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Power distribution calculations in the High Flux Isotope Reactor for various control blade tantalum loadings

William Jay Marshall

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To the Graduate Council:

I am submitting herewith a thesis written by William Jay Marshall entitled "Power distribution calculations in the High Flux Isotope Reactor for various control blade tantalum loadings." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Nuclear Engineering.

Laurence F. Miller, Major Professor

We have read this thesis and recommend its acceptance:

Ronald Pevey, Lawrence Townsend

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

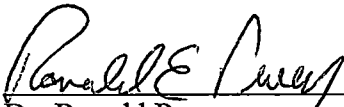
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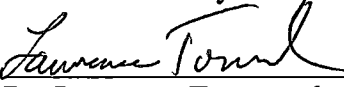
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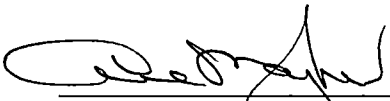

Laurence F. Miller, Major Professor

We have read this dissertation
and recommend its acceptance:


Dr. Ronald Pevey


Dr. Lawrence Townsend

Accepted for the Council:


Interim Vice Provost and
Dean of The Graduate School

**Power Distribution Calculations in the High Flux
Isotope Reactor for Various Control Blade
Tantalum Loadings**

**A Thesis
Presented for the
Master of Science
Degree
University of Tennessee-Knoxville**

**William Jay Marshall
August 2001**

To my darling Robyn,
without whom none of this
would have been possible.

Acknowledgements

The completion of this project would have been utterly impossible without the help and encouragement of many people. I would be remiss in my duties as an author not to thank them, though I must confess there are some that I will forget. To them I apologize, and I offer my profound thanks and gratitude to them as well as the people named below.

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Without them I could never have come close to this. My brother James and his wife Lori

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Abstract

The High Flux Isotope Reactor (HFIR), located at the Oak Ridge National Laboratory, has seen occasional cladding damage (local swelling or blistering) in the reactor control elements over the past several years. The control elements are located in an annulus between the core and reflector, and contain three regions: a "black" region containing Eu_2O_3 dispersed in an aluminum matrix; a "gray" region with Tantalum particles in an aluminum matrix; and a "white" region (or follower) of perforated aluminum. The cladding damage has been limited to the tantalum region, and it is expected that reduction in the tantalum fraction in this segment will reduce or eliminate the potential for clad damage. The purpose of this research is to determine the extent to which the tantalum fraction can be reduced, without unacceptable impacts on core power shape.

A two dimensional R-Z geometry model of the HFIR has been created for use in DORT for neutronics calculations. Weighted cross sections are generated using the SCALE package by running BONAMI, NITAWL, and XSDRN-PM. XSDRN is used for cell weighting and then region weighting of the cross sections. These cross sections are mixed into the necessary mixtures for use in DORT by GIP. These cross sections are used in the DORT R-Z model to generate flux distributions and eigenvalues for different combinations of tantalum concentration and blade position.

An initial reference case has been run using the HFIRCE-3 (Critical Experiment Series 3) core to determine the bias introduced by simplifying the HFIR to an R-Z model. The modeled critical configuration yielded an eigenvalue of 0.9907. This value is used later as a value that represents criticality in the core. This bias is introduced by azimuthal asymmetries not included in the R-Z model, by approximations in cross section generation, and by various other discretization of continuous variables. Spatial power distributions, however, are not affected by the bias.

A set of runs has been used to determine an approximate relationship between k -effective and blade position for a series of different tantalum concentrations. The current initial loading of 38 volume percent and the target loading of 30 volume percent are the focus of this study. For each concentration, k is calculated with the control blades at heights of 14", 17.5", 20" and 25". These values are used to calculate an approximate critical blade position for each of the concentrations.

The main concern with reduced tantalum loadings is an increase in power peaking in the core. This increase could occur because the control elements must be run closer together at beginning of cycle conditions, thus pinching the power shape with the large absorber regions closer together. The limiting thermal constraint is power peaking on the core exit of the inner fuel element. Peaking factors are calculated by dividing the fission

neutron production rate in any interval by the average fission rate. Fission rates are assumed to be proportional to power.

The results indicate that there is no difference in power shape between the initial loadings of 38 and 30 volume percent Ta. Such a modification is feasible since the peaking is not increased. A further decrease in loading would not be feasible, as peaking increases are observed for initial loadings below 25%.

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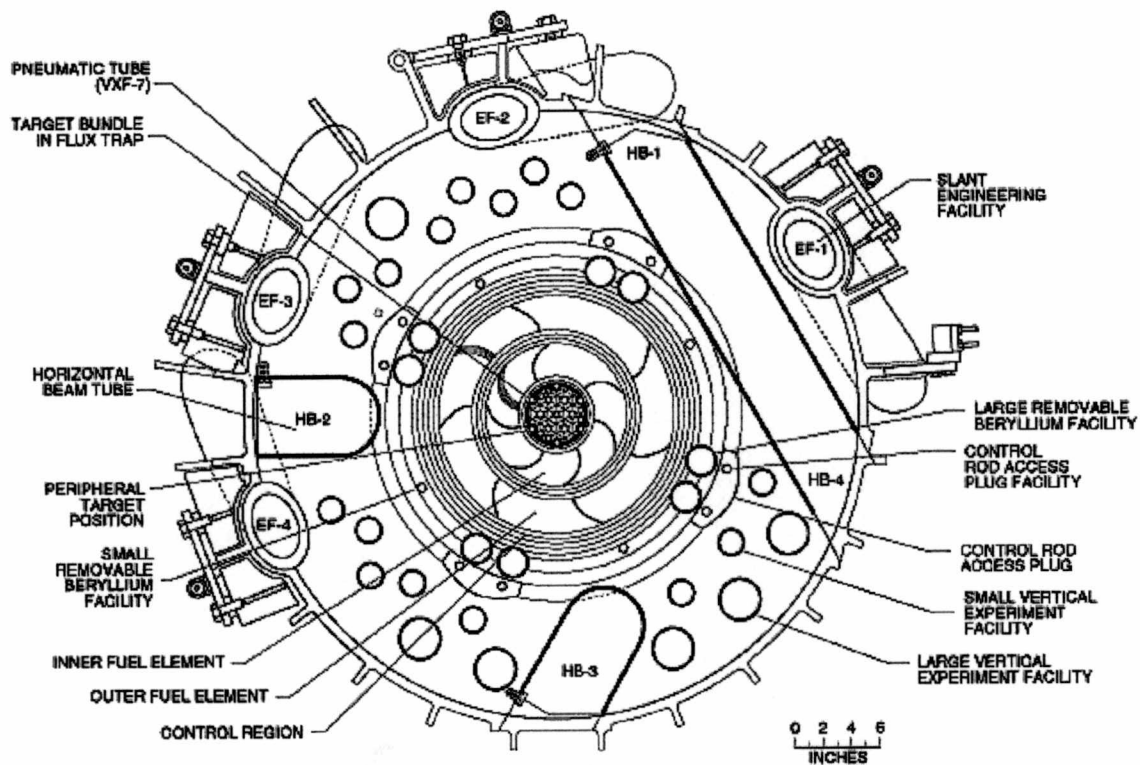
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1. Introduction

The purpose of this research is to evaluate the effects of changing the High Flux Isotope Reactor (HFIR) control blade tantalum loading on the power distribution in the core. The HFIR has seen occasional cladding damage, local blistering or swelling, in the control blades over the past several years. The control blades are located in an annulus between the core and the beryllium reflector¹, as illustrated in Figure 1.1. Note that each control blade contains three axial regions: a “black” region, which is a dispersion of Eu_2O_3 in aluminum, a “gray” region with Ta in aluminum, and a “white” region of perforated aluminum. A detailed drawing of the control blades is presented in Figure 1.2. Cladding damage has only been witnessed in the gray region, and it is believed that a reduction in the Ta fraction will reduce or eliminate the future occurrence of such damage. It is estimated that a reduction in Ta loading from the current level of 38 volume percent to 30 volume percent would eliminate this problem.²

The remainder of this chapter is dedicated to a description of the HFIR. Chapter 2 provides a detailed description of the computation procedure used in this research. The various models used in these calculations are discussed in Chapter 3. The calculations that are performed are presented in Chapter 4 and their results in Chapter 5. Chapter 6 provides the conclusions drawn as a result of this project. Appendix A includes instructions for running the codes used in this research on the UNIX machines operated by the College of Engineering at the University of Tennessee-Knoxville.



Cross section of reactor core at horizontal midplane

Figure 1.1. HFIR Core Cross Section

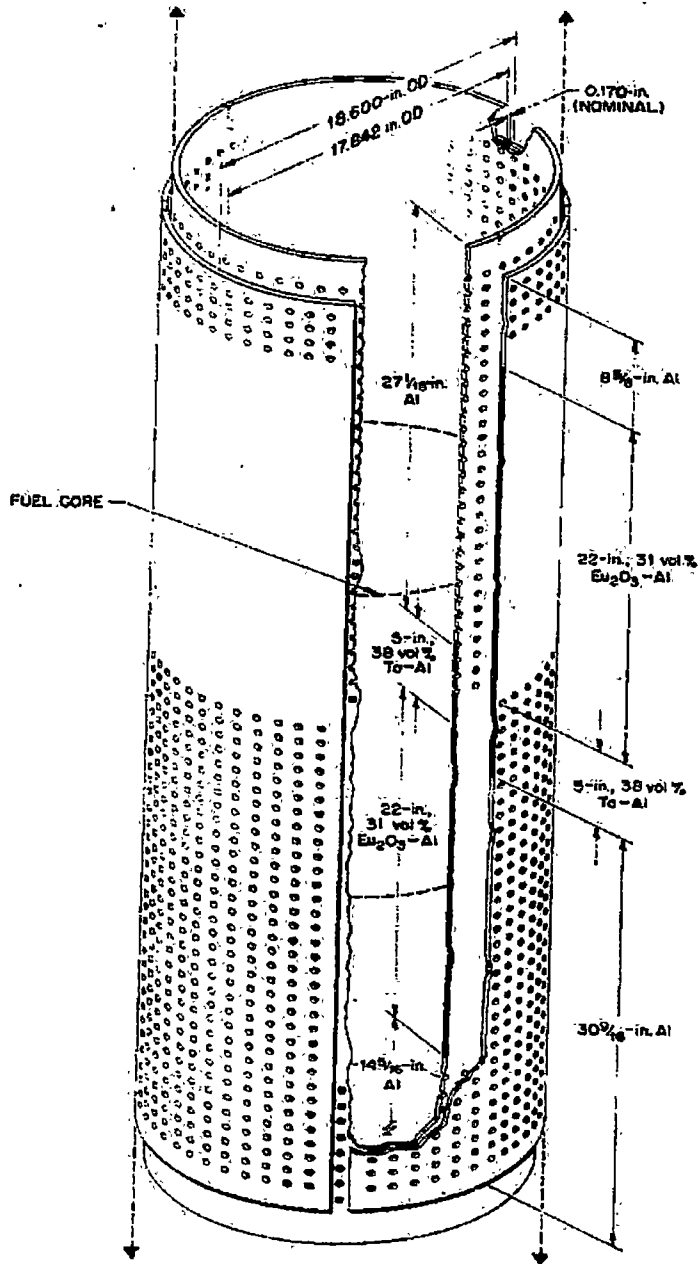


Figure 1.2. Detailed Drawing of Control Blades

1.1 Core Description

The High Flux Isotope Reactor (HFIR) is a leakage controlled core, and as such has no internal control surfaces. The core itself is approximately 50.8 cm tall and consists of two cylindrical fuel elements each containing involute-geometry fuel plates. The fuel is approximately 93% enriched U-235 in a U_3O_8 and aluminum cermet. The fuel is clad with aluminum, and water is the coolant and primary moderator. The inner fuel element contains a boron carbide burnable poison. At the center of the core is a flux trap whose primary purpose is production of transplutonium isotopes. The core is surrounded by a thin control region and by a beryllium-water reflector. Several beam ports and other experimental facilities are present in the reflector. Figure 1.1 shows a cross section of these regions, and Figure 1.3 illustrates the core and the experimental facilities inside the pressure vessel. Figure 1.4 is a schematic diagram of the entire core, control region, and reflector.

The control region surrounds the outer fuel region, and this annular region contains two 0.25 inch thick concentric cylindrical blades. The inner blade is used for shim and regulation and is a solid cylinder of four welded quadrants. A 1 inch aluminum gap between quadrants is introduced by this weld. The outer cylinder is a set of 4 individual plates separated by approximately 1.1 inch water gaps. These blades are used for shim and safety, and each has its own drive mechanism. Figure 1.2 is a detailed drawing of the control blades, note that the inner and outer blades each have three axial regions: white, gray and black. The white region is pure aluminum while the gray and black regions contain absorber cores clad in aluminum. The gray region core is a

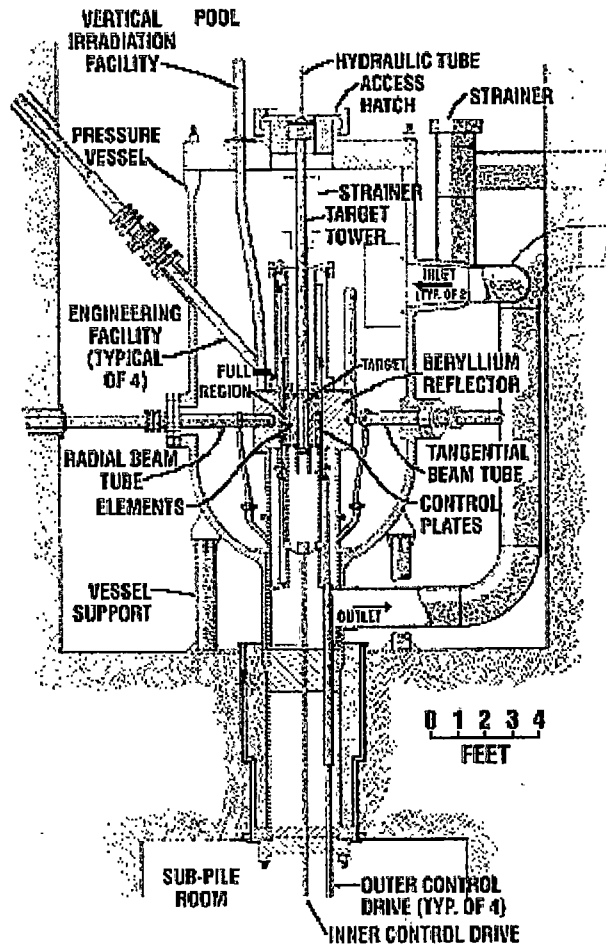


Figure 1.3. Core and Experimental Facilities Inside Pressure Vessel

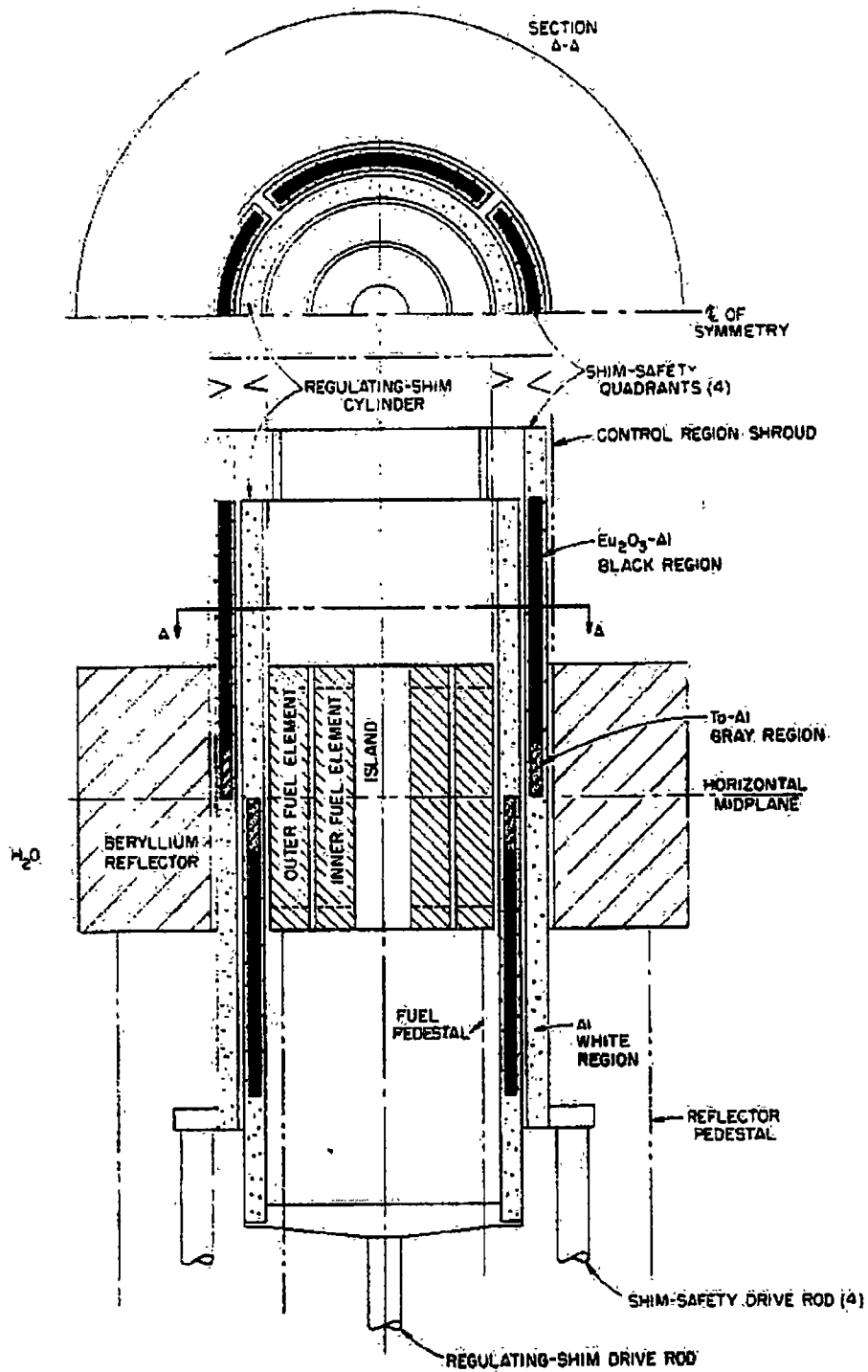


Figure 1.4. Schematic Drawing of Core and Control Blades

tantalum-aluminum mixture and the black region is Eu_2O_3 mixed with aluminum. The white and gray regions have holes drilled through the blades to equalize the pressure on the opposite sides of the plates. Aluminum was chosen for its low absorption cross section and relative ease of manufacture. Tantalum was chosen as the gray region absorber because of its medium cross section and some past fabrication success at ORNL.¹ Other absorbers such as boron, cadmium, gadolinium, and dysprosium were also considered but rejected for various reasons. Europium was selected as the black region absorber for its high thermal and epithermal cross sections as well as the high cross sections of its daughter products.

Atom densities for regions 1-21 and 25-31 were obtained from reference 1. These densities were first tabulated for the HFIR Critical Experiment series 3 (HFIRCE-3) core and are used for the reference calculations. Figure 1.5 is a schematic representation of the locations of these various regions. Atom densities for the control region are calculated as described below based on information provided in reference 2. The densities of uranium, boron, and carbon are corrected for the smearing performed in reference 1. The densities reported reflect the density if the nuclides were smeared through the entire region. The atom densities in these distinct materials within each region must be calculated because, in reality, discrete lumps of fuel, filler, aluminum and water exist. Figures A-9 and A-10 in reference 1 show the thickness of fuel and filler regions in the fuel plates. The correction factor is based on the fraction of the fuel plate and coolant channel cell occupied by any region. The fuel plate cladding is pure aluminum, and the coolant channel is pure water at operating temperature and pressures.

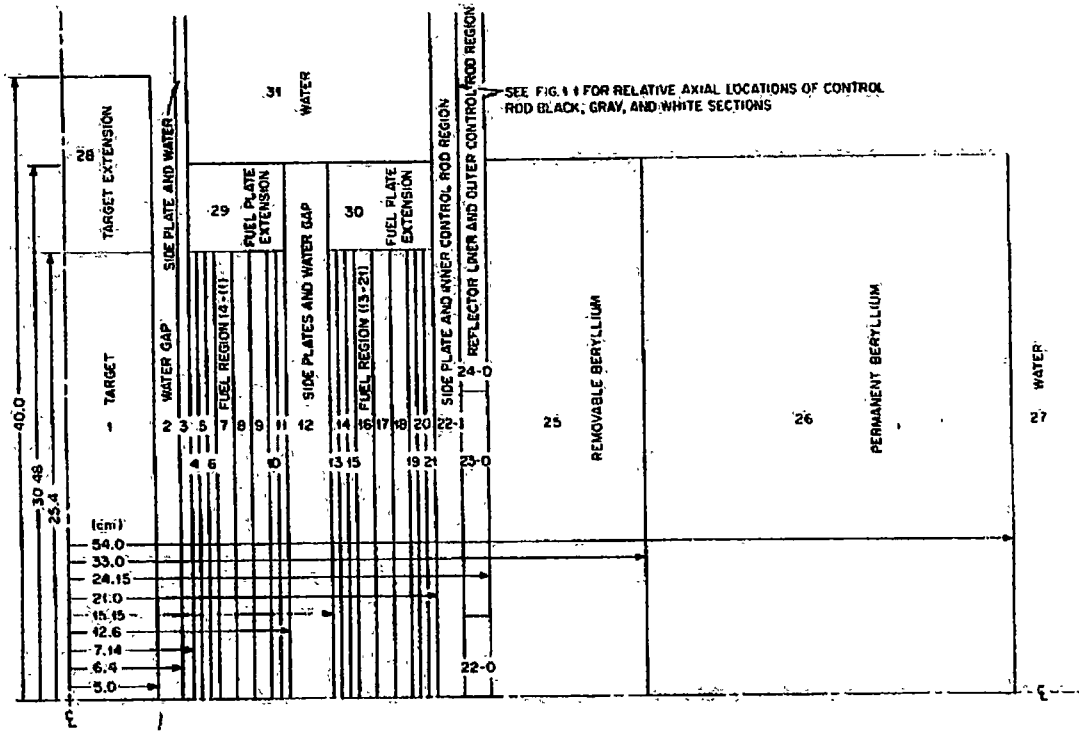


Figure 1.5. Schematic Drawing of Core Regions

Standard densities for aluminum and water subjected to the elevated temperatures and pressures have been calculated and utilized.

The boron loadings in the inner fuel element are defined by the mass of B-10 added as natural B_4C . The densities of B-11 and C-12 can be calculated from isotopic abundances and the known boron to carbon ratio. Natural boron is 19.8% B-10 and 80.2% B-11.³ The atom density of carbon in the region is equal to one fourth of the sum of the B-10 and B-11 loadings. The entire carbon loading was assumed to be C-12, since this is 98.9% of natural carbon.³ The HFIR CE-3 core that is detailed in reference 1 had a boron loading of 2.12 g B-10, but the production cores in use today have 2.8 g B-10. The B-10, B-11, and C-12 densities in the current cores are determined by multiplying the CE-3 concentrations by 1.321, which is the ratio of the boron loadings.

The atoms densities of Ta, Eu, O, and Al in the control blades are calculated from information provided in reference 2. Table 1.1 presents the key data on dimensions of the blades and absorber loadings. The blades are a mixture of Al and Ta or Eu_2O_3 . The fraction of the region that is composed of Al, therefore, is the fraction not made up of the absorber. The Ta-Al and Eu_2O_3 -Al mixtures are clad with 0.02 inches of Al. The atom densities calculated in the absorber regions thus have to be multiplied by a factor of 0.84 since the absorber region is only 84% of the total thickness of the blade. The absorber regions are 13 inches wide with gaps of Al or water in between, as mentioned above. The atom densities of the absorbers are corrected by a factor of 0.929 in the inner blades and 0.922 in the outer blades to correct for these gaps. In the inner blade, the gap is filled with an Al weld, so the overall Al density increases to 1.0714 times the full density of Al.

Table 1.1. Finished Core Loadings and Dimension for Control Elements

Absorber material	Core Thickness (in)	Finished Width (in)	Dimensions Length (in)	Absorber Loading (g)	Vol Fraction Absorber (%)
Ta	0.210	13	5	1300	38
Eu ₂ O ₃	0.210	13	22	1922	31

The factor is given by the fact that 1 inch out of every 14 is made of this Al weld. In the outer blades, the gap is 1.1 inches of water, so H and O are added with atom densities corrected to 0.0780 times the full density. This value corresponds to 1.1 inches out of every 14.1. Water is also added to fill the holes in the gray and white regions by lowering the density of water by the area fraction of the holes compared to the solid parts of the plate. This ratio is 0.049.

2. Computational Procedure

The computational procedure used in this research breaks down into five basic steps: resonance correction, cross section weighting, conversion and formatting, transport, and analysis. Resonance correction is performed by BONAMI and NITAWL, cross section weighting is accomplished with XSDRN-PM, conversion and formatting is done with ALPO and GIP, transport is calculated by DORT, and analysis is performed with Excel and SigmaPlot. Figure 2.1 is a block diagram of the data flow in a calculation, and each of the steps is described in detail below. All the calculations for steps one through four are carried out on the UNIX machines operated by the University of Tennessee College of Engineering. Several of the codes utilized are part of larger code packages, namely SCALE and DOORS. The codes that are part of these packages are given in Figure 2.1, and explanations of how these packages are used are provided in detail below. Sample input decks for each of the codes are included in Appendix B.

A total of three models are used in the computational procedure: a slab cell representing a fuel plate in a coolant channel, a one dimensional infinite cylinder model of HFIR, and a two dimensional RZ model. The slab cell is used in BONAMI and NITAWL for resonance processing. The one dimensional infinite cylinder model is used for generating weighted cross sections in XSDRN-PM, and the two dimensional RZ model is used in DORT for neutron transport. All three of these models are described in detail in Chapter 3.

STEPS

PACKAGE

Resonance
Correction

BONAMI

NITAWL

Cross Section
Weighting

XSDRN-PM

XSDRN-PM

Conversion and
Formatting

ALPO

GIP

Transport

DORT

Analysis

Excel

SigmaPlot

SCALE 4.4a

DOORS 3.2

Figure 2.1. Computational Procedure

2.1 Resonance Processing

Cross section master libraries contain cross section information that is problem independent. For this reason, the first step of generating problem specific cross sections is resonance treatment, where unresolved and resolved resonances are treated separately in calculations. BONAMI and NITAWL are the codes in the AMPX and SCALE packages that perform these corrections.

2.1.1 BONAMI

BONAMI (BONDarenko AMpx Interpolator) is the first code utilized in the computational procedure, as shown in Figure 2.1. It performs unresolved resonance treatment. BONAMI creates a new master library by copying the data for all the nuclides from the original master library, in this case the ENDF-V 238 neutron group library, to a new problem dependent library. The resonance treatment is performed using the Bondarenko method. This method interpolates the problem specific cross section from a table of calculated cross sections as a function of temperature.⁴ Heterogeneous effects are included by the use of an effective leakage cross section. BONAMI also uses Dancoff factors to correct for the effects of multiple pin or cell lattice structures.

2.1.2 NITAWL

NITAWL (Nordheim's Integral Treatment And Working Library)⁵ uses the Nordheim Integral Treatment to determine the neutron flux as a function of energy in the presence of an absorber and up to two moderators to correct cross sections with resolved resonances.⁶ NITAWL also creates a working library containing only the nuclides used for the problem. As with BONAMI, multiple absorber lumps are accounted for with the

use of Dancoff factors. In the absence of BONAMI, NITAWL creates the working library from the original master library. The calculation is dependent on temperature, geometry, moderators and absorbers. This code is used only for heavy nuclides such as tantalum, europium, and uranium.

2.2 Cross Section Weighting

It is necessary to weight cross sections for space-dependent material effects. Two types of weighting are used: cell weighting and region weighting. Cell weighting adjusts the cross sections based on the neutron flux in an individual cell as if the entire universe were just that cell or repetitions of that cell. It is used to adjust the cross sections used in the fuel regions where many repetitions of fuel plates and coolant channels make this a good approximation. Region weighting corrects cross sections based on the neutron flux in a region as it is affected by adjacent regions. These corrections are especially important near region borders near absorbers or reflectors. Both types of weighting are performed using XSDRN-PM.

2.2.1 XSDRN-PM

XSDRN-PM is a one dimensional discrete ordinates transport code. XSDRN performs a transport calculation and then uses these fluxes to weight and collapse cross sections.⁷ XSDRN is used twice in succession: first for cell weighting and group collapsing, and then for region weighting. The cell weighting is performed on a fuel plate and coolant channel cell from the middle of the inner fuel element. These weighted uranium cross sections are used in all fuel regions of both fuel elements. In these

calculations, XSDRN collapses the ENDF/B-V 238 group library to the recommended collapsed set of 44 groups.⁸ The region weighting is performed on a one dimensional infinite cylinder model of HFIR. Cross sections are treated with fifth order scattering and eighth order angular quadrature. For a more complete description of the cell and infinite cylinder models, see Chapter 3. XSDRN allows cross section output in several formats. In these calculations the AMPX format is used. XSDRN also calculates the fission neutron spectrum, which is used later in DORT.

2.3 Conversion and Formatting

After cross sections are generated in the first two steps, they must be converted to ANISN format, mixed, and formatted for use in DORT. The conversion is performed by ALPO for reasons described below. GIP is used to generate the macroscopic material cross sections from the microscopic nuclide cross sections and to format them for use in DORT.

2.3.1 ALPO

ALPO (Anisn Library Production Option) is a utility module that converts AMPX working libraries to ANISN format.⁹ ALPO is used to convert the libraries because of the table of contents it produces in the output file. This table describes the nuclides on the ANISN library in order, which is essential for use in GIP. No such table is produced by XSDRN if the ANISN format output option is used.

2.3.2 GIP

GIP is a code that produces the cross section file used by DORT. GIP reads the microscopic cross sections for each nuclide and generates macroscopic cross sections for each material used in the transport calculation. The cross sections are also ordered by group across all materials as this is how DORT performs the discrete ordinates calculation. GIP is used to generate the DORT cross section file so that the same file can be used any time multiple DORT runs are made with the same materials. This saves computing time by creating a cross section file which can be used in multiple DORT calculations. GIP uses the ANISN cross section format.

2.4 Transport

The HFIR's near azimuthal symmetry permits a two dimensional R-Z calculation to effectively model the three-dimensional power distributions. The deterministic approach is preferred over the Monte Carlo method since very detailed spatial distributions are required to assure that all thermal constraints are satisfied.

2.4.1 DORT

DORT (Discrete ORdinates Transport)¹⁰ is a two-dimensional discrete ordinates neutron transport code, with choices of several two-dimensional geometries. For this research, an R-Z coordinate system is used. A complete description of the model used in DORT is included later in this document. Scattering is treated with a third order expansion, and eighth order symmetric angular quadrature is used. DORT uses an iterative solution technique to converge the group fluxes for inner iterations and for the k-

effective eigenvalue in outer iterations. Output from DORT includes fission neutron production rates and neutron balance tables. The fission neutron production rates are used to calculate normalized power plots in the analysis of the calculation since power is proportional to fission rate and since decay heat contributions are estimated to be small compared to fission power. Another feature available in DORT is the output of fluxes at key mesh points. This option is utilized in some calculations to determine fluxes in the tantalum region of the control blades.

2.5 Analysis

An analysis of the results of these calculations must be performed for any useful knowledge to be gained as a result of this work. The majority of the analysis is based on fairly simple calculations that must be performed on a large array of data. This makes a spreadsheet program, specifically Excel, an ideal tool for these calculations. The final step of the calculation is the production of tables and graphs showing the results. The necessary graphs are prepared in SigmaPlot.

2.5.1 Excel

Microsoft Excel is the spreadsheet program in Microsoft Office, which is useful for the manipulation of the data. Over 1,000 data points are needed to generate the power plots used in this project. Excel is used to calculate average core powers and to generate the normalized power for each mesh point in the fuel elements. Excel spreadsheets can be used directly by SigmaPlot for plotting.

2.5.2 SigmaPlot

SigmaPlot is a graphics package produced by SPSS and is used in this project to generate plots of normalized power in HFIR.¹¹ Two different types of plots are generated for each DORT run: a three dimension R-Z-Power plot and a two dimensional R-Z-Power contour plot. The three dimensional plot is useful for showing the shape of the power distributions in the core while the contour plots illustrate quantitative data more clearly. Both of these graphs are generated in SigmaPlot from the same set of data.

2.6 Code Packages

Two code packages, SCALE and DOORS, are utilized in the calculations, as mentioned earlier in this section. SCALE contains BONAMI, NITAWL, XSDRN-PM, and ALPO. DOORS includes GIP and DORT. Each package is used for specific tasks required for cross section processing and transport calculations, as described below.

2.6.1 SCALE

SCALE is a code package developed at the Oak Ridge National Laboratory based on the older AMPX system. The system was designed to allow control modules to determine the calculational flow, and it contains functional modules to perform the actual calculations.¹² These control modules can be bypassed in favor of direct input to the functional modules; thus, making SCALE an AMPX driver. In this research, SCALE 4.4a is used in this latter mode. Even though the control modules are not used, the input decks for each functional module executed can be included in one file. The SCALE driver executes each functional module in sequence in a single execution.

SCALE execution is accomplished by running a batch file that creates a temporary directory for all data storage. It also writes the output file and, if necessary, a messages file. The output file contains all the output from each module run. The messages file contains any error messages generated by the operating system itself. At the end of the execution, the temporary directory is deleted. The cross section libraries are stored in this temporary directory, and are deleted at the termination of the run. In order to save these libraries, a UNIX shell command must be written into the input file to copy the libraries to a specified location before it is deleted.¹³ If these libraries are needed in other modules they can be linked to the copied location. An example of these shell commands is given below:

```
#shell
cp ft03f001 /ne1/wmarshal/scalelib/Taife4lib
ln -s /ne1/wmarshal/scalelib/Taife4lib ft90f001
end
```

2.6.2 DOORS

The DOORS system has also been developed at the Oak Ridge National Laboratory. This code package is built around DORT and its three dimensional analog TORT. Unlike SCALE, there is no driver available to run multiple codes in a single execution. The two codes utilized from DOORS 3.2, GIP and DORT, are each executed separately with individual input decks. All output is produced directly by the code being executed, and any file management must be performed by the user.

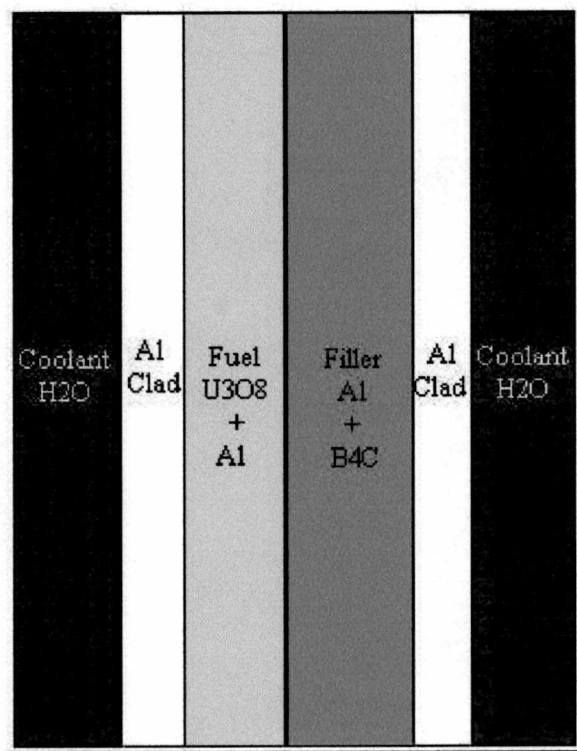
3. Models

Three different models are used for calculations in this project. A slab cell of a fuel plate and coolant channel is used for resonance processing and cell weighting. A one dimensional infinite cylinder model is used for region weighting, and a two dimensional R-Z model is used for transport calculations. Each is described in detail below.

3.1 Slab Cell

The slab cell model used for resonance processing and cross section cell weighting is shown in Figure 3.1. There are six regions in this model: two half coolant channels, two aluminum claddings, the fuel, and the filler. The coolant is pure water at 468 psig and 120 °F, which are the operating pressure and inlet temperature of HFIR.¹ All fuel plates are a total of 0.127 cm thick, of which 0.0254 cm on each side is aluminum cladding. The thicknesses of the fuel and filler add to 0.0762 cm, but the fraction of each differs along the radius of each plate.¹ Figure A9 in reference 1 illustrates the thickness of the fuel and filler as a function of position in the inner fuel element. As discussed below, the inner fuel element is broken into eight radial regions: region four was selected as the representative region for the cell weighting. The fuel thickness from this diagram is 0.6033 cm, and the filler is therefore 0.01587 cm.

Atom densities for each isotope in each region are reported in reference 1. These densities have been volume averaged over the entire cell to represent a homogenous



Note: Not to scale

Figure 3.1. Slab Cell Model

region. The slab cell model is not one homogenous zone, so these densities are corrected by dividing the reported density by the fraction of the cell each region occupies.

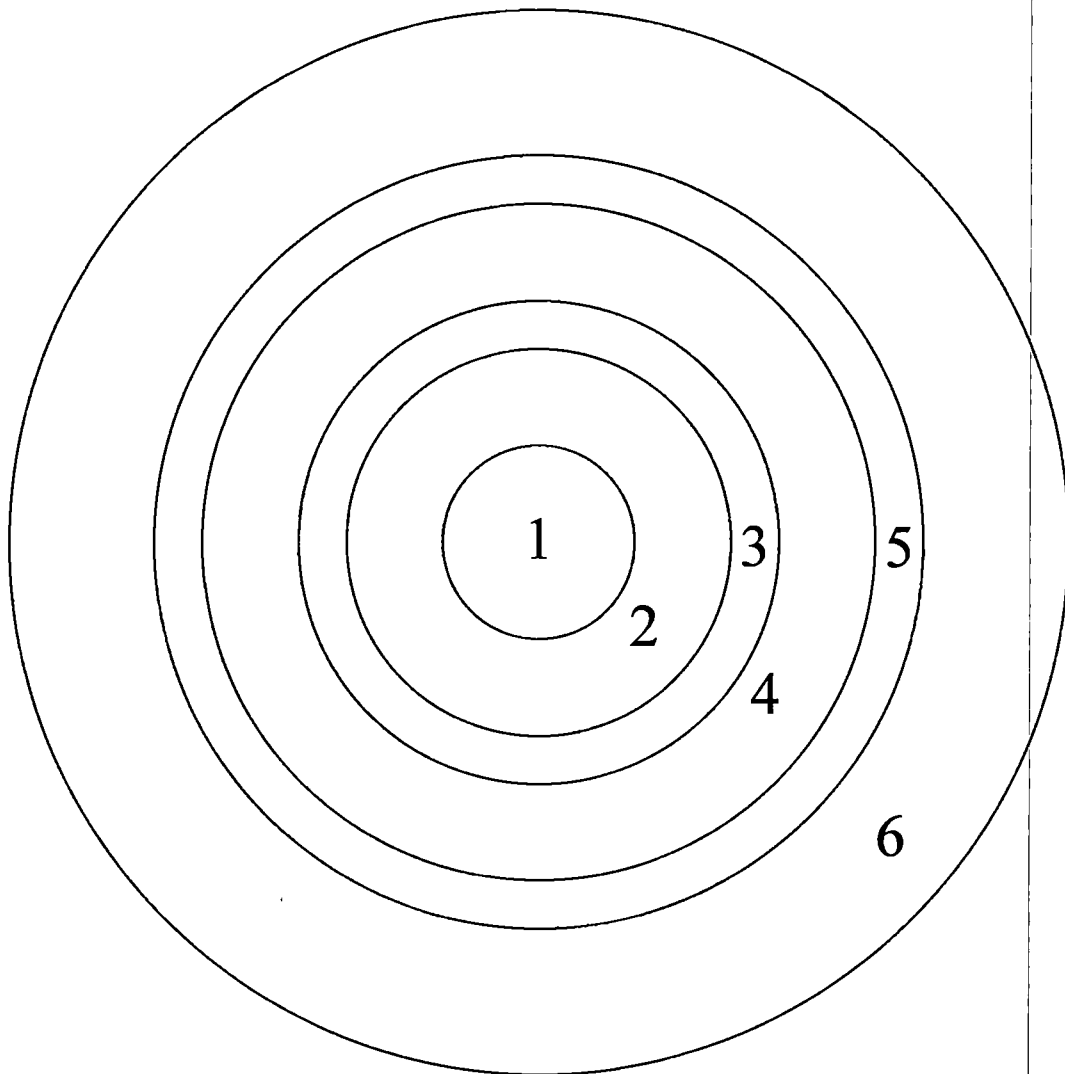
3.2 One Dimensional Infinite Cylinder

The one dimensional infinite cylinder model used for region weighting is shown in Figure 3.2. The model consists of six broad regions that represent regions of the HFIR. The six regions are: the flux trap, the inner fuel element, the coolant channel between the fuel elements, the outer fuel element, the control blades, and the reflector. The inner fuel element is further subdivided into eight regions, and the outer fuel element is broken into nine regions. The dimensions for the regions in this model are given below in Table 3.1. The mesh spacing is set such that each fuel region and the control region contain two mesh points, and interval spacing outside these absorber regions is approximately 1cm, which is approximately one mean free path for thermal reactors.

Atom densities for each isotope are used as provided in reference 1 for the fuel regions. The flux trap and coolant channel are used as pure water at the operating temperature and pressure described above. Atom densities in the reflector are volume averaged values over the applicable regions. Control blade atom densities are also calculated from data provided in reference 2 and volume averaged over the control region.

3.3 R-Z Full Core

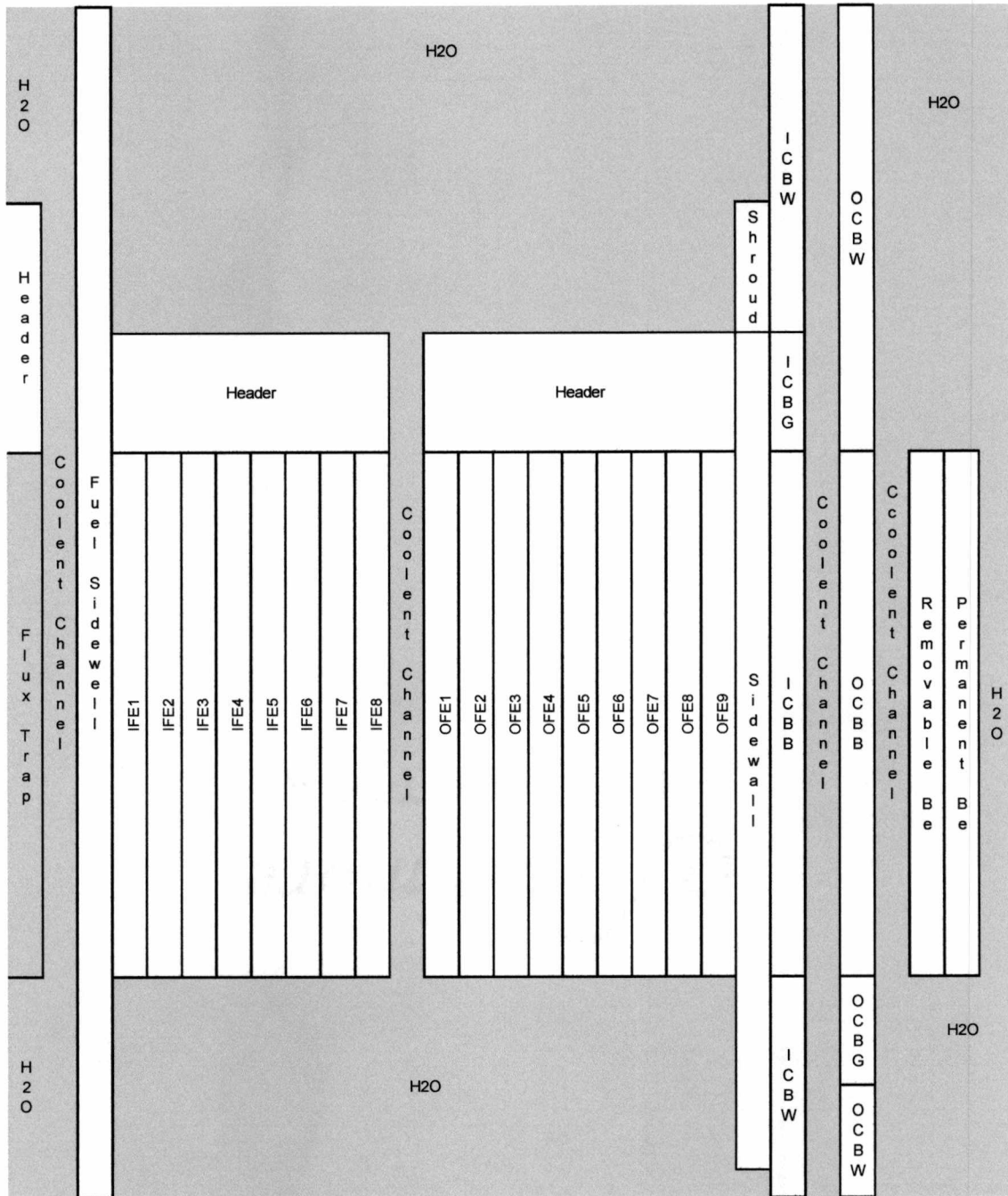
The R-Z full core model used for transport is shown in Figure 3.3. The R-Z geometry is selected because of the high degree of azimuthal symmetry present in the



Region	Inner Radius (cm)	Outer Radius (cm)
1 Flux Trap	0	7.14
2 Inner Fuel Element	7.14	12.6
3 Coolant Channel	12.6	15.15
4 Outer Fuel Element	15.15	21
5 Control Blades	21	24.15
6 Reflector	24.15	54

Note: Not to Scale

Figure 3.2. One Dimension Infinite Cylinder Model



Legend

IFE - Inner Fuel Element OFE - Outer Fuel Element ICB - Inner Control Blade
 OCB - Outer Control Blade B - Black (Eu2O3) G - Gray (Ta) W - White (Al)

Note: Not to Scale

Figure 3.3. R-Z Full Core Model

Table 3.1. 1D Cylinder Region Boundaries

Region	Inner Radius	Outer Radius
Flux Trap	0	7.14
IFE1	7.14	7.5
IFE2	7.5	8
IFE3	8	8.5
IFE4	8.5	9.5
IFE5	9.5	10.5
IFE6	10.5	11.5
IFE7	11.5	12
IFE8	12	12.6
Coolant Channel	12.6	15.15
OFE1	15.15	15.5
OFE2	15.5	16
OFE3	16	16.5
OFE4	16.5	17.5
OFE5	17.5	18.5
OFE6	18.5	19.5
OFE7	19.5	20
OFE8	20	20.5
OFE9	20.5	21
Control	21	24.15
Reflectors	24.15	54

HFIR. The main violations of this symmetry are the gaps separating the quarter cylinders in the control blades. The region definitions for the model are provided in Table 3.2, below; these are defined in Table A.6 of reference 1 and augmented by reference 2. The axial position of the control blades is varied to establish critical positions for the different T_a loadings and concentrations modeled. A discussion of the determination of critical blade heights is included in Chapter 4.

Atom densities for the fuel regions and the reflector regions are from reference 1. Control blade atom densities are calculated from data provided in reference 2. All water atom densities in the model, in the flux trap and coolant channel for example, reflect pure water at operating temperature and pressure. Other water regions, such as in the sidewall and fuel regions, have pure water atom densities reduced for the fraction of the region occupied by water.

Table 3.2. R-Z Region Boundaries

Description	Outside Radius	Axial Boundary	
		Upper	Lower
Flux Trap	5	25.4	-25.4
Coolant Channel	6.4	100	-100
Fuel Sidewall	7.14	100	-100
Inner Fuel El. 1	7.5	25.4	-25.4
Inner Fuel El. 2	8	25.4	-25.4
Inner Fuel El. 3	8.5	25.4	-25.4
Inner Fuel El. 4	9.5	25.4	-25.4
Inner Fuel El. 5	10.5	25.4	-25.4
Inner Fuel El. 6	11.5	25.4	-25.4
Inner Fuel El. 7	12	25.4	-25.4
Inner Fuel El. 8	12.6	25.4	-25.4
Coolant Channel	15.15	30.48	-30.48
Outer Fuel El. 1	15.5	25.4	-25.4
Outer Fuel El. 2	16	25.4	-25.4
Outer Fuel El. 3	16.5	25.4	-25.4
Outer Fuel El. 4	17.5	25.4	-25.4
Outer Fuel El. 5	18.5	25.4	-25.4
Outer Fuel El. 6	19.5	25.4	-25.4
Outer Fuel El. 7	20	25.4	-25.4
Outer Fuel El. 8	20.5	25.4	-25.4
Outer Fuel El. 9	21	25.4	-25.4
Fuel Sidewall	21.76	30.48	-30.48
Inner Shroud	21.76	30.48	40
Coolant Channel	22.02	40	-30.48
Inner C.B. White	22.66	36.35	0
Inner C.B. Black		92.23	36.35
Inner C.B. Gray		104.93	92.23
Inner C.B. White		173.67	104.93
Coolant Channel	22.99	40	-30.48
Outer C.B. White	23.62	77.63	0
Outer C.B. Gray		90.33	77.63
Outer C.B. Black		146.21	90.33
Outer C.B. White		168.12	146.21
Coolant Channel	23.97	40	-30.48
Replaceable Be	33	30.48	-30.48
Permanent Be	54	30.48	-30.48
Water Channel			
Target Header	5	40	25.4
Inner Fuel Header	12.6	30.48	25.4
Outer Fuel Header	21	30.48	25.4
Water Above Core	21	100	30.48

Note: Control blade (C.B.) axial boundaries measured from bottom of blade.

4. Calculations

As was discussed in Chapter 2, Computational Procedure, the calculations performed in this research involve many steps and many different processes. Before any transport runs are possible, cross section libraries must be generated and weighted properly to account for resonances, self shielding, and spatial effects. These libraries must also be processed into the correct format for use in DORT for each core calculation. In addition to the number of calculations that must be performed prior to any core calculations, it is also necessary to check the validity of the model used. The application of the codes discussed earlier to perform these calculations is discussed in detail in this chapter.

The control blades in the HFIR operate for a lifetime of approximately 100,000 MWd, which for normal operating conditions is about 3 years and 10 months. Over this operating lifetime a significant fraction of the initial Ta loading is burned out. It is necessary to calculate the Ta depletion as well as the effects of the depletion on the core over the lifetime of the control blades. These calculations are discussed in detail later in this chapter.

4.1 Cross Section Processing

The cross section libraries installed in the SCALE package, such as the 238 group ENDF-V library used in this research, are provided in a problem independent form. This means that before any calculations using these cross sections are performed, they must be processed for resonances and for cell and region weighting. This results in cross section

working libraries that are problem dependent and yield more accurate solutions than unprocessed cross sections. A sample input deck for all the cross section processing used in SCALE is included in Appendix B.

4.1.1 Resonance Correction

The first step of generating a working library for a particular problem is resonance processing. As discussed in Chapter 2, the two codes used in the SCALE package for this are BONAMI, for unresolved resonances, and NITAWL, for resolved resonances. The slab cell discussed in Section 3.1 is used as the geometrical model for resonance processing.

While some nuclides require little or no unresolved resonance treatment, all nuclides used in the transport calculation are processed in BONAMI since it creates a new master library for the problem. Nuclides that are used only in the control blades or reflector, such as Ta, Eu, and Be, are included at concentrations of 10^{-10} atoms/barn-cm, so their presence in the cell has a minimal effect on the fuel nuclides.

NITAWL is necessary to correct the cross sections for isotopes with resolved resonances, which tend to be the heavier elements, and create the working library for the problem. For this reason, only isotopes of Eu, Ta, and U are processed in NITAWL. The Dancoff factors used are those calculated for an earlier practice problem.¹⁴

4.1.2 Cross Section Weighting

The second step of cross section processing is weighting. Weighting modifies cross sections based on the changes in spectral shape introduced by the effects of nearby moderators, reflectors, or absorbers. Two different weighting schemes are used: cell

weighting and region weighting, both executed by XSDRN-PM. Cell weighting uses the slab cell model of Section 3.1 for the fourth region of the inner fuel element (IFE4). The cross sections for H₂O, Al, and the isotopes of U are weighted for the effects of the fuel plate arrangement. These cross sections are then used for all fuel regions in region weighting. Region weighting uses the one dimensional infinite cylinder model described in Section 3.2 to adjust the cross sections of all the isotopes in the core calculation for effects caused by surrounding regions. The cross sections are now ready to be formatted for use in a transport calculation in DORT.

4.2 Full Core Model Benchmark

In order to determine the accuracy of the full core model incorporating the cross section processing discussed above, a known critical configuration of HFIR must be run. The critical case used for this test comes from the HFIR CE-3 experiments. Table A-3 in reference 1 lists the complete series of critical configurations determined in these tests. The experiment selected was the first critical configuration with the source removed, which corresponds to a blade height of 17.547 inches. In this experiment, and all instances of blade height discussed later in this report, the blade height refers to the distance from shut down position the blades are moved. The inner blade is lowered by this "height" and the outer blade is raised by it. The blades are always operated in a symmetric configuration.

The k-effective calculated by DORT for this test case is 0.9907, where the bias is probably due to azimuthal asymmetry not included in the R-Z model; however, other

factors such as cross section processing procedures impact this bias. The spatial power distributions calculated in this project are not effected by this bias. These results show that the R-Z core model of HFIR and the cross section processing produce sufficiently accurate results, however the k of 0.9907 is used to represent the bias in the model, that is a calculated k of 0.9907 represents criticality. This bias is caused by the gaps between the control plates that cannot be modeled in an R-Z configuration. The outer control plates are separated by 1.1 inch water gaps. A one inch aluminum weld is present between quarter cylinders in the inner control blade. These two gaps allow neutron streaming which is not present in the HFIR model used in these calculations.

4.3 Determination of Critical Blade Positions

Power distribution comparisons for cores with different control blade Ta loadings are only meaningful in critical configurations. Since the only difference in the models is a difference in the Ta loading, there is no change in total power generated in the core. A reduction in Ta loading decreases critical blade height because some absorber has been removed. The blades must be moved in by the amount necessary to replace that amount of absorption. The change in the position of the black blade sections coupled with lower absorption in the gray regions might lead to a change in the power distribution across the core. Critical positions must be calculated so that these power distributions can be compared.

A straightforward process is used to determine the critical blade positions for any Ta concentration. Critical blade heights vary between about 17 inches and 25 inches over

a single cycle¹⁵, so these numbers provide a guide for the range in heights that should be bracketed in a critical position search. A series of DORT calculations are performed at blade heights of 14, 17.5, 20 and 25 inches. These heights are then plotted versus the calculated k-effective. A smoothed line is fit to the four points in Excel, and the critical positions are read off the graph at the heights corresponding to a k of 0.9907. An example is given in Figure 4.1, which shows the determination of critical blade heights at the beginning of control blade life for blades with Ta loadings of 38, 35, 30, and 25 volume percent. The current initial HFIR control blade Ta loading is 38 volume percent. After each critical blade position is determined, a full core model is run to verify the criticality of the configuration and to generate the power distribution.

4.4 Calculation of Power Distributions

The power distributions for each critical blade position are calculated from data provided in each DORT full core run. One section of the output of each DORT calculation is the fission neutron production rate in each mesh point. Fission neutron production rate is directly proportional to fission rate and is nearly equal to power. What is of greatest import in this research is the power peaking at certain positions in the core.

Before normalized power can be determined, the core average power must be calculated. The fission neutron production rates for each mesh point in the core are combined into a volume-weighted average. The rates are multiplied by the height and width of the mesh intervals and the radius of the midpoint of the interval. Each region of each fuel element is summed, and then the eight regions of the inner fuel element and the

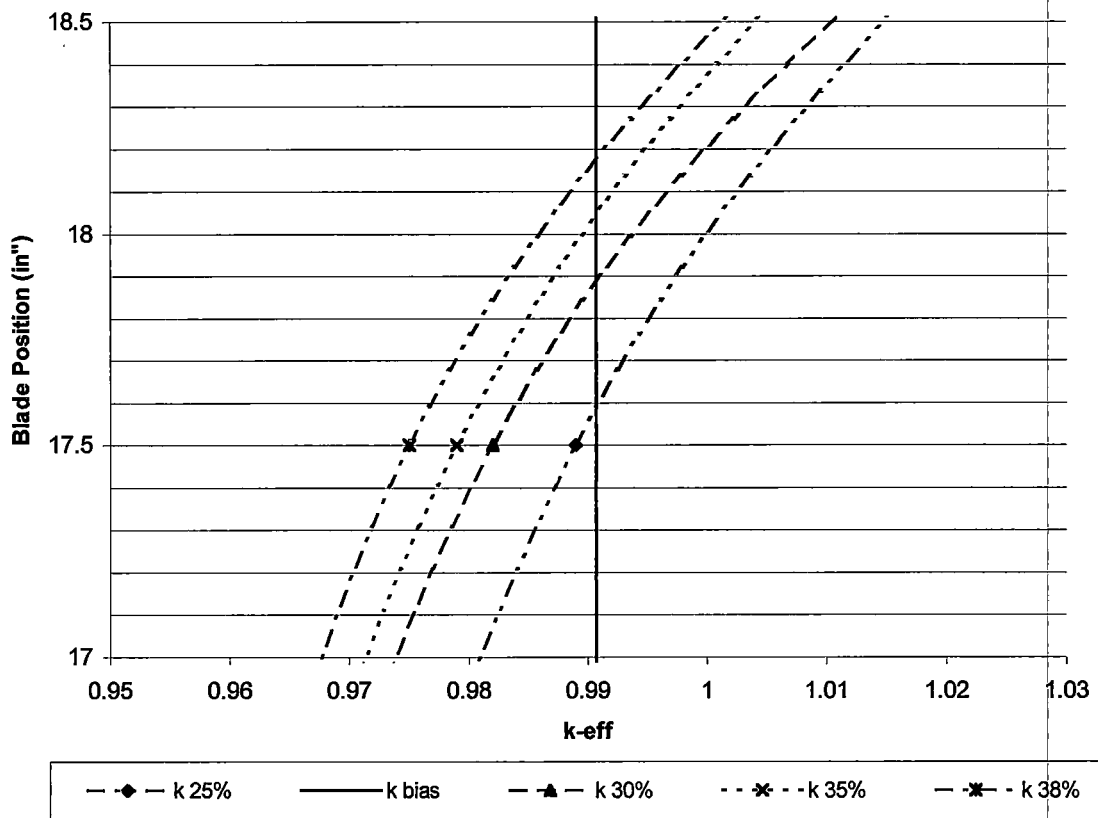


Figure 4.1. Blade Position vs. k-effective for Various Ta Loadings

nine regions of the outer fuel element are summed. The two fuel element totals are combined for the total fission neutron production rate in the core. This total is then divided by the volume of the active fuel to determine the whole core average fission neutron production rate. Each individual mesh point rate is then divided by this average rate to yield the normalized fission neutron production rate. As discussed above, this is equal to the normalized power.

4.5 Tantalum Depletion

In order to determine power distributions over the life cycle of a control blade, a detailed Ta depletion analysis is necessary. The first step is determining what isotopes are important in neutron absorption based on their cross sections and abundances. The next step is calculating the concentrations of the key isotopes over time. The third step is verifying that the depletion calculations performed are accurate compared to Ta depletion measured in HFIR control blades. The final step is performing full core calculations at various points over the control blade lifetime to study possible effects of Ta depletion on power distributions over the control blade life.

4.5.1 Important Isotopes

Naturally occurring Ta is 99.988% Ta-181³, so Ta-181 is an obvious important isotope. It is assumed in these calculations that the Ta in new control blades is pure Ta-181. Ta-182 is produced after Ta-181 captures a neutron, so it is also an important isotope. Ta-182 has a 114 day half-life³ and a thermal neutron absorption cross section on the order of 600 times higher than that of Ta-181. These cross sections were

calculated using XSDRN-PM. Ta-183, which is produced by a Ta-182 capture, has a half-life of about 5.1 days. It can be ignored as a significant source of absorption because of its small cross section. W-182 and W-183, the decay products of Ta-182 and Ta-183, both are stable but have low cross sections, so they can be ignored as well. Thus, the Ta depletion needs only account for two isotopes: Ta-181 and Ta-182.

4.5.2 Concentration Calculations

As mentioned above, new control blades are considered as having pure Ta-181 in the gray region. This means that Ta-181 burns out over time, and Ta-182 burns in until it reaches equilibrium with Ta-181. The equilibrium point is reached when the destruction rates of the two isotopes are equal. The production and destruction terms are controlled by the significantly larger cross section of Ta-182 and by its radioactive decay. After a sufficient length of time, the concentration of Ta-182 also begins to fall in equilibrium with the decreasing concentration of Ta-181. By solving the differential equations governing the concentrations over time, the following equations can be determined for Ta-181 and Ta-182¹⁶:

$$N_{181}(t) = N(0) \times e^{-S_1 t}$$

where: N_{181} is the concentration of Ta-181

$N_{181}(0)$ is the initial concentration of Ta-181

$$S_1 = \sum_{g=1}^n N_{181}(t) \sigma_{a,g}^{181} \times \phi_g$$

t is the time in seconds since the beginning of life

ϕ is the neutron flux in n/cm^2-s

$\sigma_{a,g}^{181}$ is the Ta-181 absorption cross section in group g

$$N_{182}(t) = \frac{N_{181}(0) \times S_1}{\lambda_{182} + S_2 - S_1} \times (e^{-(S_1 \times t)} - e^{-(\lambda_{182} + S_2) \times t}) + N_{182}(0)$$

where: $N_{182}(t)$ is the concentration of Ta-182

λ_{182} is the decay constant of Ta-182 in s^{-1}

$$S_1 = \sum_{g=1}^n N_{181}(t) \sigma_{\gamma,g}^{181} \times \phi_g$$

$$S_2 = \sum_{g=1}^n N_{182}(t) \sigma_{a,g}^{182} \times \phi_g$$

$N_{182}(0)$ is the initial concentration of Ta-182

$\sigma_{\gamma,g}^{181}$ is the (n,γ) cross section in Ta-181 in group g

$\sigma_{a,g}^{182}$ is the absorption cross section in Ta-182 in group g

These two equations were then coded into a FORTRAN program, which is included in Appendix C. The program evaluates the concentrations of Ta-181 and Ta-182 separately in the inner and outer control blade, for operational reasons described below, every 12 hours throughout the 100,000 MWd life of the control blades. The necessary inputs are the group flux-weighted cross sections and initial concentrations of both isotopes. The outputs are: the time since beginning of life, the concentration of Ta-181 and Ta-182, the total concentration of both isotopes, the ratio of Ta-181 to the total concentration of Ta, and the accumulated life of the control blades in MWd.

The Ta depletion calculations are complicated by several operational issues that are considered in the program. First, the average operational cycle for the HFIR is 24 days with an average 4.5 day refueling outage. This short irradiation time prevents the two isotopes from ever reaching a true equilibrium ratio. Although equilibrium is approached near the end of each cycle, it is upset during the refueling outages as Ta-182 decays. A second operational consideration is that the outer control blades are switched

after every seven cycles due to bearing concerns. The replacement set of outer control blades has cooled in the reactor pool for a period of several years, which allows all Ta-182 to decay. This requires that the initial concentration of Ta-182 in the outer blade be set to zero at the beginning of each set of seven cycles. In order to perform a conservative calculation, it is assumed that the inner and outer control blades in each set of cycles have the same total exposure. This insures that both sets of blades will reach the end of life at the same time, and therefore the sum total Ta present in both blades is at a minimum.

4.5.3 Depletion Calculation Verification

During the operating history of the HFIR, a single study has been published concerning the measurement of Ta depletion. This report contains only one data point, which is at 48,000 MWd, which is halfway through control blade life. The results of mass spectrographic analysis suggest each initial Ta atom absorbed 0.7 neutrons.¹⁷ Because of the presence of Ta-182, absorption of 0.7 neutrons per initial atom means that approximately 35% of the initial Ta-181 loading is destroyed in the first 48,000 MWd since Ta-181 and Ta-182 absorption rates are approximately equal. The Ta depletion code calculates 31% Ta depletion at this same data point. This 4% difference is judged to be well within the experimental error of the datum and is used to validate the accuracy of the calculations.

4.5.4 Core Calculations Over Time

In order to determine the effects of accumulated irradiation on the control blades, full core calculations are performed approximately every 20,000 MWd. The time steps in

the Ta depletion code do not yield these intervals exactly, so the actual intervals vary slightly: 19,975, 39,992.5, 60,010, 79,985, and 99,960 MWd. Another two calculations are considered: the fresh control blades, and control blades after one cycle. After one cycle, Ta-182 has achieved quasi-equilibrium with Ta-181, which represents the most absorption present in the gray region of the control blade at any point in its lifetime. The concentrations of Ta-181 and Ta-182 are taken from the output of the Ta depletion code at these time steps, and full core calculations are performed as described in Sections 4.3 and 4.4.

5.0 Results

The calculations discussed in the previous chapter yield results that fall into two main categories: Ta depletion, and power distributions and peaking factors. These results are presented in this chapter.

5.1 Tantalum Depletion

The first result of the Ta depletion calculations is a validation of the results. For a 38 volume percent loading, the expected Ta-181 concentration after 48,000 MWd is approximately 65% of the initial concentration. Table 5.1 lists the initial Ta-181 concentrations and the measured and calculated concentrations in the inner and outer control blades at 48,000 MWd. The depletion code calculates values with good agreement with experimental data.

One significant task of the Ta depletion calculations is to determine the concentrations of Ta-181 and Ta-182 over time. In order to track changes in peaking over time, five specific time steps of approximately 20, 40, 60, 80, and 100 GWd are selected for core calculations. Table 5.2 lists the concentrations at these time steps in the inner control blade, the outer control blade, and the sum of the two blades for both the 38 and 30 volume percent loadings. Figure 5.1 illustrates the Ta-181 concentration versus accumulated power in the inner control blade. The outer control blade concentrations follow the same pattern although the values are slightly lower. Figure 5.2 shows the Ta-182 concentration in the inner control blade over time. Note that the Ta-182 concentration increases in each cycle approaches equilibrium, and then drops during the

Table 5.1. Ta Depletion Verification

	Initial Concentration (a/b-cm)	Concentration at 48,000 MWd (a/b-cm)	% Original Ta-181
Measured	4.1790×10^{-2}	2.7164×10^{-2}	65.00
Calculated Inner CB	4.1790×10^{-2}	2.8778×10^{-2}	68.86
Calculated Outer CB	4.150×10^{-2}	2.873×10^{-2}	69.23

Table 5.2. Ta Concentrations Over Time

Burnup (MWd)	38 Vol %					
	ICB		OCB		Total	
	Ta-181	Ta-182	Ta-181	Ta-182	181	182
0	4.179E-02	0	4.150E-02	0	8.329E-02	0
20018	3.577E-02	3.350E-04	3.560E-02	3.178E-04	7.137E-02	6.528E-04
39993	3.062E-02	2.858E-04	3.055E-02	2.737E-04	6.117E-02	5.595E-04
60010	2.621E-02	2.435E-04	2.620E-02	2.143E-04	5.241E-02	4.579E-04
79985	2.244E-02	2.071E-04	2.248E-02	1.990E-04	4.492E-02	4.061E-04
99960	1.921E-02	1.804E-04	1.929E-02	1.739E-04	3.850E-02	3.542E-04

Burnup (MWd)	30 Vol %					
	ICB		OCB		Total	
	Ta-181	Ta-182	Ta-181	Ta-182	181	182
0	3.299E-02	0	3.276E-02	0	6.575E-02	0
20018	2.763E-02	2.362E-04	2.748E-02	2.247E-04	5.511E-02	4.608E-04
39993	2.315E-02	1.973E-04	2.306E-02	1.884E-04	4.621E-02	3.856E-04
60010	1.938E-02	1.645E-04	1.934E-02	1.505E-04	3.873E-02	3.149E-04
79985	1.624E-02	1.368E-04	1.623E-02	1.311E-04	3.247E-02	2.679E-04
99960	1.361E-02	1.165E-04	1.362E-02	1.118E-04	2.723E-02	2.283E-04

Note: All concentrations in atoms/barn-cm

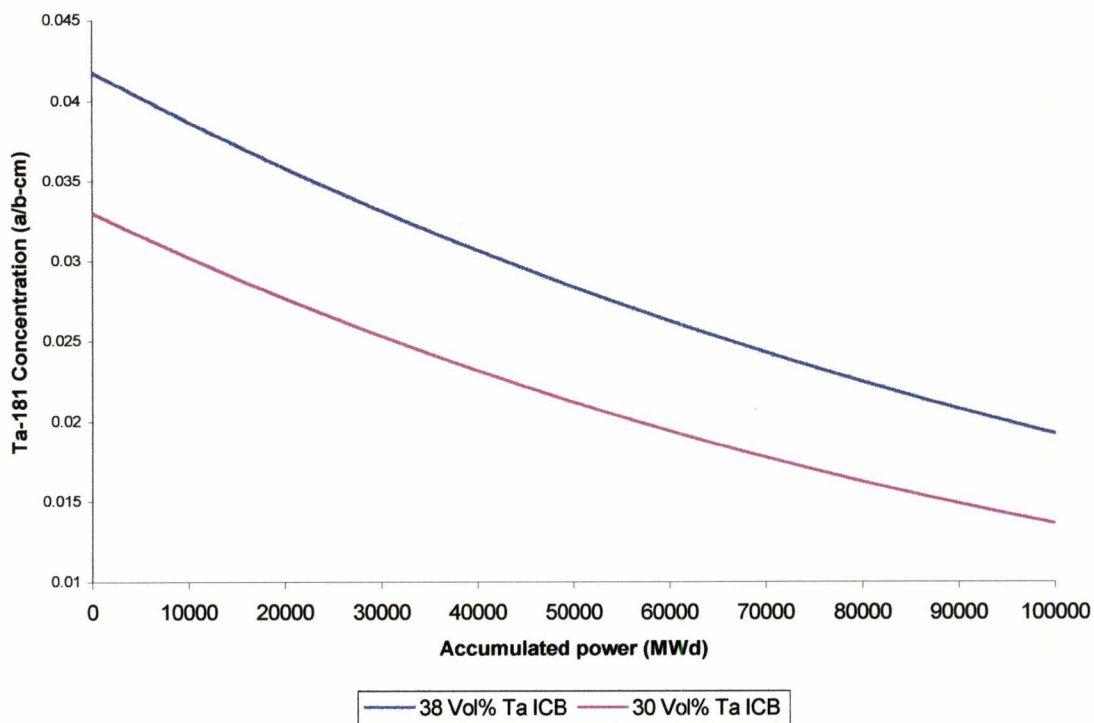


Figure 5.1. Ta-181 Concentration vs. Accumulated Power in the Inner Control Blade

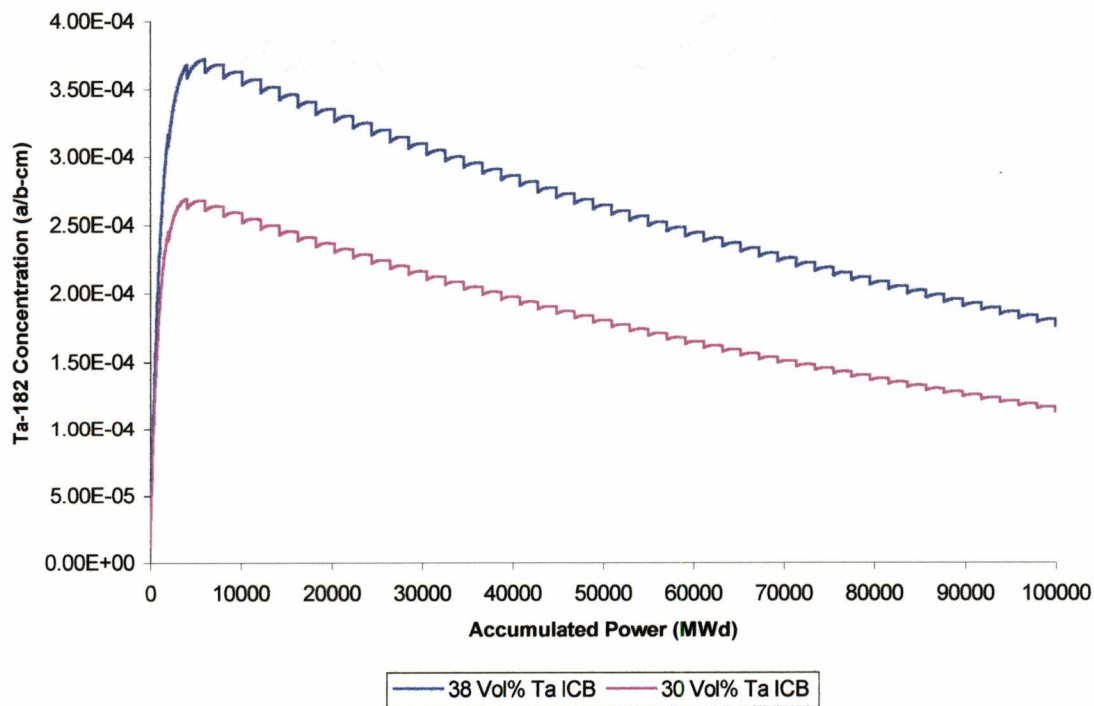


Figure 5.2. Ta-182 Concentration vs. Accumulated Power in the Inner Control Blade

refueling outage. The outage appears as a vertical drop because no more power is accumulated even though 4.5 days pass. Figure 5.3 illustrates the Ta-182 concentration in the outer control blade. The major difference between the inner and outer blades is the replacement of the outer control blades after each set of seven cycles. The replacement blades have cooled in the reactor pool long enough to reduce the Ta-182 concentration to zero. Figure 5.4 shows the ratio of Ta-181 to the total Ta in the outer control blade as a function of accumulated power. The large spike is caused by the lack of Ta-182 in the replacement blades. The ratio for the inner control blade looks very similar except for the lack of the spike.

A part of performing Ta depletion is the determination of the neutron flux in the Ta region of the control blades. Figures 5.5 and 5.6 illustrate the spectrum in the inner and outer control blades, respectively, for both 38 and 30 volume percent Ta loadings.

5.2 Power Distributions and Peaking Factors

The primary concern for reducing control blade Ta concentrations in the HFIR is an increase in power peaking that could exceed thermal margins in some regions of the core. This increase in peaking could be caused by lowering the control blades to account for the reduced absorption in Ta. The lowered blades bring the black regions closer together. For this reason the normalized power for every mesh cell in the core is calculated. From these data, it can be determined what affect the difference in Ta concentration will have on the power distribution and the peaking factors.

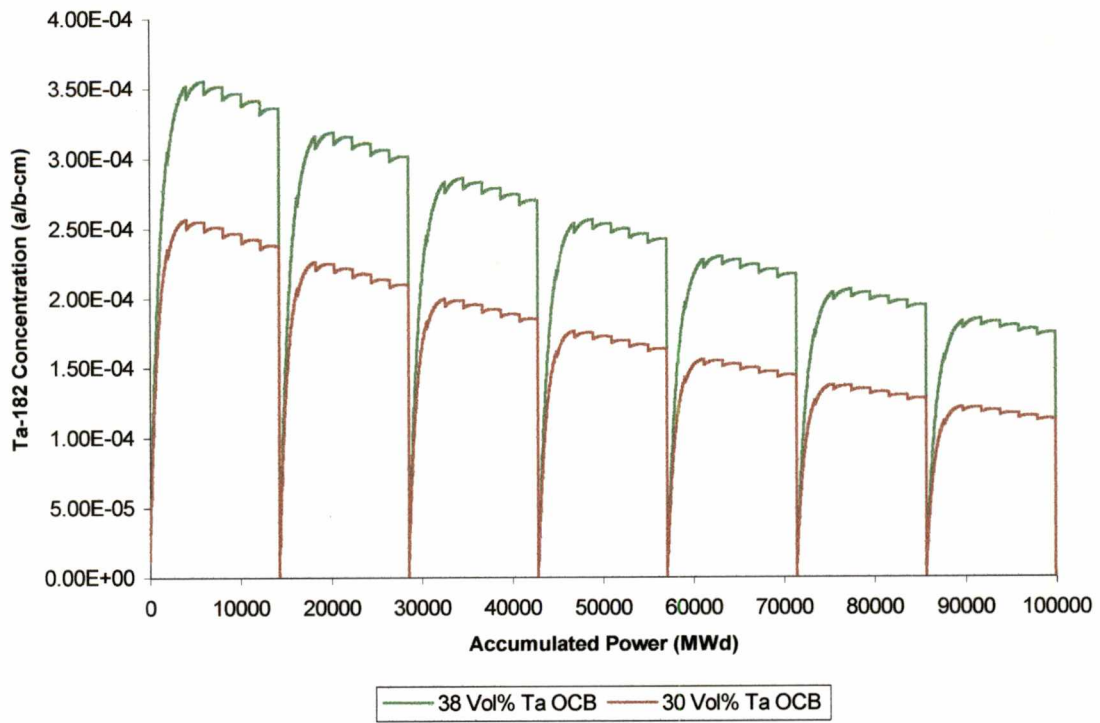


Figure 5.3. Ta-182 Concentration vs. Accumulated Power in the Outer Control Blade

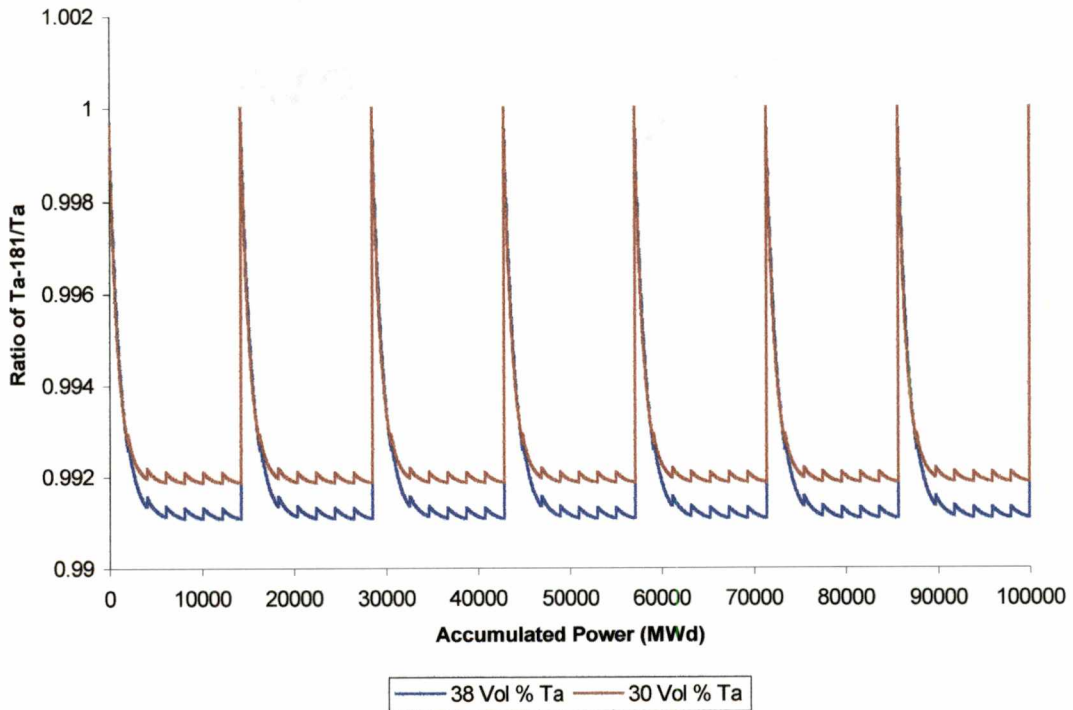


Figure 5.4. Ratio Ta-181/Total Ta vs. Accumulated Power in Outer Control Blade

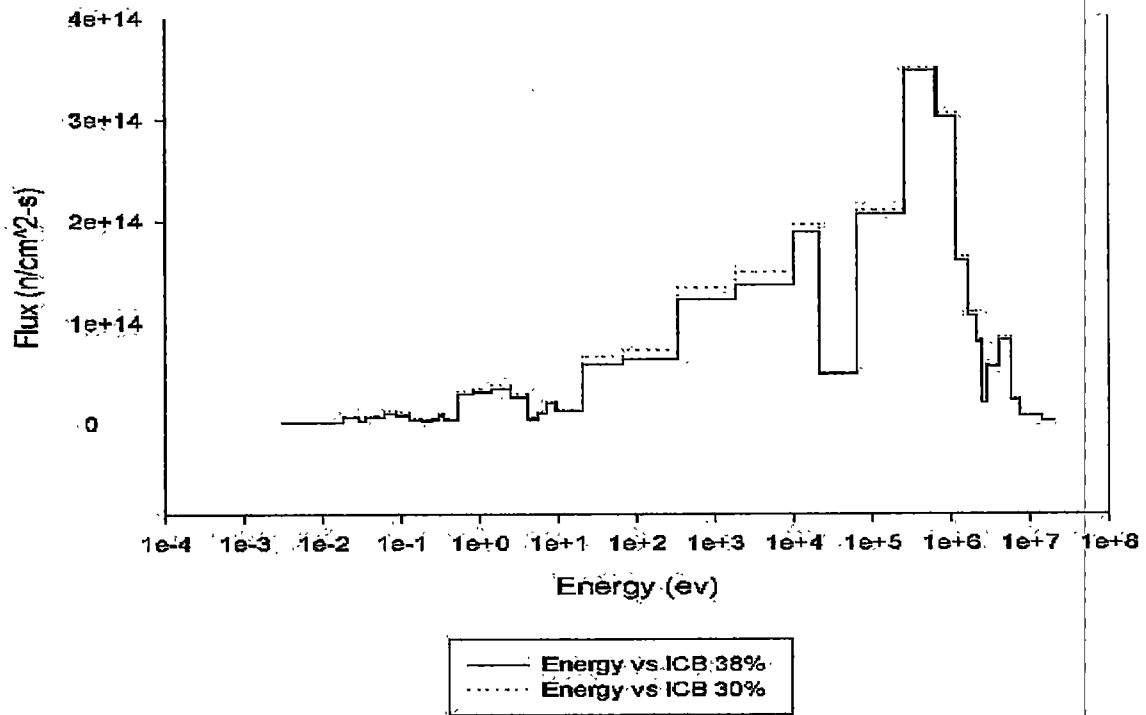


Figure 5.5. Neutron Flux in the Inner Control Blade Ta Region

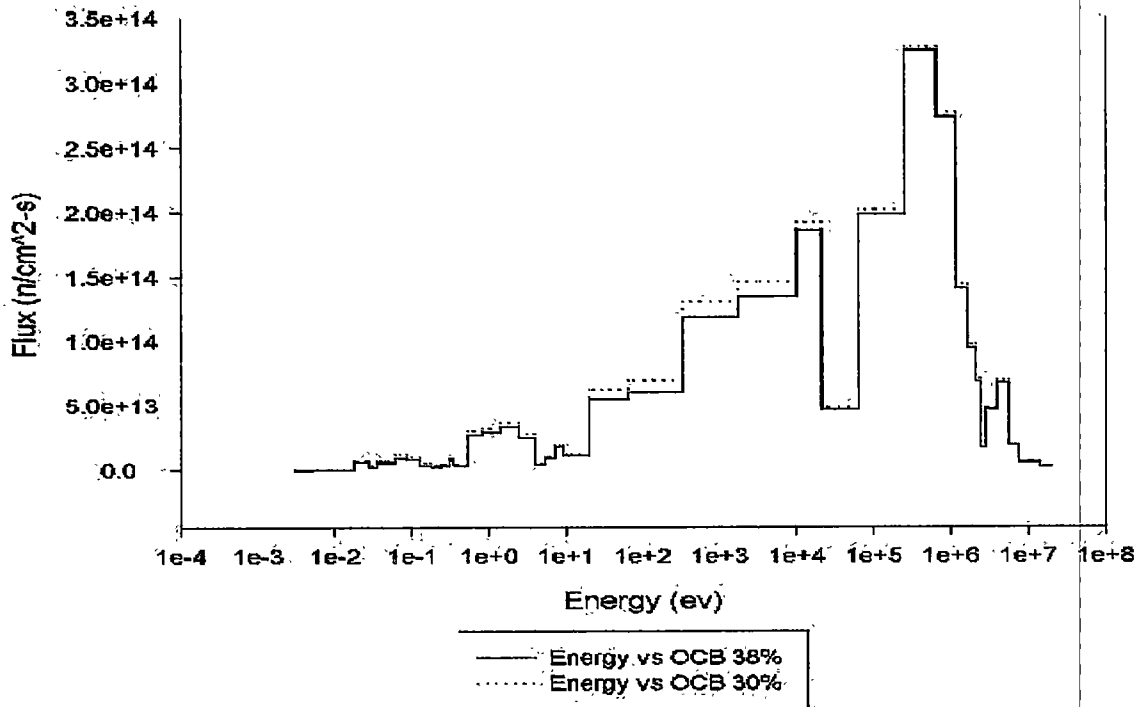


Figure 5.6. Neutron Flux in the Outer Control Blade Ta Region

The power distributions are plotted in two ways. An R-Z-Power three-dimensional plot is prepared because it is easy to visualize the power distribution in this form. To determine quantitative values, a contour plot of the same data is prepared. Taken together, these two presentations illustrate the power distributions both qualitatively and quantitatively.

Power distributions with fresh control blades are calculated first. Figures 5.7 and 5.8 are 3D and contour plots, respectively, which show the power distribution in the HFIR with 38 volume percent initial Ta loading. These figures represent the current HFIR configuration. Figures 5.9 and 5.10 show the power distribution for a 30 volume percent initial loading.

The Ta depletion calculations described above provide the concentrations of Ta at various times over the life of the control blades. At each of these time steps, power distributions are generated. The first step is to determine critical positions, as described in Section 4.3. Figure 5.11 presents these critical blade heights over time. Based on operations data from the HFIR, the core regions closest to exceeding thermal margins are near the inner radius of the inner and the outer fuel elements at the core outlet.² Figures 5.12 and 5.13 illustrate the normalized power over time for two axial positions at the inner radius of the inner and outer fuel elements, respectively. The two intervals shown are the core outlet, at -25 cm, and at an interval about 3 cm higher in the core. Both 38 and 30 volume percent loading are shown on both figures. The data points in the inner fuel element are presented in Table 5.3 along with the percent difference between the 38 and 30 volume percent loadings for each point, as well as an arithmetic mean of these

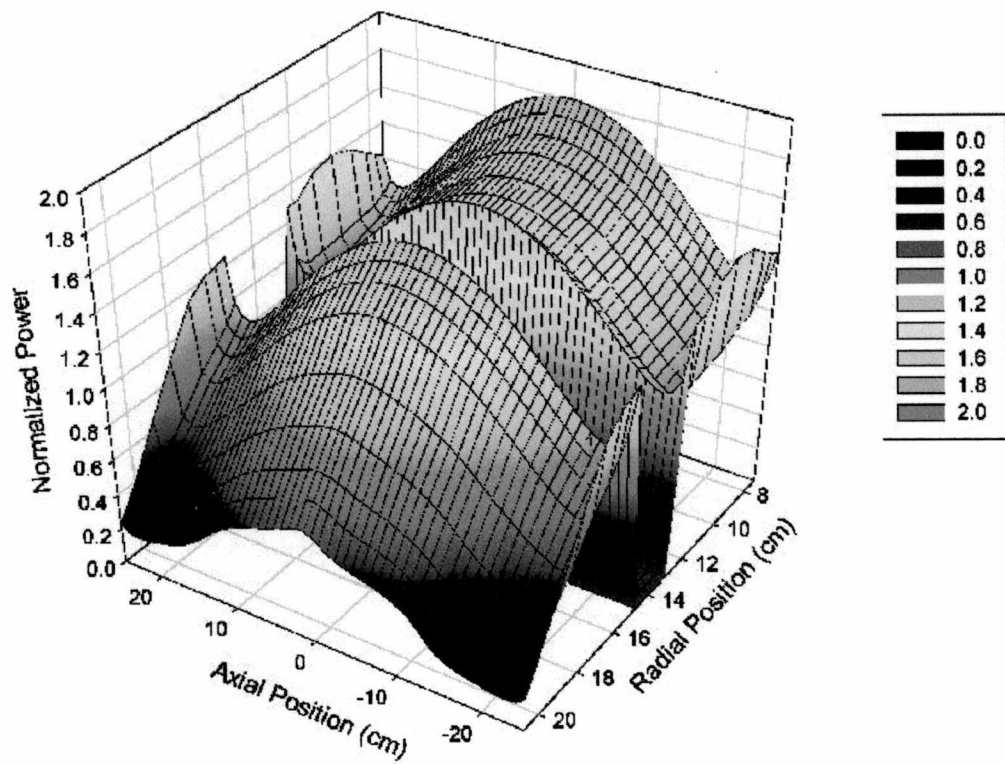


Figure 5.7. Normalized R-Z-Power for 38 Vol % Ta Control Blades, 0 MWd

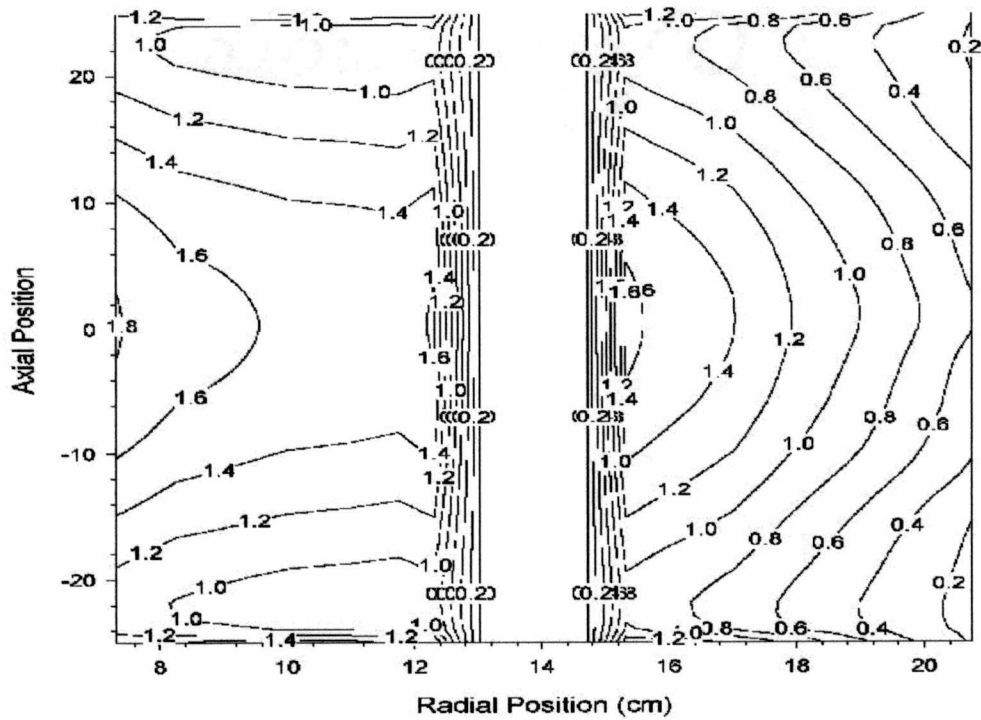


Figure 5.8. Normalized Contour for 38 Vol % Ta Control Blades, 0 MWd

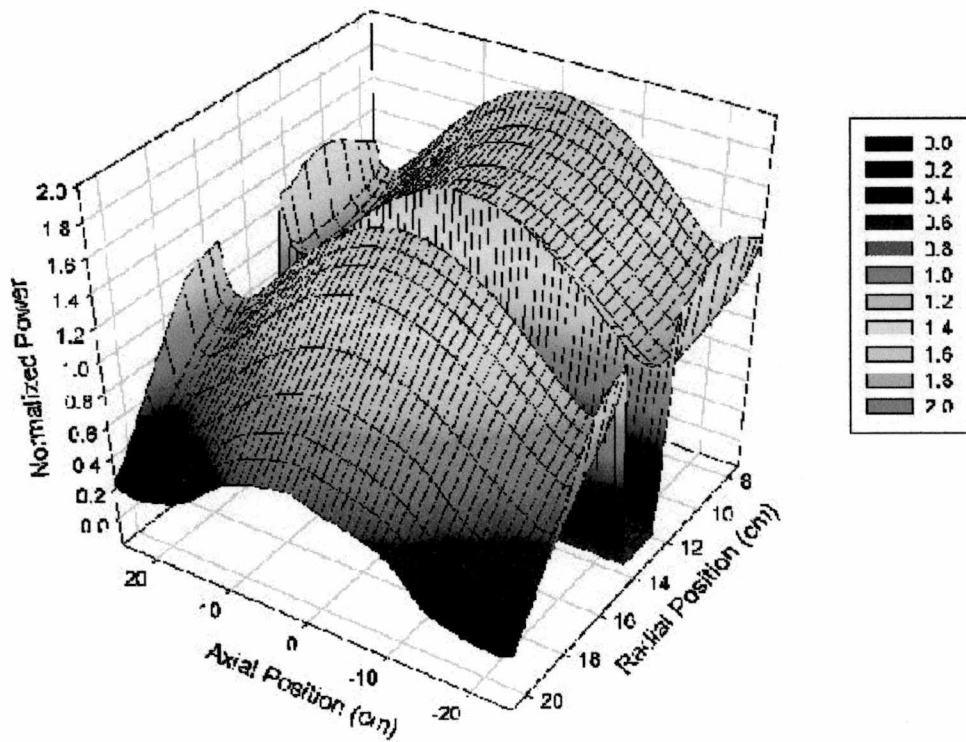


Figure 5.9. Normalized R-Z-Power for 30 Vol % Ta Control Blades, 0 MWd

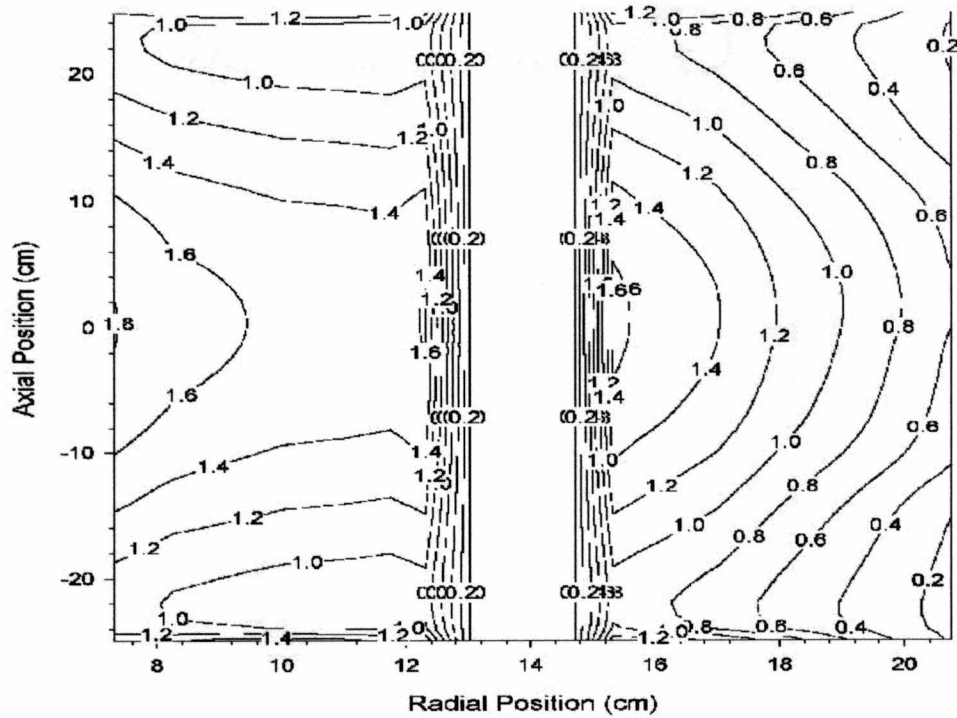


Figure 5.10. Normalized Contour for 30 Vol % Ta Control Blades, 0 MWd

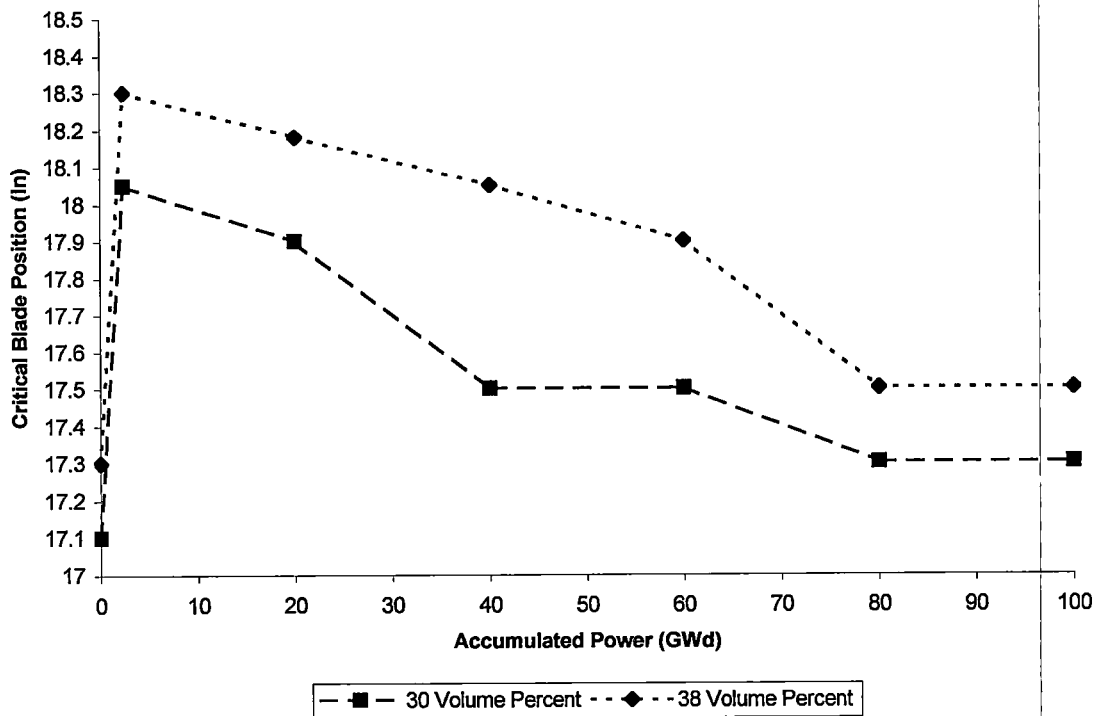


Figure 5.11. Critical Blade Positions Over Time for 38 and 30 vol % Loadings

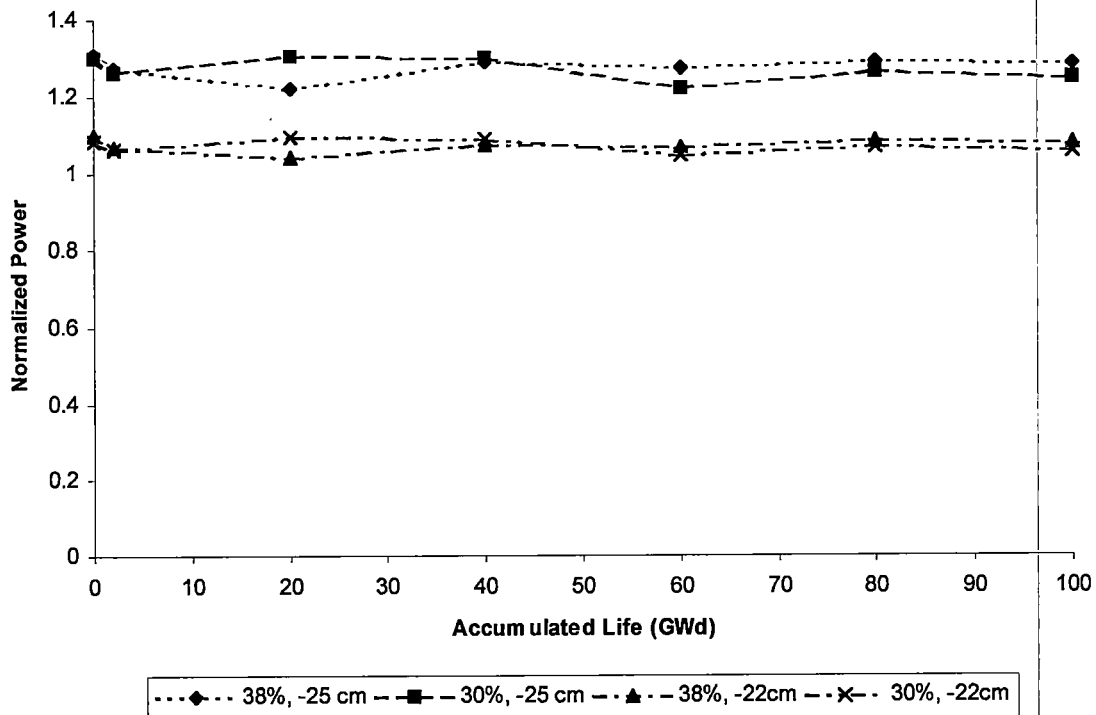


Figure 5.12. Normalized Power for Two Positions in Inner Fuel Element

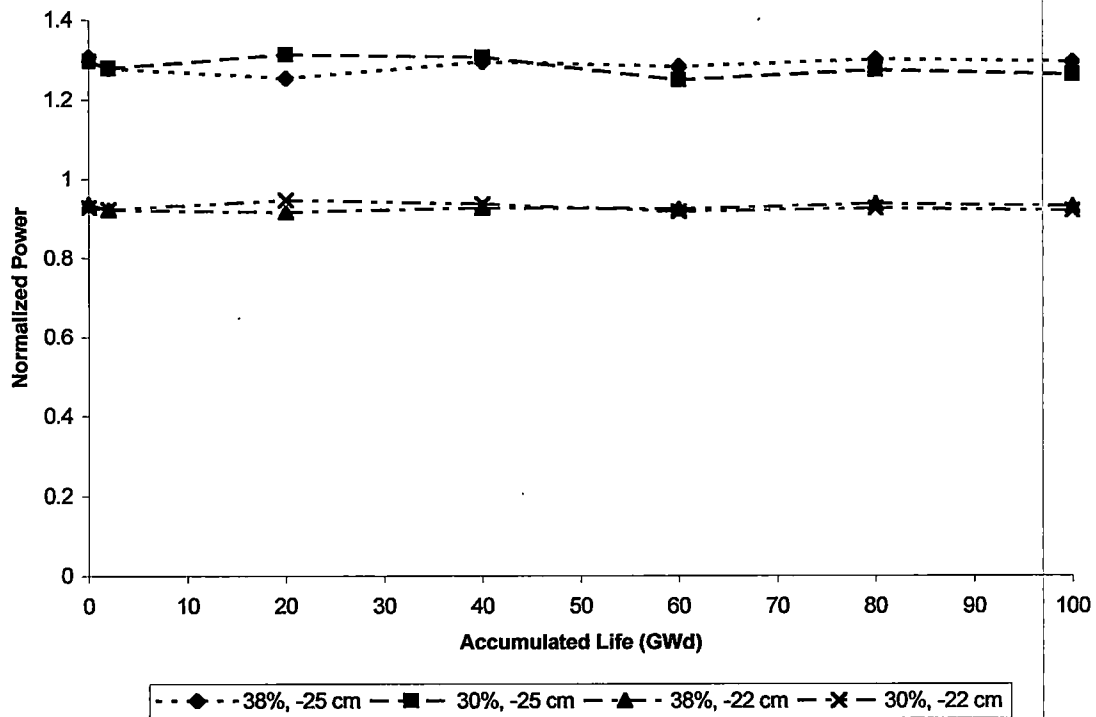


Figure 5.13. Normalized Power for Two Positions in Outer Fuel Element

Table 5.3. Comparison of Normalized Power in Inner Fuel Element

Normalized Power for IFE1 (7.32 cm) at Two Axial Positions								
Power	0	2.04	20	40	60	80	100	Avg % Diff.
-25								
38%	1.307	1.280	1.254	1.295	1.281	1.300	1.292	1.89%
30%	1.298	1.281	1.313	1.306	1.249	1.273	1.261	
% Diff	0.710%	0.083%	4.687%	0.829%	2.457%	2.068%	2.391%	
-22								
38%	0.936	0.922	0.915	0.926	0.924	0.935	0.930	1.25%
30%	0.927	0.923	0.946	0.937	0.917	0.925	0.918	
% Diff	0.977%	0.139%	3.414%	1.190%	0.702%	1.087%	1.248%	

percentages. The same information is provided for the outer fuel element in Table 5.4. From these data, it is evident that in the inner fuel element each data point is within 5% of its corresponding value for the other Ta loading. In the outer fuel element, the differences are comparable: less than 7%. In both cases, the average difference is less than half the maximum difference.

As mentioned previously, a matter of great concern in this project is the possible increase in power peaking. Such peaking increases could occur because blade heights would be lowered to compensate for a reduced Ta loading. These new blade positions bring the highly absorbing Eu_2O_3 (black) regions closer together. As shown by Tables 5.3 and 5.4, however, the reduction of initial Ta loading from 38% to 30% causes no appreciable increase in power peaking in the core. The peaking factors also appear to be nearly constant over the life of the control blades.

A further reduction in Ta loading is most likely not feasible because power peaking in the HFIR core does start to increase as Ta concentrations become low. A set of scoping calculations has been run to determine the concentration at which peaking increases. As shown in Figure 5.14, between 25 and 15 volume percent a dramatic increase in power peaking occurs. According to Ta depletion calculations, the final concentration for control blades with an initial loading of 30% is about 12 volume percent. Initial loadings below 30%, therefore, could see a noticeable increase in peaking towards the end of control blade life. The effort and expense invested in a set of control blades eliminates shortening control blade life as a solution to this problem.

Table 5.4. Comparison of Normalized Power in Outer Fuel Element

Normalized Power for OFE1 (15.325 cm) at Two Axial Positions								
Power	0	2.04	20	40	60	80	100 Avg	% Diff.
-25								
38%	1.313	1.273	1.223	1.290	1.272	1.292	1.285	2.57%
30%	1.302	1.266	1.304	1.302	1.223	1.262	1.249	
% Diff	0.907%	0.583%	6.606%	0.921%	3.824%	2.362%	2.782%	
-22								
38%	1.100	1.072	1.042	1.077	1.071	1.087	1.080	1.94%
30%	1.087	1.065	1.098	1.092	1.049	1.072	1.062	
% Diff	1.167%	0.573%	5.410%	1.328%	2.076%	1.402%	1.648%	

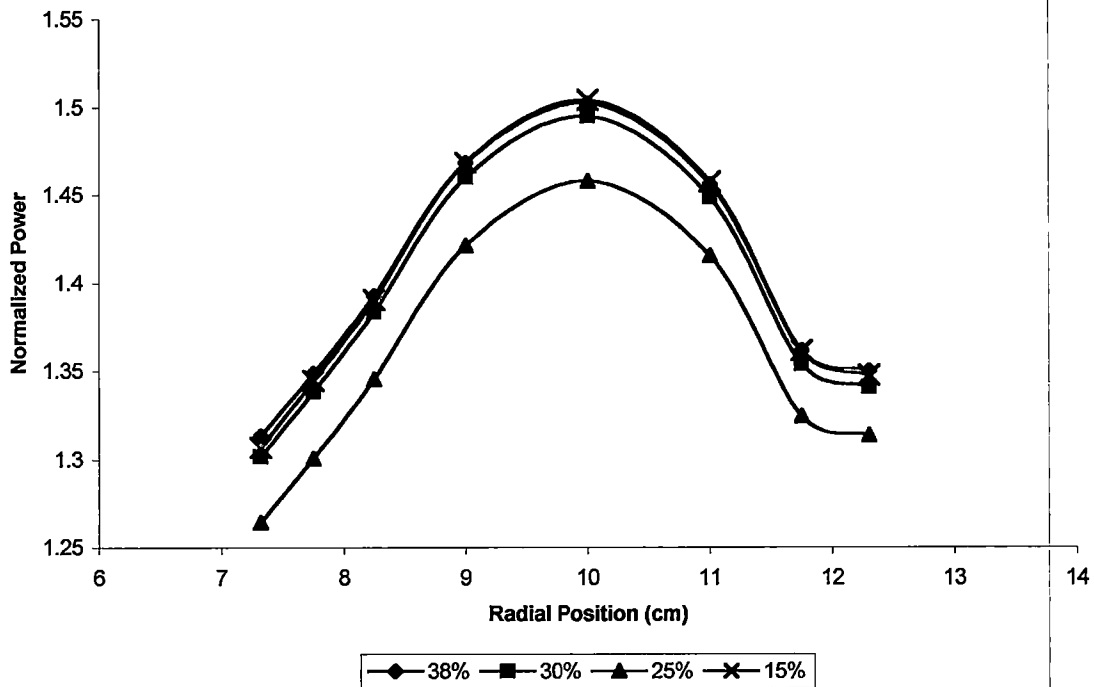


Figure 5.14. Normalized Power at Outlet of Inner Fuel Element

6. Conclusions and Future Work

Considering only thermal margins, a change in HFIR control blade Ta loading from 38 volume percent to 30 volume percent is feasible. The calculations performed in this project demonstrate that such a change has no effect on the HFIR power distributions throughout the control blade life cycle. Further reductions, however, may prove problematic.

Further work may be needed to investigate the effects of the Ta loading change on other factors. The HFIR shut down margin may be affected directly or indirectly by such a change. The control rod worths will be changed and the effect on the flux in the entire core might impact the target and experiments as well.

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Appendices

Appendix A

Performing Calculations on the College of Engineering UNIX System at the University of Tennessee-Knoxville

A. Performing Calculations at UT

The information presented in this appendix was gained over a period of several frustrating months from many different sources. It is with the hope of saving other students these painful and aggravating explorations that this section is added to this thesis.

A.1 Account Setup

The first step to running the codes utilized in this research on the UNIX system in the College of Engineering is to get an account on these machines. A simple request form approved by a faculty member is all that is required for such an account.

The next step is to modify the user profile to add paths pointing to the codes being utilized. The paths to the codes must be added to the “.cshrc” file in the user’s root directory. This file may be edited either with the VI editor or with pico. Each new path added must be assigned a number that is not used for any other paths in the .cshrc file, but the actual number selected is unimportant. Many different versions of these codes are on the system in different locations. At this writing, the most recent versions of the codes loaded on the machines are SCALE 4.4a and DOORS 3.2. The execution of the codes is somewhat different in each case, so the target of the path is also different. For SCALE, the path must be pointed to the “/cmds” directory, and for DOORS, the path must be pointed to the “/bin” directory. The batch file or executables used in both cases are located in the specified directories. Both codes are located in the /ne5/codes directory. Given below are examples for the paths set to SCALE 4.4a and DOORS 3.2:


```
set path16 = (/ne5/codes/scale4.4a/cmds)
set path15 = (/ne5/codes/doors32/bin)
```

A final set path statement is needed to apply these paths. An example is given below:

```
set path = ($path15 $path16)
```

It is possible, and even likely, that there will be many other paths in the final set path statement. An additional step is necessary before these modifications become effective.

The user can either logout of the account and log back in, or issue the command “source .cshrc”. At this point, the paths have been added and are active for use.

A.2 Running SCALE

SCALE has been programmed with pre-processors to generate input for various computational sequences using AMPX modules, but can also be used as an AMPX driver. The execution of the program is the same in either mode. To perform a run, a batch file is executed. This batch file creates a temporary directory for storing cross section files and other data, and it creates a messages file and an output file. The messages file contains error messages generated by the operating system. The output file contains all output generated by the execution of the SCALE system. At the end of the run, the temporary directory is removed and all data in it is deleted. The process for retrieving these files before they are deleted is described below as well as in Section 2.6.1 of the body of this thesis. The execution command for SCALE 4.4a with an input file called sample.in is:

```
batch44 sample.in
```

Note that no redirection symbols, such as "<", are needed. It is also possible to issue the same command without using ".in". The names of the messages and output files are based on the name of the input file. Whatever precedes a ".", in this case sample, is used adding ".msgs" for the messages file and ".output" for the output file. The messages and output files for this case would be "sample.msgs" and "sample.output", respectively. If there is no ".in", the complete file name is used. The messages file should be empty if the run is successful, while the output file should be quite large.

A UNIX shell command must be included to retrieve a file from the temporary directory before it is deleted. The shell command allows normal UNIX commands to be executed between modules in a SCALE run. The example given below copies a weighted cross section library generated by XSDRN to a specific location and then links it to another logical unit for use in a later module. The logical unit number for the linked library is specified in the link statement by the number used after "ft". Any logical unit number that has already been used in the SCALE run is not allowed.

```
#shell
cp ft03f001 /ne1/username/location
ln -s /ne1/username/location ftxxf001
end
```

The use of italics indicates information that must be specific to each user or situation.

A.3 Running DOORS

The various codes in the DOORS system are used separately, unlike the many modules of the SCALE system. The execution of the different codes within DOORS is the same, however, and follows a standard UNIX form. The code name is used as the

executable, and the input and output files are supplied with proper direction symbols. A DORT run, for example, with input file Sample.in and output file Sample.out would be executed with:

```
dort <Sample.in >Sample.out
```

Note that UNIX is case sensitive and that any legal file names can be used. GIP is run in the same fashion, except that “gip” is issued instead of “dort”.

A.4 Batching Commands

The capacity to batch several commands for sequential execution is included in UNIX. Any UNIX commands can be used in a batch, so file management between runs is also possible. The syntax for the batch command is as follows:

```
batch <<!
  command list
!
```

The command list is any number of commands to be executed. When the batch job is finished, an email notification is sent to the user if the job has taken more than a few seconds. This command is very useful in performing large numbers of similar calculations in a short period of time. The batch command also allows a user to logout of their account without losing the job or jobs being executed. One drawback to the batch command is that the jobs are executed as background jobs, and as such may receive a smaller fraction of the available computing time. An example of the batch command is given below. The commands copy a library, run DORT, move the output file, perform another DORT run, and move the second output file.

```

batch <<!
cp dortlib/library1 fort.8
dort <Sample.in >Sample.out
mv Sample.out dortout/run1
dort <Other.in >Other.out
mv Other.out dortout/run2
!

```

A.5 Excerpted .cshrc File

```

#####
# .cshrc file
#   initial setups for both interactive and noninteractive C-shells
#   last updated: 6/4/95
#   latest version should be available in ~defaults/.cshrc
#####
# Setup path and environment variables based on OS major verion
setenv OPENWINHOME /usr/openwin
set path1 = (/opt/SUNWspr0/bin /usr/openwin/bin)
set path2 = (/usr/x11/bin /usr/bin /usr/ccs/bin)
set path3 = (/usr/ucb /usr/sbin /usr/etc /bin)
set path4 = (/usr/www/bin /usr/local/bin)
set path5 = (/usr/tex/bin)
set path6 = (/usr/gnu/bin /usr/misc/bin)
set path7 = (/usr/transcript/bin)
set path8 = (/usr/mh/bin)
set path9 = (/usr/openwin/demo .)
set path15 = (/ne5/codes/doors32/bin)
set path16 = (/ne5/codes/scale4.4a/cmds)
set path17 = (/ne5/codes/Scale4.3/bin)
set path = ($path1 $path2 $path3 $path4 $path5 $path6 $path7 $path8
$path9 $path15 $path16 $path17)

#   other aliases
alias push 'pushd $1; set prompt = "[`hostname`:$cwd]% "'
alias pop 'popd; set prompt = "[`hostname`:$cwd]% "'
alias l 'ls'
alias .. 'cd ..'
alias type more
alias ls 'ls -CF'
alias ll 'ls -alg'
alias ff 'find . -name \!* -print'
alias pr 'lp -d nepr1'
alias ba 'batch44'

```

Appendix B

Input Files for Selected Calculations

B.1 SCALE Input File

```
=bonami
'hfir ife 4
0$$ 84 a4 1
1$$ 1 6 19 0 0 7 t
3$$ 1 6r2 4r3 6r4 2r5
4$$ 13027
    92234 92235 92236 92238 8016 13027
    5010 5011 6012 13027
    13027 4309 63151 63153 73181 73182
    8016 1001
5** 6.03e-2
    1.7012e-5 1.5854e-3 6.8008e-6 9.1842e-5 4.5363e-3 4.221e-2
    1.6592e-4 6.7186e-4 2.0951e-4 5.97-2
    6.03e-2 1-10 1-10 1-10 1-10 1-10
    3.309e-2 6.618e-2
6$$ 5 1 2 3 4 5
7** 0.0635 0.0889 0.14923 0.1651 0.1905 0.254
8** f322.0
10$$ 13027
    92234 92235 92236 92238 8016 130272
    5010 5011 6012 130273
    1302744 4309 63151 63153 73181 73182
    80165 1001
11$$ 1 2 0 2 2 1 t
end
=nitawl
1$$ 0 15 0 0 0 0 0 8 0 0 0 0 t
2$$ 8016 1001
    92234 92235 92236 92238 13027 5010 5011 6012
    63151 63153
    73181 73182
    4309
3** 92234 322.0 1.0 0.02985 0.7066 0.0 1.8779e-5 1.0 26.982 2758.7 1.0
    15.995 3355.5 1.0 1.0
    92235 322.0 1.0 0.02985 0.7066 0.0 1.7503e-3 1.0 26.982 45.816 1.0
    15.995 36.001 1.0 1.0
    92236 322.0 1.0 0.02985 0.7066 0.0 7.5409e-6 1.0 26.982 1.068e4 1.0
    15.995 8356.1 1.0 1.0
    92238 322.0 1.0 0.02985 0.7066 0.0 1.0143e-4 1.0 26.982 790.81 1.0
    15.995 621.24 1.0 1.0
    63151 322.0 1 0.5334 0.2236 0.0 8.40e-3 1 15.9994 11.867 1 26.982
    8.0426 1 1.0
    63153 322.0 1 0.5334 0.2236 0.0 8.78e-3 1 15.9994 10.866 1 26.982
    7.3647 1 1.0
    73181 322.0 1.0 0.5334 0.2236 0.0 4.179e-2 1.0 26.982 1.3724 1.0
    1.0078 1.5307 1.0 1.0
    73182 322.0 1.0 0.5334 0.2236 0.0 1-10 1.0 26.982 1.3724 1.0 1.0078
    1.5307 1.0 1.0
4** f322.0 t
end
=xsdrrn
HFIR IFE 4
```

```

-1$$ 5000000
1$$ 1 7 30 1 1 5 18 8 5 1 20 100 0 0 0
2$$ -2 9r0
3$$ 1 3r0 5 0 3 5r0
4$$ -1 238 0 -2 3 151 388 -1 0
5** a7 81 2460 e t
13$$ 1 6r2 4r3 2r4 5r5
14$$ 13027
      92234 92235 92236 92238 8016 13027
      5010 5011 6012 13027
      8016 1001
      4309 73181 73182 63151 63153
15** 6.03e-2
      1.7012e-5 1.5854e-3 6.8008-6 9.1842e-5 1.667e-2 3.01e-2
      1.6592e-4 6.7186e-4 2.0951e-4 5.97-2
      3.309e-2 6.618e-2
      1-10 1-10 1-10 1-10 1-10 t
33## f1.0 t
35** 4i 0.0 4i 0.0635 4i 0.08889 4i 0.14923 4i 0.1651 3i 0.1905 0.250
      0.254
36$$ 5r1 5r2 5r3 5r4 5r5 4r6 7
39$$ 4 1 2 3 1 4 5
40$$ 5 5 5 5 5 5 5
51$$ 236i 1 238 t
end
#shell
cp ft03f001 /nel/wmarshal/scalelib/Taife4lib
ln -s /nel/wmarshal/scalelib/Taife4lib ft90f001
end
=xsdrrn
HFIR Ta 1D calculations
-1$$ 5000000
0$$ a3 90 e
1$$ 2 21 90 1 0 20 156 8 5 1 20 100 0 0 0
2$$ -2 5r0 0 3r0
3$$ 1 3r0 5 0 3 5r0
4$$ 0 44 0 -2 3 26 69 -1 0
5** a4 1.0 a7 100 2460 e t
13$$ 2r1 10r2 10r3 10r4 10r5 10r6 10r7 10r8 10r9 7r10 7r11 7r12 7r13
      7r14 7r15 7r16 7r17 7r18 7r19 4r20
14$$ 8016 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 8016 13027 5010 5011 6012 1001
      92234 92235 92236 92238 13027 8016 1001
      92234 92235 92236 92238 13027 8016 1001
      92234 92235 92236 92238 13027 8016 1001
      92234 92235 92236 92238 13027 8016 1001
      92234 92235 92236 92238 13027 8016 1001
      92234 92235 92236 92238 13027 8016 1001

```

```

92234 92235 92236 92238 13027 8016 1001
92234 92235 92236 92238 13027 8016 1001
92234 92235 92236 92238 13027 8016 1001
92234 92235 92236 92238 13027 8016 1001
73181 73182 63151 63153 13027 8016 1001
4309 13027 8016 1001
15** 3.309-2 6.618-2
2.2070-6 2.0570-4 8.8200-7 1.1920-5 1.667-2 3.01-2 1.3143-5
5.3231-5 1.6593-5 3.333-2
2.6930-6 2.5100-4 1.0770-6 1.4540-5 1.667-2 3.01-2 2.3155-5
9.3786-5 2.9237-5 3.333-2
3.2520-6 3.0310-4 1.3000-6 1.7560-5 1.667-2 3.01-2 3.2953-5
1.3347-4 4.1606-5 3.333-2
4.0400-6 3.7650-4 1.1650-6 2.1810-5 1.667-2 3.01-2 3.9402-5
1.5955-4 4.9753-5 3.333-2
4.8070-6 4.4800-4 1.9220-6 2.5960-5 1.667-2 3.01-2 3.0765-5
1.2464-4 3.8838-5 3.333-2
4.8770-6 4.5450-4 1.9500-6 2.6330-5 1.667-2 3.01-2 2.5730-5
1.0420-4 3.2491-5 3.333-2
4.4750-6 4.1710-4 1.7890-6 2.4170-5 1.667-2 3.01-2 2.4137-5
9.7758-5 3.0475-5 3.333-2
3.9890-6 3.7180-4 1.5950-6 2.1540-5 1.667-2 3.01-2 2.1270-5
8.6156-5 2.6870-5 3.333-2
4.5280-6 4.2200-4 1.8100-6 2.4450-5 3.01-2 1.667-2 3.333-2
5.4220-6 5.0530-4 2.1680-6 2.9280-5 3.01-2 1.667-2 3.333-2
6.3750-6 5.9410-4 2.5490-6 3.4420-5 3.01-2 1.667-2 3.333-2
7.2400-6 6.7470-4 2.8940-6 3.9090-5 3.01-2 1.667-2 3.333-2
6.8991-6 6.4299-4 2.7596-6 3.7255-5 3.01-2 1.667-2 3.333-2
5.6780-6 5.2920-4 2.2700-6 3.0660-5 3.01-2 1.667-2 3.333-2
4.4480-6 4.1450-4 1.7780-6 2.4020-5 3.01-2 1.667-2 3.333-2
3.6340-6 3.3870-4 1.4530-6 1.9620-5 3.01-2 1.667-2 3.333-2
2.8950-6 2.6980-4 1.1570-6 1.5630-5 3.01-2 1.667-2 3.333-2
6.576-2 1-10 1-10 1-10 3.828-2 2.8935-3 5.7875-3
1.197-1 5.579-4 7.963-4 1.593-3
t t
33## f1.0 t
35** 2i 0.0 2i 7.14 2i 7.5 2i 8.0 2i 8.5 2i 9.5 2i 10.5 2i 11.5
2i 12.0 2i 12.6 2i 15.15 2i 15.5 2i 16.0 2i 16.5 2i 17.5
2i 18.5 2i 19.5 2i 20.0 2i 20.5 2i 21.0 29i 24.15 54.0
36$$ 3r1 3r2 3r3 3r4 3r5 3r6 3r7 3r8 3r9 3r10 3r11 3r12 3r13 3r14
3r15 3r16 3r17 3r18 3r19 3r20 30r21
39$$ 1 2 3 4 5 6 7 8 9 1 10 11 12 13 14 15 16 17 18 19 20
40$$ 21r5
51$$ 7r1 2 3 2r4 5 6 7 2r8 8r9 14r10 6r11 10r12 13 7r14 11r15 12r16
30r17 16r18 2r19 6r20 3r21 6r22 14r23 27r24 10r25 5r26 27 28 29
2r30 31 32 33 2r34 2r35 3r36 2r37 38 39 40 41 42 3r43 9r44 t
end
=shell
cp ft03f001 /nel/wmarshal/scalelib/30Ta100_ampx
ln -s /nel/wmarshal/scalelib/30Ta100_ampx ft91f001
end
=alpo
0$$ 20 91
1$$ 1 3 26 69 5 e t

```



```
2$$ 91 0 t t
end
=shell
cp ft20f001 /nel/wmarshal/scalelib/30Ta100_anisn
end
```

B.2 GIP Input File

```
/gip for full clean core from 1d model
1$$ 44 3 26 69 189 0 948 1134 0 5 2 2 2 e t
13$$ 946i 1 948
10$$ 10r-949 10r-955 10r-961 10r-967 10r-973 10r-979 10r-985
    10r-991
    7r-997 7r-1003 7r-1009 7r-1015 7r-1021 7r-1027 7r-1033
    7r-1039 7r-1045
    4r-1051 5r-1057 4r-1063 4r-1069
    4r-1075 4r-1081
    3r-1087 3r-1093 3r-1099 3r-1105 3r-1111 3r-1117
    -1123
    2r-1129
11$$ 499 373 253 7 55 103 631 847 733 151
    505 379 259 13 61 109 637 853 739 157
    511 385 265 19 67 115 643 859 745 163
    517 391 271 25 73 121 649 865 751 169
    523 397 277 31 79 127 655 871 757 175
    529 403 283 37 85 133 661 877 763 181
    535 409 289 43 91 139 667 883 769 187
    541 415 295 49 97 145 673 889 775 193
    553 427 301 679 895 781 199
    559 433 307 685 901 787 205
    565 439 313 691 907 793 211
    571 445 319 697 913 799 217
    577 451 325 703 919 805 223
    583 457 331 709 925 811 229
    589 463 337 715 931 817 235
    595 469 343 721 937 823 241
    601 475 349 727 943 829 247
    619 835 355 481
    619 835 355 607 481
    625 355 607 481
    625 355 607 481
    1 361 613 487
    1 361 613 487
    355 547 421
    355 547 421
    355 547 421
    355 547 421
    355 547 421
    355 547 421
    355 547 421
    355
    493 367
```

12** 3.309-2 1.655-2 3.01-2 1.5448-5 6.2570-5 1.9505-5 2.2070-6
2.0570-4 8.8200-7 1.1920-5
3.309-2 1.655-2 3.01-2 1.3404-5 5.4290-5 1.6924-5 2.6930-6
2.5100-4 1.0770-6 1.4540-5
3.309-2 1.655-2 3.01-2 1.1117-5 4.5030-5 1.4037-5 3.2520-6
3.0310-4 1.3000-6 1.7560-5
3.309-2 1.655-2 3.01-2 7.847-6 3.178-5 9.907-6 4.0400-6
3.7650-4 1.6150-6 2.1810-5
3.309-2 1.655-2 3.01-2 4.658-6 1.887-5 5.882-6 4.8070-6
4.4800-4 1.9220-6 2.5960-5
3.309-2 1.655-2 3.01-2 4.373-6 1.771-5 5.521-6 4.8770-6
4.5450-4 1.9500-6 2.6330-5
3.309-2 1.655-2 3.01-2 6.089-6 2.466-5 7.687-6 4.4750-6
4.1710-4 1.7890-6 2.417-5
3.309-2 1.655-2 3.01-2 8.051-6 3.261-5 1.017-5 3.9890-6
3.7180-4 1.5950-6 2.1540-5
3.309-2 1.655-2 3.01-2 4.5280-6 4.2200-4 1.8100-6 2.4450-5
3.309-2 1.655-2 3.01-2 4.5220-6 5.0530-4 2.1680-6 2.9280-5
3.309-2 1.655-2 3.01-2 6.3750-6 5.9410-4 2.5490-6 3.4420-5
3.309-2 1.655-2 3.01-2 7.2400-6 6.7470-4 2.8940-6 3.9090-5
3.309-2 1.655-2 3.01-2 6.8991-6 6.4299-4 2.7596-6 3.7255-5
3.309-2 1.655-2 3.01-2 5.6780-6 5.2920-4 2.2700-6 3.0660-5
3.309-2 1.655-2 3.01-2 4.4480-6 4.1450-4 1.7780-6 2.4020-5
3.309-2 1.655-2 3.01-2 3.6340-6 3.3870-4 1.4530-6 1.9620-5
3.309-2 1.655-2 3.01-2 2.8950-6 2.6980-4 1.1570-6 1.5630-5
8.042-3 8.782-3 4.573-2 2.524-2
7.985-3 8.720-3 4.113-2 5.347-3 2.774-2
3.299-2 4.056-2 3.125-3 1.562-3
3.276-2 3.600-2 8.450-3 4.225-3
1.1670-1 5.5200-4 3.2800-3 1.6400-3
1.2080-1 5.6000-4 9.9400-4 4.9700-4
3.5300-2 2.6553-2 1.328-2
2.3600-2 3.698-2 1.854-2
3.0100-2 3.309-2 1.655-2
4.80-2 1.0370-2 5.1851-3
5.756-2 3.125-3 1.652-3
5.288-2 8.450-3 4.225-3
6.03-2
3.309-2 6.618-2
t

B.3 DORT Input File

HFIR RZ Core Model from 1D Region Weighting - 17.5" Blade Heights
61\$\$ 0 0 8 e
62\$\$ 0 3 31 88 102 44 3 26 69 0 0 0 186 0 48 1 3 5 5 5
60 20 0 4 1 2 0 0 3 0 0 0 0 0 0 32 0 1 1 0 0 0 0 0 0
0 1 1 1 1 4 50 0 0 5 0 0 0 0 0 0 -1 5000 0 0 4 -1 0 0 0
e
63** 200 e t
t
82*

```

0 -30861- 5 0 -21822- 5 0 +21822- 5 0 -61721- 5 0 -57735- 5 0 -21822-
5
0 +21822- 5 0 +57735- 5 0 -81650- 5 0 -78680- 5 0 -57735- 5 0 -21822-
5
0 +21822- 5 0 +57735- 5 0 +78680- 5 0 -97590- 5 0 -95119- 5 0 -78680-
5
0 -57735- 5 0 -21822- 5 0 +21822- 5 0 +57735- 5 0 +78680- 5 0 +95119-
5
0 -30861- 5 0 -21822- 5 0 +21822- 5 0 -61721- 5 0 -57735- 5 0 -21822-
5
0 +21822- 5 0 +57735- 5 0 -81650- 5 0 -78680- 5 0 -57735- 5 0 -21822-
5
0 +21822- 5 0 +57735- 5 0 +78680- 5 0 -97590- 5 0 -95119- 5 0 -78680-
5
0 -57735- 5 0 -21822- 5 0 +21822- 5 0 +57735- 5 0 +78680- 5 0 +95119-
5
83*
3r-95119- 5 5r-78680- 5 7r-57735- 5 9r-21822- 5 3r+95119- 5 5r+78680-
5
7r+57735- 5 9r+21822- 5
81*
0 + 0+ 0 2r+30247- 6 0 + 0+ 0 0 +22685- 6 2r+22685- 6 0 +22685-
6
0 + 0+ 0 0 +22685- 6 0 +23148- 6 2r+22685- 6 0 +23148- 6 0 +22685-
6
0 + 0+ 0 0 +30247- 6 0 +22685- 6 0 +22685- 6 2r+30247- 6 0 +22685-
6
0 +22685- 6 0 +30247- 6 0 + 0+ 0 2r+30247- 6 0 + 0+ 0 0 +22685-
6
2r+22685- 6 0 +22685- 6 0 + 0+ 0 0 +22685- 6 0 +23148- 6 2r+22685-
6
0 +23148- 6 0 +22685- 6 0 + 0+ 0 0 +30247- 6 0 +22685- 6 0 +22685-
6
2r+30247- 6 0 +22685- 6 0 +22685- 6 0 +30247- 6
t
1** 5.09e-3 1.40e-2 4.39e-2 1.53e-1 8.52e-2 2.41e-2 1.15e-1
1.27e-1 1.65e-1 1.73e-1 8.29e-2 1.18e-2 7.61e-4 9.05e-4
6.72e-5 5.28e-6 3.71e-7 5.89e-8 3.81e-9 3.71e-9 1.93e-9
2.29e-9 1.26e-9 6.02e-10 2.25e-10 1.07e-10 1.04e-11 1e-11
9.68e-12 1.82e-11 8.53e-12 8.12e-12 7.68e-12 1.39e-11
1.18e-11 5.82e-12 3.26e-12 1.41e-12 1.25e-12 5.21e-13
1.34e-12 1.56e-13 2.16e-13 7.30e-14
2** 19i -50 4i -30.5 11i -25.4 12i -13.6 2i -0.9 12i 1.7 10i 14.4
4i 25.4 9i 30.5 9i 40 50
4** 4i 0 5 5.7 6.4 7.14 7.5 8.0 8.5 9.5 10.5 11.5 12.0 2i 12.6 15.15
15.5 16 16.5 17.5 18.5 19.5 20.0 20.5 21 21.76 2i 22.02 22.66
2i 22.99 23.62 8i 23.97 20i 33 19i 54 74
5** 2e7 8.1873e6 6.434e6 4.8e6 3e6 2.479e6 2.354e6 1.85e6
1.4e6
9e5 4e5 1e5 2.5e4 1.7e4 3e3 5.5e2 1e2 3e1 1e1 8.1 6.0
4.75
3.0 1.77 1.0 6.25e-1 4e-1 3.75e-1 3.5e-1 3.25e-1 2.75e-1
2.5e-1 2.25e-1 2e-1 1.5e-1 1e-1 7e-2 5e-2 4e-2 3e-2 2.53e-2
1e-2 7.5e-3 3e-3 1e-5 0

```

8\$\$ 7r1 6 22r1 3r25 1 3r3 51r1 19q88
 7r1 6 8r1 3r15 9r1 31 1 3r25 1 3r3 1 9r26 21r27 20r1 4q88
 7r1 6 7 8 9 10 11 12 13 14 3r15 16 17 18 19 20 21 22 23 24 31 1
 3r25 1 3r3 1 9r26 21r27 20r1 11q88
 7r1 6 7 8 9 10 11 12 13 14 3r15 16 17 18 19 20 21 22 23 24 31 1
 3r28 1 3r3 1 9r26 21r27 20r1 12q88
 7r1 6 7 8 9 10 11 12 13 14 3r15 16 17 18 19 20 21 22 23 24 31 1
 3r2 1 3r3 1 9r26 21r27 20r1 2q88
 7r1 6 7 8 9 10 11 12 13 14 3r15 16 17 18 19 20 21 22 23 24 31 1
 3r2 1 3r4 1 9r26 21r27 20r1 12q88
 7r1 6 7 8 9 10 11 12 13 14 3r15 16 17 18 19 20 21 22 23 24 31 1
 3r2 1 3r5 1 9r26 21r27 20r1 10q88
 5r29 2r1 6 8r30 3r15 9r30 31 1 3r2 1 3r5 1 9r26 21r27 20r1 4q88
 5r29 2r1 6 20r1 31 1 3r2 1 3r5 51r1 9q88
 7r1 6 22r1 3r2 1 3r5 51r1 9q88
 9\$\$ 181 163 169 121 109 157 1 7 13 19 25 31 37 43 139 49 55 61 67 73
 79
 85 91 97 103 127 133 115 145 151 175
 21** f 0.2
 22** f 0.2
 23** f 0.2
 t
 93** f 1.0 t
 94** f 1.0 t
 95** f 1.0 t
 t

Appendix C

FORTRAN Code for Tantalum Depletion

```

*****
*       Program Tantalum Depleter                               *
*       Written by: B.J. Marshall                               *
*       February 23, 2001                                       *
*       May 11, 2001                                           *
*****
*       This program is designed to perform Ta depletion      *
* over time in the control blades at the High Flux Isotope   *
* Reactor located at the Oak Ridge National Laboratory.      *
* The inputs required are: the summation of absorption       *
* cross section times flux for Ta-181, the summation of     *
* (n,gamma) cross section times flux for Ta-181, the       *
* summation of absorption cross section times flux for     *
* Ta-182, and the initial concentration of Ta-181 in that  *
* order for the inner control blade and then the outer     *
* control blade. The concentration of Ta-181 and Ta-182 is  *
* calculated every 12 hours over a 24.0 day cycle and       *
* every 12 hours over a 4.5 day refueling outage. A total  *
* of 49 cycles are run, which corresponds to 100,000 MWD.  *
* These cycles are run in 7 sets of 7 cycles because the    *
* outer control blades are replaced every 7 cycles. This   *
* reduces the initial concentration of Ta-182 in the outer  *
* blades to zero as these blades have been cooling in the    *
* pool long enough for all Ta-182 to decay. In this       *
* program it is assumed that the outer blades have the     *
* same accumulated power history as the inner blade. This  *
* is a conservative assumption as it guarantees the least  *
* Ta left in the combined blades at the end of CB life.    *
* The inner and outer blades are modeled separately.       *
* The outputs include: cumulative time since beginning of  *
* life, concentrations of Ta-181 and Ta-182 at every time  *
* step, total concentration of Ta, the ratio of Ta-181 to  *
* total Ta, and the accumulated power in MWD. The formulae *
* for the concentrations of Ta-181 and Ta-182 were derived *
* by solving the differential equations describing the      *
* change in concentration with respect to time. Cross     *
* sections were generated using XSDRN-PM in 44 groups.     *
* Fluxes were determined from DORT runs in positions      *
* within the Ta regions of the control blades.             *
*****
* VARIABLES USED                                             *
* OneI(t)           N-181(t) in inner control blade        *
* TwoI(t)           N-182(t) in inner control blade        *
* OneInitI(cycle)  N-181(0) in inner blade for each cycle *
* TwoInitI(cycle)  N-182(0) in inner blade for each cycle *
* OneO(t)           N-181(t) in outer control blade        *
* TwoO(t)           N-182(t) in outer control blade        *
* OneInitO(cycle)  N-181(0) in outer blade for each cycle *
* TwoInitO(cycle)  N-182(0) in outer blade for each cycle *
* Time(t)          Cumulative time since start of run in s *
* t                Time since beginning of cycle           *
* cycle            Cycle number in each set                *
* cumcycle         Cycle number since beginning of blade life *
* TotalI(t)        N-181(t) + N-182(t) in inner blade     *

```

```

* RatioI(t)      N-181(t) / Total(t) in inner blade      *
* TotalO(t)      N-181(t) + N-182(t) in outer blade      *
* RatioO(t)      N-181(t) / Total(t) in outer blade      *
* sigaoneI       Summation of Ta-181 absorption xsec ICB  *
* siggoneI       Summation of Ta-181 (n,gamma) xsec ICB  *
* sigatwoI       Summation of Ta-182 absorption xsec ICB  *
* sigaoneO       Summation of Ta-181 absorption xsec OCB  *
* siggoneO       Summation of Ta-181 (n,gamma) xsec OCB  *
* sigatwoO       Summation of Ta-182 absorption xsec OCB  *
* lambda         Decay constant for Ta-182                *
* siglamI        sigatwoI + lambda                        *
* siglamO        sigatwoO + lambda                        *
* i              counter                                   *
* tcyc           Time since beginning of cycle            *
* set            Number of set of cycles                  *
* AccPower       Accumulated power (MWd)                 *
*****
*
* Variable Declarations
*
  implicit none
  real oneI(3000),twoI(3000),totalI(3000),ratioI(3000)
  real oneinitI(50),twoinitI(50)
  real oneo(3000),twoo(3000),totalO(3000),ratioO(3000)
  real oneinitO(50),twoinitO(50)
  real time(3000),AccPower(3000)
  real sigaoneI,siggoneI,sigatwoI,lambda,siglamI,tcyc
  real sigaoneO,siggoneO,sigatwoO,siglamO
  integer t,cycle,i,set,cumcycle
  character*15 infile,IBoutfil,OBoutfil
*
* Read Input and Output File Names
*
  write(*,'(a)') 'What is the input file name?'
  read('a') infile
  write(*,'(a)') 'What is the inner blade output file name?'
  read('a') IBoutfil
  write(*,'(a)') 'What is the outer blade output file name?'
  read('a') OBoutfil
*
* Read Variables from infile and Assign Initial Values
*
  open(8,file=infile)
  read(8,*)sigaoneI
  read(8,*)siggoneI
  read(8,*)sigatwoI
  read(8,*)oneinitI(1)
  read(8,*)sigaoneO
  read(8,*)siggoneO
  read(8,*)sigatwoO
  read(8,*)oneinitO(1)
  lambda = 7.01e-8
  siglamI = lambda + sigatwoI
  siglamO = lambda + sigatwoO

```

```

    twoinitI(1) = 0
    twoinitO(1) = 0
    time(0) = 0
    AccPower(0) = 0
    i = 0
    cumcycle = 0
*
* Write initial conditions, inner blade then outer
*
    open(9,file=IBoutfil)
    write(9,100) 'Sig a-181','Sig g-181','Sig a-182','lambda ',
+ 'lambda + sig a-182'
    write(9,110) sigaoneI,siggoneI,sigatwoI,lambda,siglamI
    write(9,*)
    write(9,*)
    write(9,120) 'Time  ','Ta-181  ','Ta-182  ','Total  ',
+ 'Ratio  ','  Acc Power'
    write(9,130) '0',oneinitI(1),'0',oneinitI(1),'1.000000','0.00'
*
* Now outer blade output
*
    open(19,file=OBoutfil)
    write(19,100) 'Sig a-181','Sig g-181','Sig a-182','lambda ',
+ 'lambda + sig a-182'
    write(19,110) sigaoneO,siggoneO,sigatwoO,lambda,siglamO
    write(19,*)
    write(19,*)
    write(19,120) 'Time  ','Ta-181  ','Ta-182  ','Total  ',
+ 'Ratio  ','  Acc Power'
    write(19,130) '0',oneinitO(1),'0',oneinitO(1),'1.000000','0.00'
*
* DO loop for each set
*
    do set = 1,7
*
* DO loop for each cycle
*
        do cycle=1,7
            tcyc = 0
            cumcycle = cumcycle + 1
            write(9,150) 'Cycle: ',cumcycle
            write(19,150) 'Cycle: ',cumcycle
*
* Inner DO loop calculated concentrations at each time step (12 hours)
*
            do t=1,48
                i = i + 1
                time(i) = time(i-1) + 43200
                tcyc = tcyc + 43200
                AccPower(i) = AccPower(i-1) + 42.5
*
* Calculate N-181(t), inner blade then outer

```



```

*
      oneI(i) = oneinitI(cumcycle) * EXP(-sigaoneI * tcyc)
      oneO(i) = oneinitO(cumcycle) * EXP(-sigaoneO * tcyc)
*
* Calculate N-182(t), inner blade
*
      twoI(i) = (siggoneI*oneinitI(cumcycle)/(siglamI-siggoneI) *
+             EXP(-siggoneI*tcyc)) + ((twoinitI(cumcycle) -
+             (siggoneI * oneinitI(cumcycle)/(siglamI - siggoneI))) *
+             EXP(-siglamI*tcyc))
*
* Calculate N-182(t), outer blade
*
      twoO(i) = (siggoneO*oneinitO(cumcycle)/(siglamO-siggoneO) *
+             EXP(-siggoneO*tcyc)) + ((twoinitO(cumcycle) -
+             (siggoneO * oneinitO(cumcycle)/(siglamO - siggoneO))) *
+             EXP(-siglamO*tcyc))
*
* Calculate total(t) and ratio(t), inner blade then outer
*
      totalI(i) = oneI(i) + twoI(i)
      ratioI(i) = oneI(i) / totalI(i)
      totalO(i) = oneO(i) + twoO(i)
      ratioO(i) = oneO(i) / totalO(i)
*
* Print to output file, inner blade then outer
*
      write(9,140) time(i),oneI(i),twoI(i),totalI(i),
+             ratioI(i),AccPower(i)
      write(19,140) time(i),oneO(i),twoO(i),totalO(i),
+             ratioO(i),AccPower(i)

      enddo
*
* Store initial Ta-181 concentration for next cycle
* Calculate initial Ta-182 concentration for next cycle accounting for
* decay during refueling outage
*
      oneinitI(cumcycle+1) = oneI(i)
      twoinitI(cumcycle+1) = twoI(i) * exp(-lambda * 388800)
      oneinitO(cumcycle+1) = oneO(i)
      if (cycle .eq. 7) then
          twoinitO(cumcycle+1) = 0
      else
          twoinitO(cumcycle+1) = twoO(i) * exp(-lambda * 388800)
      endif
      time(i) = time(i) + 388800
      totalI(i) = oneI(i) + twoinitI(cumcycle+1)
      ratioI(i) = oneI(i) / totalI(i)
      totalO(i) = oneO(i) + twoinitO(cumcycle+1)
      ratioO(i) = oneO(i) / totalO(i)
      write(9,140) time(i),oneinitI(cumcycle+1),
+             twoinitI(cumcycle+1),totalI(i),ratioI(i),AccPower(i)
      write(19,140) time(i),oneinitO(cumcycle+1),

```

```
+      twoinitO(cumcycle+1),totalO(i),ratioO(i),AccPower(i)

      enddo
    enddo
*
* Format statements
*
100  format (1x,a9,3a11,1x,a18)
110  format (1x,e9.3e2,3e11.3e2,3x,e11.3e2)
120  format (1x,a9,2a13,2a11,a12)
130  format (1x,f9.1,e13.5e2,f13.1,e11.3e2,f11.6,f10.2)
140  format (1x,e9.4e2,2e13.5e2,e11.3e2,f11.6,f10.2)
150  format (1x,a7,i2)
      end
```

Vita

William Marshall was born and raised in northwest suburban Chicago. He attended the public schools for his elementary and high school education, graduating from Prospect High School on June 2, 1996. That fall he enrolled at the University of Missouri-Rolla, graduating Cum Laude with a Bachelor of Science Degree in Nuclear Engineering on December 18, 1999. In January of 2000, William began his graduate studies at the University of Tennessee-Knoxville. He received his Master of Science Degree in Nuclear Engineering in August, 2001.