB

Based upon the analytical laboratory measurements, the CRB, RCCA, and BPRA were classified. Results can be reported in several different manners, depending upon the assumptions used in sectioning the components. For this document, results are reported in two ways. First, each component as a whole is classified. Second, each NFA component is sectioned and classified according to the experimental measurements. Since data were limited, it was assumed that they varied step-wise over the component. In certain instances, when data points were several feet apart and differed greatly in magnitude, simple averaging was performed to estimate the concentrations between the data points.

- *Method 1: Entire component.* The radionuclide concentrations may always be averaged over the entire component if the component is not cut. In other words, the total activity of the NFA component is divided by the total displaced water volume of the component. Since experimental data were limited, data points were assumed to vary step-wise across the components. As anticipated, the three NFA components studied were Class C when averaged in this fashion (Table 5.4).
- *Method 2: Section Averaging.* NFA components will likely be cut prior to waste classification and disposal. For this section averaging method, it was assumed that each NFA was cut into

Table 5.4. Classification of Entire Component

Component	Waste Class
CRB	Class C
RCCA	Class C
BPRA	Class C

four sections. Since the laboratory data were rather limited, each NFA section was classified according to the nearest laboratory measurement(s). The radionuclide concentrations were volume-averaged over each individual section. The absorber material in the RCCA and the poison in the BPRA did not activate appreciably and, thus, were assumed to contribute negligibly to the overall radioisotope concentrations. Therefore, volume averaging the BPRA and RCCA clad, which contain the 10 CFR 61.55 nuclides of interest, over the entire cross section of the rods will significantly decrease the radionuclide concentrations.

It must be stressed that the sectioning used in the following analysis was somewhat arbitrary. Sections sizes would likely be picked to facilitate packaging and to minimize GTCC waste. Table 5.5 shows the actual percentage of Class A, B, and C limits used to arrive at these classifications.

5.2.1 Burnable Poison Rod Assembly

The BPRA was divided into four sections: one section for the hold-down assembly and thimble plugs, and three equal sections for the poison rods. Only the hold-down assembly was GTCC. The primary reason the hold-down assembly was GTCC is the inconel springs, which have a high niobium concentration. If it were feasible to do so, the springs could be removed and the remainder of the BPRA would be Class C waste. Again, if all of the BPRA sections were placed in the same waste package it would be classified as Class C waste. Table 5.6 summarizes the results.

5.2.2 Rod Cluster Control Assembly

The RCCA was divided into four sections: one section for the entire spider assembly, and three equal sections for the absorber rods. Note that all sections but the bottom of the absorber are within Class A limits. This result is rather interesting, since the entire RCCA was classified as Class C. Table 5.7 summarizes the results.

For the sections listed as Class A, a "B" is also listed in parentheses, which indicates that there is a small possibility that the section may be Class B. An investigation of Table 5.1 reveals that there is a Class A limit to the quantity of nuclides with a half-life less than 5 years. Since the activity of every short-lived nuclide was not measured, it cannot be said with certainty that the section is within Class A limits. Iron-55 has a short half-life and may be present in non-trivial concentrations because iron is a primary component of stainless steel. However, judging by the relatively low cobalt-60 concentrations, it is reasonable to assume that the sections were within Class A limits.

5.2.3 Control Rod Blade

The CRB was divided into four sections: one section for the velocity limiter, and three sections for the cruciform portion. All of the sections were within Class C limits. As with the RCCA, there is a possibility that sections considered Class A might be Class B. However, this is not anticipated to be the case. As an indication of this possibility, a "B" has been placed next to the "A" in Table 5.8.

Table 5.5. Percentages of 10 CFR 61.55 Radionuclide Limits

Component	Classification	% Class C Limit						% Class B Limit	% Class A Limit	
		C-14	Ni-59	Nb-94	Tc-99	Total long-lived	Ni-63	Ni-63	Ni-63	Co-60
RCCA Total	C	4	5	1	< 1	9	18	179	3575	114
Spider Assembly	A (B)	3	< 1	< 1	< 1	3	< 1	< 1	1	< 1
Top 1/3	A (B)	1	< 1	< 1	< 1	1	< 1	< 1	< 1	< 1
Middle 1/3	A (B)	1	< 1	< 1	< 1	1	< 1	< 1	< 1	< 1
Bottom 1/3	C	8	20	2	< 1	31	79	791	15829	504
BPRA Total	C	15	20	27	< 1	62	70	Concentrations not listed exceed Class A and B limits.		
Hold-down Assembly	GTCC	16	26	66	< 1	108	89			
Top 1/3	C	12	15	7	< 1	34	51			
Middle 1/3	C	13	16	8	< 1	37	56			
Bottom 1/3	C	9	12	9	< 1	30	40			
CRB Total	C	5	12	24	1	42	47	467	9338	2780
Top 1/3	C	9	24	55	2	90	96	964	19282	5846
Middle 1/3	C	6	12	18	1	37	47	471	9421	2679
Bottom 1/3	C	1	3	4	< 1	8	10	100	2003	564
Velocity Limiter	A (B)	< 1	0	< 1	< 1	< 1	< 1	3	56	< 1

Table 5.6. BPRA Classification by Section

BPRA Section	Waste Classification
Hold-down Assembly, Including Thimble Plugs	GTCC
Top 1/3 of Poison Rod	Class C
Middle 1/3 of Poison Rod	Class C
Bottom 1/3 of Poison Rod	Class C

Table 5.7. RCCA Classification by Section

RCCA Section	Waste Classification
Spider Assembly	Class A (B)
Top 1/3 of Absorber Rod	Class A (B)
Middle 1/3 of Absorber Rod	Class A (B)
Bottom 1/3 of Absorber Rod	Class C

Table 5.8. CRB Classification by Section

CRB Section	Waste Classification
Top 1/3 of Blade (including handle)	Class C
Middle 1/3 of Blade	Class C
Bottom 1/3 of Blade (including support shaft)	Class C
Velocity Limiter	Class A (B)

Because all sections of the RCCA and CRB were within Class C limits, it would not matter if pieces of these components were placed in different containers. In fact, for the RCCA and CRB, it would be beneficial to separate the pieces, since Class A or B waste would be expected to be less expensive to dispose of than Class C waste.

5.3 Extrapolation to Other NFA Components

Based upon the measurements of the three NFA components studied, general statements can be made about the classification of these particular components in other reactors.

5.3.1 General Comments

The CRB studied had been exposed to 10 cycles. However, except for the handle, the blade was out of the core much of the time. Figures 2.2 through 2.11 show the irradiation history of the CRB. The 10 CFR 61.55 nuclides in the CRB as a whole had reached only about 50% of the Class C limits. Therefore, a CRB with an exposure history similar to, or even greater than, this blade should still be within Class C limits. However, cutting the blade into four or five pieces instead of three could force the tip of the same CRB to be GTCC.

The RCCA studied had been placed above the reactor for 12 cycles. Based upon the best available information, the RCCA was not in the reactor during regular operations. It is not expected, then, that other stainless steel RCCA components would have a different waste classification than this one, unless they had been in the reactor when the reactor was producing power.

The BPRA studied had been in the reactor for only one cycle, which lasted approximately 1.5 years. It is expected, therefore, that most BPRA's which have been exposed to only one cycle of operation would be within Class C limits. *However, BPRA assemblies which are burned for two cycles would likely be classified as GTCC waste.*

5.3.2 ORIGEN2 Scaling Factors

The three NFA components obtained were classified based upon laboratory measurements. However, laboratory measurements generally will not be available to support waste classification activities by reactor operators. Recourse must be made to computer codes or other methods in order to estimate radionuclide concentrations. The ORIGEN2 computer code is able to predict radionuclide concentrations in NFA components that are inserted into the fueled region of the core. However, ORIGEN2 cannot be directly used to calculate the activation of components outside the fueled region without incurring large uncertainties. Scaling factors have been used in the past in an attempt to address these shortcomings. Knowledge of the appropriate scaling factors will enable ORIGEN2 to provide rough estimates of the radionuclide concentrations for many NFA components. These concentrations can then be used to classify the components.

These scaling factors were developed by comparing the available laboratory data with the results of ORIGEN2 models. In Section 4.2 the ORIGEN2 models for the BPRA and RCCA were based on exposure data, while the model for the CRB was based upon boron-10 depletion data. The results were further normalized by the parent isotope concentrations. These scaling factors were then averaged over general regions of the NFA components studied.

It was originally believed that MCNP could be used to fill in the gaps between the limited number of laboratory data points. ORIGEN2 scaling factors could then be developed at any point along the NFA components. The MCNP results were able to match only the shape, and not the magnitude, of the concentration profile. MCNP also matched the shape of the concentration profile in the far-core regions. Because the magnitudes computed by MCNP were not sufficiently accurate, the scaling factors were based upon the laboratory measurements alone.

Scaling factors for general regions of the BPRA, RCCA, and CRB are presented in Table 5.9. These scaling factors are necessarily uncertain because of the limited quantity of laboratory data and should be used with caution. Based upon examination of the laboratory data, development of scaling factors for each individual radionuclide did not appear to be technically justifiable. The scaling factors were chosen to conservatively estimate the radionuclide concentrations, although they do not bound the true value in all cases. The scaling factors should be able to serve as a relatively simple way to estimate radionuclide concentrations for 10 CFR 61.55 waste classification. These scaling factors may also be used for other types of NFA components at similar locations outside of the core.

The scaling factors presented in Table 5.9 are applicable only to components with relatively simple irradiation histories, such as components that are either fully inserted or fully withdrawn. For components such as the CRB, which is both in and out of the core throughout its lifetime, these scaling factors do not apply. Because of the complex irradiation history of the CRB, it was difficult to precisely model the irradiation history using ORIGEN2. Since boron depletion data were available for the CRB, ORIGEN2 was run in a trial-and-error mode until the boron depletion matched the known depletion. The ORIGEN2 calculation using this methodology matched the laboratory measurements of the CRB within a factor of four.

To apply this methodology, information on a component's irradiation history and materials of construction must first be either known or estimated. An ORIGEN2 model may then be developed for the component. ORIGEN2 will output radionuclide concentrations that can be multiplied by the appropriate scaling factors in Table 5.9. These modified concentrations may then be used to classify the component, as described in Sections 5.1 and 5.2.

Table 5.9. ORIGEN2 Scaling Factors

Component Region	Typical NFA Components	Approximate Scaling Factors
In-core	BPRA clad	1.0
	CRB handle and tip	
Within 12 inches of core periphery	BPRA hold-down assembly	0.1
	RCCA end caps	
More than 12 inches outside core	RCCA spider assembly and clad	1.0E-5
	CRB velocity limiter	

As an alternate methodology, the laboratory activity ratios presented in Tables 4.5 through 4.7 can be used to estimate the activity of the remaining nuclides once the activity of one is known. For instance, one may use ORIGEN2 to calculate the cobalt-60 concentration, or use dose profiling to measure the cobalt-60 concentration, and then use Tables 4.5 through 4.7 to estimate the remaining nuclide concentrations.

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Appendix A

Photos of Non-Fuel Assembly Component Samples

Appendix A

Photos of Non-Fuel Assembly Component Samples

Appendix A presents photographs of samples that the Pacific Northwest Laboratory cut from three non-fuel assembly (NFA) components to obtain radionuclide measurements for estimating radionuclide inventories. The control rod blade (CRB) samples are shown in Figures A.1 through A.13. Next, Figures A.4 through A.22b display the burnable poison rod assembly (BPRA) samples. Finally, the rod cluster control assembly (RCCA) samples are exhibited in Figures A.23a through A.30b.

Figure A.1. CRB: Drill Bit Failure Using Original Cutting Technique

Figure A.2. CRB: Typical Cut Section from Sheath

Figure A.3. C-1: CRB Handle

Figure A.4. C-2: Top of CRB Sheath

Figure A.5. C-3: CRB Sheath, 1 Foot from Top

Figure A.6. C-4: CRB Sheath, 3 Feet from Top

Figure A.7. C-5: CRB Sheath, 5 Feet from Top

Figure A.8. C-6: CRB Sheath, 7 Feet from Top

Figure A.9. C-7: CRB Sheath, 9 Feet from Top

Figure A.10. C-8: CRB Sheath, 11 Feet from Top

Figure A.11. C-9: CRB Sheath, Bottom of Blade

Figure A.12. C-10: CRB Shaft

Figure A.13. C-11: CRB Velocity Limiter

Figure A.14. BPRA-1: BPRA Hold-down Bar at the Tip

Figure A.15. BPRA-2: Outer Inconel Spring in the BPRA Hold-down Assembly

a. Side View

b. End View

Figure A.16. BPRA-3: BPRA Assembly Plate and the Burnable Poison Rod Attachment Nut

a. Side View

b. End View

Figure A.17. BPRA-4: BPRA Clad, 2 Feet from Hold-down Assembly

a. Side View

b. End View

Figure A.18. BPRA-5: BPRA Clad, 4 Feet from Hold-down Assembly

a. Side View

Figure A.19. BPRC-6: BPRC Clad, 6 Feet from Hold-down Assembly

a. Side View

b. End View

Figure A.20. BPRA-7: BPRA Clad, 8 Feet from Hold-down Assembly

a. Side View

b. End View

Figure A.21. BPRA-8: BPRA Clad, 10 Feet from Hold-down Assembly

a. Side View

b. End View

Figure A.22. BPRA-9: BPRA End Cap

a. Top of RCCA Spider Assembly at Connect with Drive Mechanism

b. Different Angle

Figure A.23. RCCA-1: Top of RCCA Spider Assembly at Connect with Drive Mechanism

a. Top of RCCA Spider Assembly at the Top of a Control Rod

b. Different Angle

Figure A.24. RCCA-2: Top of RCCA Spider Assembly at the Top of a Control Rod

a. Side View

b. End View

Figure A.25. RCCA-3: Top of Control Rod at Bottom of Spider Assembly

a. Side View

b. End View

Figure A.26. RCCA-4: RCCA Clad, 2 Feet Below Spider Assembly

a. Side View

b. End View

Figure A.27. RCCA-5: RCCA Clad, 4 Feet Below Spider Assembly

a. Side View

b. End View

Figure A.28. RCCA-6: RCCA Clad, 6 Feet Below Spider Assembly

Figure A.29. RCCA-7: Clad, 8 Feet Below Spider Assembly

a. Side View

b. End View

Figure A.30. RCCA-8: RCCA End Cap

Appendix B

Laboratory Results

Appendix B

Laboratory Results

Appendix B presents drawings of three non-fuel assembly (NFA) components from which the Pacific Northwest Laboratory took samples for measuring radionuclide concentrations. Arrows mark the approximate locations from which samples were taken. The laboratory results are provided next to each arrow. Specific data presented are the radionuclide content (in Ci/g metal), the concentration of the dominant parent (in $\mu\text{g/g}$ metal), and radionuclide content (in Ci/g dominant parent) for all nuclides of interest.

Figure B.1. Results of CRB Laboratory Analysis, ⁶⁰Co

Figure B.2. Results of CRB Laboratory Analysis, ⁹⁴Nb

Figure B.3. Results of CRB Laboratory Analysis, ⁶³Ni

Figure B.4. Results of CRB Laboratory Analysis, ⁵⁹Ni

Figure B.5. Results of CRB Laboratory Analysis, ¹⁴C

Figure B.6. Results of CRB Laboratory Analysis, ⁹⁹Tc

Figure B.7. Results of RCCA Laboratory Analysis, ⁶⁰Co

Figure B.8. Results of RCCA Laboratory Analysis, ⁹⁴Nb

Figure B.9. Results of RCCA Laboratory Analysis, ⁶³Ni

Figure B.10. Results of RCCA Laboratory Analysis, ⁵⁹Ni

C-14
Ci/g Metal

Dominant Parent
 $\mu\text{g/g Metal}$

$<3.5\text{E-}07$

N. A.

$<5.2\text{E-}07$

$<5.8\text{E-}07$

$<6.0\text{E-}07$

$<4.5\text{E-}07$

$<3.2\text{E-}07$

$<3.9\text{E-}07$

$1.1\text{E-}05$

Figure B.11. Results of RCCA Laboratory Analysis, ^{14}C

Figure B.12. Results of RCCA Laboratory Analysis, ⁹⁹Tc

Figure B.13. Results of BPRA Laboratory Analysis, ^{60}Co

Figure B.14. Results of BPRA Laboratory Analysis, ⁹⁴Nb

Figure B.15. Results of BPRA Laboratory Analysis, ⁶³Ni

Figure B.16. Results of BPRA Laboratory Analysis, ⁵⁹Ni

Figure B.17. Results of BPRA Laboratory Analysis, ¹⁴C

Figure B.18. Results of BPRA Laboratory Analysis, ^{99}Tc

Appendix C

Comparison of Computer and Laboratory Results

Appendix C

Comparison of Computer and Laboratory Results

Appendix C presents the laboratory and computational data, in an alternate format, that was obtained from samples of three non-fuel assembly (NFA) components by the Pacific Northwest Laboratory. Arrows mark the approximate locations on the component drawings from which the samples were taken. The laboratory and computational results are provided next to each arrow. Radionuclide concentrations are presented in units of Ci/m³.

Figure C.1. Comparison of CRB Laboratory and ORIGEN2 Results, ⁶⁰Co

Figure C.2. Comparison of CRB Laboratory and ORIGEN2 Results, ⁹⁴Nb

Figure C.3. Comparison of CRB Laboratory and ORIGEN2 Results, ⁶³Ni

Figure C.4. Comparison of CRB Laboratory and ORIGEN2 Results, ⁵⁹Ni

Figure C.5. Comparison of CRB Laboratory and ORIGEN2 Results, ¹⁴C

Figure C.6. Comparison of CRB Laboratory and ORIGEN2 Results, ⁹⁹Tc

Co-60 Ci/m³
LABORATORY

Ci/m³
MCNP

Figure C.7. Comparison of RCCA Laboratory and MCNP Results, ⁶⁰Co

Nb-94 Ci/m³
LABORATORY

Ci/m³
MCNP

Figure C.8. Comparison of RCCA Laboratory and MCNP Results, ⁹⁴Nb

Ni-63 Ci/m³
LABORATORY

Ci/m³
MCNP

Figure C.9. Comparison of RCCA Laboratory and MCNP Results, ⁶³Ni

Figure C.10. Comparison of RCCA Laboratory and MCNP Results, ^{59}Ni

Figure C.11. Comparison of RCCA Laboratory and MCNP Results, ¹⁴C

Figure C.12. Comparison of RCCA Laboratory and MCNP Results, ⁹⁹Tc

Figure C.13. Comparison of BPR Laboratory, MCNP, and ORIGEN2 Results, ^{60}Co

Figure C.14. Comparison of BPRA Laboratory, MCNP, and ORIGEN2 Results, ⁹⁴Nb

Figure C.15. Comparison of BPRA Laboratory, MCNP, and ORIGEN2 Results, ⁶³Ni

Figure C.16. Comparison of BPRA Laboratory, MCNP, and ORIGEN2 Results, ⁵⁹Ni

Figure C.17. Comparison of BPRA Laboratory, MCNP, and ORIGEN2 Results, ¹⁴C

Figure C.18. Comparison of BPRA Laboratory, MCNP, and ORIGEN2 Results, ⁹⁹Tc

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