DEVELOPMENT OF TECHNICAL NUCLEAR FORENSICS FOR SPENT RESEARCH REACTOR FUEL

A Dissertation

by

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ABSTRACT

Pre-detonation technical nuclear forensics techniques for research reactor spent fuel were developed in a collaborative project with Savannah River National Laboratory. An inverse analysis method was employed to reconstruct reactor parameters from a spent fuel sample using results from a radiochemical analysis. In the inverse analysis, a reactor physics code is used as a forward model. Verification and validation of different reactor physics codes was performed for usage in the inverse analysis.

The verification and validation process consisted of two parts. The first is a variance analysis of Monte Carlo reactor physics burnup simulation results. The codes used in this work are MONTEBURNS and MCNPX/CINDER. Both utilize Monte Carlo transport calculations for reaction rate and flux results. Neither code has a variance analysis that will propagate through depletion steps, so a method to quantify and understand the variance propagation through these depletion calculations was developed.

The second verification and validation process consisted of comparing reactor physics code output isotopic compositions to radiochemical analysis results. A sample from an Oak Ridge Research Reactor spent fuel assembly was acquired through a drilling process. This sample was then dissolved in nitric acid and diluted in three different quantities, creating three separate samples. A radiochemical analysis was completed and the results were compared to simulation outputs at different levels of detail.

After establishing a forward model, an inverse analysis was developed to reconstruct the burnup, initial uranium isotopic compositions, and cooling time of a research reactor spent fuel sample. A convergence acceleration technique was used that consisted of an analytical calculation to predict burnup, initial ^{235}U, and ^{236}U

enrichments. The analytic calculation results may also be used stand alone or in a database search algorithm. In this work, a reactor physics code is used as a forward model with the analytic results as initial conditions in a numerical optimization algorithm. In the numerical analysis, the burnup and initial uranium isotopic compositions are reconstructed until the iterative spent fuel characteristics converge with the measured data.

Upon convergence of the sample's burnup and initial uranium isotopic composition, the cooling time can be reconstructed. To reconstruct cooling time, the standard decay equation is inverted and solved for time. Two methods were developed. One method uses the converged burnup and initial uranium isotopic compositions along in a reactor depletion simulation. The second method uses an isotopic signature that does not decay out of its mass bin and has a simple production chain. An example would be ^{137}Cs which decays into the stable ^{137}Ba. Similar results are achieved with both methods, but extended shutdown time or time away from power results in over prediction of the cooling time.

The over prediction of cooling time and comparison of different burnup reconstruction isotope results are indicator signatures of extended shutdown or time away from power. Due to dynamic operation in time and function, detailed power history reconstruction for research reactors is very challenging. Frequent variations in power, repeated variable shutdown time length, and experimentation history affect the spectrum an individual assembly is burned with such that full reactor parameter reconstruction is difficult.

The results from this technical nuclear forensic analysis may be used with law enforcement, intelligence data, macroscopic and microscopic sample characteristics in a process called attribution to suggest or exclude possible sources of origin for a sample.

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1. INTRODUCTION

1.1 Research Reactors

Research Reactors are typically the least safeguarded type of reactors [1]. There exists many research reactors worldwide with large ranges in operating power, initial enrichment, fuel material form, fuel type, moderator/coolant type, and purpose. In addition to tremendous variety, the reactors generally operate very dynamically, causing standardized safeguard systems to be troublesome [2]. The spent fuel produced from this dynamic operation has the potential to possess a large variance in output isotopic composition.

Many research reactors are used for experimentation purposes. These experiments may range from anything involving strong absorbers in an experimentation tube to miniature power reactor assemblies being tested in a water hole. The criticality control in research reactors typically consists of injectable absorbers into the coolant/moderator, fuel followed control rods, standard control rod elements, or a combination of these. Some research reactors also often change their grid configuration depending on the facility's objectives [3]. Variance in function as well as dynamic operation in time presents many challenges in accurate simulation of reactors of this type.

Presently there are 241 research reactors operating and 413 shutdown. Of the shutdown reactors, only 210 are fully decommissioned and 13 are on temporary shutdown. Two additional reactors are planned, three are under construction, five have been canceled, and one exists with an unverified status. This totals to 678 reactors. Twenty percent of all research reactors are located in undeveloped countries including 40% of operating reactors in 2011 [4,5]. Figure 1.1 shows a map displaying countries with research reactors [6]. The total reactor quantities are high because they include subcritical piles, training, and research tools.

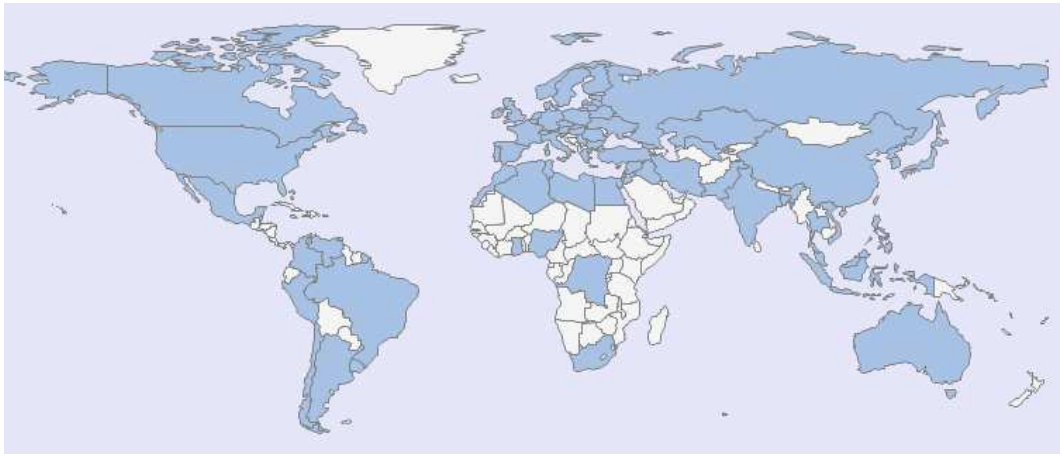


Fig. 1.1. Worldwide Map of Countries With Research Reactors [6].

Approximately 130 of these research reactors operate on weapons-grade highly enriched uranium (HEU) with enrichments of over 90% ^{235}U [4]. There have existed programs beginning as early as 1978 in the United States and the Soviet Union to convert highly enriched reactors to low enriched fuels, but many highly enriched reactors still exist today [5, 7]. Figure 1.2 shows a map displaying the worldwide civilian HEU inventory by country. The United States has refueled approximately 30 of the 80 domestic and foreign U.S. supplied HEU fueled reactors with LEU. The U.S. has received approximately 20% of the HEU fuel back that it has supplied worldwide.

Russia has not converted their domestic and foreign fuel supplied reactors to LEU, but has been refueling with a reduced HEU enrichment; converting from >90% to 36% ^{235}U. Russia has not received any of its HEU fuel back that was supplied for foreign reactors and approximately 60 HEU fueled research reactors operate in Russia and Eastern Europe today [8].

The HEU and high activity from spent fuel may be an attractive target for an adversary for an improvised nuclear device or radiation dispersal device (RDD). A major concern is that many shutdown reactors have not been decommissioned yet

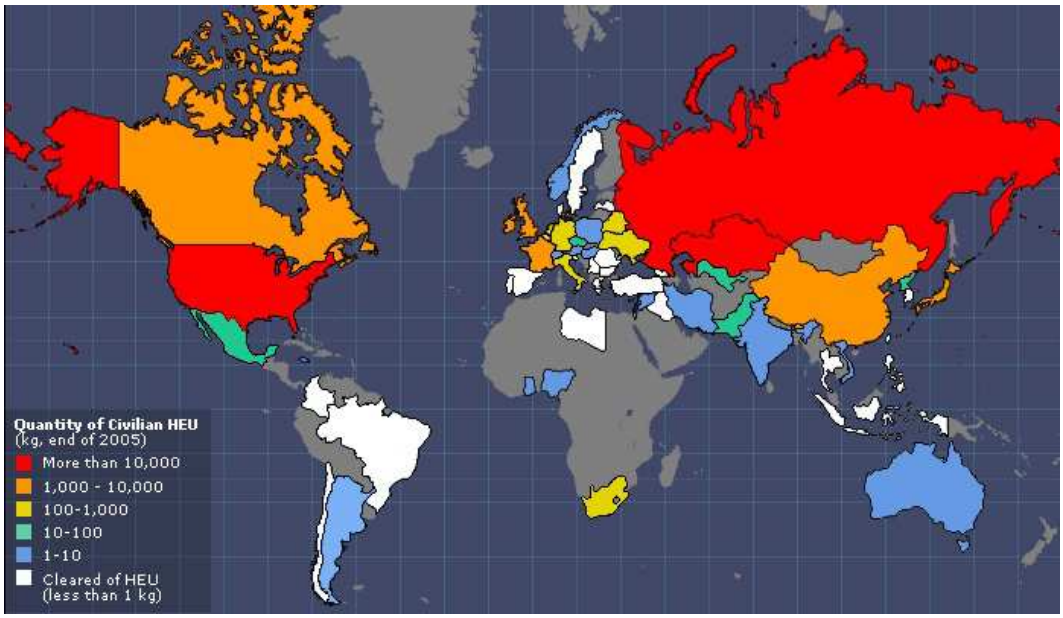


Fig. 1.2. Worldwide Map of Civilian HEU Inventory by Country (2005) [8].

and still have an inventory of fresh and/or spent fuel. The most probable scenario for a substate adversary would involve a RDD since reprocessing separations would be required to extract HEU from the spent fuel. The possibility of a fresh fuel diversion must not be overlooked but would still require chemical separations to obtain useable HEU. The radiation emitted from a spent fuel assembly is of multiple types and energies including gamma, beta, alpha, and neutron emissions. An effective RDD may be as basic as a spent fuel assembly alongside high explosives or possibly an incendiary device to spread radioactive material rapidly in multiple phases of state [9, 10].

When technical nuclear forensics tools are applied to spent research reactor fuel, detailed signatures can be obtained from a sample. Reconstruction of spent fuel parameters may begin with simple analytic spent fuel calculations utilizing isotopic signatures. For example, using an isotopic ratio to estimate burnup with the assumption that all fissions are from ^{235}U [11]. More complicated models exist utilizing multiple burnup monitor isotopes and fissionable isotopes to produce more accurate

results. Similar methods may be used to reconstruct estimates of other reactor parameters such as initial enrichment and time since discharge [10]. The combination of reconstructed spent fuel reactor parameters, as well as macroscopic and microscopic signatures, may provide strong information to help identify an unknown sample [10].

1.2 Reactor Physics Code Descriptions

Isotopic compositions of spent fuel can be simulated using reactor burnup codes. ORIGEN 2.2 is a basic depletion code that can perform spent fuel calculations using either constant power or constant neutron flux. Several more detailed deterministic and probabilistic codes are available that have burnup capabilities. Three probabilistic codes that are appropriate for modeling research reactors include MONTEBURNS, MCNPX/CINDER, and the SCALE package, all three of which use Monte Carlo methods to solve the transport of neutrons across a model producing neutron flux and reaction rate estimations. These can be iterated with burnup and depletion calculations to produce the output isotopic compositions of research reactor spent fuel.

The quality of reconstructed reactor parameters is directly dependent upon the uncertainty in the isotopic compositions from either measured or simulated results. When using results produced using Monte Carlo methods, there are two types of uncertainty: random and systematic uncertainty. Systematic uncertainty is present in simulations due to differences between the model and reality while random uncertainty is present due to the statistical variance in repeatable Monte Carlo results. The random uncertainty may be decreased through repeated histories at the penalty of computational runtime [12].

The systematic uncertainty is difficult to quantify for research reactors due to unknowns in their dynamic operation and experimentation history potentially changing an individual assembly's flux magnitude and spectrum. If a reactor's complete operation history were documented, a balance of model detail versus computational

runtime must be established. Detailed simulations are limited by the number of simultaneous cells in which a reactor system can be depleted. With the addition of an extended list of isotopes to track per fuel material modeled, basic models may become complicated very quickly.

1.2.1 ORIGEN

ORIGEN 2.2 is a code developed by Oak Ridge National Laboratory to burn and decay nuclear fuel. The code utilizes collapsed one group cross sections which are provided for approximately 30 different reactor types. Unfortunately, this cross section library does not contain any specific research reactors; however, a generic thermal library is included. Input materials are broken down into two classes including actinide and non-actinide isotopes which are separate for normalized burnup calculations. An input isotopic vector may be decayed or burned with either constant power or constant flux to any user specified burnup or time period [13].

The resulting spent fuel has many options for output printing which is separated into three classes of isotopes: activation products, actinides, and fission products. While there are approximately 27 different print options for each of these classes of isotopes, only output isotopic masses and activities are useful in this work.

Many research reactors are used for their high flux magnitude capabilities. There are several methods and positions for experimentation to be exposed to this high flux. Unlike reactors that are used for producing power, the flux profile across a research reactor core is not very flat. There is no way to account for spectrum changes or flux shapes when using ORIGEN and a more detailed calculation may be desired [13].

1.2.2 MONTEBURNS

MONTEBURNS links MCNP to ORIGEN 2.2 and consists of a Perl script and a Fortran executable. Other software requirements for execution include ORIGEN 2.2

and MCNP5; however, simple modifications may be made for usage with MCNPX or MCNP6. During execution, the software package alternates between ORIGEN 2.2 depletion steps and MCNP5 neutron transport calculations. Operation is performed using data saved in text files when passing between codes and calculations. Running the software requires two input files: a MONTEBURNS input file, which contains depletion parameters, and a standard MCNP model using certain format ensuring proper read in from the Perl script [13–15].

A third optional input file, a feed file, may be used for user specified variable time steps, operating power, and input/output of isotopic vectors. Without usage of a feed file, the code burns the fuel the desired time length in equally spaced steps. Variable length time steps are often desired to account for ^{135}Xe accumulation and other similar effects.

In the MONTEBURNS input file, an ORIGEN 2.2 starting collapsed one group cross section library is required. This collection does not include libraries for research reactors, so the thermal library or some representative library is often chosen. In the MCNP steps of execution, reaction rate tallies are performed in addition to total flux tallies. Cross sections are effectively updated in one energy group spectrum collapsed form:

$$\bar{\sigma}^j = \frac{ReactionRate^j}{Flux} = \frac{\int_0^\infty \sigma^j(E)\phi(E,t)dE}{\int_0^\infty \phi(E,t)dE}. \tag{1.1}$$

The user manual states that up to 49 materials may be burned simultaneously within a model. Multiple materials are desired to create accurate neutron flux and depletion profiles throughout a model in both two and three dimensional simulations. This limit was established by the numbering system for flux tallies in the version of MCNP available during MONTEBURNS development. The present day numbering system allows for significantly more tallies, but an update to the code has not been released yet. Upon testing, the RSICC released version 2.0 only allows for a maximum of 40 materials due to a potential bug in the tally numbering system [14, 15].

The code uses a fractional importance system to determine which isotopes produced are critical to include in the transport calculations. In addition to any user specified isotopes, additional isotopes are added based on mass fraction, atomic fraction, absorption cross sections or fission cross sections. When any of these parameters fractionally exceeds the importance factor, that particular isotope is included in the next step's transport calculation but detailed information is not included in the output file. Only user specified isotopes listed on the MONTEBURNS input file are included in the output [14].

1.2.3 MCNPX/CINDER

MCNPX is a Monte Carlo transport code that branched from MCNP5 and added charged particle transport along with a variety of other features including CINDER 90 depletion capabilities. Using CINDER in MCNPX only requires the addition of a BURN card with depletion parameters in a standard MCNP style input. Cell volumes may be required to be added if they cannot be determined by the code. This package performs similar to MONTEBURNS, using alternating depletion and transport calculation steps, but has a few notable differences. CINDER uses Markov chains to solve the series of differential decay equations while ORIGEN 2.2 uses the matrix exponential method [16]. A fractional importance is used in a similar way to MONTEBURNS, but is only based on mass fraction.

In MCNPX/CINDER, only one input file is required. A similar MCNP input is used, but a BURN card is added providing the model depletion parameters. Instead of explicitly listing all isotopes which are to be place in the output file, one of three tiers of isotopes is chosen. Tier 1 is a basic list compromised of a few common fission products, uranium isotopes and plutonium isotopes. Tier 2 adds additional fission products and actinides to the tier 1 list, while tier 3 includes a very large list of isotopes [16].

The newest version of MCNP is MCNP6 which merged MCNP5 with MCNPX. The CINDER package is still available when using MCNP6. One thing to consider when using MCNPX/CINDER for depletion purposes is that only versions after 2.7.0 for MCNPX can be executed in parallel. When any detailed simulation is to be performed, parallel execution may greatly reduce runtime.

1.3 Technical Nuclear Forensic Techniques and Usage in Material Attribution

Technical nuclear forensics is a means of how nuclear material is characterized and interpreted though various measurement techniques [17]. This process may include obtaining representative samples of material, laboratory analyses, simulations, and comparison to databases. There are many laboratories in the United States capable of performing nuclear forensic analyses including Lawrence Livermore National Laboratory and Savannah River National Laboratory.

Upon completion of a forensic measurement analysis, a sample may be well characterized and the results used to reconstruct identifying information about the sample. Typical nuclear forensic measurements include mass, atomic emission, gamma, and alpha spectrometry. For nuclear forensics purposes, trace nuclides are often desired and can be measured in quantities ranging from nanograms to picograms using mass spectrometry [18]. In this work, these material characteristic signatures are broken into four categories: destructive assay signatures, non-destructive assay signatures, macroscopic signatures, and microscopic signatures.

1.3.1 Signatures from Destructive Assay Techniques

In destructive assay techniques, the sample is destroyed in the analysis process. Typically several representative subsamples of the material are acquired for analysis. The most common destructive assay technique is mass spectrometry. In any mass spectroscopy method, the sample is ionized by removing an outer shell electron.

Removal of additional electrons requires much greater ionization energy than the first. The ions are then sorted into bins by mass per charge using a magnetic field. There are multiple methods to produce the ionized sample; the two most common being thermal ionization and in an inductively coupled plasma torch.

In thermal ionization mass spectrometry (TIMS), the sample is dehydrated onto a filament and heated using an electric current. The likelihood of ionization depends on the temperature of the filament but has limitations and difficulty creating atomic ions which require high ionization energy such as tungsten or osmium. The design and process is simple, produces stable ion emissions, and is less expensive than other mass spectrometers [19, 20].

In inductively coupled plasma mass spectrometry (ICP-MS), a liquid sample is passed into an argon plasma torch most commonly using a nebulizer. The sample is then vaporized, molecules are broken down into atoms, and ionized inside the plasma torch. While ICP-MS is much more expensive and complex than TIMS, sample preparation is much faster. The plasma's extreme temperatures allows complete separation of molecules into atoms and no element restrictions from ionization energy [18]. Figure 1.3 displays a mass spectrograph from a research reactor sample, where the mass per unit charge bins (m/z) are sorted by concentration. In the mass spectrograph several features are recognizable: the double hump fission spectrum of fission products, actinide signatures (m/z 234+), and double ionizations from the actinide signatures (m/z 117-119).

Uncertainty in mass spectrometry is characterized by the number of counts in the mass per charge bins. As the count time increases the relative uncertainty is driven down. Sources of error include double ionizations and chemical reactions on the ions. Multiple ionization occurs when two or more electrons are stripped from a sample atom. While the ionization energy for the second electron is much greater than the first, complete prevention of multiple ionizations is not obtainable. Chemical reactions may also occur to the ions before they reach their destination detection

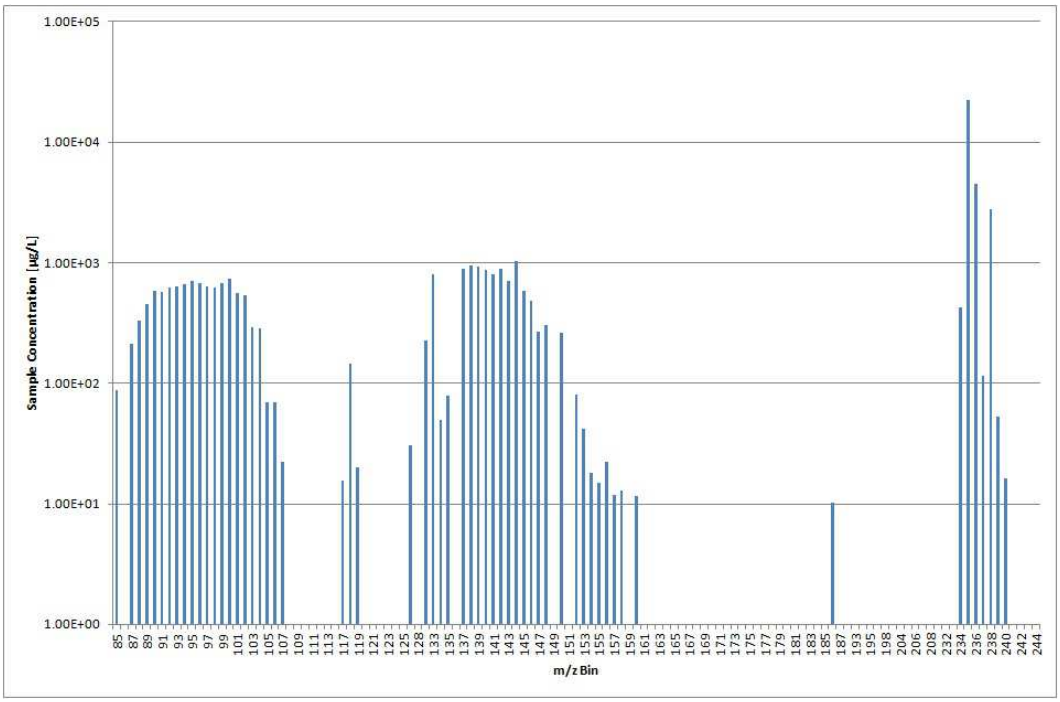


Fig. 1.3. Spent Research Reactor ICP-MS Spectrum.

bins. Two of the most probable chemical bonds include hydrogen and argon from the plasma torch. Upon chemically bonding, these two reactions would add +1 or +36 to the traveling ion.

Another type of destructive analysis is atomic emission spectrometry (AES). In atomic emission spectrometry, a sample is excited using various techniques. Upon deexcitation, the sample emits photons which are characterized by intensity and wavelenth to quantify its elemental composition. A common system using a plasma torch for sample excitation, similar to ICP-MS, is inductively coupled plasma atomic emission spectrometry (ICP-AES) [11].

Through any material process, small quantities of residual isotopes from processing materials and process equipment may be found in a sample. This can be an information identifier to a particular process or production method for a sample. These may be identified by elemental or isotopic characteristics.

1.3.2 Signatures from Non-destructive Assay Techniques

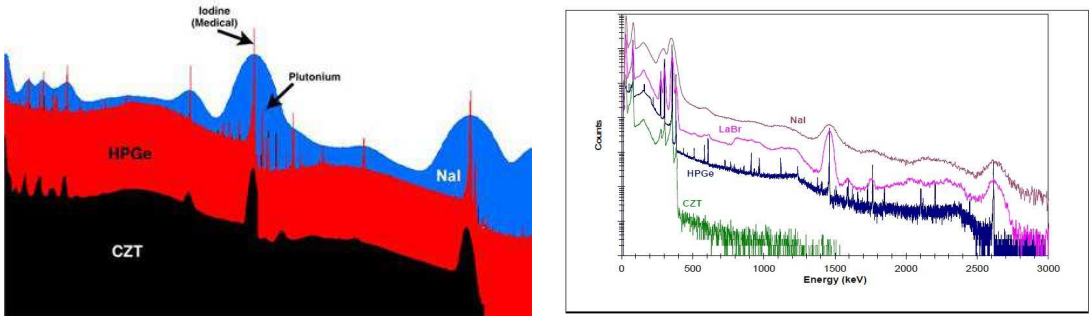
Unlike destructive analysis techniques, in non-destructive techniques the sample is not consumed. Measurements of this type can either be performed on subsamples or entire samples themselves. In nuclear safeguards, the most basic non-destructive assay methods are item counting and gravimetric measurements, typically on closed containers with safeguard seals.

Non-destructive techniques utilizing radiation detectors can be broken into two categories: active and passive measurements. In both measurement types, qualitative or quantitative analysis is performed on a sample using the radiation emitted. In active measurements, an external radiation source is used to irradiate the sample and all radiation emitted is used for analysis. Passive measurements use only radiation directly emitted from a sample.

The most common non-destructive assay technique is gamma spectrometry. Many isotopes decay by gamma emission which escapes the sample and may be absorbed in a radiation detector. An image showing sodium iodide (NaI), high purity germanium (HPGe), and cadmium zinc telluride (CZT) spectra resolution displays how material may potentially be identified using this type of measurement in Figure 1.4 [21, 22]. These are the most common types of gamma spectrometers, each of which has purposes based on price, size, precision, and efficiency [23].

Another type of non-destructive assay technique involving passive radiation emission is alpha spectrometry. Several actinides decay by alpha emission. Emitted alphas vary greatly in energy and their energy spectrum can be measured using detectors. However, the mean free path of emitted alphas is short, so a subsample may be required for analysis.

There are several non-destructive assay techniques that involve neutron measurement too. These include neutron coincidence counting, multiplicity counting, and standard neutron detection measurements. These are used to quantify fissile mate-



(a) Pu peak (b) ^{133}Ba Calibration

Fig. 1.4. Spectra Resolution Comparison Between NaI, HPGe, $LaBr_3$, and CZT γ-Detectors on Pu and ^{133}Ba Calibration Sources [21, 22].

rial inside a sample using active and passive methods to calculate a ^{240}Pu equivalent mass that would replicate the sample's neutron signal.

1.3.3 Macroscopic and Microscopic Signatures

Information can also be recovered from a sample beyond just elemental and isotopic compositions. Macroscopic and microscopic signatures describe information about how a sample was created. Macroscopic signatures may consist of the shape, design, or mass of a sample [17]. A lot of identifying information may be obtained from a sample by simple exterior characteristics.

Microscopic signatures require more detailed analysis. These signature types include material form, particle morphology, and particulate shape or size. Some microscopic signatures may also utilize destructive assay techniques. They are distinctly different than the previous techniques that describe ways to classify material by isotopic or elemental composition. Microscopic signatures may provide information about a sample's process history, fabrication technique, or temperature [17].

Material science characteristics of a sample may be examined to reveal different allotropes or crystalline structures within. This can provide additional information about a sample's production process and determine if the material has been blended with another from a different production process.

1.3.4 Nuclear Forensics Interpretation and Deterrence Value

The results from a forensic analysis may be interpreted in several ways. They may either be used in a technical nuclear forensics technique or compared to database information. Using technical nuclear forensics techniques, more information may be revealed about a sample than from direct measurements.

When technical nuclear forensics is combined with law enforcement and intelligence data, possible sources of origin for a sample may be suggested or excluded in a process known as attribution [17]. The tools in technical nuclear forensics may be applied directly in an attribution method. The key to a successful analysis is controlling uncertainty. Proper propagation and minimization of uncertainty through measurements, post process analytic calculations, and inverse analysis is critical in a successful analysis.

In the case of a diversion and seizure of spent fuel at a United States border, critical information may be obtained from the analysis results and associated method uncertainty. Due to dynamic operation and similarities among multiple reactors worldwide, it is highly unlikely to ever be able to perfectly identify a sample to a specific reactor and discharge time based on reactor parameters alone. A much more likely scenario, is the combination of reconstructed parameters with sample macroscopic characteristics and intelligence data to eliminate the majority of possible sources of origin of a sample.

With increasing nuclear forensics and attribution capability, the likelihood of a successful attribution process increases. This inherent ability may act as a deterrence to prevent nuclear terrorism or state sponsorship of nuclear terrorism. When material

used in a terrorist attack can be traced back to its source, terrorist organization sponsors cannot transfer material or devices anonymously.

Several parties are required in an act of nuclear terrorism including the terrorist group itself, nuclear or device specialists, material/device supplier, and support for intermediate activities such as transportation, funding, and cover operations. Each of these groups likely has different motivations for the act of nuclear terrorism and may not necessarily be stopped by the same means. For example, nuclear or device specialists may be primarily motivated for financial reasons. If these specialists come from within the organization itself, they would likely have similar motivations as the organization.

The terrorist organization itself may not be deterred by nuclear forensics capability depending on motivations. A terrorist organization would more likely be deterred by the possibility of a device failing or being seized than nuclear forensics capability. An organization would require a great investment in obtaining a device, seizure of such device would likely be a sizable loss for the organization.

A state sponsor or material/device supplier may be discouraged to provide support as consequential action likely outweighs sponsorship benefit. This is the primary benefit of the deterrence value of nuclear forensics, as it is unlikely for terrorists to create their own material. Well characterized material that is seized before the act of terrorism will likely be traced back to its source of origin.

2. OAK RIDGE RESEARCH REACTOR INFORMATION AND RADIOCHEMICAL ANALYSIS RESULTS

2.1 Reactor Selection Process and Reactor Information

The Savannah River Site possesses many different types of spent research reactor fuel in the L-basin storage. Spent fuel assemblies can be selected and sent to the Shielded Cells at Savannah River National Laboratory for analysis. The selection process begins by looking at various limiting factors, such as burnup, ^{235}U enrichment, ^{239}Pu fissile gram equivalent mass, and activity. Every assembly in the L-basin has an Appendix-A document which contains shipper-receiver declarations of the spent fuel with details such as initial and final ^{235}U content, ^{239}Pu and total plutonium content, relative burnup, assembly dimensions, and material compositions. Some of the assemblies include detailed blueprints [24].

The reactor chosen for analysis in this work was the Oak Ridge Research Reactor (ORR). The ORR was fueled by 93.1% enriched HEU in the form of U_3O_8 in an aluminum matrix. The assemblies are of the Materials Test Reactor (MTR) type which consists of 21 thin, aluminum-cladded, curved fuel plates attached to aluminum side plates. Assembly T-397 was selected due to it's reported 54% burnup after 126 MWd according to the Appendix-A shipping/storage documentation [24]. Upon selection, all information pertaining to the assembly was collected for model development and calculations. Figure 2.1 shows the assembly cross-sectional dimensions (in the XY plane).

The axial profile of an assembly consists of much more than only fuel. There are extended grid plate spacers on either end of the assembly. There is another piece called the comb, which sits across into the fuel plates for support. These features can be viewed in Figure 2.2.

The ORR changed core configurations several times through the active 3 year life of assembly T-397. The core configuration consists of a 9 by 7 grid spacing

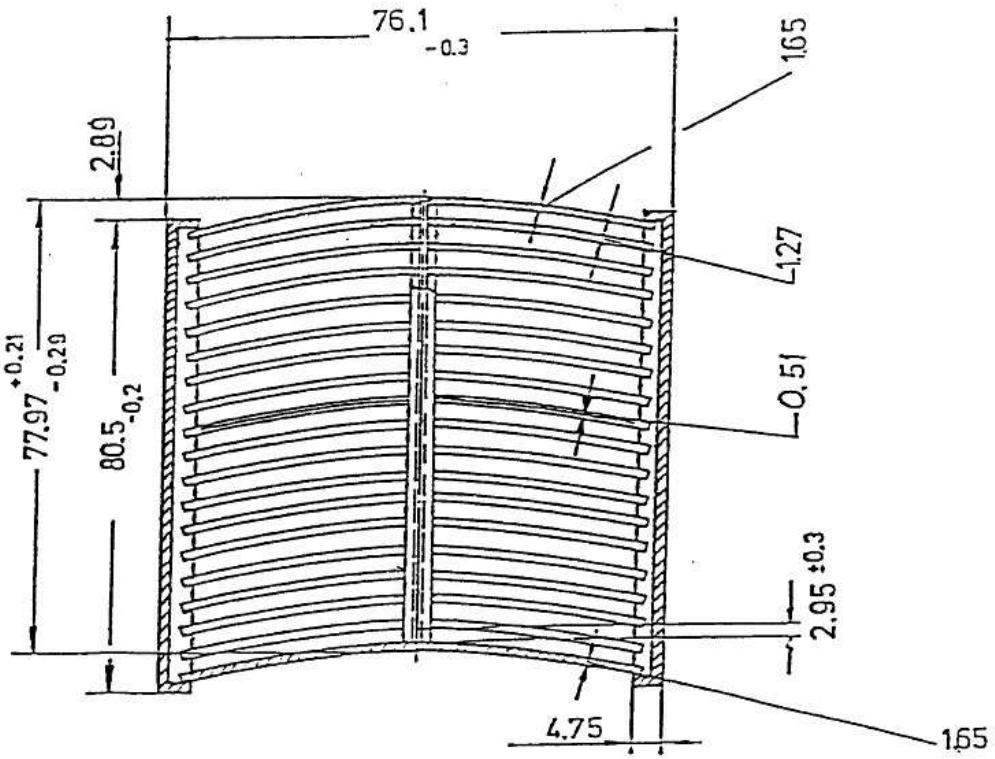


Fig. 2.1. ORR XY Plane Assembly Dimensions (Expressed in mm)

system that can be filled with different types of elements including: fuel elements, beryllium reflector elements, aluminum shelled experimentation tubes, fuel followed control elements, or empty water locations. An example of a core configuration is in Figure 2.3, which also displays some beam ports and external features.

Assembly T-397 spent only 108.9 d (approximately 10%) of its active 1198 d life at power. This time at power consisted of five cycles operating at 3.62 MW/kgHM. The rest of the time the assembly was either out of the core or the reactor was shutdown. In a cooling pool area, there was an extensive inventory of active fuel that could be swapped into the core at any time. Frequent core shuffling, swapping fuel out of the core, and frequent shutdowns provide a large amount of facility operation

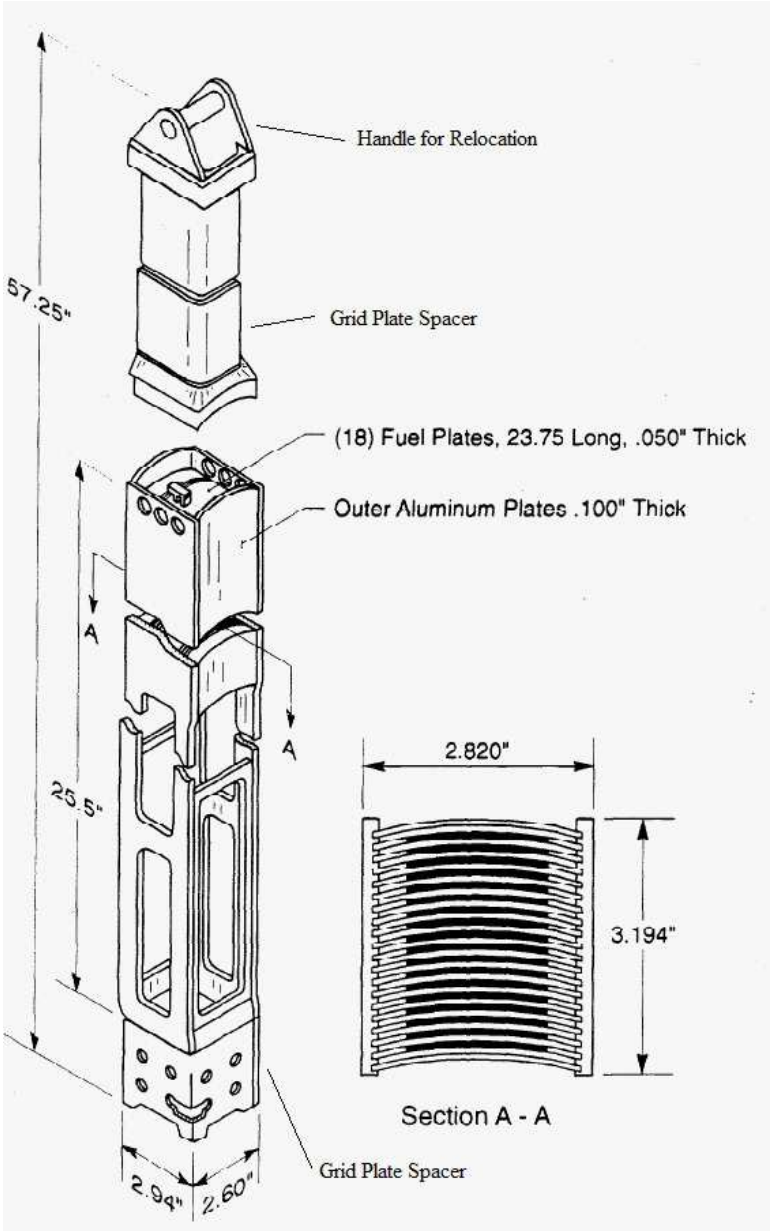


Fig. 2.2. ORR Axial Assembly Profile

data to keep track of and will affect the accuracy of the information provided in the Appendix-A documentation.

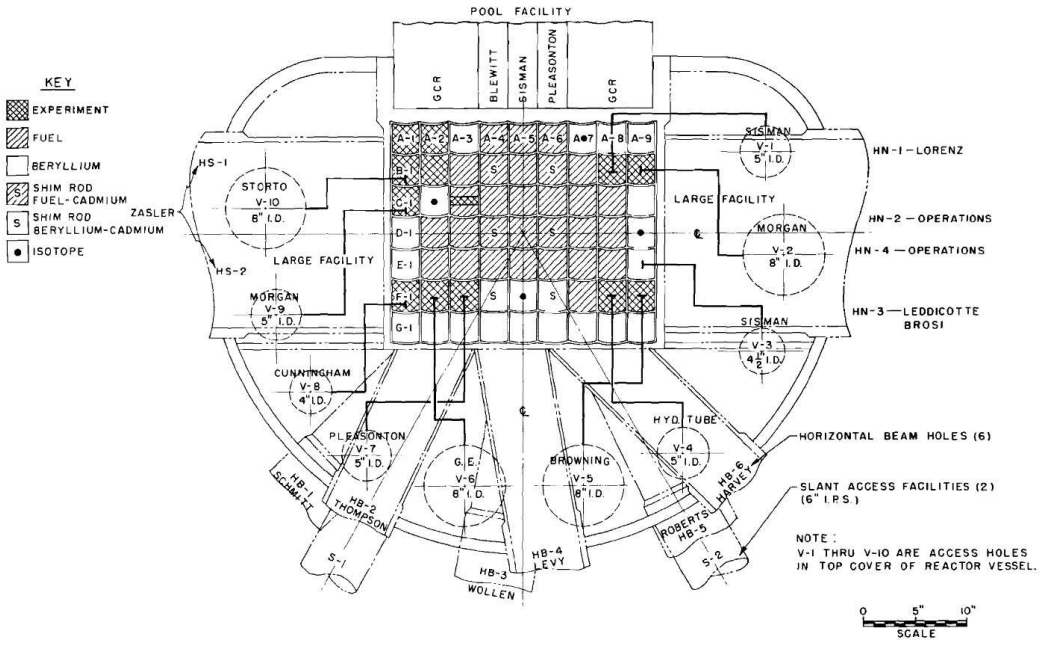


Fig. 2.3. ORR Example Core Configuration

The fresh fuel contained 306g of 93.1% enriched uranium fuel (285 ^{235}U) in the material form of U_3O_8 mixed in an aluminum matrix. The fuel density was 3.396 g/cc and was enclosed in an aluminum cladding with a density of 2.70 g/cc.

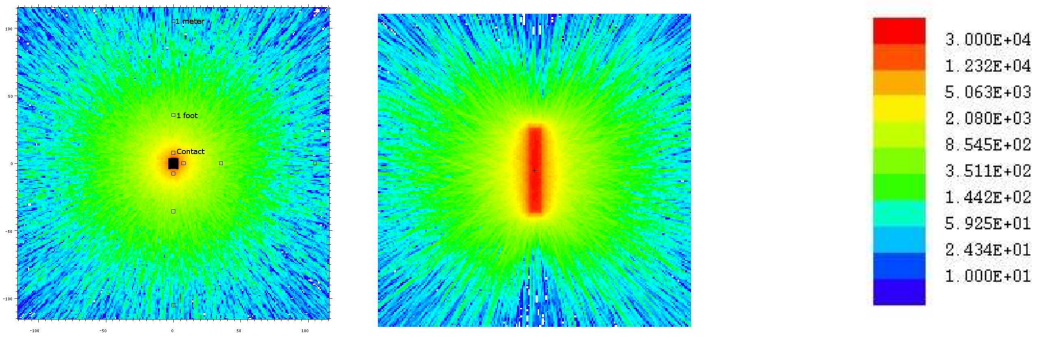
2.2 Radiochemical Analysis at Savannah River National Laboratory

2.2.1 Dissolution Process and Fuel Sample Acquisition

The Savannah River Site is a very large complex consisting of several separate areas spread over 310 square miles. The spent research reactor fuel is stored in L-Basin, while the hotcells are located in SRNL at A-Area. To ship a fuel assembly from the L-Basin to SRNL, many calculations are required and many criteria must be met. The assembly must be shipped under formal shipping standards depending on the ^{239}Pu fissile gram equivalent mass and dose rate in air at contact, one foot

and one meter. These results must be calculated and approved prior to any physical movement of material.

To calculate these dose rates, a model of the fuel was burned using ORIGEN 2.2 to create a present day gamma spectrum. This gamma spectrum was then transported to simulated detectors in air at contact, one foot and one meter using MCNP. The results of this calculation are in Figure 2.4.



(a) XY Detectors at Z=0 (b) YZ Doserate at X=0 (c) Scale Rad/Hr

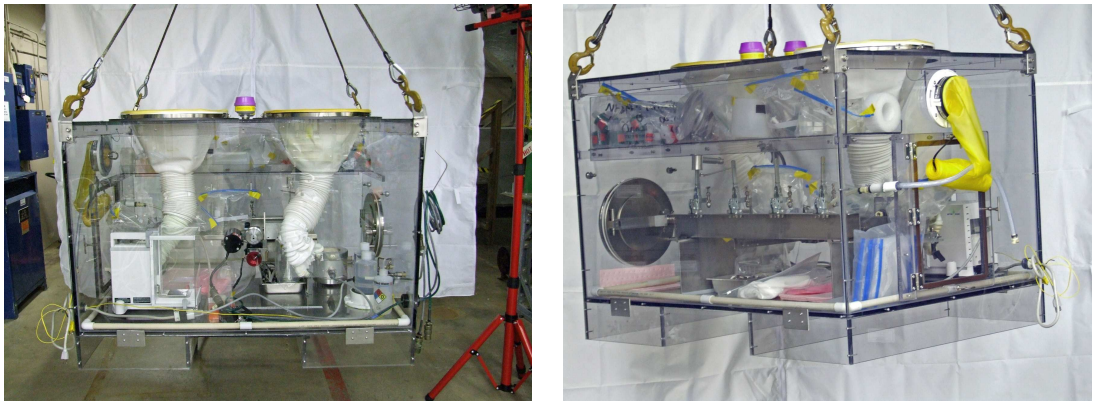
Fig. 2.4. Simulated Gamma Radiation Dose Rates at Various Distances From the Spent ORR Assembly.

To ship the assembly in an 8 ton cask without damaging it, a smaller cannister was fabricated. Figure 2.5 shows the fabricated fuel cannister by itself and inside an 8 ton shipping cask.

A glove box specially made for remote manipulators was engineered to be used in the Shielded Cells at Savannah River National Laboratory is shown in Figure 2.6. This glove box produced a clean environment, safe from legacy contamination in the hot cells, to drill a representative spent fuel sample from the assembly using the configuration in Figure 2.7. The glove box was fabricated with a very detailed set of features to prevent escape of material and preserve the cleanliness of the sample. The glove box operated at a slight positive pressure versus the hotcell environment, preventing anything undesired from entering the glovebox.

(a) Stand Alone (b) Inside 8-ton Cask

Fig. 2.5. L-Basin to SRNL Spent Fuel Shipment Canister

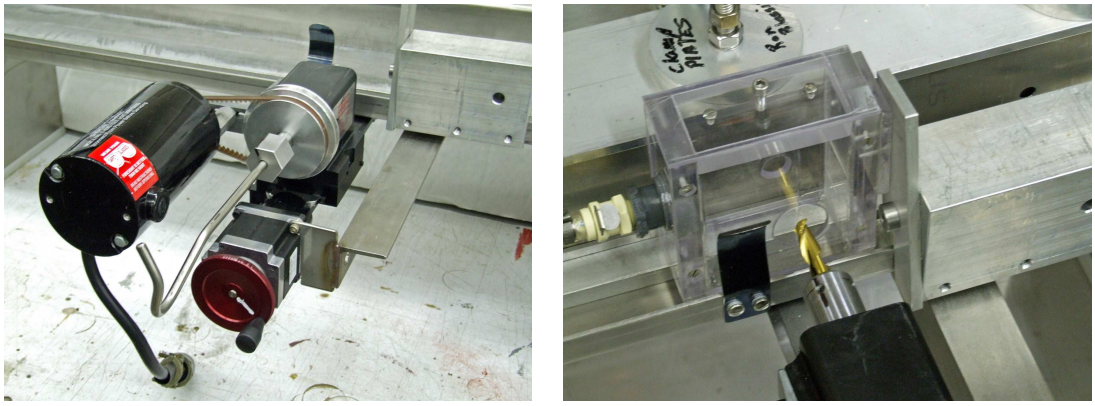


(a) Front (b) Back

Fig. 2.6. SRNL Shielded Cells Isolation Glove Box

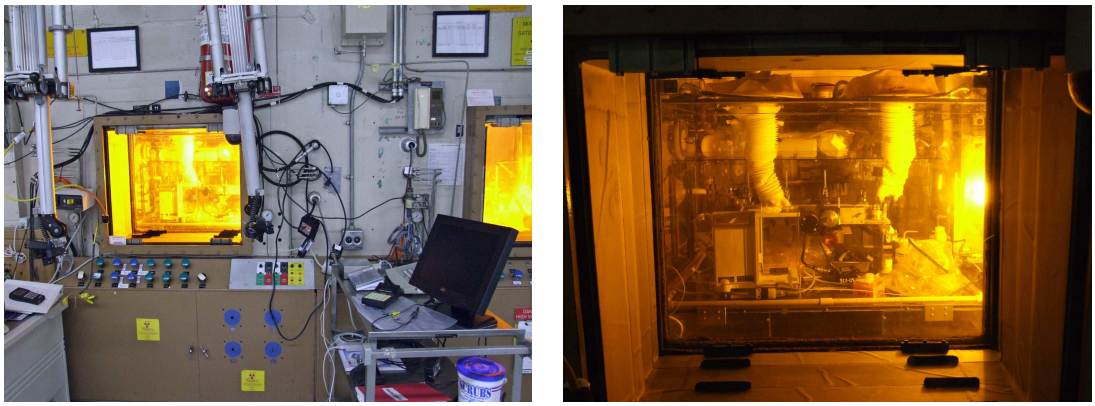
The quantity and diameter of the holes drilled depended on the material form and enrichment of the fuel meat. The mass of the drill shavings was measured and compared to the precalculated theoretical mass to establish how much of the material has been recovered and accounted for. The drill shavings were then dissolved in nitric acid and the solution is diluted for safe removal from the hot cell. Figure 2.8 shows the view area of the isolation box while inside the hotcell and some of the monitoring

equipment used. Mirrors and cameras were used frequently to view difficult positions within the isolation box.



(a) Drill (b) Collection Cannister

Fig. 2.7. Isolation Box Computerized Drill and Vacuum Drill Shaving Collection Cannister

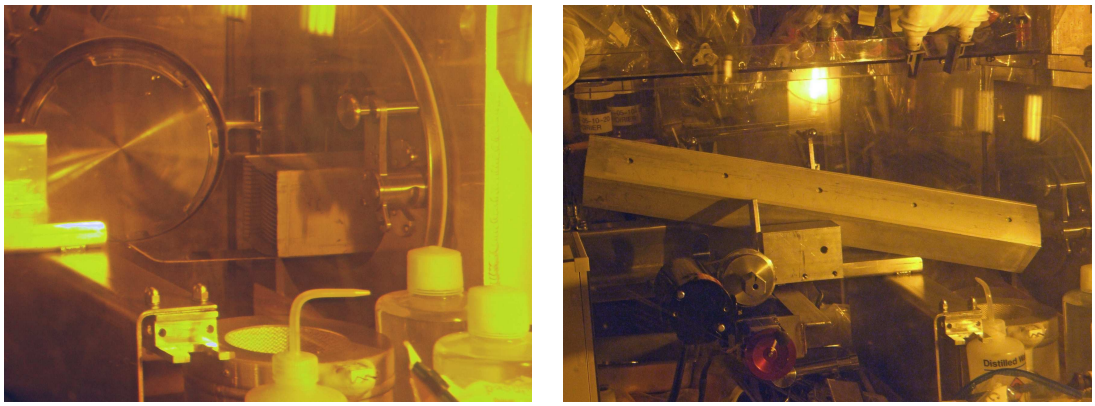


(a) Equipment (b) Hotcell Window

Fig. 2.8. SRNL Hotcell Equipment and Window

Five holes were drilled symmetrically down the assembly shown in Figure 2.9. The theoretical mass of the shavings was 1.70 g using the fuel plate dimensions from blueprints. The measured mass of the shavings was 1.67 g which amounts to a recovery of 98% of the theoretical mass and was greater than the threshhold goal

of >90%. The shavings were dissolved in 107.8 g of nitric acid. Three samples of this mixture were separated with masses of 3.87 g, 4.11 g, and 5.48 g; then diluted to lower the specific activity of the samples so measurements outside of the hotcell could be performed.



(a) Assembly in Cannister (b) After 5 Drilled Holes

Fig. 2.9. Pre and Post Drill ORR Assembly Pictures Inside the Isolation Box.

2.2.2 Radiochemistry Results and Uncertainty Analysis

Using various nuclear forensics measurement techniques, this sample of spent fuel was characterized so that it can be compared to simulation results, declaration documentation for the spent fuel, and other similar reactors. There were four primary analysis performed on the ORR spent fuel samples: ICP-AES, ICP-MS, gamma spectrometry, and alpha spectrometry. The results from the ICP-MS and gamma spectrometry measurements were used in the inverse analysis developed in this project.

The gamma spectrometry results were obtained for several key isotopes using a HPGe detector. The results for the measurement were reported in dpm/ml along with associated uncertainties. The blank sample had less than the detection limit for all isotopes and Table 2.1 shows the results from all three ORR samples. Out of

these results, only the ^{137}Cs values were used in the inverse analysis to reconstruct the sample's cooling time.

Table 2.1
ORR HPGe Gamma Spectrometry Results

Isotope	Sample 1 $[dpm/mL]$	Sample 2 $[dpm/mL]$	Sample 3 $[dpm/mL]$
Sr-90	8.17E+07 ± 7.59%	5.47E+07 ± 7.54%	7.45E+07 ± 7.90%
Tc-99	2.50E+04 ± 5.76%	1.84E+04 ± 5.83%	1.89E+04 ± 5.74%
Cs-137	9.28E+07 ± 5.00%	6.69E+07 ± 5.00%	7.19E+07 ± 5.00%
Eu-154	4.45E+05 ± 5.00%	3.16E+05 ± 5.00%	3.65E+05 ± 5.00%

An ICP-MS analysis was then performed for all three of the ORR spent fuel samples. Unfortunately the mass spectrometry results stopped at m/z 239, the results from m/z = 234-239 are shown in Table 2.2. There was signal in the 240 m/z bin only for one sample; increased count time would have likely resulted in more signal for higher mass bins. The bin width was equal to 1 m/z unit centered equally over m/z of interest.

Table 2.2
ORR Mass Spectrometry Results for m/z [μg/L] Bins Numbers 234-240

m/z	Sample 1	Sample 2	Sample 3
234	4.26E+02	3.07E+02	3.26E+02
235	2.23E+04	1.59E+04	1.72E+04
236	4.53E+03	3.20E+03	3.33E+03
237	1.14E+02	8.42E+01	9.99E+01
238	2.77E+03	1.94E+03	2.08E+03
239	5.30E+01	4.04E+01	4.29E+01
240	1.64E+01	<1.50E+01	<1.50E+01

As predicted from ORIGEN 2.2 in the shipping dose rate calculations, there was not much plutonium produced due to the low ^{238}U initial content. However, there is ^{238}Pu produced from the ^{235}U chain which simulations predict to be roughly 25%

of the final plutonium content and less than 1% of the 238 mass chain. Assuming the ^{238}Pu contribution is negligible in the 238 m/z bin, the uranium isotopics and enrichment was determined from the measured results (Table 2.3).

Table 2.3
Measured and Appendix-A Uranium Isotopic Results

Isotope	Sample 1	Sample 2	Sample 3	Appendix-A
^{234}U	1.42%	1.44%	1.42%	-
^{235}U	74.24%	74.45%	75.01%	74.58%
^{236}U	15.11%	15.02%	14.51%	13.56%
^{238}U	9.23%	9.10%	9.06%	-

The Appendix-A documentation only contains total uranium along with ^{235}U and ^{236}U masses. Using this information, the spent fuel final ^{235}U enrichment was calculated to be 74.58% and ^{236}U content to be 13.56% [24]. The measured samples compared well with the Appendix-A data. The average of the three samples was 74.57% ^{235}U. The three sample averaged measured ^{234}U, ^{236}U, and ^{238}U concentrations were 1.43%, 14.88%, and 9.13%, respectively. It is unknown if the fuel contained any ^{236}U initially and if that was accounted for in the Appendix-A estimation for the final ^{236}U quantity.

The isotopic compositions of the fission products used for forensic signatures were analyzed. The ICP-MS analysis covered all of the relevant mass per charge bins to include cesium, lanthanum, and neodymium isotopes considered for analysis. As expected, the blank standard contained no signal for isotopes in the mass bins between 137 and 148. The same three ORR spent fuel samples were analyzed and the results are shown in Table 2.4. The samples were then converted to isotopic ratios to ^{238}U for comparison to the simulation results (Table 2.5). The raw data was inconsistent among samples due to different dilution factors. The dilution factor should not affect the results when expressed as a ratio.

Table 2.4
ORR Mass Spectrometry Results for Relevant m/z Bins 137 Through 148 [μg/L]

m/z	Sample 1	Sample 2	Sample 3
137	8.85E+02	6.13E+02	6.75E+02
139	9.24E+02	6.61E+02	7.27E+02
145	5.85E+02	3.95E+02	4.38E+02
146	4.81E+02	3.36E+02	3.70E+02
148	3.04E+02	2.22E+02	2.34E+02

Table 2.5
ORR ICP-MS Results for Relevant Isotopic Ratios for m/z Bins 137 Through 148 Versus ^{238}U

Ratio	Sample 1	Sample 2	Sample 3
137/238	0.556	0.549	0.564
139/238	0.572	0.584	0.598
145/238	0.347	0.334	0.346
146/238	0.283	0.282	0.290
148/238	0.177	0.184	0.181

The ICP-MS results did not include uncertainties associated with counting statistics. To estimate the uncertainty in the results, an assumption is made for the uncertainty of the ^{235}U signal. This is the strongest signal in the results and therefore should have the lowest measurement uncertainty. Comparisons are then made by scaling the set ^{235}U relative uncertainty to other isotopes by the ratio of the square root of their ICP-MS signals in Equation 2.1 for example isotope j,

$$\sigma_j = \sigma_{U235}\sqrt{\frac{S_{U235}}{S_j}}\sqrt{\frac{M_{U235}}{M_j}}, \tag{2.1}$$

where σ_j is the estimated relative 1σ standard deviation for isotope j, σ_{U235} is the assumed 1σ relative standard deviation for ^{235}U, S_j is the ICP-MS signal for isotope j, and M_j is the atomic mass for isotope j. Using this scaling, the measurement

uncertainty would be largest where the ICP-MS signal was the weakest. This uncertainty estimator is valid only if the following assumptions are accurate: the ionization probability is equal for all isotopes and the count time is the same for every mass per charge bin. The results for a few of the key mass per charge bins are shown in Table 2.6.

Table 2.6
ORR ICP-MS Uncertainty Estimation Scaled From ^{235}U at 1.00%

m/z	Sample 1		Sample 2		Sample 3	
	Concentration $[\mu g/L]$	RSD [%]	Concentration $[\mu g/L]$	RSD [%]	Concentration $[\mu g/L]$	RSD [%]
235	2.23E+04	1.00	1.59E+04	1.00	1.72E+04	1.00
137	8.85E+02	8.60	6.13E+02	8.73	6.75E+02	8.66
139	9.24E+02	8.30	6.61E+02	8.28	7.27E+02	8.23
145	5.85E+02	10.0	3.95E+02	10.3	4.38E+02	10.2
146	4.81E+02	11.0	3.36E+02	11.1	3.70E+02	11.0
148	3.04E+02	13.6	2.22E+02	13.4	2.34E+02	13.6
234	4.26E+02	7.26	3.07E+02	7.22	3.26E+02	7.31
236	4.53E+03	2.21	3.20E+03	2.22	3.33E+03	2.26
237	1.14E+02	13.8	8.42E+01	13.6	9.99E+01	13.0
238	2.77E+03	2.80	1.94E+03	2.83	2.08E+03	2.84
239	5.30E+01	20.1	4.04E+01	19.5	4.29E+01	19.8
240	1.64E+01	36.1	-	-	-	-

*RSD is the relative standard deviation

These uncertainties scale based on the accuracy of the ^{235}U measurement. The uncertainty for isotopes with lower mass scales much higher than ^{235}U due to a weaker signal and conversion from mass density to atom density in the sample. The small plutonium quantity has a weak signal in the results as well, creating large uncertainties. If the ^{235}U uncertainty were to be reduced from 1.0% to 0.1%, the other isotope's uncertainty will scale down by a factor of 10 as well. To reduce individual uncertainties, more measurement time can be spent in mass per charge bins of interest to acquire more signal.

3. VERIFICATION AND VALIDATION OF REACTOR DEPLETION CODES FOR MODELING RESEARCH REACTORS

Prior to usage of reactor depletion codes as a forward model in an inverse analysis, verification and validation for modeling research reactor fuel must be performed. None of the code packages considered here were designed specifically for modeling research reactors. However, the physics built in to the codes does allow for reasonably accurate estimation of the research reactor spent fuel isotopic inventories. Proper fuel depletion and production of forensic signature isotopes with minimal uncertainty was desired, and it was crucial that good estimates of simulation uncertainty were generated.

The effect on nuclear forensics signature isotopes or isotopic ratios was determined at various levels of model detail. Complete operation and experimentation history for a reactor is likely not obtainable, so models are to be compared at levels of detail likely acquirable from basic reactor and assembly information. This allowed for determining the required level of model fidelity to achieve the desired accuracy.

3.1 Variance Estimation in Monte Carlo Depletion Code Output

The primary reactor burnup codes to be used with this project are MONTEBURNS and MCNPX/CINDER. Both of these codes use a Monte Carlo transport calculation which possesses a statistical variance that is not passed or propagated through the depletion calculations. This variance is controllable by adding additional Monte Carlo histories and must be minimized to maintain a consistent precision level.

3.1.1 Method Development

To determine the variance in the gram quantity output from these calculations, an approach involving multiple repeated runs using different Monte Carlo random

number seeds was performed. The output from each run is treated as an independent measure of the isotopic masses for the system. The output gram quantity isotopic compositions may then be tabulated into histograms where normal distributions are expected. The sample mean and standard deviation can then be calculated. The David W. Scott normal reference rule was applied to calculate the optimal histogram bin width:

$$h = \frac{3.5\hat{\sigma}}{n^{1/3}}, \tag{3.1}$$

where $\hat{\sigma}$ is the sample standard deviation and n is sample size. These results should follow Poisson statistics and result in normally distributed data as the sample size increases. If the sample is normally distributed, the Scott rule attempts to minimize the integrated mean squared error of the density estimate [25]. This process may be repeated for varying quantities of active Monte Carlo histories to examine the variance reduction by adding additional histories. A limit should arise where further increasing the quantity of histories provides no meaningful benefit [12, 26].

There are fundamental uncertainties not considered here such as model, fission yield, and cross section uncertainty. The uncertainty in a simulation's output would be larger if the uncertainties in all of the parameters was propagated. Accountability for these uncertainties, along with the statistical variance, is desirable, but not achieved in this work.

3.1.2 Model Description

The model used in this work was a 1 cm axial slice of an ORR MTR assembly. The assembly was modeled explicitly. The model had periodic conditions on all four sides in the XY plane and reflecting conditions on the top and bottom. This creates the equivalent of a MTR pin cell model. A cross section of the model is shown in Figure 3.1.

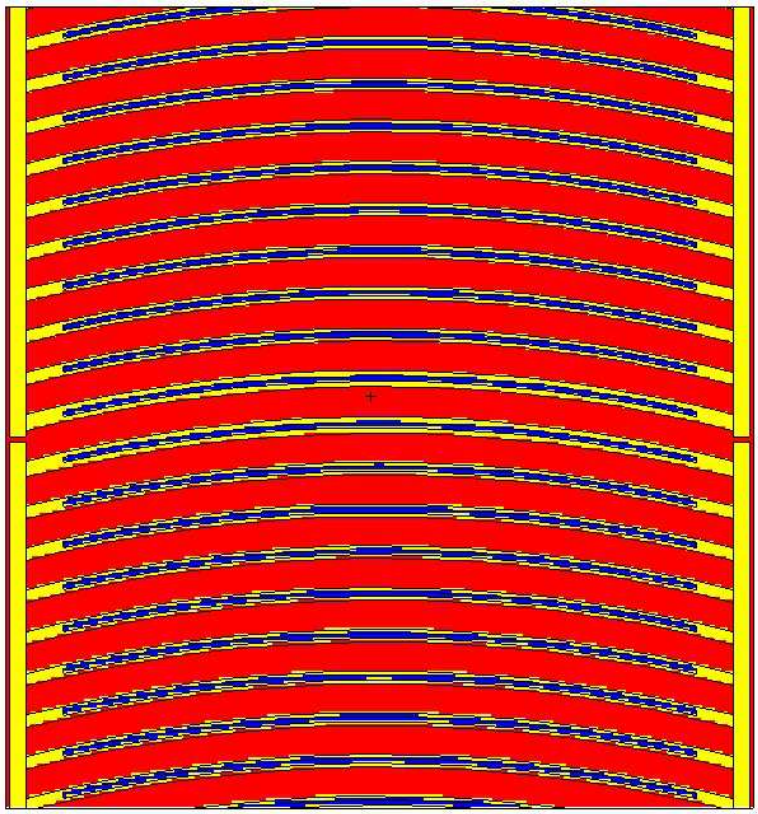


Fig. 3.1. 2D Image of the Model Used in the Statistical Variance Estimation

Due to the random nature of the Monte Carlo process, this procedure was expected to produce results that formed a normal distribution. Three fission products, three uranium isotopes and 13 transuranic isotopes were forcefully tracked during all runs. The isotopes used are shown in Table 3.1.

Table 3.1
Isotopes Tracked For All Runs in the Statistical Analysis.

Xe-135	U-238	Pu-241	Am-243
Cs-134	Np-237	Pu-242	Cm-242
Cs-137	Pu-238	Pu-244	Cm-243
U-234	Pu-239	Am-241	Cm-244
U-235	Pu-240	Am-242	-

The assembly's initial uranium isotopics consisted of ^{234}U, ^{235}U, ^{236}U, and ^{238}U in the quantities shown in Table 3.2. The uranium was in the form of U_3O_8 mixed with aluminum. Of the initial four uranium isotopes, only ^{234}U, ^{235}U, and ^{238}U were forced into both codes's output files.

Table 3.2
ORR Assembly Initial Uranium Isotopics.

Isotope	Mass Percent [%]	Assembly Initial Mass [g]	Initial Mass in 1 cm Tall Model[g]
^{234}U	0.2489	3.064	0.0511
^{235}U	23.16	285.1	4.751
^{236}U	0.1076	1.325	0.0221
^{238}U	1.347	16.58	0.2764

3.1.3 Resulting Distributions

The first isotope examined was ^{135}Xe which has a short half-life of 9.1h and a strong thermal absorption cross section of over 2x10^{6}b. During a constant irradiation, it establishes an equilibrium concentration in about 1-2 days [27]. The average mass for ^{135}Xe and ^{137}Cs as well as other isotopes of interest for both MONTEBURNS and MCNPX/CINDER calculations at the end of burnup step three, the last full power step, is given in Table 3.3. These results are shown for simulations using 5000, 75000, and 375000 histories.

One general conclusion for these results is that the standard deviation in the results generally gets larger as you move up into higher actinide chains. This is due to the inherent propagation of error in these longer chains. The estimated standard deviation results from both codes for ^{135}Xe and ^{137}Cs are plotted in Figure 3.2. As can be seen, the standard deviation decreases significantly by adding histories, but the difference between 75000 and 375000 histories is relatively small (approximately a factor of 2) considering the increase in histories (approximately a factor of 4).

Table 3.3
Summary of Isotopic Mass Results.

Parameter	Code	5000 Histories [g]	75000 Histories [g]	375000 Histories [g]
^{135}Xe Mass	MB	1.30E-05 ± 1.99%	1.30E-05 ± 0.54%	1.30E-05 ± 0.21%
^{135}Xe Mass	MX	1.20E-05 ± 1.74%	1.20E-05 ± 0.42%	1.20E-05 ± 0.21%
^{134}Cs Mass	MB	1.23E-02 ± 3.32%	1.23E-02 ± 0.81%	1.23E-02 ± 0.37%
^{134}Cs Mass	MX	1.25E-02 ± 3.08%	1.25E-02 ± 0.86%	1.26E-02 ± 0.35%
^{137}Cs Mass	MB	9.78E-02 ± 0.79%	9.77E-02 ± 0.21%	9.78E-02 ± 0.08%
^{137}Cs Mass	MX	9.94E-02 ± 0.65%	9.94E-02 ± 0.15%	9.94E-02 ± 0.07%
^{234}U Mass	MB	3.07E-02 ± 1.85%	3.07E-02 ± 0.44%	3.08E-02 ± 0.22%
^{234}U Mass	MX	2.70E-02 ± 2.10%	2.70E-02 ± 0.54%	2.69E-02 ± 0.22%
^{235}U Mass	MB	1.41E-00 ± 1.74%	1.42E-00 ± 0.46%	1.42E-00 ± 0.18%
^{235}U Mass	MX	1.37E-00 ± 1.50%	1.37E-00 ± 0.34%	1.37E-00 ± 0.16%
^{238}U Mass	MB	2.37E-01 ± 0.63%	2.37E-01 ± 0.16%	2.37E-01 ± 0.07%
^{238}U Mass	MX	2.39E-01 ± 0.74%	2.39E-01 ± 0.19%	2.39E-01 ± 0.08%
^{237}Np Mass	MB	3.91E-02 ± 4.36%	3.91E-02 ± 1.18%	3.91E-02 ± 0.50%
^{237}Np Mass	MX	3.61E-02 ± 5.06%	3.60E-02 ± 1.24%	3.60E-02 ± 0.65%
^{238}Pu Mass	MB	9.40E-03 ± 4.34%	9.40E-03 ± 1.20%	9.42E-03 ± 0.53%
^{238}Pu Mass	MX	9.55E-03 ± 5.27%	9.53E-03 ± 1.25%	9.54E-03 ± 0.67%
^{239}Pu Mass	MB	7.13E-03 ± 4.64%	7.11E-03 ± 1.11%	7.11E-03 ± 0.52%
^{239}Pu Mass	MX	6.58E-03 ± 5.47%	6.60E-03 ± 1.54%	6.59E-03 ± 0.68%
^{240}Pu Mass	MB	2.81E-03 ± 6.32%	2.79E-03 ± 1.39%	2.79E-03 ± 0.67%
^{240}Pu Mass	MX	2.78E-03 ± 6.54%	2.77E-03 ± 1.74%	2.76E-03 ± 0.77%
^{241}Pu Mass	MB	3.30E-03 ± 3.56%	3.30E-03 ± 0.91%	3.30E-03 ± 0.40%
^{241}Pu Mass	MX	3.14E-03 ± 4.56%	3.14E-03 ± 1.21%	3.14E-03 ± 0.53%
^{242}Pu Mass	MB	1.77E-03 ± 4.28%	1.76E-03 ± 1.22%	1.76E-03 ± 0.51%
^{242}Pu Mass	MX	1.74E-03 ± 5.18%	1.74E-03 ± 1.31%	1.74E-03 ± 0.55%
^{244}Pu Mass	MB	1.27E-06 ± 7.41%	1.27E-06 ± 2.11%	1.27E-06 ± 0.85%
^{244}Pu Mass	MX	2.65E-07 ± 10.5%	2.67E-07 ± 2.08%	2.67E-07 ± 1.03%
^{241}Am Mass	MB	1.22E-05 ± 3.98%	1.23E-05 ± 1.02%	1.23E-05 ± 0.45%
^{241}Am Mass	MX	1.06E-05 ± 4.76%	1.07E-05 ± 1.24%	1.07E-05 ± 0.57%
^{242}Am Mass	MB	2.23E-07 ± 4.09%	2.23E-07 ± 1.09%	2.23E-07 ± 0.48%
^{242}Am Mass	MX	6.39E-08 ± 7.89%	6.44E-08 ± 1.32%	6.44E-08 ± 0.61%
^{243}Am Mass	MB	3.44E-04 ± 7.06%	3.43E-04 ± 1.98%	3.43E-04 ± 0.81%
^{243}Am Mass	MX	2.58E-04 ± 10.5%	2.60E-04 ± 2.04%	2.60E-04 ± 1.01%
^{242}Cm Mass	MB	8.60E-06 ± 4.01%	8.60E-06 ± 1.15%	8.60E-06 ± 0.48%
^{242}Cm Mass	MX	1.01E-05 ± 8.51%	1.01E-05 ± 1.63%	1.01E-05 ± 0.67%
^{243}Cm Mass	MB	1.56E-07 ± 5.71%	1.55E-07 ± 1.53%	1.56E-07 ± 0.66%
^{243}Cm Mass	MX	1.83E-07 ± 8.36%	1.84E-07 ± 1.83%	1.85E-07 ± 0.84%
^{244}Cm Mass	MB	9.60E-05 ± 7.65%	9.58E-05 ± 2.24%	9.58E-05 ± 0.84%
^{244}Cm Mass	MX	7.78E-05 ± 9.38%	7.79E-05 ± 2.12%	7.81E-05 ± 1.04%
k_{eff} Step 0	MB	1.783 ± 0.369%	1.783 ± 0.0864%	1.783 ± 0.0385%
k_{eff} Step 0	MX	1.787 ± 0.348%	1.786 ± 0.0940%	1.786 ± 0.0422%
k_{eff} Step 3	MB	1.366 ± 0.727%	1.366 ± 0.170%	1.366 ± 0.0799%
k_{eff} Step 3	MX	1.283 ± 0.766%	1.284 ± 0.187%	1.284 ± 0.0836%
k_{eff} Step 5	MB	1.381 ± 0.730%	1.383 ± 0.176%	1.384 ± 0.0872%
k_{eff} Step 5	MX	1.268 ± 0.838%	1.269 ± 0.184%	1.269 ± 0.0875%

*MB represents MONTEBURNS and MX represents MCNPX/CINDER

The two codes converged to different ^{135}Xe quantities which may be attributed to slight differences in the flux between the two models. Each code handles their

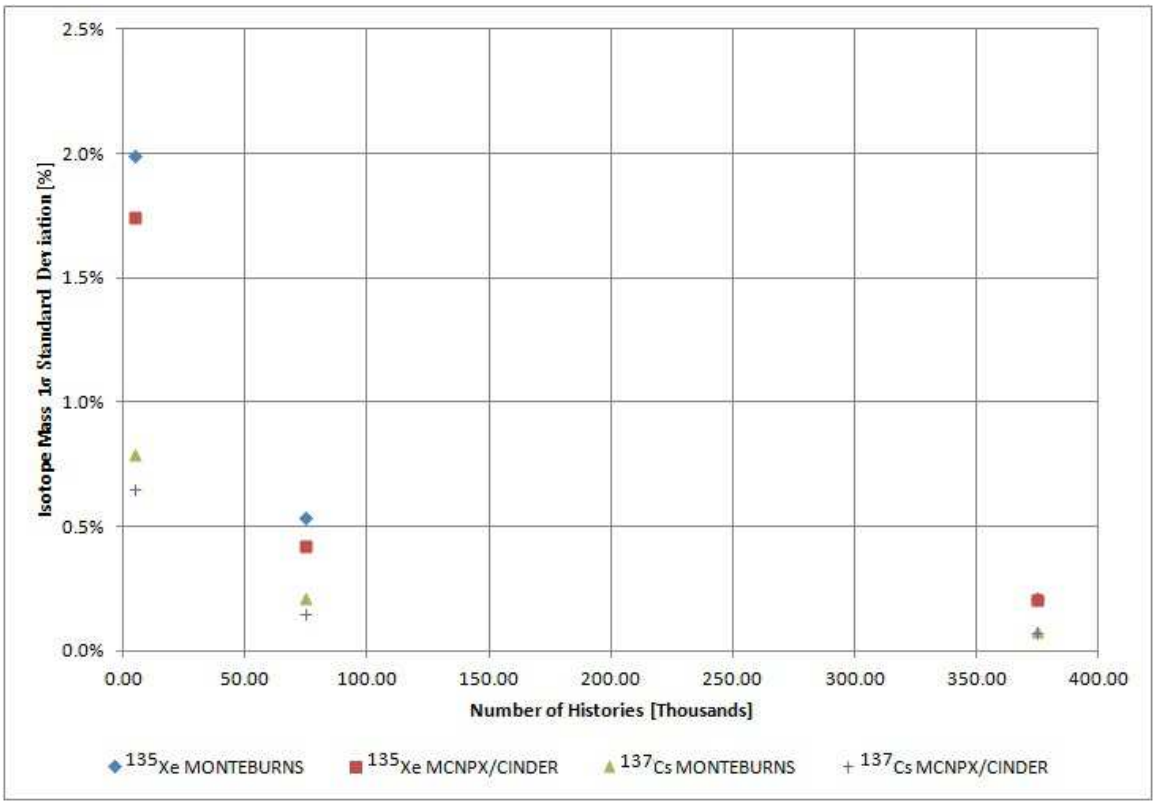
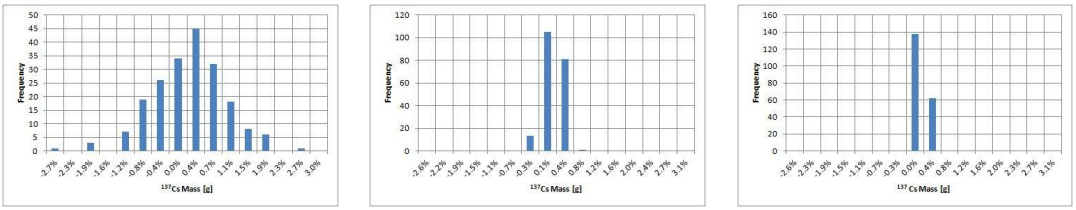


Fig. 3.2. ^{135}Xe and ^{137}Cs Mass Standard Deviation Reduction as the Quantity of Histories Increases.

transport calculation's importance threshold differently. This can be avoided by forcing both codes to track a set of approximately 140 isotopes at every step; however, this penalizes CPU time for multiple or repeated runs.

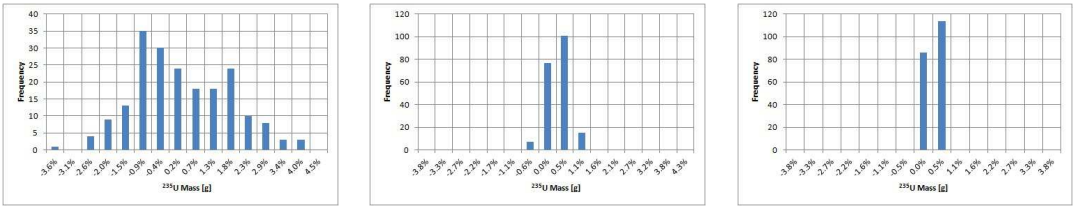
Histogram plots for the ^{137}Cs and ^{235}U results, with bins created using the Scott rule for 5000 histories, are shown in Figures 3.3 and 3.4 respectively. This shows a strong convergence for both the 75000 and 375000 history cases.

Similar to ^{135}Xe, the two codes' uranium results converged to statistically different quantities as a result of different fluxes due to the transport calculation's importance threshold functioning differently. For most steps, the ^{234}U and ^{238}U uncertainties are lower using MONTEBURNS while the ^{235}U uncertainty is lower using MCNPX/CINDER.



(a) 5,000 Histories (b) 75,000 Histories (c) 375,000 Histories

Fig. 3.3. Histograms of ^{137}Cs Results at the End of Step 5 Using MONTEBURNS



(a) 5,000 Histories (b) 75,000 Histories (c) 375,000 Histories

Fig. 3.4. Histograms of ^{235}U Results at the End of Step 5 Using MCNPX/CINDER

The MCNPX/CINDER package only outputs four significant digits. In this model, the large quantity of ^{235}U causes minor round off effects where the statistically varying and round off digits fall in the same place. If a full histogram were created using the 375,000 history results, the low uncertainty and round off effects may create false empty bins.

At all three quantities of histories, the output isotopic concentrations were very similar. This shows convergence of the reaction rate tallies in the model. The model used in this analysis only consisted of one material being burned. Convergence in more complicated models could vary greatly depending on geometry.

The MONTEBURNS variance was generally lower than MCNPX/CINDER using the same quantity of histories. For fission products and uranium isotopes, the variances were in much greater agreement, but MCNPX/CINDER seemed to produce larger values overall.

Table 3.3 also shows the sample mean k_{eff} and standard deviation at steps 0, 3, and 5. MONTEBURNS and MCNPX routinely report a 1σ standard deviation for the individual k-effective calculations, but these don't include the error propagations. Thus it is expected that these results reported by both codes will underestimate the actual variance in the k_{eff} value. This was verified by comparing the standard deviations directly from both codes with that obtained by propagating errors. A plot of this is shown in Figure 3.5, displaying the calculated sample standard deviation and the average code reported standard deviation for each burnup step. As the number of steps and burnup increases, the propagated error diverges from that reported from the codes.

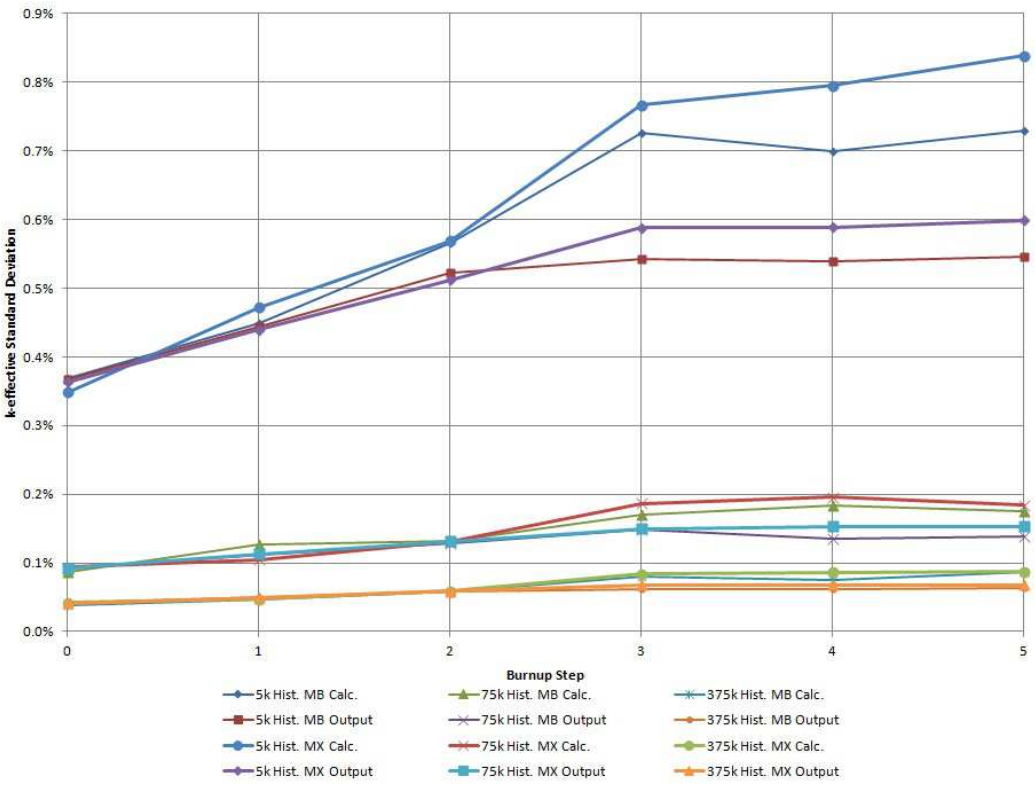


Fig. 3.5. k_{eff} Variance Results.

It should be noted that, convergence of the k-effective results is not an indicator of overall simulation convergence. k-effective is an overall system parameter, while

depletion simulation convergence is model dependent and is determined by the total neutron path length tallied in the region of interest.

3.1.4 Statistical Tests Versus the Normal Distribution

To test if the isotopic composition and k-effective distribution results were normally distributed they were tested against a normal distribution using the χ^2 test at α of 0.05. These tests were performed using 14 bins with 11 degrees of freedom since two parameters are estimated. The null hypothesis in these tests is that the distribution is normal. The results of these tests for ^{137}Cs after burnup step 3 are shown in Table 3.4. The test statistic was compared to the χ^2 value of 19.68 for all tests.

Table 3.4
χ^2 Test vs. Normal Distribution for ^{137}Cs After Step 3 (End of Power)

Histories	MONTEBURNS χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)	MCNPX/CINDER χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)
5000	15.49	No	9.735	No
75000	8.889	No	9.389	No
375000	5.951	No	12.78	No

In all the simulation results, the χ^2 statistic was sufficiently low and the null hypothesis was not rejected. The same test was performed on the mass distributions for ^{239}Pu with 375,000 histories at all full power burnup steps. The results are shown in Table 3.5.

Table 3.5
χ^2 Test vs. Normal Distribution for ^{239}Pu Using 375,000 Histories

Step	MONTEBURNS χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)	MCNPX/CINDER χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)
1	12.46	No	6.593	No
2	8.886	No	6.995	No
3	13.39	No	11.27	No

While some of the histograms do not make these distributions appear to be normal, the null hypothesis that the distribution is normal is failed to be rejected in each step. This same test was performed on ^{235}U, in which all six tests failed to reject the null hypothesis as well.

Statistical tests on k-effective were also performed using the results from 5,000 and 375,000 histories with both code packages. Although both codes have capabilities of creating mid-step k-effective calculations for burnup steps, the statistical tests were performed on the end of step results. For decay steps, there is only a k-effective calculation if the mid-step option is turned on. The null hypothesis was failed to be rejected at every step from both codes. The results from the MCNPX/CINDER χ^2 tests are shown in Table 3.6.

Table 3.6
χ^2 Test vs. Normal Distribution for keff Using MCNPX/CINDER

Step	5000 Histories χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)	375000 Histories χ^2 Statistic	Reject Null ($\alpha = 0.05$, $\chi^2 < 19.68$)
0	6.383	No	6.428	No
1	14.14	No	7.373	No
2	13.60	No	8.114	No
3	10.35	No	12.33	No
4	8.183	No	13.59	No
5	8.239	No	8.193	No

The precision of the spent fuel composition estimates was quantifiable through these techniques. The accuracy of reactor physics codes at predicting particular nuclear forensic signatures is also important.

3.2 Radiochemistry Analysis Actinide Isotopic Comparisons to Simulation Results

The ICP-MS results were compared in detail to simulation outputs at various levels of detail. The actinide isotopes were compared first, primarily uranium and plutonium isotopes.

Using the SRNL Appendix-A burnup, the fuel was modeled using ORIGEN 2.2, MONTEBURNS, and MCNPX/CINDER. Two different cross section sets were used for ORIGEN 2.2 including the standard RSICC issued thermal library and a custom MTR HEU research reactor library. Initial MONTEBURNS and MCNPX/CINDER assembly models were simulated to design dimensions but burned all of the fuel material as a whole. Another MONTEBURNS and MCNPX/CINDER assembly level model was created which broke the fuel into 35 burnable regions and simulated the drilled holes separately. This detailed model enables simulation of a 3D burnup and flux profile throughout the assembly. Throughout the results, these two different types of MONTEBURNS and MCNPX/CINDER models are referred to as basic and detailed. The uranium isotopic results are shown in Table 3.7 and Table 3.8 displaying total assembly masses and converted atom percentages.

Table 3.7
Simulated Assembly Uranium Mass Results

	Isotope Mass [g]			
Code	^{234}U	^{235}U	^{236}U	^{238}U
ORIGEN 2.2 (Thermal XS)	2.82	138	22.5	16.3
ORIGEN 2.2 (MTR XS)	2.64	135	25.6	15.9
MONTEBURNS Basic	2.54	133	26.2	16.0
MONTEBURNS Detailed	2.58	137	25.3	16.2
MCNPX/CINDER Basic	2.43	134	26.2	16.0
MCNPX/CINDER Detailed	2.44	135	25.0	16.0

The uranium results were fairly consistent among the different models created. Slight spectrum changes affected ^{234}U and ^{236}U the greatest. The basic one material assembly model produced the most dissimilar results. In a model such as this, the fuel material has no position dependence and is burned evenly across the entire assembly. This does not portray reality well, but is a simple and computationally efficient model.

Table 3.8
Simulated Assembly Uranium Isotopic Results

	U Isotope Percent [%]			
Code	^{234}U	^{235}U	^{236}U	^{238}U
ORIGEN 2.2 (Thermal XS)	1.56	76.9	11.5	9.08
ORIGEN 2.2 (MTR XS)	1.47	75.5	14.2	8.84
MONTEBURNS Basic	1.43	74.8	14.7	9.00
MONTEBURNS Detailed	1.42	75.7	13.9	8.93
MCNPX/CINDER Basic	1.37	75.1	14.6	8.93
MCNPX/CINDER Detailed	1.36	75.7	14.0	8.95

To examine possible sources of variance in the ^{235}U and ^{236}U content, the burnup from each simulation was documented and compared. The exact same power, specific power, and time steps were used in each simulation, so the overall assembly burnup should be consistent among models. The burnup for each simulation is in Table 3.9.

Table 3.9
Comparisons of Total Assembly Burnup From Models of Various Levels of Detail.

Simulation	Total Assembly Burnup [GWd/MTU]
ORIGEN 2.2 (Thermal XS)	394.2
ORIGEN 2.2 (MTR XS)	394.2
MONTEBURNS Basic	394.7
MONTEBURNS Detailed	394.9
MCNPX/CINDER Basic	395.0
MCNPX/CINDER Detailed	395.0

The burnup from all simulations was consistent and a way to check the power, step length, and specific power were setup correctly depending on code used. There were slight differences in the code's reported burnup. Each code requires a slightly different set of input parameters. Through high burnup broken into multiple steps, there is significant room for accumulation of round off effects.

The plutonium and neptunium ICP-MS results were analyzed and compared to simulation outputs. These results in Table 3.10 had much greater differences among the simulations than uranium. MONTEBURNS and MCNPX/CINDER actively update the spectrum through the depletion routine, while ORIGEN 2.2 uses the specified library for every step. The spectrum used to create the collapsed one-group cross section library has a significant impact on the results.

Table 3.10
Simulated Assembly Neptunium and Plutonium Mass Results

	Isotope Mass [g]				
Code	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu
ORIGEN 2.2 (Thermal XS)	6.73E-02	2.55E-03	3.01E-02	4.23E-03	1.05E-04
ORIGEN 2.2 (MTR XS)	5.23E-01	3.32E-02	1.64E-01	8.42E-02	9.79E-03
MONTEBURNS Basic	5.93E-01	4.34E-02	1.68E-01	9.92E-02	1.20E-02
MONTEBURNS Detailed	5.95E-01	3.50E-02	2.89E-01	7.03E-02	9.02E-03
MCNPX/CINDER Basic	5.98E-01	5.40E-02	1.68E-01	9.84E-02	1.19E-02
MCNPX/CINDER Detailed	5.90E-01	4.25E-02	2.86E-01	6.82E-02	8.54E-03

Using ORIGEN 2.2 with two different cross section sets shows the importance of an accurate flux spectrum. Great variance is present when comparing the neptunium and plutonium isotopic concentrations between the simulations. It is common for a flux spectrum to shift through the life of the fuel, which is not accounted for in ORIGEN. Another issue is that the thermal cross section library included with ORIGEN 2.2 does not account for any fast flux interactions. This creates problems with all of the (n, α), (n, p), etc. reactions. The more thorough codes have the potential to provide a more accurate flux spectrum at every burn step. The change in spectrum between the simulations had a significant effect on the quantity of neptunium and plutonium produced.

The plutonium results were then converted into percentages by isotopic composition and compared in Table 3.11. It is obvious that changes in spectrum and the level of detail in the model will have a great effect on the plutonium quantities

and isotopic compositions. The MONTEBURNS and MCNPX/CINDER detailed models had very similar results.

Table 3.11
Simulated Assembly Plutonium Isotopic Results

	Pu Isotope Percent [%]			
Code	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu
ORIGEN 2.2 (Thermal XS)	6.89	81.31	11.41	0.28
ORIGEN 2.2 (MTR XS)	11.1	54.73	28.15	3.27
MONTEBURNS Basic	13.0	50.27	29.68	3.59
MONTEBURNS Detailed	8.56	70.70	17.17	2.21
MCNPX/CINDER Basic	15.7	49.01	28.57	3.45
MCNPX/CINDER Detailed	10.4	69.63	16.62	2.08

3.3 Radiochemistry Analysis Forensic Signature Isotope Comparisons to Simulation Results for Fission Products

The isotopic compositions for fission products used for forensic signatures were also compared to simulation results. The ICP-MS analysis covered all of the relevant mass per charge bins to include cesium, lanthanum, and neodymium isotopes considered for analysis.

The results expressed as ratios were consistent among samples. The average of all three samples was used for comparisons to the results from the simulations in Table 3.12.

The 137 to 238 mass bin ratio consisted of ^{137}Cs and ^{137}Ba and the 148 to 238 mass bin ratio consisted of ^{148}Nd and ^{148}Sm. At the end of power, the 137 mass bin primarily consisted of ^{137}Cs, which beta decays to ^{137}Ba. A more complex production method produces ^{148}Sm in the 148 mass bin, which is discussed later. All of the mass bin ratios were consistently above their associated simulation results. Several possibilities may have caused this disagreement. The samples which were

Table 3.12
Measured and Simulated Assembly Fission Product Isotopic Ratio Results Versus ^{238}U

	Isotopic Ratio vs. ^{238}U				
Code	137	139	145	146	148
Measured Sample Average	0.557	0.585	0.343	0.286	0.181
ORIGEN 2.2 (Thermal XS)	0.478	0.503	0.299	0.240	0.139
ORIGEN 2.2 (MTR XS)	0.493	0.518	0.302	0.254	0.156
MONTEBURNS Basic	0.493	0.521	0.302	0.266	0.157
MONTEBURNS Detailed	0.492	0.520	0.301	0.266	0.158
MCNPX/CINDER Basic	0.496	0.506	0.301	0.254	0.154
MCNPX/CINDER Detailed	0.496	0.506	0.300	0.254	0.155

extracted from the fuel assembly were five equally spaced symmetric holes that were drilled. This may not be an accurate representation of the overall assembly average composition. To further examine these differences, the simulations were modified to specifically model the holes drilled. The results from this modified simulation were compared to the measured results. These results are in Table 3.13.

Table 3.13
Measured Fission Product Isotopic Ratio Comparisons to Simulations of the Holes Drilled.

	Isotopic Ratio vs. ^{238}U				
Code	137	139	145	146	148
Measured Sample Average	0.557	0.585	0.343	0.286	0.181
MONTEBURNS Detailed	0.468	0.495	0.287	0.252	0.150
MCNPX/CINDER Detailed	0.471	0.481	0.286	0.240	0.146

The simulated average isotopic ratios for holes drilled were below the assembly average and measured results. While the simulations reproduced the documentation burnup and isotopic compositions well, they did not reproduce the isotopic compositions and burnup of the measured results. Each isotopic ratio was under the

corresponding ICP-MS measured ratio. This is an indicator that the burnup declared in the documentation is underestimated. The simulated hole punches spent ^{235}U enrichment was 76.9% and 76.64% for MOTNEBURNS and MCNPX/CINDER respectively. These enrichments are both higher than the reported 74.58% in the Appendix-A documentation, further verifying the burnup underestimation.

The corresponding burnup difference is significantly less then the variance in the other stored ORR spent fuel assemblies. The SRNL ORR Appendix-A documentation states that the stored spent fuel assemblies range in burnup from 11-54% providing a very large range in output isotopic concentrations. Similarities and variance in output isotopic composition among all reactors provides a significant challenge for an attribution methodology.

Due to the large content of ^{235}U in the fuel, the remaining uranium is split between ^{234}U, ^{236}U, and ^{238}U. There is variance in the ^{234}U and ^{236}U content due to potential fractional enrichment differences from the uranium enrichment method and HEU fuel recycling and re-enriching. This variance carries over to the leftover ^{238}U content. To eliminate this source of variance from the forensic signature comparisons, the results are reanalyzed as a ratio to the 137 mass bin (^{137}Cs and ^{137}Ba). The resulting ratios were in great agreement with the measured results in Table 3.14.

Table 3.14
Measured and Simulated Assembly Fission Product Isotopic Ratio Results Versus 137 Mass Bin

	Isotopic Ratio vs. 137 Mass Bin				
Code	137	139	145	146	148
Measured Sample Average	1.000	1.051	0.615	0.513	0.325
ORIGEN 2.2 (MTR XS)	1.000	1.051	0.613	0.516	0.318
MONTEBURNS Basic	1.000	1.057	0.612	0.539	0.319
MONTEBURNS Detailed	1.000	1.057	0.611	0.541	0.321

4. ADVANCED FORENSICS SIGNATURE ANALYSIS AND DEVELOPMENT

4.1 Power History Effects on Mass Bin Ratios

There was excess signal in several mass bins compared to the simulation results. A contribution to this difference was the inaccurate reported burnup numbers from the ORR documentation. The 148 mass bin stood out among the others and was further investigated.

After a long decay period, the only present isotopes are ^{148}Nd and ^{148}Sm in the 148 mass bin. Chemical separations were not performed on the measured samples to observe the isotopic breakdown of the 148 mass bin, so a code was developed to examine its signal through repeated simulations with variable power history.

The code developed consisted of repeated ORIGEN 2.2 simulations of varying length alternating burn and decay steps. The burnup and specific power for all the simulations were held constant to preserve the number of fissions. A full matrix of results was created by dividing user specified burn and decay step ranges to be observed. The user also specifies the number of intervals in which to divide the burn and decay ranges.

For example, if the user selected the burn and decay step length range to be 1 to 10 days (the burnup of these steps would depend on the specified specific power) and the number of intervals to be 10 for both, the code would begin by performing a simulation of alternating burn and decay steps of length 1 day each. Then holding the burn step length constant, simulations would be performed alternating 1 day burn and 2 day decay steps, 1 day burn and 3 day decay steps, 1 day burn and 4 day decay steps, etc. After the decay interval was filled for the first burn step length, the process would repeat but for the next interval burn step (2 day burn and 1 day decay steps, 2 day burn and 2 day decay steps, 2 day burn and 3 day decay steps, etc.), until the entire matrix of simulations is complete.

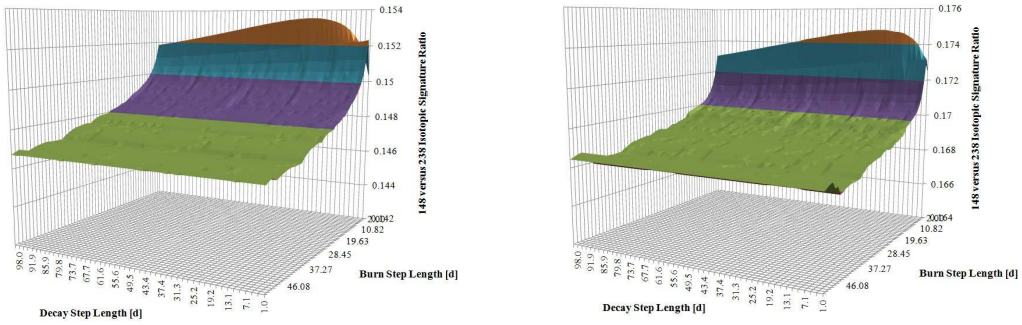
The recorded isotopic composition or ratio of isotopic compositions is up to the user. In this case the ratio of the sum of the ^{148}Nd and ^{148}Sm isotopic compositions to ^{238}U was reported. This simulation was performed using both previously mentioned cross section sets consisting of thermal and MTR HEU libraries. The same parameters in Table 4.1 were used in both code runs.

Table 4.1
Code Parameters for Isotopic Ratio Comparisons.

Parameter	Value [%]
Burnup Axis Minimum [d]	2.0
Burnup Axis Maximum [d]	50.0
Burnup Axis Intervals	50.0
Decay Axis Minimum [d]	1.0
Decay Axis Maximum [d]	100.
Decay Axis Intervals	50.0
Simulation Constant Burnup [GWd/MTHM]	394.5
Simulation Specific Power [W/g]	3.62
Additional Decay Time [d]	8800

The fuel consisted of 93% enriched ^{235}U and 1% of both ^{234}U and ^{236}U. The calculated total burn time based on specific power and total burnup was 109.22 days. The corresponding burn step and decay step increments were 0.979 and 2.02 days respectively. The result from both runs are displayed as surface plots in Figure 4.1.

Using both cross section sets, adjusting the burn and decay step length in the simulation resulted in sizable changes in the output 148 to 238 atomic ratio. The same amount of ^{148}Nd was produced regardless of the parameters chosen, but the primary differences can be attributed to ^{148}Sm. During steady-state operation, the mid-strength absorber ^{147}Pm creates both ^{148}Pm and ^{148m}Pm which have half lives of 5.37d and 41.3d respectively. Both of these isotopes have large absorption cross sections and frequently absorb a neutron forming ^{149}Pm instead of decaying to ^{148}Sm. However, during repeated brief or extended shutdown time periods there is signifi-



(a) Thermal Cross Section Set

(b) MTR HEU Cross Section Set

Fig. 4.1. 148 Versus 238 Atomic Ratio as a Function of Burn Step Length, Decay Step Length, and Cross Section Set

cantly more decay to ^{148}Sm present. This ^{148}Sm originates from the 147 mass chain and increases the 148 mass bin signal reducing accuracy in standard burnup reconstruction methods.

For research reactors, frequent brief and extended shutdown is common. This gives plenty of time for excess ^{148}Sm accumulation, which poisons the ICP-MS 148 mass bin without neodymium and samarium separations. This information can be used as a power history identifier of extended shutdown time.

4.2 Simulated ORR Radial and Axial Burnup Profiles.

To further understand the 3D burnup profile in ORR and other MTR fuel assemblies, the burnup results from the MONTEBURNS and MCNPX/CINDER detailed models were analyzed as well as new models developed. In the case of a spent fuel assembly seizure and sample acquisition required, knowledge of the burnup profile axially and radially may help provide information to obtain a representative sample of the assembly.

4.2.1 ORR Axial Burnup Profile

The results from the existing detailed MONTEBURNS and MCNPX/CINDER simulations were analyzed further. These models burned the inside fuel plates and the outside fuel plates separately, each split into 15 axial regions. The five holes were also modeled individually totaling 35 materials. Figure 4.2 displays images of the XY and XZ planes from the model. In this display, the aluminum cladding is purple, the water coolant/moderator is red, and the fuel meat is various colors depending on location.

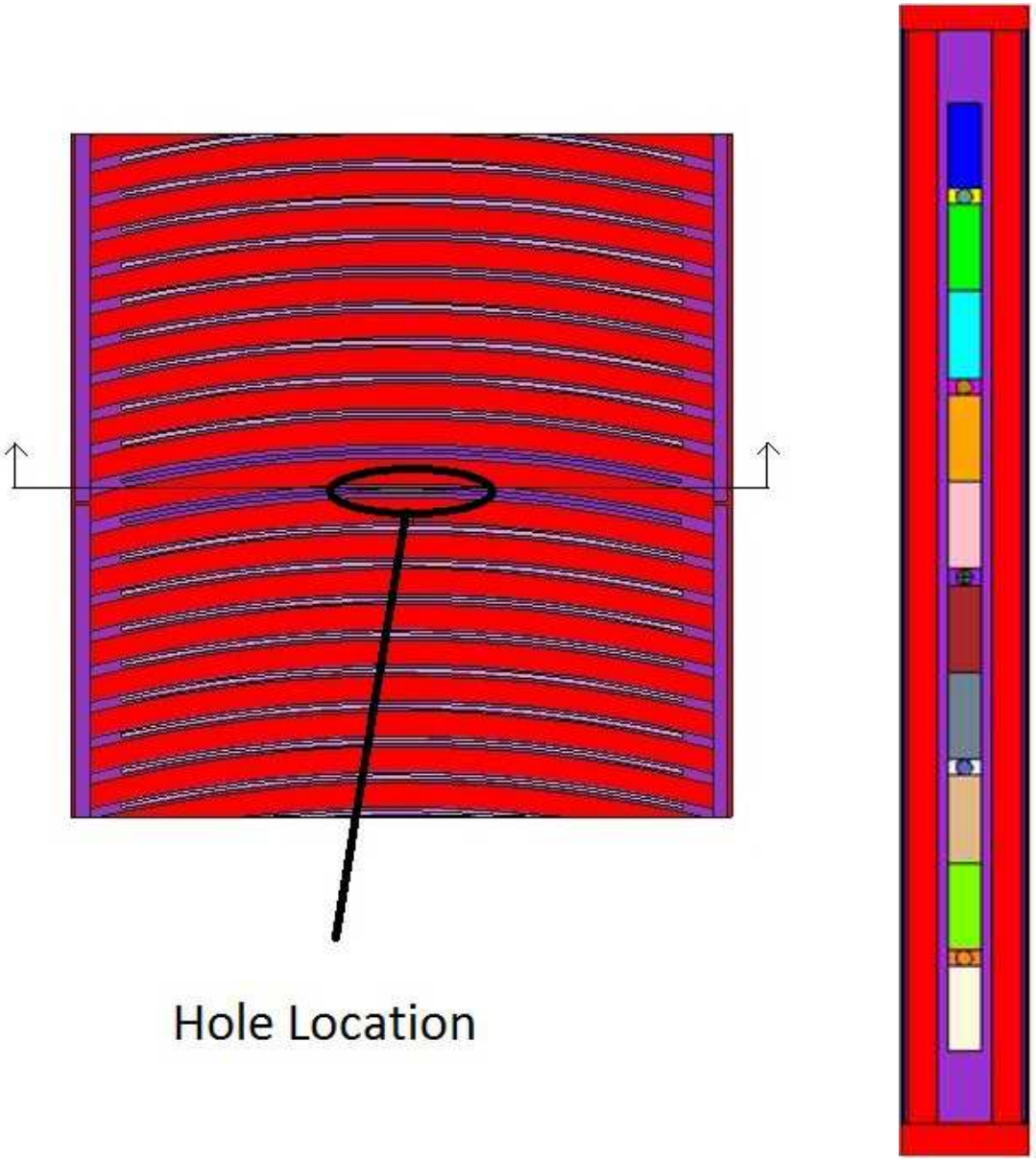
Figure 4.2(a) shows the XY plane at $z = 0$ of the translated portion of the assembly. This overlays the location of the center hole drilled in the convex outer fuel plate. Figure 4.2(b) displays the XZ plane overlaying the convex outer fuel plate to show the 15 axial layers and 5 symmetric hole locations. The 1m of water above and below the assembly is cropped.

A symmetric cosine shaped axial burnup distribution was expected due to model symmetry and basic reactor physics principals. The resulting burnup from all 35 materials is displayed in Figure 4.3 as a function of axial location.

The burnup for the inner and outer plates was identical due to the equal spacing between all of the plates in the Y dimension. The burnup for the five hole punches was slightly lower than their axial surrounding regions. This difference in burnup is explained in Section 4.2.2 in detail describing the radial burnup profile.

To examine the burnup profile of the five drilled holes as a function of time, the burnup profile as a ratio to the assembly average burnup was plotted at every burnup step. The burnup profile was consistent throughout the life of the fuel and slightly flattened as burnup increased. This effect is shown in Figure 4.4.

In a real fuel followed control element MTR reactor, this perfect cosine shaped burnup profile is unlikely. Depending on the fuel's location within the reactor core, the peak burnup may shift as far as 10cm from the center. Reactor core locations next to experimentation or water hole locations may affect the burnup profile as well.



(a) XY Plane (z=0) (b) XZ Plane

Fig. 4.2. ORR Axial Burnup Model.

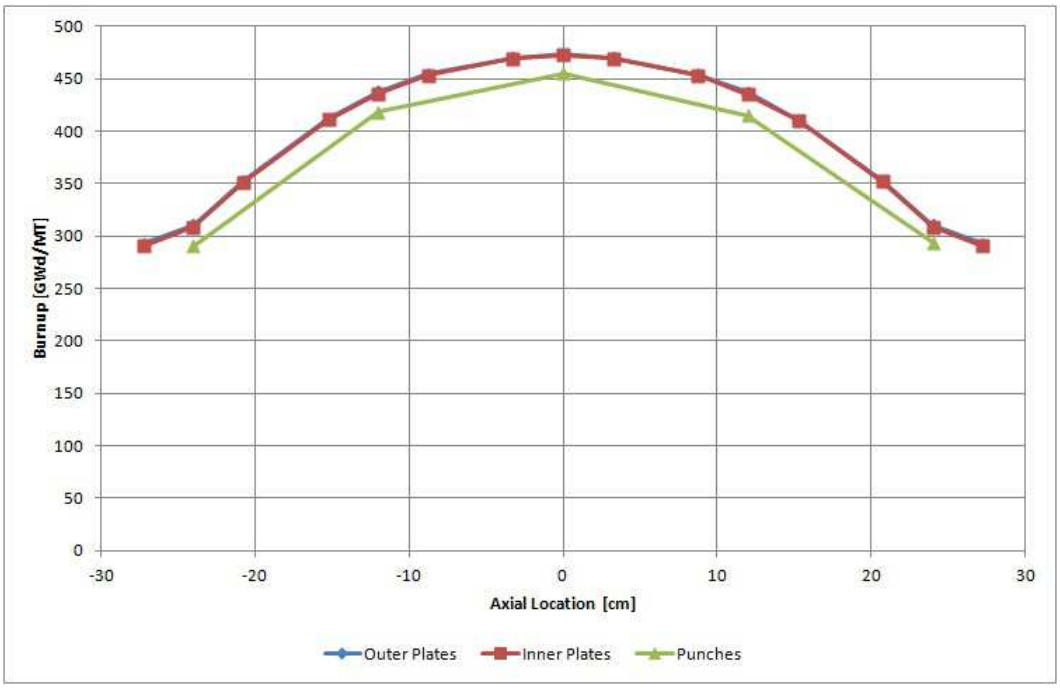


Fig. 4.3. Axial Burnup Profile for ORR Assembly and Hole Punches.

4.2.2 ORR Radial Burnup Profile

The radial burnup profile was also examined. The lower burnup in the five hole drilling locations from the previous model suggests that the radial burnup profile is not flat. The radial burnup profile was examined in two ways. One consisted of a 2D simulation and another verified the burnup profile by moving the hole drilling location in the detailed 3D model to the edge of the fuel plate.

The first model created to represent the ORR radial burnup profile was a 1cm tall section of the MTR assembly. The model was symmetric in the X dimension, so it was cut in half and reflective boundary conditions were used. Periodic conditions were used in the Y and Z dimensions. A Vised picture of the model is shown in Figure 4.5.

The modeled section of the assembly was split in the XY plane into a six by six grid of burnable material regions. The volume for each material was calculated

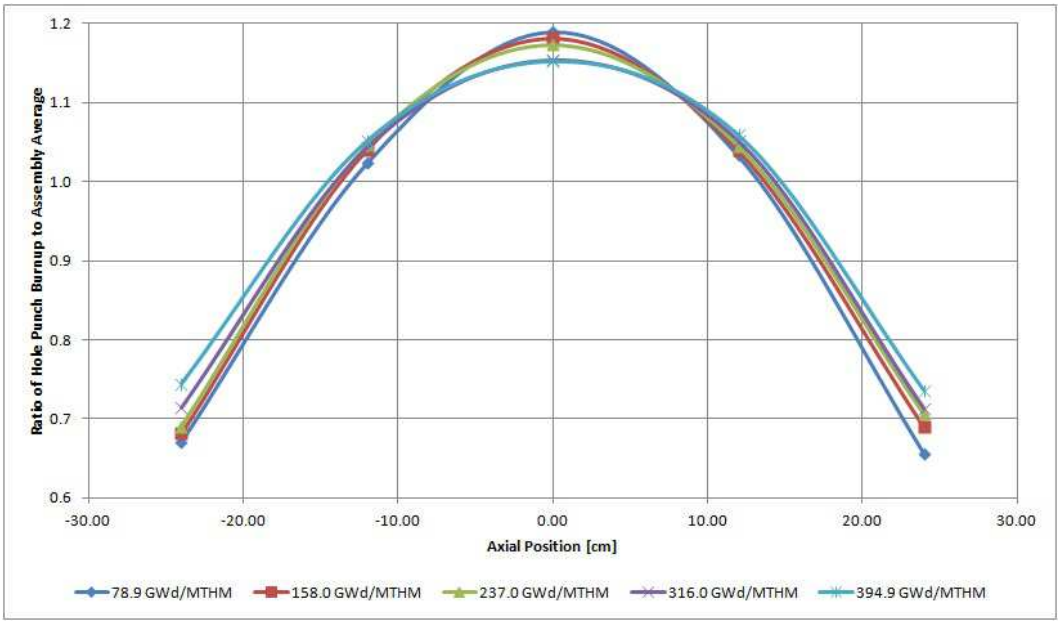


Fig. 4.4. Axial Burnup Profile for ORR Assembly Hole Punches Throughout Fuel Life.

based on a 1cm tall subsection of an individual fuel plate divided into subsections. The burnup profile in the Y dimension was expected to be flat because of the lattice pattern and equal spacing between fuel plates. In the X dimension, there is excess water between adjacent assemblies sideplates which may cause additional neutron thermalization. Thus, it was expected that the burnup profile in the x-dimension would not be flat

At approximately 10% burnup, the burnup profile in the XY plane was not flat in the x-dimension. The burnup peaked at the edges of the fuel plates with a peak to average burnup ratio of 1.052 and was at a minimum in the center. The burnup profile results for 10% burnup are replicated to represent the entire XY plane for visualization purposes in Figure 4.6. Table 4.2 contains the ratio of the burnup at each XY position to the peak burnup. At low burnup, the minimum is approximately 87% of the peak. This minimum is located in the center of the fuel plates. The relative results show the symmetry in the Y dimension well.

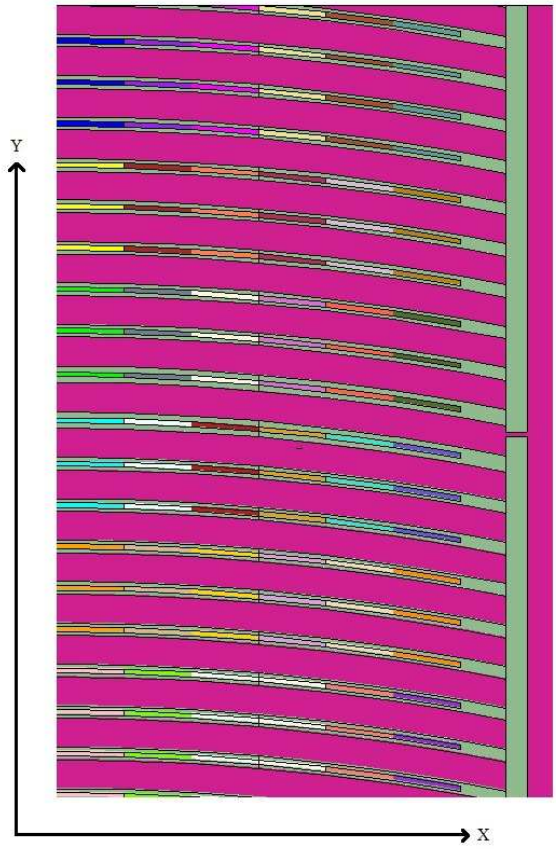


Fig. 4.5. Model for Radial Burnup Profile Calculation for a Section of an ORR Assembly.

Table 4.2
ORR Relative Radial Burnup Profile at Burnup Step 4 (∼10% of total burnup)

	X					
Y	89.14%	89.40%	89.21%	90.93%	94.20%	100.00%
	87.98%	88.53%	89.70%	91.53%	94.84%	99.95%
	87.81%	88.35%	89.47%	91.74%	94.79%	100.00%
	87.85%	88.52%	89.85%	91.71%	94.88%	99.91%
	87.22%	87.66%	89.08%	91.50%	94.51%	100.00%
	84.98%	86.05%	89.77%	92.07%	95.48%	100.00%

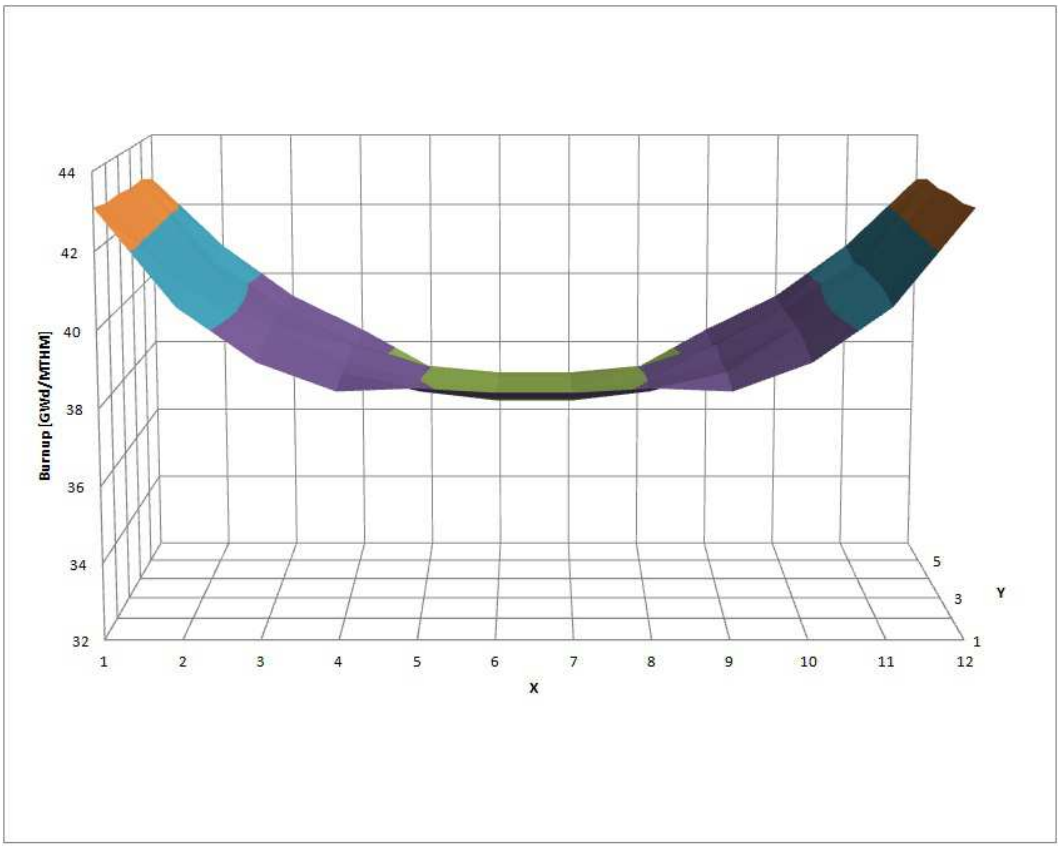


Fig. 4.6. Radial Burnup Profile for a Section of an ORR Assembly After Burnup Step 4 (Approximately 10% of Final Burnup).

At the end of life (Figure 4.7), a similar cosine shape is present. The distribution does appear to have less curvature, however, the peak to average burnup ratio is increased to 1.09. The relative burnup with respect to the peak burnup was calculated to show the change in shape early and at the end of life. At end of life, flattening of the profile does occur. The general shape though does not change significantly, only the magnitude of the minimum. The relative minimum at the end of life is approximately 92% peak.

To verify this shape in the 3D detailed model, the previously used axial burnup model was then modified with the hole drilling locations moved to the edge of the fuel meat. Figure 4.8 displayed the new location for the holes.

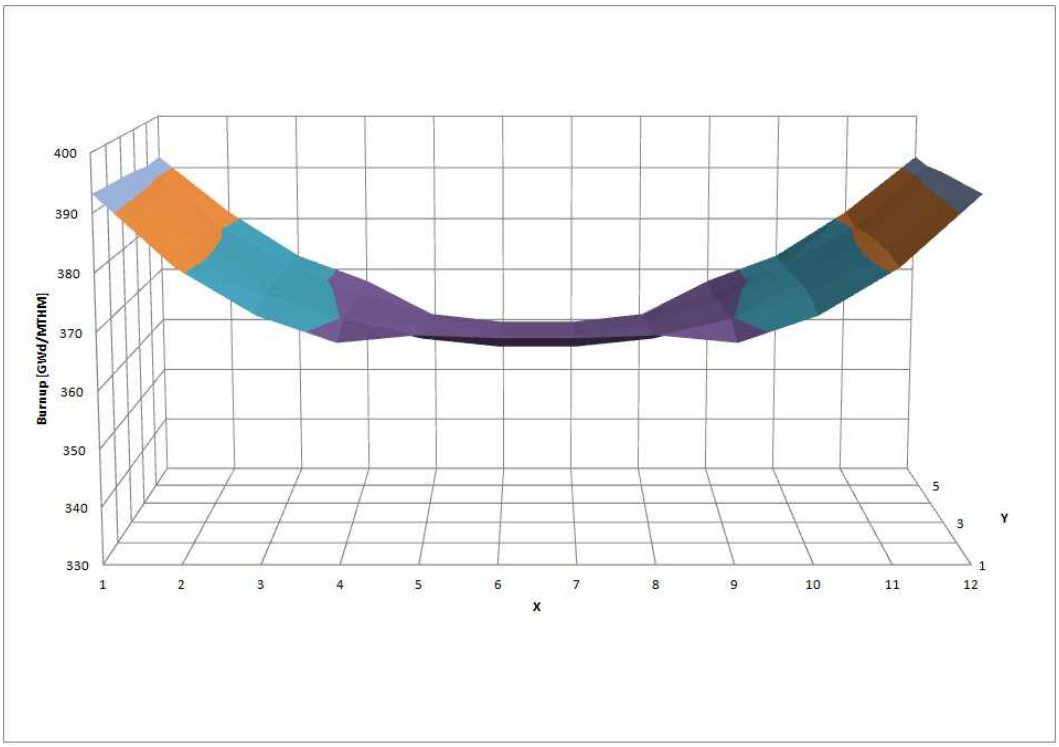


Fig. 4.7. Radial Burnup Profile for a Section of an ORR Assembly After Final Burnup Step.

Table 4.3
ORR Relative Radial Burnup Profile at End of Life

	X					
Y	93.85%	93.97%	93.64%	94.81%	96.87%	100.00%
	92.90%	93.26%	94.12%	95.24%	97.12%	100.00%
	92.84%	93.28%	93.99%	95.24%	97.17%	100.00%
	92.61%	93.07%	93.88%	95.21%	97.15%	100.00%
	92.32%	92.71%	93.65%	95.10%	96.99%	99.92%
	90.69%	91.43%	93.78%	95.05%	97.25%	100.00%

The results from this simulation were expected to produce burnup in the hole locations higher than inner and outer fuel plates. The burnup of a sample extracted from a location at the peak should have higher burnup than it's surrounding regions.

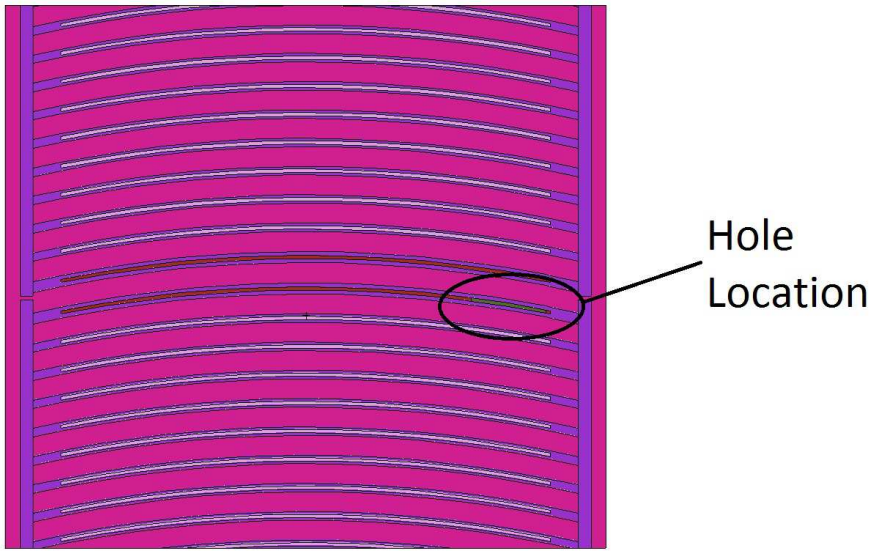


Fig. 4.8. Radially Moved Hole Punch Burnup Model.

Figure 4.9 shows the simulation results and includes the previous hole location's burnup for comparison.

The results verify the burnup distribution across the entire assembly. The peak burnup is located at the edges of the fuel plates where excess water between assemblies causes additional thermalization. The true axial profile will likely depend on many factors such as control element locations and experimentation history, but the radial burnup profile should be much more consistent among assemblies [28]. In the event that a sample must be acquired for characterization, knowledge of this burnup profile can be critical in an analysis process.

4.3 Effects of Initial ^{236}U Content on Spent Fuel Actinide Signatures

The axially detailed 35 material MONTEBURNS ORR model was used again and the effects on uranium, neptunium, and plutonium signatures were observed while changing the initial ^{236}U content in the fuel. The ^{236}U enrichment was analyzed at

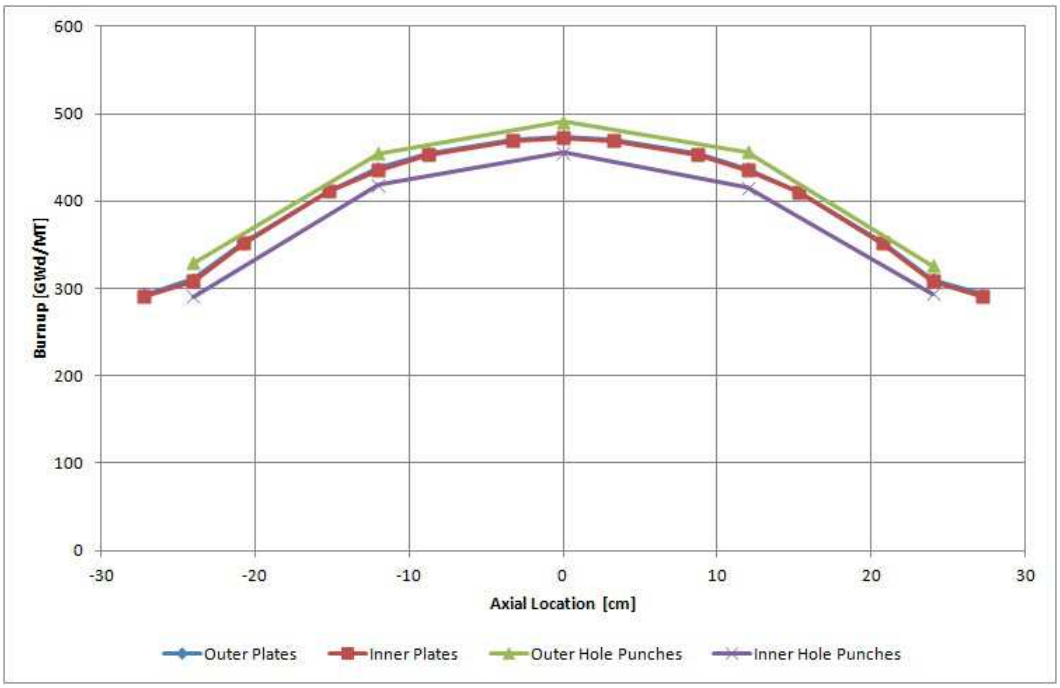
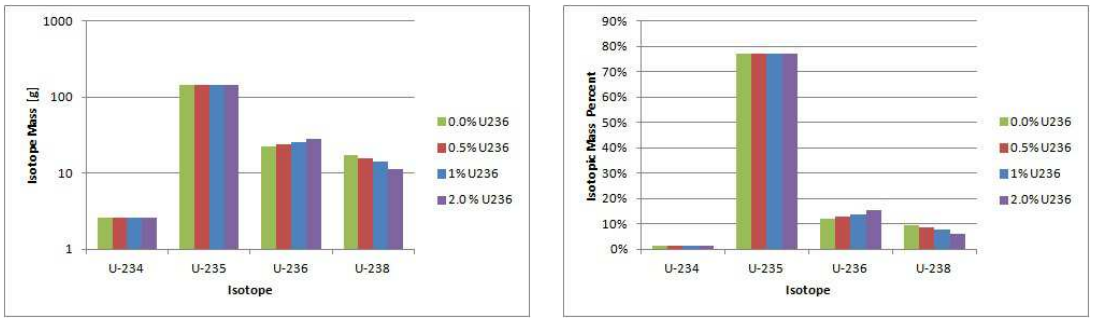


Fig. 4.9. Radial Burnup Profile With Moved Hole Punches.

0.0%, 0.5%, 1.0%, and 2.0%. The effects were analyzed on the whole assembly and the drilled holes. The ^{235}U enrichment was held constant at 93.1% and the initial ^{234}U concentration was held constant. In reality, re-enrichment of HEU fuel would potentially further increase the ^{234}U content, however this is unaccounted for in this simulation.

The main differences between the uranium isotopes in the assembly are within ^{236}U and ^{238}U. Initially, as the ^{236}U increased, the ^{238}U decreased enough to show in the final results too. The final uranium isotopic mass and enrichments are shown in Figure 4.10.

Changing the ^{236}U content has no direct effect on the depletion or transmutation of ^{234}U and ^{235}U. The final ^{236}U concentration increases directly from the initial concentration. Additional ^{236}U created from ^{235}U absorption simply linearly contributed versus burnup. The ^{236}U concentration is plotted versus burnup in Figure 4.11.



(a) Uranium Mass (b) Uranium Isotopic

Fig. 4.10. Initial ^{236}U Effects on Final Assembly Uranium Isotopic Concentrations.

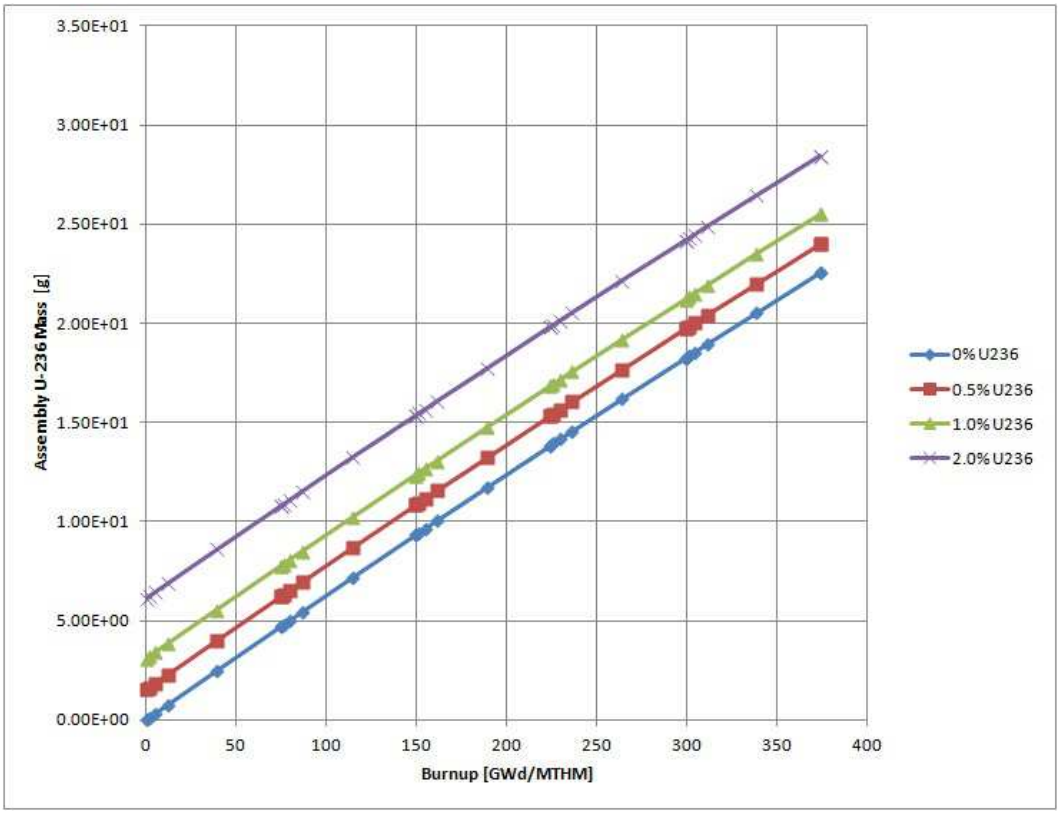


Fig. 4.11. Assembly Effects on Final ^{236}U vs Burnup From Initial ^{236}U Perturbations.

^{236}U also absorbs neutrons to form ^{237}U, which decays into ^{237}Np. A similar effect appears when ^{237}Np absorbs a neutron forming ^{238}Np, which decays into ^{238}Pu. The absorption rate of ^{236}U increases as it accumulates versus burnup. To compare the transmutation of ^{236}U at higher burnup versus destruction of ^{235}U, their ratio was plotted versus burnup in Figure 4.12. With linear accumulation of ^{236}U and depletion of ^{235}U versus burnup, the ratio of the two was expected to be nonlinear.

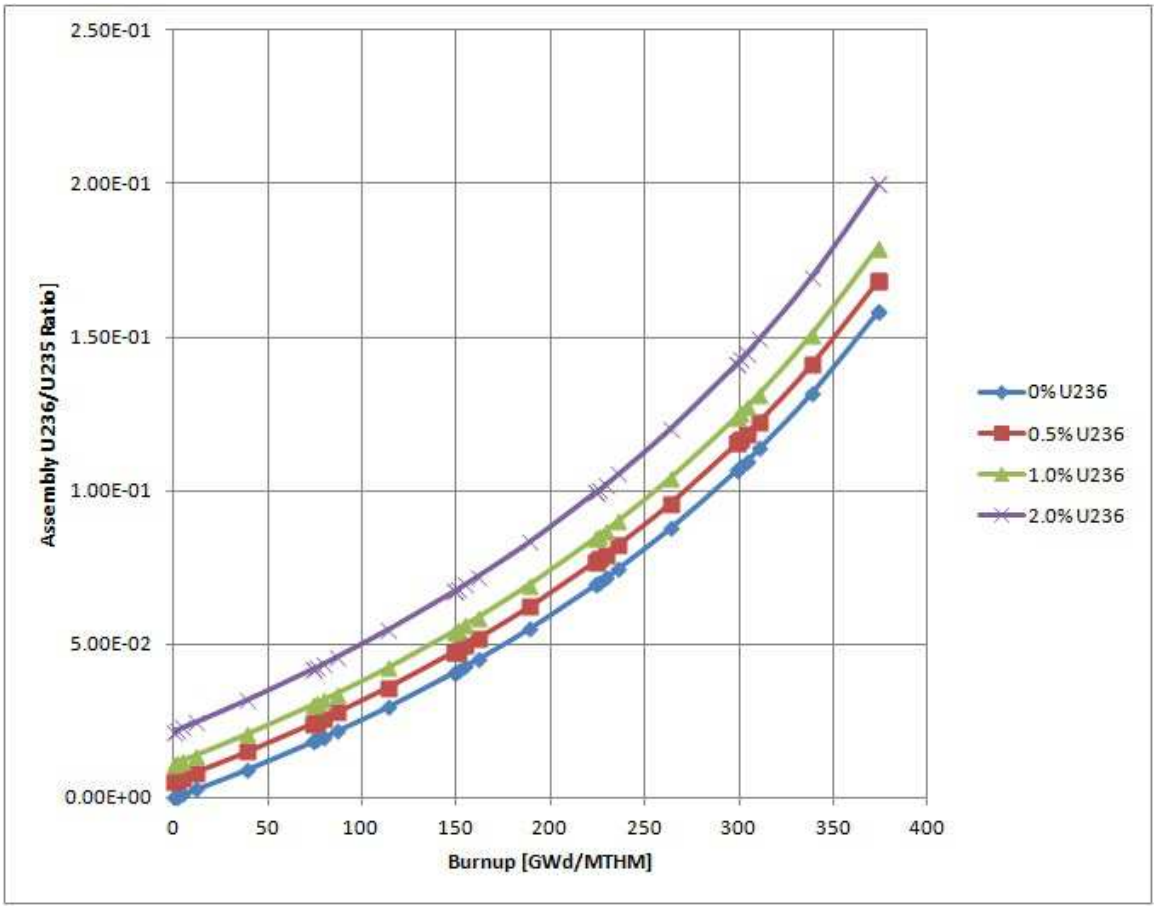


Fig. 4.12. Assembly Effects on ^{236}U/^{235}U Ratio vs Burnup From Initial ^{236}U Perturbations.

The ratio of ^{236}U to ^{235}U versus burnup shows that independently of the initial ^{236}U concentration, even at high burnup the results are equally spaced depending on initial ^{236}U concentration. A linear relationship between the initial ^{236}U con-

centration and burnup is formed by using a linear best fit average for the results from all four simulations. The initial ^{236}U concentration can be calculated using this relationship, a measured sample's burnup, and final ^{236}U concentration.

The measured final ^{236}U concentration is used as a ratio to ^{238}U. Then using the ratio of ^{238}U to the initial uranium atom concentration which results from the burnup reconstruction, the resulting measurable product $\frac{N^{U236}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}$ is plotted versus burnup in Figure 4.13.

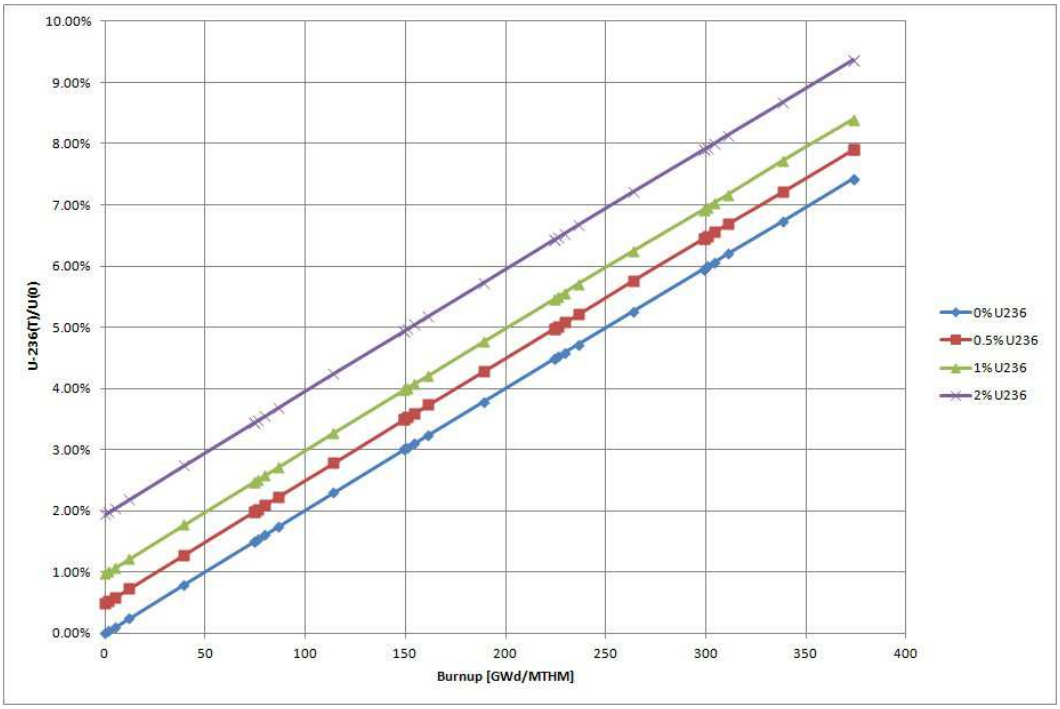


Fig. 4.13. Assembly ^{236}U Enrichment vs Burnup From Initial ^{236}U Perturbations.

Using a linear regression for each simulation's results, Table 4.4 shows the resulting slopes and intercepts. The average regression slope was 1.9870x10^{-4} [MTHM/GWd]. The initial ^{236}U enrichment can be reconstructed from measured data using:

$$\frac{N_0^{U236}}{N_0^U} = \frac{N^{U236}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U} - 0.00019870BU(T). \tag{4.1}$$

Table 4.4
Regression Results for Initial ^{236}U Enrichment Calculation

^{236}U Initial Enrichment [%]	Slope [MTHM/GWd]	Y-intercept [%]
0.0	1.870E-04	0.019
0.5	1.876E-04	0.508
1.0	1.869E-04	0.992
2.0	1.865E-04	1.963

This correlation can be used in an analysis to determine if a sample has any initial ^{236}U resulting from HEU spent fuel separations in a recycle program. Historically, only the United States and Russia have recycled and down blended frequently [5]. This capability determination may aid in an attribution process.

4.4 Effects on Nuclear Forensics Signatures in Critical Spectrum Versus Non-Critical Depletion Simulations.

Using MONTEBURNS or MCNPX/CINDER, there is no direct way to enforce a criticality condition automatically. In these simulations, k-effective is generally greater than one. The spectrum shift between critical to non-critical depletion and the effects on nuclear forensic signature isotopes were observed.

A simple infinite lattice model was created using SCALE 6.1 consisting of one assembly to be burned using the critical search function. SCALE 6.1 has the capability to perform a criticality search by adjusting variable dimensions or material compositions until criticality is achieved. However, this function is can only be performed on an individual eigenvalue calculation and not every step in a depletion routine.

The previously used model for MONTEBURNS and MCNPX/CINDER was modified and converted to have the water as a burnable material with adjustable boron concentrations. Using this method, along with stepwise material feed capabilities, boron was added to the simulation to achieve a k-effective of 1.00 $\pm$ 1.0% at every burn step. The boron was only added to the water contained in the active fuel region.

The water located above and below the assembly remained unaffected to preserve some reflective functionality. The resulting k-effective at every step is in Table 4.5.

Table 4.5
Assembly Model k_{eff} Results From Critical Spectrum and Non-Critical Spectrum Depletion.

Burnup Step	k_{eff} Critical	k_{eff} Non-Critical	Burnup Step	k_{eff} Critical	k_{eff} Non-Critical
0	1.01582	1.60905	16	1.00048	1.414
1	1.00491	1.55993	17	0.99936	1.38648
2	0.99564	1.53680	18	0.99936	1.4115
3	1.00713	1.52709	19	0.99418	1.38659
4	1.00077	1.50738	20	0.99495	1.38244
5	1.00461	1.48742	21	1.00521	1.38013
6	1.00461	1.52421	22	0.99989	1.35514
7	0.99783	1.48982	23	1.00741	1.32281
8	0.99227	1.48099	24	1.00741	1.33947
9	1.00043	1.48061	25	0.99371	1.32041
10	1.00399	1.46322	26	0.99682	1.31919
11	1.00039	1.44011	27	1.00611	1.31544
12	1.00039	1.47186	28	0.99184	1.28352
13	1.00441	1.44151	29	0.99339	1.24397
14	1.00236	1.43567	30	0.99339	1.24949
15	1.01162	1.43453			

The k-effective at step 0 cannot be 1.00 and also be 1.00 during the middle of the first step. The step 0 k-effective calculation is the only one that is calculated at the beginning of the burn step. The rest are performed using the material isotopic compositions from the predictor calculation at the middle of each burn step.

The effects on the nuclear forensic signature isotopic concentrations was to be observed. The ^{235}U concentration was expected to have minimal change due to the number of fissions not changing. However, with the slight spectrum changes some isotopes may have significant differences. The six group fluxes were volume averaged for all of the different regions burned in the simulations and compared.

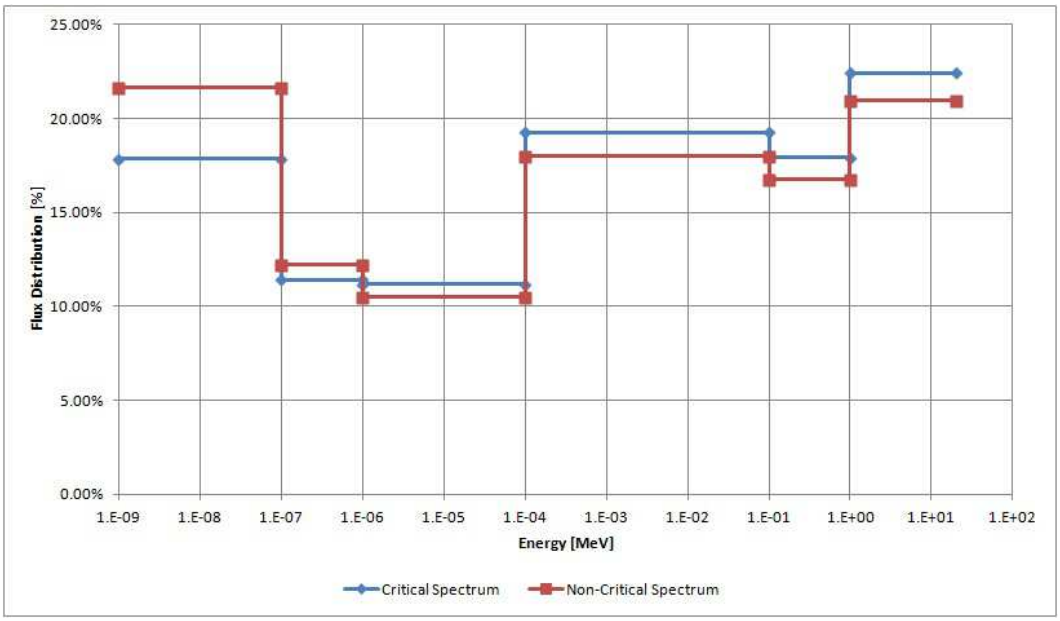


Fig. 4.14. Assembly Model Critical and Non-Critical Flux Spectrum Results.

As expected, the injected boron absorbed a portion of the thermal neutron flux to achieve criticality shown in Figure 4.14. The flux in the epithermal and fast energy ranges showed slight increases in magnitude. The fast energy flux appears to have similar magnitude to the thermal flux, however the size of the energy bins must also be considered in the analysis. The fast flux magnitude is sizable, but also has the largest energy bin width.

The burnup in each of the model's regions was also analyzed. The burnup in the inner fuel plates, outer fuel plates, and hole drilling locations were compared in Figure 4.15 to the non-critical simulation results.

The burnup in the inner and outer fuel plate regions was very similar between the two simulations. Due to absorptions at the top and bottom boundaries in boron, there was lower thermal flux and burnup in those regions in the critical spectrum model. Reflected neutrons in the upper and lower surrounding water have a much lower chance to cause fission upon reentering the fuel assembly area due to the boron.

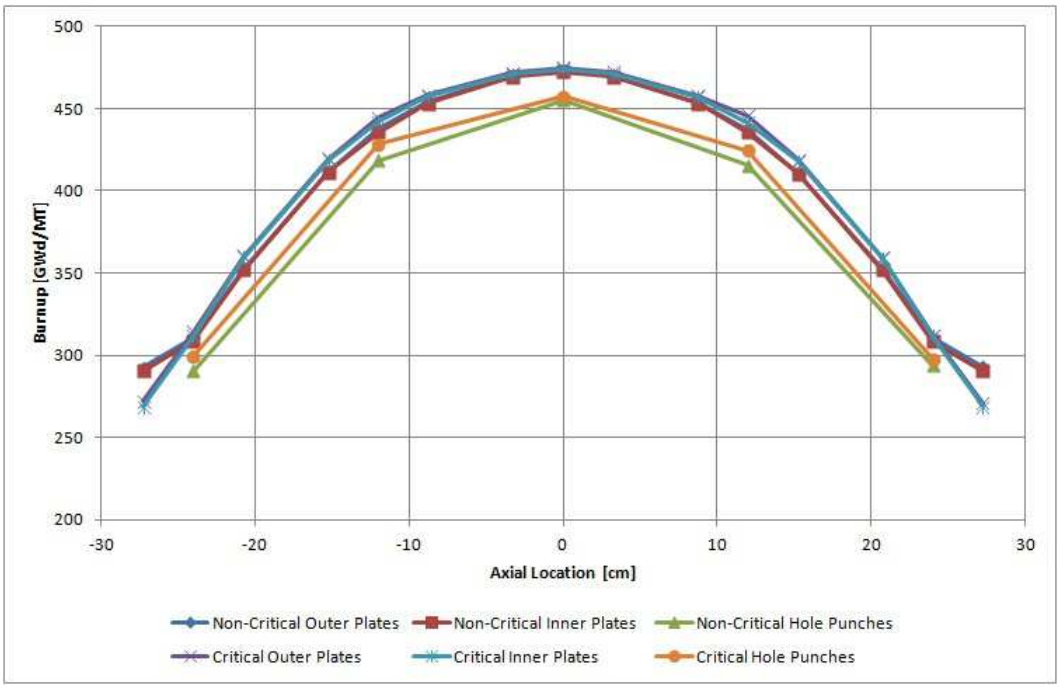


Fig. 4.15. Assembly Model Critical and Non-Critical Spectrum Burnup Results.

The resulting axial flux shape resembled a simulation with vacuum conditions due to suppressed neutron reflection. The overall axial flux shape remained very similar with slight flattening effects.

The burnup in the hole drilling locations were all consistently higher than the non-critical spectrum model. In the non-critical model, hole drilling locations have the lowest burnup in the radial burnup profile. Constant overall average radial burnup, but increased local burnup suggests there is flattening in the radial burnup profile. To examine this potential change, the model with the hole drilling locations at the edge of the fuel plates was run with the critical conditions. To preserve the same average radial burnup with increased burnup at the minimum, lower burnup at the edges was expected.

Table 4.6 shows the simulated hole punch burnup for the critical and non-critical simulations for models with both hole drilling locations. Due to the increased burnup

Table 4.6
Critical and Non-Critical Simulation Burnup Comparison.

Hole Punch	1	2	3	4	5
Axial Location [cm]	24.0	12.0	0.0	-12.0	-24.0
Non-Critical Standard Model Burnup [GWd/MTHM]	294	415	455	418	291
Critical Standard Model Burnup [GWd/MTHM]	298	424	457	428	300
Non-Critical Holes Moved Model [GWd/MTHM]	326	456	491	455	330
Critical Holes Moved Model [GWd/MTHM]	324	462	487	459	326

in the critical standard model with the center hole locations, a flatter radial burnup profile is suggested. The simulations with the hole drilling locations moved to the edge of the assembly do agree with those results for three of the drill locations. The combination of flattening axial and radial burnup distributions resulted in burnup increases in the second and fourth drill locations.

The output isotopic compositions were then compared between the critical and non-critical spectrum simulations. The output isotopic concentrations and simulation differences are in Table 4.7. A large quantity of Monte-Carlo histories was used in the simulations. The standard deviation in the output mass quantities is less than 1%.

For simple fission products and ^{235}U, there was negligible change in the results. The change for these isotopes was small enough not be distinguished from statistical variance and rounding effects. Some isotopes, such as heavier actinides, had more significant relative changes. The longer production chains produced larger differences between results too. Isotopes with complicated production chains, such as ^{148}Sm, also had significant differences. There are strong thermal absorbers involved in their production chain, which was directly affected by the change in flux spectrum. All of the isotopes considered for nuclear forensic signatures were unaffected by the change in spectrum. The change in ^{148}Sm would show up in ICP-MS results if chemical separations were not used. Isotopes such as ^{148}Sm are affected by reactor power

Table 4.7
Output Isotopic Composition Comparison Between Critical and Non-Critical Spectrum Simulations.

Isotope	Critical Spectrum Mass [g]	Non-Critical Spectrum Mass [g]	Percent Diff. [%]	Isotope	Critical Spectrum Mass [g]	Non-Critical Spectrum Mass [g]	Percent Diff. [%]
^{135}Cs	3.77E-01	3.65E-01	3.17%	^{238}Pu	4.56E-02	3.02E-02	40.73%
^{137}Cs	2.39E+00	2.39E+00	0.04%	^{239}Pu	3.57E-01	2.82E-01	23.58%
^{137}Ba	1.91E+00	1.91E+00	0.02%	^{240}Pu	8.40E-02	6.46E-02	26.19%
^{139}La	4.62E+00	4.61E+00	0.05%	^{241}Pu	1.31E-02	7.90E-03	49.40%
^{145}Nd	2.77E+00	2.79E+00	0.68%	^{242}Pu	8.30E-03	4.49E-03	59.64%
^{146}Nd	2.48E+00	2.47E+00	0.77%	^{244}Pu	7.73E-07	2.54E-07	101.15%
^{148}Nd	1.34E+00	1.34E+00	0.22%	^{241}Am	2.90E-02	1.75E-02	49.62%
^{148}Sm	1.67E-01	1.44E-01	14.91%	^{242}Am	9.91E-06	5.08E-06	64.38%
^{234}U	2.50E+00	2.57E+00	2.80%	^{243}Am	5.08E-04	2.07E-04	84.37%
^{235}U	1.42E+02	1.43E+02	0.66%	^{242}Cm	2.40E-08	1.23E-08	64.57%
^{236}U	2.47E+01	2.38E+01	3.47%	^{243}Cm	8.96E-07	3.95E-07	77.51%
^{238}U	1.58E+01	1.60E+01	1.36%	^{244}Cm	1.80E-05	5.66E-06	104.42%
^{237}Np	7.25E-01	5.37E-01	29.78%				

history, flux spectrum, and burnup. This dependence on multiple characteristics is not ideal for nuclear forensic signature for reconstruction of basic reactor parameters.

Another model to simulate critical depletion involves a full core simulation. For this particular reactor, boron is not inserted into the water to achieve criticality. With complicated core shuffling and frequent assembly movements, the isotopic composition of an individual assembly would have large variance due to too many unknowns. The average spent fuel assembly burnup across the entire core can be reproduced by burning the core as a whole.

Using MONTEBURNS or MCNPX/CINDER, the reactor dimensions and physical configuration cannot be altered through the duration of a simulation. A trick was performed using MONTEBURNS by stopping the simulation after every burn step and updating the control element height in a temporary file to preserve criticality. This process is time consuming, as it requires the user to actively monitor the simulation during the entire runtime duration.

A full core model was developed for ORR and consisted of a reactor of all fresh fuel. An image of the XY plane of the full core model is in Figure 4.16. There is a

large surrounding sphere of water which is cropped in the image. The green material represents beryllium reflector elements, the yellow material represents an aluminum core enclosure, and the purple material is water. The fuel followed control elements are located at core positions D2, D4, D6, E2, E4, and E6.

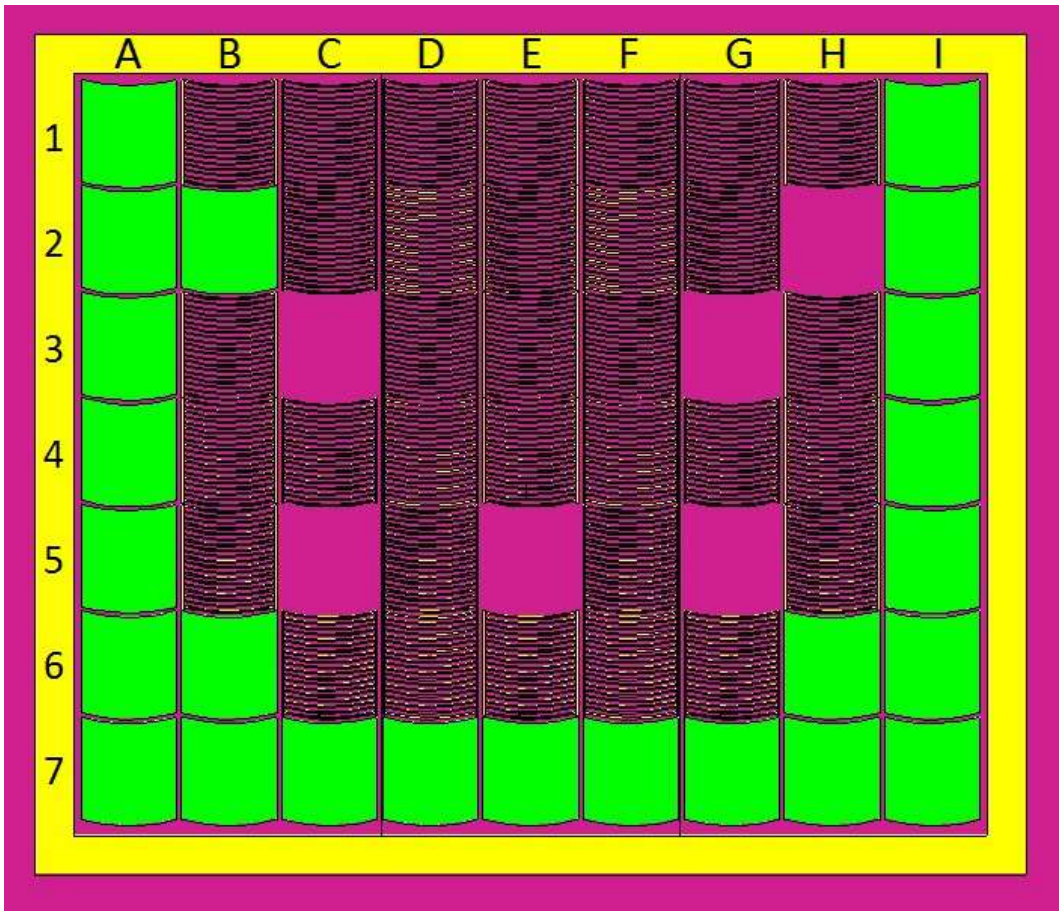


Fig. 4.16. ORR Full Core Model XY Plane at Z=0.

The system k-effective was forced to be 1.00 ± 1.0% and the output isotopic compositions were normalized per assembly for comparison. The simulation's k-effective results are in Table 4.8. Steps 6, 12, 18, 24, and 30 duplicate their previous step's results because they are decay steps. The resulting control rod locations were unrealistic. The full core of fresh fuel achieved criticality with the control rods 88.3%

inserted. At end of life, the control elements had to be extracted to a level of 3.3% insertion to achieve criticality. This drastic change in control element location could significantly alter the flux spectrum through the fuel's life.

Table 4.8
k_{eff} Results From Full Core Critical Spectrum Simulation.

Burnup Step	k_{eff}	Burnup Step	k_{eff}	Burnup Step	k_{eff}
0	1.01232	11	0.99837	22	0.99632
1	0.9981	12	0.99837	23	0.99479
2	0.9917	13	0.99535	24	0.99479
3	1.00164	14	0.99768	25	0.99592
4	1.00483	15	0.99877	26	0.99965
5	1.00272	16	0.99822	27	1.00418
6	1.00272	17	0.99236	28	0.99424
7	0.99374	18	0.99236	29	0.9933
8	0.99664	19	0.99438	30	0.9933
9	1.00551	20	0.99487		
10	1.00166	21	1.00088		

The spent fuel results accounted for all 33 fuel assemblies, which includes 27 standard assemblies and 6 fuel followed control assemblies. The results were normalized per assembly for comparison to previous simulations and documentation. The resulting spent fuel uranium compositions are in Table 4.9.

Table 4.9
Full Core Simulation Fuel Compositions

Result	^{234}U	^{235}U	^{236}U	^{238}U
Core Mass [g]	84.8	4,420	85.8	52.9
Assembly Mass [g]	2.57	134.0	26.0	16.0
Atom Percent [%]	1.44	75.0	14.6	9.98

The spent fuel uranium compositions for the critical full core model were similar to an individual assembly with the same burnup. The spent fuel ^{235}U was closer

to the measured results than most of the previous simulations. The full core ^{236}U concentration better represented the measured data than some of the simulations, but was still lower than the measured values.

The core flux spectrum was then compared to the critical spectrum assembly model. The assembly model consisted of 35 different burnable regions. Each region had a flux spectrum, which were all weighed averaged. The full core model only consisted of one burnable region and was compared to the assembly average.

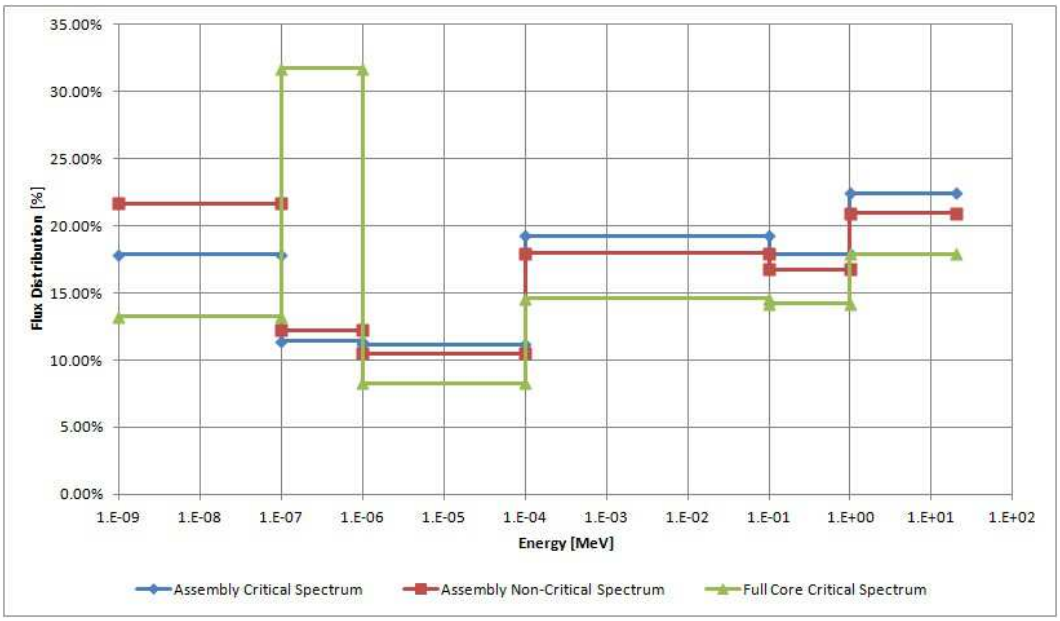


Fig. 4.17. Full Core Critical Spectrum Comparison.

Due to the flux normalization built into the results, the sum of all the flux bins totals to 100%. At the end of life, there was a much larger flux in the 0.1-1.0eV range in the full core model. The remaining flux groups were all lower in relative quantity as shown in Figure 4.17. For better comparison, the total flux magnitute was compared. In the full core model from beginning to end of life, the system flux ranged from 4.65×10^{14} to 6.81×10^{14} [n/cm^2-s]. The flux in the assembly model ranged from 3.85×10^{14} to 1.05×10^{15} [n/cm^2-s] depending on region and burnup. Individual

materials within the assembly model were more consistent through the assembly life than the full core model.

Isotopic ratios of nuclear forensic signature isotopes were compared to previous simulations and measured results. The previously discussed simulation results were compared to the critical full core model in Table 4.10. For the signatures involved in this work, there was no difference between the critical full core model and the assembly level models.

Table 4.10
Full Core Critical Depletion Fission Product Isotopic Ratio Results

	Isotopic Ratio [vs. ^{238}U]				
Code	137	139	145	146	148
Measured Sample Average	0.557	0.585	0.343	0.286	0.181
ORIGEN 2.2 (Thermal XS)	0.478	0.503	0.299	0.240	0.139
ORIGEN 2.2 (MTR XS)	0.493	0.518	0.302	0.254	0.156
MONTEBURNS Basic	0.493	0.521	0.302	0.266	0.157
MONTEBURNS Detailed	0.492	0.520	0.301	0.266	0.158
MCNPX/CINDER Basic	0.496	0.506	0.301	0.254	0.154
MCNPX/CINDER Detailed	0.496	0.506	0.300	0.254	0.155
MONTEBURNS Full Core	0.492	0.518	0.301	0.263	0.156

5. REACTOR PARAMETER RECONSTRUCTION METHOD

There are several applicable methods in which reactor parameters may be reconstructed from spent fuel radiochemistry analytical results. These range from simple analytic calculations to posing it as an optimization problem and using either continuous or discrete techniques.

When utilizing continuous optimization techniques, input parameters such as sample isotopic composition, material form and material quantity may be used to reconstruct reactor parameters in the continuous solution space to identify original (pre-irradiation) characteristics of the sample. In methods using discrete techniques, solutions are limited to the closest entry in a predefined solution space. An example of a discrete method would be to calculate a few parameters analytically and then to apply a database search algorithm for the closest match to those parameters. Potential benefits and limitations from both methods exist. If a discrete method were employed, the possibility exists that the unknown item was not in the solution space. If a continuous method were used, solution uniqueness is not guaranteed and uncertainty far worsens the problem [29, 30]. An optimal arrangement would likely involve using both methods independently and comparing results.

The method developed in this analysis involves a series of analytical and numerical methods to reconstruct a spent fuel sample's burnup, initial uranium isotopic composition, and cooling time. The process is outlined in Figure 5.1.

5.1 Analytic Iterative Burnup Reconstruction

Spent fuel burnup is defined as the amount of energy produced per initial unit mass of heavy metal fuel. This is most commonly reported in units of MWd/MTU. For research reactors, burnup is often reported as a percentage of the initial ^{235}U load. For example a reactor starting with 100g ^{235}U and ending with 60g ^{235}U would

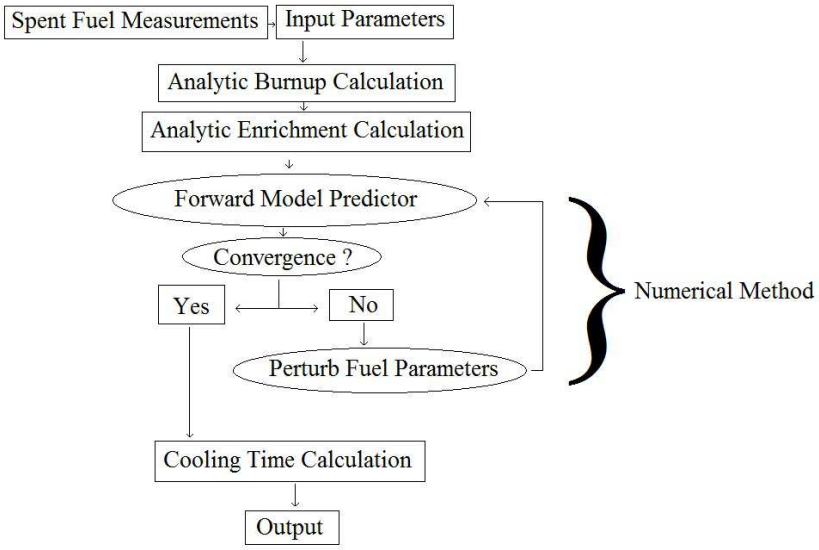


Fig. 5.1. Flowchart of Reactor Parameter Reconstruction Method.

be referred to as having a 40% burnup. In an inverse analysis, the initial heavy metal fuel load is unknown, so standard burnup units are used.

Burnup reconstruction begins by calculating the fission reaction rate, RR_f, using:

$$\begin{aligned} RR_f(t) &= N^{U235}(t)\int_0^\infty \sigma_f^{U235}(E)\phi(E,t)dE + N^{U238}(t)\int_0^\infty \sigma_f^{U238}(E)\phi(E,t)dE \\ &\quad + N^{Pu239}(t)\int_0^\infty \sigma_f^{Pu239}(E)\phi(E,t)dE + N^{Pu240}(t)\int_0^\infty \sigma_f^{Pu240}(E)\phi(E,t)dE \\ &\quad + \cdots \end{aligned} \tag{5.1}$$

where $N^{U235}(t)$ is the ^{235}U atom concentration, $\sigma_f^{U235}(E)$ is the fission cross section for ^{235}U, and $\phi(E,t)$ is the neutron flux.

Equation 5.1 extends for all fissioning isotopes. It can be simplified by integrating over energy, collapsing to one group fluxes and cross sections:

$$RR_f(t) = N^{U235}(t)\bar{\sigma}_f^{U235}\bar{\phi}(t) + N^{U238}(t)\bar{\sigma}_f^{U238}\bar{\phi}(t) + N^{Pu238}(t)\bar{\sigma}_f^{Pu239}\bar{\phi}(t) + \cdots \quad (5.2)$$

where $\bar{\sigma}_f^{U235}$ is the one group fission cross section for ^{235}U, and $\bar{\phi}(t)$ is the one group neutron flux.

This reaction rate, RR_f, is then converted to specific power, $P_s(t)$ using the average recoverable energy per fission, E_R, and the initial density of the uranium in the fuel ρ_0^U:

$$\begin{aligned} P_s(t) &= \frac{E_R}{\rho_0^U}\left[N^{U235}(t)\bar{\sigma}_f^{U235}\bar{\phi}(t) + N^{U238}(t)\bar{\sigma}_f^{U238}\bar{\phi}(t)\right. \\ &\quad \left. + N^{Pu239}(t)\bar{\sigma}_f^{Pu239}\bar{\phi}(t) + \cdots\right]. \end{aligned} \quad (5.3)$$

The fuel's burnup is the integral of the specific power over time which is given by:

$$\begin{aligned} BU(T) &= \frac{E_R}{\rho_0^U}\int_0^T \left[N^{U235}(t)\bar{\sigma}_f^{U235}\bar{\phi}(t) + N^{U238}(t)\bar{\sigma}_f^{U238}\bar{\phi}(t)\right. \\ &\quad \left. + N^{Pu239}(t)\bar{\sigma}_f^{Pu239}\bar{\phi}(t) + N^{Pu240}(t)\bar{\sigma}_f^{Pu240}\bar{\phi}(t) + \cdots\right] dt. \end{aligned} \quad (5.4)$$

The collapsed one-group cross sections can be time independent, yielding:

$$BU(T) = \frac{E_R}{\rho_0^U}\left[\bar{\sigma}_f^{U235}\int_0^T N^{U235}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{Pu239}\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt + \cdots\right]. \quad (5.5)$$

Let us now consider a balance equation for burnup monitor isotope N^B as defined by:

$$\frac{dN^B(t)}{dt} = N^B(t)\int_0^\infty \bar{\sigma}_a^B\bar{\phi}(t)dE - \lambda^B N^B(t) + N^{U235}(t)\int_0^\infty \bar{\sigma}_f^{U235}Y_B^{U235}\bar{\phi}(t)dE + N^{Pu239}(t)\int_0^\infty \bar{\sigma}_f^{Pu239}Y_B^{Pu239}\bar{\phi}(t)dE + \cdots \quad (5.6)$$

where Y_B^{U235} is the fission yield for isotope B from parent ^{235}U, λ_B is the decay constant for isotope B, and $N_B(t)$ is the atom concentration for isotope B.

An ideal burnup monitor would have a low neutron absorption cross section and be stable or beta decay directly into a stable isotope. It would also need fission yields with minimal energy dependence, so changes in a reactor's spectrum would not affect yields for isotope N^B. It would also be such that the cumulative yield for isotope N^B is the same for all fission sources. Under these assumptions, Equation 5.6 simplifies to:

$$\frac{dN^B(t)}{dt} = Y_B\left[N^{U235}(t)\bar{\sigma}_f^{U235}\bar{\phi}(t) + N^{Pu239}(t)\bar{\sigma}_f^{Pu239}\bar{\phi}(t) + \cdots\right]. \quad (5.7)$$

Converting Equation 5.7 into an integral equation over time and assuming the initial concentration for burnup monitor isotope N^B is zero:

$$N^B(T) = Y_B\left[\bar{\sigma}_f^{U235}\int_0^T N^{U235}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{Pu239}\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt + \cdots\right]. \quad (5.8)$$

Substituting burnup Equation 5.5 into Equation 5.8 yields:

$$N^B(T) = \frac{\rho_0^U}{E_R}Y_B BU(T). \quad (5.9)$$

By expressing the mass density in terms of atom density and solving for $BU(T)$, we get:

$$BU(T) = \frac{N^B(T) N_a E_R}{N_0^U M_U Y_B}. \tag{5.10}$$

where N_a is Avogadro's constant, E_R is the average recoverable energy per fission, M_U is the average molecular mass for uranium in the sample, and N_0^U is the initial uranium atom concentration. After expressing N^B as a ratio to the ^{238}U atom concentration at the time of measurement, Equation 5.10 is expressed as:

$$BU(T) = \left[\frac{N^B(T)}{N^{U238}(T)}\right]\left[\frac{N^{U238}(T)}{N_0^U}\right]\left[\frac{N_a E_R}{M_U Y_B}\right], \tag{5.11}$$

where $\frac{N^B(T)}{N^{U238}(T)}$ is measured by mass spectrometry and N_a, E_R, and Y_B are constants. The final term $\frac{N^{U238}(T)}{N_0^U}$ is not known and must be solved for iteratively with $BU(T)$.

The initial uranium atom density, N_0^U, can be expressed as the final uranium atom density and the sum of all the absorption reactions that occurred with uranium atoms. With only neutron induced fission and neutron capture, N_0^U can be expressed as:

$$\begin{aligned} N_0^U &= N^{U234}(T) + N^{U235}(T) + N^{U236}(T) + N^{U238}(T) + RR_\gamma^{U234} \\ &\quad + RR_f^{U235} + RR_f^{U236} + RR_\gamma^{U236} + RR_f^{U238} + RR_\gamma^{U238} \end{aligned} \tag{5.12}$$

Radiative capture interactions for ^{234}U and ^{235}U are not losses, but conversions to other accounted for uranium isotopes. Capture interactions are primarily associated with ^{238}U. $N^{U236}(T)$ consists of $N^{U236}(0) + \bar{\sigma}_\gamma^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt$ and alpha decay from ^{240}Pu. Since the decay time is unknown, the production from alpha decay is ignored. The total absorption reaction rate for ^{235}U is given by:

$$RR^{U235} = \bar{\sigma}_f^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt + \bar{\sigma}_\gamma^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt \tag{5.13}$$

Radiative capture reaction rate terms are then expressed as the sum of the physically measurable products and fissions. Thus for ^{235}U we have:

$$\begin{aligned}\bar{\sigma}_{\gamma}^{U235}\int_0^T N^{U235}(t)\bar{\phi}(t)dt &= N^{U236}(T) - N^{U236}(0) + \bar{\sigma}_f^{U236}\int_0^T N^{U236}(t)\bar{\phi}(t)dt \\ &+N^{Np237}(T) + \bar{\sigma}_f^{Np237}\int_0^T N^{Np237}(t)\bar{\phi}(t)dt + N^{Pu238}(T) \\ &+\bar{\sigma}_f^{Pu238}\int_0^T N^{Pu238}(t)\bar{\phi}(t)dt \qquad (5.14)\end{aligned}$$

For ^{238}U we have:

$$\begin{aligned}\bar{\sigma}_{\gamma}^{U238}\int_0^T N^{U238}(t)\bar{\phi}(t)dt &= N^{Pu239}(T) + \bar{\sigma}_f^{Pu239}\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt \\ &N^{Pu240}(T) + \bar{\sigma}_f^{Pu240}\int_0^T N^{Pu240}(t)\bar{\phi}(t)dt \\ &N^{Pu241}(T) + \bar{\sigma}_f^{Pu241}\int_0^T N^{Pu241}(t)\bar{\phi}(t)dt + \cdot\cdot (5.15)\end{aligned}$$

There are several assumptions embedded into the reaction rate equations. The radiative capture reaction rate of ^{234}U is zero and ^{234}U is only produced from α decay from ^{238}Pu. ^{238}U radiative captures are assumed to decay instantly to ^{239}Pu. The initial enrichment of the fuel determines what portion of the produced ^{238}Pu is from the radiative capture chain in ^{235}U and what portion is produced from $(n, 2n)$ reactions with ^{239}Pu. ORIGEN 2.2 predictors show that in weapons grade HEU fueled reactors, a significant portion of the ^{238}Pu is produced from the ^{235}U radiative capture chain. By substituting the fission rate terms for $BU(T)$ with their expanded integrals, Equation 5.12 can be rewritten as:

$$
\begin{aligned}
N_0^U &= N^{U234}(T) + N^{U235}(T) + N^{U236}(T) + N^{U238}(T) + N^{Np237}(T) + N^{Pu238}(T) \\
&+ N^{Pu239}(T) + N^{Pu240}(T) + \bar{\sigma}_f^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt \\
&+ \bar{\sigma}_f^{U236} \int_0^T N^{U236}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{U238} \int_0^T N^{U238}(t)\bar{\phi}(t)dt \\
&+ \bar{\sigma}_f^{Pu238} \int_0^T N^{Pu238}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{Pu239} \int_0^T N^{Pu239}(t)\bar{\phi}(t)dt \\
&+ \bar{\sigma}_f^{Pu240} \int_0^T N^{Pu240}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{Pu241} \int_0^T N^{Pu241}(t)\bar{\phi}(t)dt. \qquad (5.16)
\end{aligned}
$$

Then substituting the sum of the fission integrals with Equation 5.5 yields:

$$
\begin{aligned}
N_0^U &= N^{U234}(T) + N^{U235}(T) + N^{U236}(T) + N^{U238}(T) + N^{Np237}(T) + N^{Pu238}(T) \\
&+ N^{Pu239}(T) + N^{Pu240}(T) + \frac{\rho_0^U}{E_R} BU(T). \qquad (5.17)
\end{aligned}
$$

The uranium mass density is then expressed in terms of atom density and by dividing both sides of Equation 5.17 by the measured ^{238}U atom concentration an equation for $\frac{N_0^U}{N^{U238}(T)}$ is formed:

$$
\frac{N_0^U}{N^{U238}(T)} = \frac{N^U(T)}{N^{U238}(T)} + \frac{N^{Pu239}(T)}{N^{U238}(T)} + \frac{N^{Pu240}(T)}{N^{U238}(T)} + \cdots + \frac{N_0^U}{N^{U238}(T)} \frac{M_0^U BU(T)}{N_a E_R} \qquad (5.18)
$$

By combining like terms and solving for $\frac{N_0^U}{N^{U238}(T)}$, we acquire:

$$
\left[\frac{N_0^U}{N^{U238}(T)}\right] = \frac{\left[\frac{N^U(T)}{N^{U238}(T)}\right] + \left[\frac{N^{Np237}(T)}{N^{U238}(T)}\right] + \left[\frac{N^{Pu239}(T)}{N^{U238}(T)}\right] + \left[\frac{N^{Pu240}(T)}{N^{U238}(T)}\right] + \cdots}{1 - \frac{M_0^U BU(T)}{N_a E_R}} \qquad (5.19)
$$

A system of two equations (Equations 5.11 and 5.19) and two unknowns [$BU(T)$ and $\frac{N_0^U}{N^{U238}(T)}$] is established. Due to the nonlinearity of the system, an iterative method is used to solve this. The iteration process begins by solving for $\frac{N_0^U}{N^{U238}(T)}$ with an initial guess of $BU(T) = 0$. Alternating steps between Equations 5.11 and 5.19 converge after several steps. Larger burnup and higher enrichment lead to slower convergence, but the method is stable regardless.

5.2 Analytic Initial Enrichment Calculation

After a sample's burnup is reconstructed, its initial ^{235}U enrichment can be calculated. This is done by calculating the initial ^{235}U concentration based on fissioned, transmuted, and measured contributions. To analytically reconstruct a sample's initial ^{235}U enrichment, an equation for the initial atom concentration of ^{235}U is established:

$$N_0^{U235} = N^{U235}(T) + \bar{\sigma}_f^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt + \bar{\sigma}_\gamma^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt. \quad (5.20)$$

After expanding the radiative capture integral into its products (^{236}U, ^{237}Np, and ^{238}Pu) and ignoring the fissions of those products, we acquire:

$$\begin{aligned} N_0^{U235} &= N^{U235}(T) + N^{U236}(T) - N^{U236}(0) + N^{Np237}(T) \\ &\quad + N^{Pu238}(T) + \bar{\sigma}_f^{U235} \int_0^T N^{U235}(t)\bar{\phi}(t)dt \end{aligned} \quad (5.21)$$

^{237}Np is also produced from α decay from ^{241}Am, and ^{238}Pu is also produced from $(n, 2n)$ from ^{239}Pu and α decay from ^{242}Cm. The quantities of these isotopes is assumed to be negligible. Upon substitution of Equation 5.5 for the ^{235}U fission integral in Equation 5.21, we acquire:

$$
\begin{aligned}
N_0^{U235} &= N^{U235}(T) + N^{U236}(T) - N^{U236}(0) + \frac{\rho_0^U}{E_R} BU(T) \\
&\quad - \left[\bar{\sigma}_f^{U238} \int_0^T N^{U238}(t) \bar{\phi}(t) dt \right] \\
&\quad - \left[\bar{\sigma}_f^{Pu239} \int_0^T N^{Pu239}(t) \bar{\phi}(t) dt + \cdots \right]
\end{aligned} \tag{5.22}
$$

Equation 5.22 is then divided by the initial uranium atom density, N_0^U, to get:

$$
\begin{aligned}
\frac{N_0^{U235}}{N_0^U} &= e_0 = \frac{N^{U235}(T)}{N_0^U} + \frac{N^{U236}(T)}{N_0^U} - \frac{N^{U236}(0)}{N_0^U} + \frac{\rho_0^U BU(T)}{E_R N_0^U} \\
&\quad - \frac{1}{N_0^U} \left[\bar{\sigma}_f^{U238} \int_0^T N^{U238}(t) \bar{\phi}(t) dt + \bar{\sigma}_f^{Pu239} \int_0^T N^{Pu239}(t) \bar{\phi}(t) dt \right. \\
&\quad \left. + \bar{\sigma}_f^{Pu240} \int_0^T N^{Pu240}(t) \bar{\phi}(t) dt + \bar{\sigma}_f^{Pu241} \int_0^T N^{Pu241}(t) \bar{\phi}(t) dt \right]
\end{aligned} \tag{5.23}
$$

where e_0 is the fuel's initial enrichment. The fission rate integrals are expanded next, beginning with a balance equation for ^{238}U:

$$
\frac{dN^{U238}(t)}{dt} = -N^{U238}(t) \bar{\sigma}_a^{U328}. \tag{5.24}
$$

Note that ^{238}U production from ^{242}Pu is ignored. In integral form, this is:

$$
N^{U238}(T) - N_0^{U238} = -\bar{\sigma}_a^{U328} \int_0^T N^{U238}(t) \bar{\phi}(t) dt. \tag{5.25}
$$

Solving for the integral yields:

$$
\int_0^T N^{U238}(t) \bar{\phi}(t) dt = \frac{1}{\bar{\sigma}_a^{U238}} \left[N_0^{U238} - N^{U238}(T) \right]. \tag{5.26}
$$

This integral equation can be substituted into Equation 5.23 to acquire:

$$\begin{aligned}\frac{N_0^{U235}}{N_0^U} &= e_0 = \frac{N^{U235}(T)}{N_0^U} + \frac{N^{U236}(T)}{N_0^U} - \frac{N^{U236}(0)}{N_0^U} + \frac{\rho_0^U BU(T)}{E_R N_0^U} \\ &\quad -\frac{1}{N_0^U}\left[\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U238}}\left(N_0^{U238} - N^{U238}(T)\right) + \bar{\sigma}_f^{Pu239}\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt\right. \\ &\quad \left. +\bar{\sigma}_f^{Pu240}\int_0^T N^{Pu240}(t)\bar{\phi}(t)dt + \bar{\sigma}_f^{Pu241}\int_0^T N^{Pu241}(t)\bar{\phi}(t)dt\right] \end{aligned} \quad (5.27)$$

The ^{239}Pu integral is evaluated next beginning with the balance equation:

$$\frac{dN^{Pu239}(t)}{dt} = N^{U238}(t)\bar{\sigma}_\gamma^{U328} - N^{Pu239}(t)\bar{\sigma}_a^{Pu239}. \quad (5.28)$$

In integral form, this is

$$N^{Pu239}(T) - N_0^{Pu239} = \bar{\sigma}_\gamma^{U238}\int_0^T N^{U238}(t)\bar{\phi}(t)dt - \bar{\sigma}_a^{Pu239}\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt. \quad (5.29)$$

Solving for the ^{239}Pu integral and substituting Equation 5.26 in for the ^{238}U integral yields:

$$\int_0^T N^{Pu239}(t)\bar{\phi}(t)dt = \frac{1}{\bar{\sigma}_a^{Pu239}}\left[N_0^{Pu239} - N^{Pu239}(T) - \frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U328}}\left(N_0^{U238} - N^{U238}(T)\right)\right]. \quad (5.30)$$

The ^{240}Pu integral is evaluated next beginning with the balance equation:

$$\frac{N^{Pu240}(t)}{dt} = N^{Pu239}(t)\bar{\sigma}_\gamma^{Pu239} - N^{Pu240}(t)\bar{\sigma}_a^{Pu240}. \quad (5.31)$$

In integral form, this is:

$$N^{Pu240}(T) - N_0^{Pu240} = \bar{\sigma}_\gamma^{Pu239} \int_0^T N^{Pu239}(t)\bar{\phi}(t)dt - \bar{\sigma}_a^{Pu240} \int_0^T N^{Pu240}(t)\bar{\phi}(t)dt. \quad (5.32)$$

Solving for the ^{240}Pu integral and substituting Equation 5.30 in for the ^{239}Pu integral yields:

$$\int_0^T N^{Pu240}(t)\bar{\phi}(t)dt = \frac{1}{\bar{\sigma}_a^{Pu240}} \left[N_0^{Pu240} - N^{Pu240}(T) + X^{239}\right], \quad (5.33)$$

where,

$$X^{239} \equiv \frac{\bar{\sigma}_\gamma^{Pu239}}{\bar{\sigma}_a^{Pu239}} \left[N_0^{Pu239} - N^{Pu239}(T) + \frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U238}} \left[N_0^{U238} - N^{U238}(T)\right]\right]. \quad (5.34)$$

Lastly, the ^{241}Pu integral is evaluated beginning with the balance equation:

$$\frac{dN^{Pu241}(t)}{dt} = N^{Pu240}(t)\bar{\sigma}_\gamma^{Pu240} - N^{Pu241}(t)\bar{\sigma}_a^{Pu241}. \quad (5.35)$$

In integral form, this is:

$$N^{Pu241}(T) - N_0^{Pu241} = \bar{\sigma}_\gamma^{Pu240} \int_0^T N^{Pu240}(t)\bar{\phi}(t)dt - \bar{\sigma}_a^{Pu241} \int_0^T N^{Pu241}(t)\bar{\phi}(t)dt. \quad (5.36)$$

Solving for the ^{241}Pu integral and substituting Equation 5.33 in for the ^{240}Pu integral yields:

$$\int_0^T N^{Pu241}(t)\bar{\phi}(t)dt = \frac{1}{\bar{\sigma}_a^{Pu241}} \left[N_0^{Pu241} - N^{Pu241}(T) + X^{240}\right], \quad (5.37)$$

where,

$$X^{240} \equiv \frac{\bar{\sigma}_{\gamma}^{Pu240}}{\bar{\sigma}_{a}^{Pu240}} \left[N_0^{Pu240} - N^{Pu240}(T) + X^{239} \right]. \tag{5.38}$$

Substituting all the simplified integrals (Equations 5.26, 5.30, 5.33, and 5.37) back into Equation 5.23:

$$\begin{aligned}
\frac{N_0^{U235}}{N_0^U} &= e_0 = \frac{N^{U235}(T)}{N_0^U} + \frac{N^{U236}(T)}{N_0^U} - \frac{N^{U236}(0)}{N_0^U} + \frac{\rho_0^U BU(T)}{E_R N_0^U} \\
&\quad -\frac{1}{N_0^U}\left[\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}\left(N_0^{U238} - N^{U238}(T)\right)\right] \\
&\quad -\frac{1}{N_0^U}\left[\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left(N_0^{Pu239} - N^{Pu239}(T) + \frac{\bar{\sigma}_{\gamma}^{U238}}{\bar{\sigma}_a^{U328}}\left(N_0^{U238} - N^{U238}(T)\right)\right)\right] \\
&\quad -\frac{1}{N_0^U}\left[\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left(N_0^{Pu240} - N^{Pu240}(T) + X^{239}\right)\right] \\
&\quad -\frac{1}{N_0^U}\left[\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\left(N_0^{Pu241} - N^{Pu241}(T) + X^{240}\right)\right]
\end{aligned} \tag{5.39}$$

The plutonium initial isotopic concentrations are assumed to be zero. The term $\frac{1}{N_0^U}$ is passed through its associated terms to form isotopic ratios.

$$\begin{aligned}
\frac{N_0^{U235}}{N_0^U} &= e_0 = \frac{N^{U235}(T)}{N_0^U} + \frac{N^{U236}(T)}{N_0^U} - \frac{N^{U236}(0)}{N_0^U} + \frac{\rho_0^U BU(T)}{E_R N_0^U} \\
&\quad -\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}\left(\frac{N_0^{U238}}{N_0^U} - \frac{N^{U238}(T)}{N_0^U}\right) \\
&\quad -\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left(-\frac{N^{Pu239}(T)}{N_0^U} + \frac{\bar{\sigma}_{\gamma}^{U238}}{\bar{\sigma}_a^{U328}}\left[\frac{N_0^{U238}}{N_0^U} - \frac{N^{U238}(T)}{N_0^U}\right]\right) \\
&\quad -\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left(-\frac{N^{Pu240}(T)}{N_0^U} + \frac{X^{239}}{N_0^U}\right) \\
&\quad -\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\left(-\frac{N^{Pu241}(T)}{N_0^U} + \frac{X^{240}}{N_0^U}\right)
\end{aligned} \tag{5.40}$$

The term $\frac{N^{U238}(T)}{N^{U238}(T)}$ is applied to the atom concentrations in Equation 5.40 to form measurable isotopic ratios and the known $\frac{N^{U238}(T)}{N_0^U}$:

$$\begin{aligned} e_0 &= \frac{N^{U238}(T)}{N_0^U}\left[\frac{N^{U235}(T)}{N^{U238}(T)}+\frac{N^{U236}(T)}{N^{U238}(T)}\right]-\frac{N^{U236}(0)}{N_0^U}+\frac{\rho_0^U BU(T)}{E_R N_0^U} \\ &-\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}\left(\frac{N_0^{U238}}{N_0^U}-\frac{N^{U238}(T)}{N_0^U}\right) \\ &-\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left(-\frac{N^{Pu239}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U328}}\left[\frac{N_0^{U238}}{N_0^U}-\frac{N^{U238}(T)}{N_0^U}\right]\right) \\ &-\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left(-\frac{N^{Pu240}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{X^{239}}{N_0^U}\right) \\ &-\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\left(-\frac{N^{Pu241}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{X^{240}}{N_0^U}\right) \end{aligned} \tag{5.41}$$

The unknown term $\frac{N_0^{U238}}{N_0^U}$ is replaced by subtracting the remaining uranium isotopes from unity:

$$\frac{N_0^{U238}}{N_0^U}=1-e_0-\frac{N_0^{U234}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}-\frac{N_0^{U236}}{N_0^U} \tag{5.42}$$

Since $N^{U234}(T)\approx N_0^{U234}$ and is directly measurable by mass spectrometry, $N^{U234}(T)$ is used instead of N_0^{U234}:

$$\frac{N_0^{U238}}{N_0^U}=1-e_0-\frac{N^{U234}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}-\frac{N_0^{U236}}{N_0^U}. \tag{5.43}$$

N_0^{U236} is much different than $N^{U236}(T)$. N_0^{U236} is assumed to be zero on the first iteration of enrichment calculation. N_0^{U236} may be updated later using a predictor calculation and iteratively updated comparing $\frac{N^{U236}(T)}{N^{U238}(T)}$to mass spectrometry results. Equation 5.39 can be rewritten as:

$$e_0 = \frac{N^{U238}(T)}{N_0^U}\left[\frac{N^{U235}(T)}{N^{U238}(T)}+\frac{N^{U236}(T)}{N^{U238}(T)}\right]-\frac{N_0^{U236}}{N_0^U}+\frac{M_U BU(T)}{E_R N_0^U} - \frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}\left[W^{238}\right]-\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left[W^{239}\right]-\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left[W^{240}\right]-\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\left[W^{241}\right] \quad (5.44)$$

where,

$$W^{238} = 1 - e_0 - \frac{N^{U234}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}-\frac{N_0^{U236}}{N_0^U}-\frac{N^{U238}(T)}{N_0^U}, \quad (5.45)$$

$$W^{239} = -\frac{N^{Pu239(T)}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U238}}\left[W^{238}\right], \quad (5.46)$$

$$W^{240} = -\frac{N^{Pu240(T)}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left[W^{239}\right], \quad (5.47)$$

$$W^{241} = -\frac{N^{Pu241(T)}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left[W^{240}\right]. \quad (5.48)$$

Equation 5.44 is then solved for e_0 by grouping like terms and simplifying,

$$e_0 = \frac{\left[Z^{235}\right]-\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}\left[Z^{238}\right]-\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left[Z^{239}\right]-\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\left[Z^{240}\right]-\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\left[Z^{241}\right]}{1-\frac{\bar{\sigma}_f^{U238}}{\bar{\sigma}_a^{U328}}-\frac{\bar{\sigma}_f^{Pu239}}{\bar{\sigma}_a^{Pu239}}\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U328}}-\frac{\bar{\sigma}_f^{Pu240}}{\bar{\sigma}_a^{Pu240}}\frac{\bar{\sigma}_\gamma^{Pu239}}{\bar{\sigma}_a^{Pu239}}\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U328}}-\frac{\bar{\sigma}_f^{Pu241}}{\bar{\sigma}_a^{Pu241}}\frac{\bar{\sigma}_\gamma^{Pu240}}{\bar{\sigma}_a^{Pu240}}\frac{\bar{\sigma}_\gamma^{Pu239}}{\bar{\sigma}_a^{Pu239}}\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U328}}}, \quad (5.49)$$

where,

$$Z^{235} = \frac{N^{U238}(T)}{N_0^U}\left[\frac{N^{U235}(T)}{N^{U238}(T)}+\frac{N^{U236}(T)}{N^{U238}(T)}\right]-\frac{N_0^{U236}(T)}{N_0^U}+\frac{M_U BU(T)}{E_R N_0^U} \quad (5.50)$$

$$Z^{238} = 1 - \frac{N^{U234}(T)}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}-\frac{N_0^{U236}(T)}{N_0^U}-\frac{N^{U238}(T)}{N_0^U}, \quad (5.51)$$

$$Z^{239} = -\frac{N^{Pu239(T)}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{U238}}{\bar{\sigma}_a^{U238}}\left[Z^{238}\right], \quad (5.52)$$

$$Z^{240} = -\frac{N^{Pu240(T)}}{N^{U238}(T)}\frac{N^{U238}(T)}{N_0^U}+\frac{\bar{\sigma}_\gamma^{Pu239}}{\bar{\sigma}_a^{Pu239}}\left[Z^{239}\right], \quad (5.53)$$

$$Z^{241} = -\frac{N^{Pu241(T)}}{N^{U238}(T)} \frac{N^{U238}(T)}{N_0^U} + \frac{\bar{\sigma}_\gamma^{Pu240}}{\bar{\sigma}_a^{Pu240}} \left[Z^{240}\right]. \tag{5.54}$$

A large number of assumptions are embedded into the analytic methods which are summarized below:

- The burnup monitor isotope is stable
- The absorption rate of the burnup monitor isotope is negligible
- The initial isotopic concentration of the burnup monitor isotope is zero
- The cumulative fission yield for the burnup monitor isotope is the same for all fission sources
- ^{234}U radiative capture rate is assumed to be zero
- ^{238}U captures decay instantly to ^{239}Pu
- The only fissile isotopes for reconstructing enrichment are: ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, and ^{241}Pu
- (n,2n), (n,3n) fast reactions are ignored for actinides due to their low probability and contribution

5.3 Initial Uranium Isotopic Composition and Burnup Convergence

Prior to proceeding to the analytic cooling time reconstruction, the initial uranium isotopic compositions (^{234}U, ^{235}U and ^{236}U) and burnup are perturbed and converged using an inverse method. The burnup and initial uranium isotopic concentrations are used in the cooling time reconstruction, so their error is minimized in this numerical algorithm. The isotopes associated with numerically burnup and the initial uranium isotopic compositions are either stable or long lived, which are not affected by the cooling time. With an appropriate cross section library, the ORIGEN 2.2 code is used as a forward model in the inverse analysis.

The analytically reconstructed burnup and initial ^{235}U enrichment are fed into the forward model and the output isotopic concentration of a few isotopes are compared. To converge burnup, the selected burnup monitor isotope is used, which in this work is either ^{148}Nd or the sum of ^{137}Cs and ^{137}Ba representing the 137 mass spectrometry bin. For weapons grade HEU fuel (>60% spent ^{235}U), the method perturbs the burnup until the ratio of the iterative output's burnup monitor isotopic concentration to ^{235}U isotopic concentration matches the measured data. For enrichments with a final ^{235}U enrichment of less than 60%, the same process is performed but ^{238}U is used in the ratio instead.

The initial uranium isotopic enrichments are also reconstructed. There are multiple ways to set the initial guess for the the initial ^{234}U and ^{236}U. The first method is to use a correlation developed from simulation perturbations. Simulations can be performed at various quantities of initial minor uranium isotope concentrations and a correlation can be established dependent upon the final concentration and burnup.

For most fuels, the initial ^{236}U concentration is zero, but development of a correlation such as this can determine if a HEU spent fuel recycling capability has been used. Historically only the United States and Russia had separated, down blended, and re-enriched spent HEU fuel which could also aid as information in an attribution analysis. A correlation for ^{234}U is not developed in this manner, due to variation in ^{234}U content in nature, potential increased fractional enrichment from a HEU recycling program, and minimal documentation on variable fractional enrichment depending on ^{235}U enrichment method [31].

Another possible method is to use an already developed correlation based on enrichment and re-enrichment of recycled spent nuclear fuel from nuclear power programs. These correlations were developed using fractional enrichments based on the ^{235}U enrichment. These are not ideal for usage of HEU fuels, but serve well as an initial guess in the inverse method. The correlation for ^{234}U for gaseous diffusion enrichment processes is [32]:

$$\left(\frac{N^{U234}}{N^{U238}}\right)_0 = 0.008 \left(\frac{N^{U235}}{N^{U238}}\right)_0 \left(\frac{M^{U238}}{M^{U235}}\right). \tag{5.55}$$

The correlation for ^{234}U for gaseous centrifuge enrichment is:

$$\left(\frac{N^{U234}}{N^{U238}}\right)_0 = 0.007731 \left(\frac{N^{U235}}{N^{U238}}\right)_0^{1.0837} \left(\frac{M^{U238}}{M^{U235}}\right)^{1.0837}. \tag{5.56}$$

Either of these two ^{234}U correlations can be used. These equations were derived from correlations using low enriched power reactor fuel. They are not accurate at high enrichments and only serve as an initial guess for the numerical method. These correlations are expressed as a ratio to the initial ^{238}U concentration, which is also unknown, so an iterative procedure is used for convergence. Of all the present uranium isotopes, only the ^{235}U enrichment is known and an iterative procedure is used to solve for the initial ^{234}U enrichment. Initially in this ^{234}U predictor, the ^{238}U enrichment is set to $1 - e^{U235} - e^{U236}$. Then using either Equation 5.55 or Equation 5.56, the ^{234}U enrichment is updated. Then the ^{238}U enrichment is updated again to to $1 - e^{U234} - e^{U235} - e^{U236}$ and the process is repeated alternating ^{234}U and ^{238}U enrichment updates until the ^{234}U converges with itself sufficiently.

If only an analytic enrichment solution is desired, a ^{236}U correction to the analytic ^{235}U enrichment can be made. This method is derived analytically by subtracting the initial enrichment equation from itself with and without initial ^{236}U resulting in:

$$e_0 - e_0' = \frac{N_0^{U236}(T)}{N_0^U}, \tag{5.57}$$

where e_0 is the initial enrichment with initial ^{236}U and e_0' is the initial enrichment without ^{236}U.

The initial uranium isotopic concentrations can now be perturbed, until their corresponding final concentrations from the forward model's results converge with the measured data. The ^{238}U concentration is not solved for directly, but iteratively updated to the remaining enrichment using:

$$\frac{N_0^{U238}}{N_0^{U234}+N_0^{U235}+N_0^{U236}+N_0^{U238}} = 1 - \frac{N_0^{U234}+N_0^{U235}+N_0^{U236}}{N_0^{U234}+N_0^{U235}+N_0^{U236}+N_0^{U238}}. \quad (5.58)$$

It is desirable to have minimal uncertainties in the measured data and accurate cross sections used in the forward model. A correlation established for the initial ^{236}U concentration would be highly dependent on burnup, a suitable spectrum collapsed cross section library (for ORIGEN 2.2), and uncertainty in the sample's measured data.

In the inverse analysis, the burnup and initial uranium enrichments are updated together until convergence is achieved. The error associated with each reconstructed parameter, ϵ_z, is described in:

$$\epsilon_z = \frac{R^{measured} - R^{iterative}}{R^{measured}}. \quad (5.59)$$

The global error function is minimized in:

$$\epsilon^2 = \epsilon_{U234}^2 + \epsilon_{U235}^2 + \epsilon_{U236}^2 + \epsilon_{BU}^2. \quad (5.60)$$

The forward model and parameter perturbations are repeated until ϵ is sufficiently minimized, however convergence of all parameters is not guaranteed. Due to the ^{236}U concentration's dependence on burnup and cross sections, the method may result in an unrealistic initial ^{236}U enrichment. If the sample's measured ^{236}U enrichment exceeds the iterative enrichment, a flag is raised indicating the cross section set or burnup may need further analysis.

One option is to add the ^{236}U concentration to the burnup convergence criteria, but would cause problems and likely add additional error in the burnup reconstruction. If the measured ^{236}U final enrichment far exceeds the iterative solution, the system will reconstruct an unrealistic initial enrichment and attention to the cross section set or burnup may be required.

5.4 Fuel Age or Cooling Time Calculation

After convergence of the sample's burnup and initial enrichment, the cooling time since last shutdown, or fuel age, is determined. A cooling time monitor isotope has a simple production method and low interaction cross sections. The sample's cooling time is calculated using the cooling time monitor isotope and the decay equation:

$$N^B(T_m) = N^B(T_{shut})e^{-\lambda^B(\Delta T_c)}, \tag{5.61}$$

where T_{shut} is the time of reactor shutdown, ΔT_c is the fuel cooling time, and T_m is the time of measurement. This equation can be solved for T':

$$\Delta T_c = -\frac{1}{\lambda^B} ln \left(\frac{N^B(T_m)}{N^B(T_{shut})} \right). \tag{5.62}$$

The decayed burnup monitor isotopic concentration can be measured with mass or gamma spectrometry, but the isotopic concentration at the time of reactor shutdown is unknown. Two options arise for determining the end of power isotopic concentration, the first option is to use a forward model to predict the concentration using the sample's calculated burnup and initial enrichment. In this case, Equation 5.62 is modified to use a measurable isotopic ratio and an isotopic ratio from the predictor:

$$\Delta T_c = -\frac{1}{\lambda^B} ln \left(\frac{N^B(T_m)}{N^{U238}(T_m)} \frac{N^{U238}(T_m)}{N^B(T_{shut})} \right), \tag{5.63}$$

where $\frac{N^B(T_m)}{N^{U238}(T_m)}$ is measured and $\frac{N^{U238}(T_m)}{N^B(T_{shut})}$ is estimated from the reconstructed burnup.

The second method is to choose a burnup monitor isotope that is the primary fission product for and does not decay out of it's mass bin. In this case, at the end of power the entire mass bin primarily consists of the monitor isotope. After the monitor isotope beta decays, its mass number remains constant. The sum of the

isotopic concentrations of all isotopes with the same mass bin as the burnup monitor is used in the same decay equation:

$$\Delta T_c = -\frac{1}{\lambda^B} ln \left(\frac{N^B(T_m)}{\sum_i N^{Bi}(T_m)} \right) \tag{5.64}$$

In the case of research reactors, time away from the core or extended shutdown time causes some of the cooling time monitor isotope to decay prior to final shutdown. This will reduce the concentration of the cooling time monitor isotope, while the total mass bin concentration remains constant. A cooling time monitor with a longer half life relative to the shutdown or time away from power is ideal, but a monitor with a half life much longer than the sample cooling time may provide inaccurate results.

5.5 Summary

Pre-irradiated fuel characteristics are reconstructed from spent fuel using a series of calculations and numerical methods. The process begins with analytical burnup (Equations 5.11 and 5.19) and initial enrichment calculations (Equation 5.49. The analytic reconstructed parameters are then used in a numerical method to converge the burnup and enrichment results with measured data and reconstruct the minor uranium isotopic enrichments. The convergence criteria for this method is shown in Equations 5.59 and 5.60. The cooling time of the sample is reconstructed using two methods by inverting the decay equation (Equations 5.62 and 5.63).

6. REACTOR PARAMETER RECONSTRUCTION RESULTS

The technical nuclear forensics techniques developed for research reactor fuel were benchmarked and the results are categorized by step in the inverse analysis. The steps included analytic burnup reconstruction, analytic ^{235}U and ^{236}U reconstruction, numerical perturbations on burnup and initial uranium isotopic compositions, and cooling time reconstruction using two methods. The analysis is performed using three different classifications of data. This included results from basic simulations, detailed 3D simulations, and measured data.

The basic simulations include output isotopic compositions produced from ORIGEN 2.2 with two different one-group cross-section sets, a uniform depletion assembly level MONTEBURNS model, and a uniform depletion assembly level MCNPX/CINDER model. These were tested using two cross section libraries consisting of the standard ORIGEN 2.2 thermal library and a custom MTR-HEU cross section library. The results created with one cross section set but benchmarked with another show the effect of flux spectrum uncertainty on the method. In the MONTEBURNS and MCNPX/CINDER simulations, a large quantity of histories was used to drive the output isotope masses' standard deviations below a few tenths of a percent.

The detailed simulations include the 35 material 3D MONTEBURNS and MCNPX/CINDER models. Only 5 of the fuel regions from each simulation were tested in the analysis which represent the 5 holes drilled spaced axially across the assembly. In the simulations, each hole punch region has a slightly different flux spectrum and burnup. The results were benchmarked using both cross section libraries again. The output isotope masses' standard deviations were driven below a few tenths of a percent in these simulations too.

The third category of method results consists of tests using ICP-MS and gamma spectrometry results. These were performed on three samples of the dissolved and di-

luted ORR assembly material. The measurement uncertainty is used and propagated through the method.

6.1 Analytic Burnup Reconstruction

Several burnup monitor isotopes were considered including methods using ^{148}Nd, ^{137}Cs, ^{139}La, and a combination method using ^{145}Nd and ^{146}Nd. Through basic testing, the standard methods using either ^{148}Nd or ^{137}Cs were the most consistent.

Initially the standard analytic ^{148}Nd burnup calculation was performed on the simulation results. The first results the method was performed on were from the basic simulations. The simulation output isotopic compositions were read from input files and the method's results are in Table 6.1.

Table 6.1
Analytic Burnup Reconstruction From Basic Simulation Results.

	Simulation			
	A	B	C	D
Simulation Burnup [GWd/MTHM]	394.2	394.2	394.7	395.0
Reconstructed Burnup [GWd/MTHM]	385.8	386.1	407.3	403.0
Percent Difference [%]	2.15	2.08	3.14	2.01
Simulation $N_0^U/N^{U238}(T)$	18.77	19.25	19.13	19.13
Reconstructed $N_0^U/N^{U238}(T)$	18.80	19.26	19.73	19.73
Percent Difference [%]	0.14	0.08	3.11	3.11
Iterations	40	40	52	49

*A: ORIGEN 2.2 with Thermal Cross Sections
*B: ORIGEN 2.2 with MTR HEU Cross Sections
*C: MONTEBURNS assembly model with uniform burnup
*D: MCNP/CINDER assembly model with uniform burnup

The analytically reconstructed burnup and $N_0^U/N^{U238}(T)$ were then compared to the simulation output. The analytic calculation does not depend on cross sections, so the results were the same independent of cross section set specified in the inverse analysis. The cross section set used in the simulation may produce slight differences

though. The two classes of results (ORIGEN and Monte-Carlo depletion) were consistent with each other with all reconstructed results within a few percent of their corresponding simulation values. The number of iterations was consistent among all the two classes of results too.

The detailed MONTEBURNS model was benchmarked next. The five materials in the model, representing the holes drilled in the fuel sample acquisition process, were analyzed for comparison to the measured data. ^{137}Cs was used as the burnup monitor for these cases and results shown in Table 6.2.

Table 6.2
Analytic Burnup Reconstruction From MONTEBURNS Simulation Results.

Hole Punch	1	2	3	4	5
Simulation Burnup [GWd/MTHM]	293.8	415.3	455.1	418.3	290.5
Reconstructed Burnup [GWd/MTHM]	289.1	409.7	449.62	412.2	286.0
Percent Difference [%]	1.61	1.36	1.21	1.47	1.56
Simulation $N_0^U/N^{U238}(T)$	19.07	19.31	19.19	19.19	18.95
Reconstructed $N_0^U/N^{U238}(T)$	19.14	19.31	19.17	19.20	19.00
Percent Difference [%]	0.38	0.01	0.09	0.07	0.26
Iterations	19	54	145	57	18

The reconstructed burnup for all of the samples was within 1.56% of the MONTEBURNS reported burnup. At higher burnups, the error was smallest and was shown in both the burnup and $N_0^U/N^{U238}(T)$. The number of iterations required increased with burnup. The iterations in this section is simply alternating analytic calculations and consumes negibile time regardless. All five samples resulted in burnup that was slightly underpredicted.

The same test was performed on the results from MCNPX/CINDER using ^{137}Cs as the burnup monitor and the results are in Table 6.3.

The tests on the MCNPX/CINDER simulation results were not as accurate as from MONTEBURNS. These results were all within 2.25% of their corresponding simulation values. With the exception of hole number two's burnup, all of the errors

Table 6.3
Analytic Burnup Reconstruction From MCNPX/CINDER Simulation Results.

Hole Punch	1	2	3	4	5
Simulation Burnup [GWd/MTHM]	289.1	421.9	454.8	417.6	288.0
Reconstructed Burnup [GWd/MTHM]	285.0	412.5	450.4	413.1	286.0
Percent Difference [%]	1.43	2.25	0.97	1.08	0.70
Simulation $N_0^U/N^{U238}(T)$	18.95	19.21	19.33	19.30	18.92
Reconstructed $N_0^U/N^{U238}(T)$	19.07	19.37	19.36	19.34	19.02
Percent Difference [%]	0.63	0.82	0.14	0.23	0.55
Iterations	18	57	150	57	18

were similar to the MONTEBURNS results. In these results, the error generally decreased with burnup for the reconstructed burnup and $N_0^U/N^{U238}(T)$, which is also similar to the MONTEBURNS results.

The results from benchmarks on ICP-MS measured results were next. Both ^{148}Nd and ^{137}Cs were used as burnup monitor isotopes in this case for comparison. The ICP-MS results did not include any chemical separations of the spent fuel, only dissolution and dilution. Contaminants may be present in the 137 and 148 mass bins inflating the results without chemical separations. Chemical separations are also needed to determine the exact ^{238}U apart from ^{238}Pu. In simulation results, ^{238}Pu only consisted of <0.2% of the 238 mass bin so it is ignored here.

Table 6.4
Analytic Burnup Reconstruction From ICP-MS Measured Results.

	Sample 1	Sample 2	Sample 3
Documentation Burnup [GWd/MTHM]	395.4	395.4	395.4
^{148}Nd Reconstructed Burnup [GWd/MTHM]	464.7	471.4	466.3
^{148}Nd Reconstructed $N_0^U/N^{U238}(T)$	21.55	22.17	22.02
Iterations	384	1554	471
^{137}Cs Reconstructed Burnup [GWd/MTHM]	423.4	417.2	422.5
^{137}Cs Reconstructed $N_0^U/N^{U238}(T)$	19.85	19.89	20.18
Iterations	69	62	68

Using the ^{148}Nd method on the ICP-MS measured data, Table 6.4 shows a consistent over prediction of burnup by approximately 20% compared to the documentation. However, the results from ^{137}Cs burnup reconstructions suggests the documentation declared burnup is underestimated. An investigation was then performed on why the 148 mass bin to 238 mass bin ratio was so high in the measured results. It was discovered through pertubations of variable length burn and decay steps that accumulation of ^{148}Sm was occuring. ^{148}Sm is a stable isotope with low cross sections causing the excess 148 mass bin signal in the ICP-MS results. The ORR fuel spent approximately 90% of its three year active life out of the core due to the ORR fuel shuffling setup, which is considerable time to let ^{148}Pm and ^{148m}Pm (5.37d and 41.29d half lives) decay into ^{148}Sm.

^{137}Cs is used instead. Through ORIGEN2.2 predictors, approximately 99% of the 137 mass chain at the end of a straight constant power burn is ^{137}Cs. The 137 mass bin can be used to determine burnup.

The uncertainty from the ICP-MS analysis was propagated through the analytic burnup calculation. Due to the uncertainty magnitude in the raw data, propagation through many mathematical operations causes large uncertainty in the results. The raw data uncertainty was artificially tested at 0.1% for all isotopes which propagated to less than 1% uncertainty in the reconstructed burnup. In an analysis such as this, minimal uncertainty is desired and remeasurement should be considered.

6.2 Analytic Initial ^{235}U and ^{236}U Enrichment

The initial ^{235}U enrichment was analytically reconstructed next using Equation 5.49 through Equation 5.54. This is a direct calculation which uses the analytically reconstructed burnup and the inverse of $N_0^U/N^{U238}(T)$. There is only one unknown in Equation 5.49, which is the initial ^{236}U enrichment.

To correlate initial ^{236}U enrichment to burnup, several simulations were performed. A detailed MONTEBURNS model was created and run using several dif-

ferent ^{236}U initial enrichments. The correlation relates a measured ^{236}U ratio and reconstructed burnup to determine a sample's initial ^{236}U enrichment. The ^{236}U concentration in any sample is dependent on burnup and the flux spectrum, so reconstructing the ^{236}U for samples with vastly different flux spectra than used to develop the correlation may provide inaccurate results.

The ^{235}U and ^{236}U results can either be used as an analytic model alone or as initial conditions in a numerical method. The results from the method for reconstruction of initial ^{235}U and ^{236}U on basic simulation results are in Table 6.5. The cross sections used were from the MTR HEU cross section library, which was also used to produce the MTR HEU ORIGEN 2.2 simulation data (Simulation B).

Table 6.5
Analytic Enrichment Reconstruction From Basic Simulation Results.

	Simulation			
	A	B	C	D
Simulation ^{235}U Enrichment [%]	93.1	93.1	93.1	93.1
Reconstructed ^{235}U Enrichment [%]	93.7	93.8	94.0	94.0
Percent Difference [%]	0.64	0.75	0.96	0.96
Simulation ^{236}U Enrichment [%]	0.40	0.40	0.40	0.40
Reconstructed ^{236}U Enrichment [%]	0.0**	0.75	0.27	0.37
Percent Difference [%]	-	60.9	38.8	7.79
Corrected ^{235}U Enrichment [%]	-	93.1	93.7	93.6

*A: ORIGEN 2.2 with Thermal Cross Sections
*B: ORIGEN 2.2 with MTR HEU Cross Sections
*C: MONTEBURNS assembly model with uniform burnup
*D: MCNP/CINDER assembly model with uniform burnup
**^{236}U ignored, flag raised to change cross sections

Simulation case A consisted of data produced by using ORIGEN 2.2 and thermal cross sections. The simulation using this one-group cross section set produced less ^{236}U than the others for the specified burnup and resulted in a negative predicted initial ^{236}U enrichment. The code recognizes this and ignores the results and shows

that reconstruction of ^{235}U initial enrichment for HEU research reactor fuels is not sensitive to changes in cross sections.

The results from the other simulations were within 0.96% of their true values for the ^{235}U enrichment. Due to the spectrum dependance on ^{236}U, the largest variance was seen in it's results. After ^{236}U correction in the ^{235}U enrichment results, the corrected ^{235}U initial enrichments were within 0.64% of the true values.

Similar to the burnup results, the reconstructed initial ^{235}U and ^{236}U enrichments are calculated for the detailed MONTEBURNS and MCNPX/CINDER simulations. The MTR HEU cross section library was used to produce these results, beginning with MONTEBURNS in Table 6.6.

Table 6.6
Analytic Enrichment Reconstruction From MONTEBURNS Simulation Results.

Hole Punch	1	2	3	4	5
Simulation ^{235}U Enrichment [%]	93.1	93.1	93.1	93.1	93.1
Reconstructed ^{235}U Enrichment [%]	93.7	93.8	93.8	93.8	93.7
Percent Difference [%]	0.64	0.75	0.75	0.75	0.64
Simulation ^{236}U Enrichment [%]	0.40	0.40	0.40	0.40	0.40
Reconstructed ^{236}U Enrichment [%]	0.67	0.59	0.47	0.58	0.64
Percent Difference [%]	50.5	38.4	16.1	36.7	46.2
Corrected ^{235}U Enrichment [%]	93.1	93.2	93.3	93.2	93.1

The analytic initial ^{235}U enrichment was consistent among all five samples at 93.7-93.8% which was within 0.75% of the true values. The analytic initial ^{236}U enrichment had more error and varied with burnup. The ^{235}U enrichment was most accurate at lower burnup while the ^{236}U was most accurate at higher burnup. The ^{236}U subtracted analytic ^{235}U enrichment had a peak error of 0.21%, a reduction in error by 72%.

The same effects were produced with the MCNPX/CINDER simulation results in Table 6.7. The MTR HEU cross section library was used again in these results.

Table 6.7
Analytic Enrichment Reconstruction From MCNPX/CINDER Simulation Results.

Hole Punch	1	2	3	4	5
Simulation ^{235}U Enrichment [%]	93.1	93.1	93.1	93.1	93.1
Reconstructed ^{235}U Enrichment [%]	93.8	93.8	93.9	93.8	93.8
Percent Difference [%]	2.64	2.84	2.98	2.93	2.62
Simulation ^{236}U Enrichment [%]	0.40	0.40	0.40	0.40	0.40
Reconstructed ^{236}U Enrichment [%]	0.60	0.45	0.44	0.48	0.58
Percent Difference [%]	40.0	11.8	9.52	18.2	36.7
Corrected ^{235}U Enrichment [%]	93.2	93.4	93.5	93.3	93.2

Similar to the MONTEBURNS simulation results, the ^{235}U enrichment was most accurate at lower burnup while the ^{236}U enrichment was most accurate at higher burnup. After the ^{236}U correction, the ^{235}U enrichment was still most accurate at lower burnup too.

The results from the ICP-MS measured data were analyzed last. The results from using both the thermal and MTR HEU cross section libraries were analyzed using the burnup reconstructed from ^{137}Cs are in Table 6.8.

Table 6.8
Analytic Initial Enrichment Reconstruction for ICP-MS Data.

	Sample 1	Sample 2	Sample 3
Documentation ^{235}U [%]	93.1	93.1	93.1
Documentation ^{236}U [%]	0.40	0.40	0.40
Reconstructed ^{235}U [%] (Thermal XS)	94.0	94.1	94.2
Reconstructed ^{236}U [%] (Thermal XS)	0**	0**	0**
Corrected ^{235}U [%] (Thermal XS)	-	-	-
Reconstructed ^{235}U [%] (MTR HEU XS)	94.0	94.1	94.2
Reconstructed ^{236}U [%] (MTR HEU XS)	0**	0**	0**
Corrected ^{235}U [%] (MTR HEU XS)	-	-	-

**^{236}U ignored, flag raised to change cross sections

The reconstructed burnup from ICP-MS data consistently overpredicted the initial ^{235}U enrichment by approximately 1% for all three samples. The ^{236}U correlation resulted in negative enrichments when applied to all of the cases for both cross section libraries. Both of these may be due to overestimated burnup. When using the burnup from ^{148}Nd, the resulting initial ^{235}U enrichments were all approximately 0.5% higher. Similar to the burnup results, the ICP-MS uncertainties were artificially made to all be 0.1% and the resulting ^{235}U uncertainty was less than 1%.

6.3 Burnup and Enrichment Numerical Perturbation Results

After the burnup and initial enrichment had been analytically calculated from the ICP-MS data, numerical optimization techniques were applied using a reactor physics code as a forward model. A basic simulation is performed using ORIGEN 2.2 and the specified cross section library. The code then reads the iterative isotopic compositions from the ORIGEN 2.2 output file and compares them to the input results.

The basic simulations were analyzed first, consisting of the same data sets from the previous two sections. The burnup results are shown in Table 6.9 using a thermal and MTR HEU cross section library for the forward model calculations.

Using either cross section library, the results from ORIGEN 2.2 simulation data converged much closer to the true burnup. The number of iterations was inconsistent and initial ^{236}U had to be ignored for one case. Using the thermal cross section library for the basic MONTEBURNS and MCNPX/CINDER data, the converged numerical burnup had more error than the analytic results. When using the MTR HEU cross section library, the converged numerical burnup was much closer to the simulation output values. The converged initial uranium enrichment results for the same data sets in Table 6.10 were analyzed next.

Simulation case A was converged to more accurate results using the thermal cross section set. This was not surprising since the data set was created using thermal cross

Table 6.9
Numerical Burnup Reconstruction From Basic Simulation Results.

	Simulation			
	A	B	C	D
Simulation Burnup [GWd/MTHM]	394.2	394.2	394.7	395.0
Analytic Burnup [GWd/MTHM]	385.8	386.1	407.3	403.0
Converged Burnup [GWd/MTHM] (Thermal XS)	394.8	395.5	409.8	405.3
Iterations	139	55	64	60
Converged Burnup [GWd/MTHM] (MTR-HEU XS)	393.4	393.8	398.0	393.6
Iterations	9**	117	99	98

*A: ORIGEN 2.2 with Thermal Cross Sections
*B: ORIGEN 2.2 with MTR HEU Cross Sections
*C: MONTEBURNS assembly model with uniform burnup
*D: MCNP/CINDER assembly model with uniform burnup
**^{236}U ignored, flag raised to change cross sections

Table 6.10
Numerical Enrichment Reconstruction From Basic Simulation Results.

	Simulation			
	A	B	C	D
Simulated Initial Enrichment [%]	93.1	93.1	93.1	93.1
Analytic ^{235}U Initial Enrichment [%]	93.7	93.1	93.7	93.6
Analytic ^{236}U Initial Enrichment [%]	0.67	0.75	0.27	0.37
Converged ^{234}U Initial Enrichment [%] (Thermal XS)	1.03	0.97	0.92	0.89
Converged ^{235}U Initial Enrichment [%] (Thermal XS)	93.3	92.5	92.8	92.7
Converged ^{236}U Initial Enrichment [%] (Thermal XS)	0.39	1.41	1.20	1.29
Converged ^{234}U Initial Enrichment [%] (MTR XS)	1.13	1.06	1.03	0.99
Converged ^{235}U Initial Enrichment [%] (MTR XS)	93.9	93.0	92.9	92.8
Converged ^{236}U Initial Enrichment [%] (MTR XS)	-	0.59	0.72	0.81

*A: ORIGEN 2.2 with Thermal Cross Sections
*B: ORIGEN 2.2 with MTR HEU Cross Sections
*C: MONTEBURNS assembly model with uniform burnup
*D: MCNP/CINDER assembly model with uniform burnup

sections. The other three simulation cases were more accurate using the MTR HEU cross section library. Using either cross section set, the enrichments converged to values closer to the simulation output than the analytic solutions with the exception of simulation case B. Simulation case B's analytic solution was within 0.01% from the value in the simulation output and the numeric method strayed the results from the solution.

The results for the detailed simulations were analyzed next, beginning with MONTEBURNS. The analytic burnup results from this data set had more error than the basic simulations and are shown in Table 6.11. Convergence was attempted using both cross section libraries for these samples too.

Table 6.11
Numerical Burnup Reconstruction From MONTEBURNS Simulation Results.

Hole Punch	1	2	3	4	5
Simulation Burnup [GWd/MTHM]	293.8	415.3	455.1	418.3	290.5
Analytic Burnup [GWd/MTHM]	289.1	409.7	449.6	412.2	286.0
Converged Burnup [GWd/MTHM] (Thermal XS)	296.8	419.7	460.0	422.1	293.6
Iterations	57	59	72	72	55
Converged Burnup [GWd/MTHM] (MTR-HEU XS)	295.9	417.7	457.5	420.2	292.9
Iterations	46	112	159	64	124

The resulting converged burnup was closer to the simulation output for every sample using both cross section sets. Every case converged but the number of iterations required was inconsistent. The results using the MTR HEU cross section set were more accurate than using the thermal cross section set for every sample. The enrichment results in Table 6.12 for the same samples were analyzed next.

Using the thermal cross section set the converged initial ^{235}U enrichment had more error than the analytic solutions. Using the MTR HEU cross section set, there was a slight gain in accuracy on average. The initial ^{236}U enrichment was significantly

Table 6.12
Numerical Enrichment Reconstruction From MONTEBURNS Simulation Results.

Hole Punch	1	2	3	4	5
Simulated Initial Enrichment [%]	93.1	93.1	93.1	93.1	93.1
Analytic ^{235}U Initial Enrichment [%]	93.7	93.2	93.3	93.2	93.1
Analytic ^{236}U Initial Enrichment [%]	0.67	0.59	0.47	0.58	0.64
Converged ^{234}U Initial Enrichment [%] (Thermal XS)	0.95	0.92	0.92	0.94	0.95
Converged ^{235}U Initial Enrichment [%] (Thermal XS)	92.7	92.7	92.7	92.6	92.7
Converged ^{236}U Initial Enrichment [%] (Thermal XS)	1.15	1.28	1.23	1.27	1.12
Converged ^{234}U Initial Enrichment [%] (MTR XS)	1.01	1.01	1.03	1.04	1.01
Converged ^{235}U Initial Enrichment [%] (MTR XS)	93.2	93.2	93.2	93.1	93.2
Converged ^{236}U Initial Enrichment [%] (MTR XS)	0.44	0.43	0.36	0.42	0.42

over-predicted using the thermal cross section set, while the MTR HEU cross sections created consistent accurate results for ^{234}U and ^{236}U

The results for the same simulation results but created in MCNPX/CINDER instead of MONTEBURNS were analyzed next, beginning with burnup in Table 6.13.

Table 6.13
Numerical Burnup Reconstruction From MCNPX/CINDER Simulation Results.

Hole Punch	1	2	3	4	5
Simulation Burnup	289.1	421.9	454.8	417.6	288.0
Analytic Burnup	285.0	412.5	450.4	413.1	286.0
Converged Burnup [GWd/MTHM] (Thermal XS)	292.6	422.5	461.0	423.2	293.5
Iterations	60	66	69	68	57
Converged Burnup] [GWd/MTHM] (MTR-HEU XS)	291.8	420.4	458.6	421.2	292.8
Iterations	113	149	152	167	147

The converged burnup results using both cross section sets were closer to the simulation output values. The results using the MTR HEU cross section set were more accurate than the thermal cross sections, but took longer to converge. The number

of iterations required was more consistent than the results from the MONTEBURNS data.

Table 6.14
Numerical Initial Enrichment Reconstruction From MCNPX/CINDER Simulation Results.

Hole Punch	1	2	3	4	5
Simulated Initial Enrichment [%]	93.1	93.1	93.1	93.1	93.1
Analytic ^{235}U Initial Enrichment [%]	93.2	93.4	93.5	93.3	93.2
Analytic ^{236}U Initial Enrichment [%]	0.60	0.45	0.44	0.48	0.58
Converged ^{234}U Initial Enrichment [%] (Thermal XS)	0.91	0.89	0.88	0.89	0.93
Converged ^{235}U Initial Enrichment [%] (Thermal XS)	92.8	92.8	92.8	92.8	92.8
Converged ^{236}U Initial Enrichment [%] (Thermal XS)	1.08	1.14	1.20	1.18	1.06
Converged ^{234}U Initial Enrichment [%] (MTR XS)	0.97	0.98	0.99	0.99	0.99
Converged ^{235}U Initial Enrichment [%] (MTR XS)	93.3	93.4	93.3	93.3	93.3
Converged ^{236}U Initial Enrichment [%] (MTR XS)	0.38	0.29	0.32	0.32	0.35

Similar to the MONTEBURNS results, using the thermal cross section library the converged ^{235}U enrichment was less accurate than the analytic equivalent as shown in Table 6.14. Using the thermal library, the initial ^{234}U enrichments were slightly under predicted and the ^{236}U enrichments were highly overpredicted. However, the results for initial uranium enrichments were consistent among the five samples. Using the MTR HEU library, all of the initial enrichments were consistently more accurate than their analytic equivalents.

Table 6.15
Numerical Perturbation Results for ICP-MS Data Using ^{137}Cs Burnup.

	Sample 1	Sample 2	Sample 3
Documentation Burnup [GWd/MTHM]	395.4	395.4	395.4
Analytic Burnup [GWd/MTHM]	426.4	420.2	425.5
Converged Burnup [GWd/MTHM] (Thermal XS)	433.5	427.0	432.6
Iterations	40	92	94
Converged Burnup [GWd/MTHM] (MTR XS)	431.6	425.2	430.8
Iterations	7*	7*	8*

The numerical method results for the ICP-MS data were analyzed next. The numerically reconstructed burnup for all three measured samples, using both cross section sets, was larger than their analytic solutions, but still within one standard deviation shown in Table 6.15. These results suggest the documentation burnup may be inaccurate or a new cross section library should be created that better represents the fuel's flux profile. Using the MTR cross section library, the iterative ^{236}U final enrichment was greater than the measured counterpart using the initial guess of 10^{-4}%. Iteratively lowering the initial enrichment in this case has no effect. Convergence was not possible in this case, so initial ^{236}U was ignored. Results are shown in Table 6.16

Table 6.16
Numerical Perturbation Results for Initial Enrichment using ^{137}Cs Burnup.

	Sample 1	Sample 2	Sample 3
Documentation Initial Enrichment [%]	93.1	93.1	93.1
Analytic ^{235}U Initial Enrichment [%] (Thermal XS)	92.47	92.50	92.64
Analytic ^{235}U Initial Enrichment [%] (MTR XS)	91.83	91.87	92.02
Converged ^{234}U Initial Enrichment [%] (Thermal XS)	0.88	0.91	0.88
Converged ^{235}U Initial Enrichment [%] (Thermal XS)	93.49	93.31	93.87
Converged ^{236}U Initial Enrichment [%] (Thermal XS)	0.61	0.78	0.32
Converged ^{234}U Initial Enrichment [%] (MTR XS)	0.98	1.00	0.98
Converged ^{235}U Initial Enrichment [%] (MTR XS)	94.08	93.88	94.48
Converged ^{236}U Initial Enrichment [%] (MTR XS)	*Ignored	*Ignored	*Ignored

The numerically reconstructed initial enrichments were closer to the documentation for ^{235}U. There was no specified initial ^{234}U and ^{236}U in the Appendix-A documentation, but the results can be compared to the ANL documentation. The ^{234}U initial enrichment results were consistent with themselves for all three samples and both cross section libraries.

In general, the MTR HEU provided more accurate results for this particular assembly. The flux spectrum was similar to the model's when reconstructing param-

eters from simulation results. The ^{234}U enrichment had slight dependence on the cross section set, but was fairly consistent among the results. The ^{236}U enrichment had the greatest cross section set dependence, as well as a strong dependence on burnup accuracy. These results suggest creation of general one group cross section sets for various reactor types could be very beneficial to an inverse analysis such as this. Information from macroscopic parameters could suggest which cross section set would be appropriate.

6.4 Fuel Age Reconstruction Results

The cooling time was then analytically calculated using two methods. The first method uses the numerically converged burnup and initial enrichment as inputs into a forward model (ORIGEN 2.2 in this case) to predict the end of power ^{137}Cs isotopic concentration. The second method uses the entire 137 mass bin signature to represent the end of power ^{137}Cs concentration. The results using the second method are only calculated once since only raw data is used, which changing cross-section libraries has no effect.

The cooling time was reconstructed for the basic simulation data first. The simulation models the cooling time exactly as the documentation states at 23.94 years and the results are shown in Table 6.17.

Neither method was particularly more accurate than the other, but using the second method the results were the most consistent. Using either method and cross section set, the cooling time was overpredicted by about 5%. In both cases, the simulation output has excess shutdown time. During the fuel assembly's active lifetime, only approximately 10% of the time was under power. The shutdown time or time away from power during the fuel's active life provided time for the fuel age monitor isotope to partially decay away. This is unavoidable for research reactors that have this type of operation. Similar results were expected in the detailed simulation data.

Table 6.17
Cooling Time Results Using Both Methods for Basic Simulation Data.

	Simulation			
	A	B	C	D
Documentation [a]	23.94	23.94	23.94	23.94
Equation 5.63 [a] (Thermal XS)	25.19	25.25	27.29	26.40
Equation 5.63 [a] (MTR XS)	29.31	25.25	25.36	25.54
Equation 5.64 [a]	25.50	25.50	25.54	25.48

*A: ORIGEN 2.2 with Thermal Cross Sections
*B: ORIGEN 2.2 with MTR HEU Cross Sections
*C: MONTEBURNS assembly model with uniform burnup
*D: MCNP/CINDER assembly model with uniform burnup

Table 6.18
Cooling Time Results Using Both Methods for Detailed Simulation Data.

	Hole Punch	1	2	3	4	5
	Documentation [a]	23.94	23.94	23.94	23.94	23.94
MB	Equation 5.63 [a] (Thermal XS)	25.12	25.33	25.15	25.20	25.29
MB	Equation 5.63 [a] (MTR XS)	25.01	25.37	25.25	25.29	25.29
MB	Equation 5.64 [a]	25.35	25.52	25.45	25.46	25.53
MX	Equation 5.63 [a] (Thermal XS)	25.14	25.23	25.24	25.27	25.18
MX	Equation 5.63 [a] (MTR XS)	25.26	25.28	25.35	25.27	25.17
MX	Equation 5.64 [a]	25.42	25.47	25.51	25.48	25.42

Table 6.18 shows the same 5% overprediction occurs in all of the detailed simulation results. With the data from the detailed simulations, the first method method using Equation 5.63 was more accurate throughout. This is likely due to some ^{137}Ba produced directly, which Equation 5.64 considers to be produced from ^{137}Cs and over estimates the end of power ^{137}Cs concentration.

The results from a combination of ICP-MS and gamma spectrometry were analyzed last. ICP-MS was used to determine the 137 mass bin concentration while gamma spectrometry was used to determine the present day ^{137}Cs concentration.

The uncertainty for all of the associated measurements is accounted for in these calculations.

Table 6.19
Cooling Time Results Using Both Methods for ICP-MS Data.

	Sample 1	Sample 2	Sample 3
Documentation [a]	23.94	23.94	23.94
Equation 5.63 [a] (Thermal XS)	26.08	24.37	25.49
Equation 5.63 [a] (MTR XS)	28.65	25.31	30.89
Equation 5.64 [a]	26.43	24.70	25.77

Using both methods shown in Table 6.19, the cooling time is overpredicted likely due to extended time away from power during the fuels active life. Depending on the monitor isotope used, this excess time away from power may provide adequate time for a significant portion of the isotope to decay. Similar to burnup and initial enrichment, the large resulting uncertainty is primarily driven by the uncertainty in the raw data.

6.5 Discussion of a Sample's Power History Estimation

There are several indicator isotopes that may make suggestions of power history. If the burnup results from using ^{148}Nd are consistently higher than from using ^{137}Cs, this is a signal that extended shutdown time or shuffling time out of the reactor is present. The excess signal in the 148 mass bin from ^{148}Sm can be attempted to be reconstructed using the ^{137}Cs predicted burnup and addition of decay steps throughout the fuel's burn time. As long decay steps are added between burn steps using ORIGEN2.2 and burnup held constant, the signal in the 148 mass bin will increase. A rough estimation of the reactor's power history can be performed using this process.

In addition to the addition of decay time, the flux spectrum can greatly change chain production isotopes such as ^{148}Sm. This power history will not be very representative of the actual operations but a solid identifier of long decay steps throughout the sample's power history. However if the cross section set is not accurate, the results from an analysis such as this may be very inaccurate.

The large number of unknowns throughout a known sample's power history are difficult to reproduce or simulate. In an unknown sample, it is unlikely that any meaningful results will be produced from a method like this without further development.

6.6 Inverse Method Uncertainty Propagation Estimation

In Section 2.2.2, an estimate on the relative uncertainty compared to ^{235}U was performed based on the ICP-MS signal strength. These uncertainties were analyzed and propagated through the inverse analysis at four different ^{235}U uncertainty quantities: 0.1%, 0.5%, 1.0%, and 5.0%. The effects on the uncertainty in the reconstructed burnup, uranium isotopic compositions, and cooling time were compared to provide an estimate of the measurement uncertainty required for accurate results. ORIGEN 2.2 is used for the forward model in the inverse analysis and has negligible uncertainty propagation. The benchmark was performed using sample 1 from the ORR and results are in Table 6.20. The gamma spectrometry uncertainty for ^{137}Cs was 5.0% and used in the cooling time calculation.

The initial enrichment was much more sensitive to measurement uncertainty than burnup and cooling time due to the large number of mathematical operations involved in the calculation. The cooling time uncertainty using Equation 5.64 uses the ICP-MS measurement uncertainty for the end of power ^{137}Cs concentration and gamma spectrometry measurement uncertainty for the present day concentration. Using Equation 5.63, burnup and enrichment uncertainty is not propagated through the forward model calculation to predict the ^{137}Cs concentration at the end of power.

Table 6.20
Inverse Analysis Uncertainty Propagation Results

^{235}U Measured Uncertainty	0.1%	0.5%	1.0%	5.0%
Burnup Uncertainty	1.61%	8.07%	16.1%	80.7%
$N_0^U/N^{U238}(T)$ Uncertainty	1.33%	6.68%	13.4%	66.8%
^{235}U Enrichment Uncertainty	11.4%	57.2%	117.4%	572%
Cooling Time Uncertainty (Equation 5.63) [a]	7.58%	7.86%	8.68%	22.5%
Cooling Time Uncertainty (Equation 5.64) [a]	8.33%	10.8%	16.3%	71.1%

In the method, only the present day ^{137}Cs and ^{238}U ICP-MS uncertainties are propagated through the cooling time equation. In reality, this uncertainty will be higher due to propagation from burnup and enrichment.

7. CONCLUSIONS

Technical nuclear forensics techniques specifically for research reactor spent fuel were developed. Part of the method development included establishment of an accurate forward model to be used in the inverse analysis. Verification and validation of various reactor physics codes was performed, particularly in cases involving simulations with minimal known details.

Several of the forward models considered use Monte-Carlo methods for neutron transport and reaction rate calculations. Variance in the k-effective results is reported for the simulations at each burn/decay step, however convergence of k-effective does not guarantee reaction rate convergence. k-effective is an overall system parameter, where the reaction rate in every region of a particular model likely will not converge at the same time.

Quantification and understanding of the variance associated with Monte-Carlo depletion methods was determined by repeating many consecutive simulations using different starting random number seeds. This method produces a distribution of results and the ability to quantify variance in the output isotopic compositions for any simulation. 200 simulations were performed using MCNPX/CINDER and MONTEBURNS at 5000, 75000, and 375000 active Monte-Carlo histories each. This produced random distributions of results with a sample size of 200, where normal distributions were expected.

The χ^2 test versus the normal distribution was performed on the results, to determine if true random sampling was occurring. All isotopic compositions and k-effective results passed the χ^2 tests using an α of 0.05. The variance propagation was examined for all three different quantities of histories for both burn and decay steps. It was determined that the standard deviations reported by the code packages was only representative of that step by step individual calculation. When variance in the isotopic composition propagates through repeated burn/decay steps, the actual

standard deviation for the k-effective results is greater than the codes report and must be considered when attempting to optimize CPU time.

Through a technical nuclear forensic inverse analysis, the burnup, initial uranium isotopic compositions, and cooling time of a research reactor spent fuel sample can be reconstructed. Initially, the burnup, initial ^{235}U enrichment, and initial ^{236}U enrichment are solved for analytically. These results are then fed into a numerical code which perturbs a forward models input parameters until convergence with measured values.

The burnup convergence is determined by the iterative ratio of burnup monitor isotope (^{137}Cs or ^{148}Nd) to either ^{235}U or ^{238}U depending on the sample's enrichment. For sample final enrichments less than 60% ^{235}U, the burnup monitor isotope is ratioed to ^{238}U. For sample final enrichments greater than 60%, the burnup monitor isotope is ratioed to ^{235}U. In either case, the uranim isotope used is more stable when minor uranium isotopes are rapidly changing through the inverse analysis.

The initial ^{234}U, ^{235}U, and ^{236}U enrichments are converged to the measured data by their own final enrichments. A uranium isotope is considered converged when it's iterative final concentration matches the measured data.

The error in each parameter is calculated and convergence is determined by the sum their squares. Numerical optimization techniques are used to perturb the input parameters differently depending on magnitude and sign of their errors.

The spent fuel sample's cooling time is then reconstructed using two methods. One using the converged burnup and enrichment in a forward model to determine end of power ^{137}Cs concentration, while the other uses the entire 137 mass bin. Both methods provide similar results, however extended time away from power during the fuels active life causes an over prediction of the cooling time.

The over prediction of cooling time and variance between ^{148}Nd and ^{137}Cs burnup reconstruction results is a strong indicator of extended time away from power or frequent extended shutdown periods. A more in-depth analysis using multiple

isotopes could provide a greater indicator of a samples power history, however these isotopes are spectrum dependent. With large unknowns any known samples power history and time dependent flux spectrum, even basic power history characteristics are embedded with large uncertainty.

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APPENDIX A: SIMULATION MODEL INPUTS

A.1 ORIGEN 2.2 Model

A.1.1 ORIGEN 2.2 Batch Execution File

```
echo off
echo ********  running  *************
del tape* output.txt
copy prob_0.u5 tape5.inp >nul
copy XS.lib tape9.inp >nul
copy gxuo2brm.lib tape10.inp >nul
o2_therm
rem  combine and save files from run
copy TAPE6.out output.txt
del tape*
echo ***** done *******
echo on
```

A.1.2 ORIGEN 2.2 Input File

```
-1
-1
-1
  RDA  Irradiation of 1 ORR assembly
  RDA  Fuel enrichment is 93 w/o U-235
  RDA
  LIB  0  1 2 3  201 202 203  9 50 0 1 0
  PHO     101 102 103  10
  INP  1   1  -1  -1   1   1
  BUP
  IRP 00.5   3.62 1 2 4 0
  IRP 01.5   3.62 2 2 4 0
  IRP 03.5   3.62 2 2 4 0
  IRP 11.5   3.62 2 2 4 0
  IRP 21.78  3.62 2 2 4 0
  DEC 239.58     2 3 4 0
  IRP 240.08 3.62 3 3 4 0
  IRP 241.08 3.62 3 3 4 0
  IRP 243.08 3.62 3 3 4 0
  IRP 251.08 3.62 3 3 4 0
  IRP 261.36 3.62 3 3 4 0
  DEC 479.16     3 4 4 0
  IRP 479.66 3.62 4 4 4 0
  IRP 480.66 3.62 4 4 4 0
  IRP 482.66 3.62 4 4 4 0
  IRP 490.66 3.62 4 4 4 0
  IRP 500.94 3.62 4 4 4 0
  DEC 718.74     4 5 4 0
  IRP 719.24 3.62 5 5 4 0
  IRP 720.24 3.62 5 5 4 0
  IRP 722.24 3.62 5 5 4 0
  IRP 730.24 3.62 5 5 4 0
  IRP 740.52 3.62 5 5 4 0
  DEC 958.32     5 6 4 0
  IRP 958.82 3.62 6 6 4 0
  IRP 959.82 3.62 6 6 4 0
  IRP 961.82 3.62 6 6 4 0
  IRP 969.82 3.62 6 6 4 0
  IRP 980.10 3.62 6 6 4 0
  DEC 9780       6 7 4 0
  BUP
  OPTL 8 8 8 8 8 8 8 8 8 18*8 8 8 8
  OPTA 8 8 8 8 5 8 8 8 8 18*8 8 8 8
  OPTF 8 8 8 8 5 8 8 8 8 18*8 8 8 8
  OUT     7   1  -1   0
  END
1 80160  181    130270 2840   0 0   0 0
2 922340 10.247 922350 932.2346 922360 3.829 922380 53.578
0
```

A.2 Basic MONTEBURNS ORR Model

A.2.1 Basic MONTEBURNS Input File

```
ORR inf lattice
UNSU       ! Type of operating system
1          ! Number of MCNP materials to burn
3          ! MCNP material number #1 (must be less than 100)
362.38662  ! Material #1 volume (cc), input 0 to use mcnp value (if exists)
1.11       ! Power in MWt (for the entire system modeled in mcnp deck)
-200.      ! Recov. energy/fis (MeV); if negative use for U235, ratio other isos
0          ! Total number of days burned (used if no feed)
30         ! Number of outer burn steps
50         ! Number of internal burn steps (multiple of 10)
1          ! Number of predictor steps (+1 on first step), 1 usually sufficient
0          ! Step number to restart after (0=beginning)
thermal    ! number of default origen2 lib - next line is origen2 lib location
/usr/local/origen-2.2/libs
.0001      ! fractional importance (track isos with abs,fis,atom,mass fraction)
1          ! Intermediate keff calc. 0) No 1) Yes
143         ! Number of automatic tally isotopes, followed by list. #1
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
```

```
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
```

A.2.2 Basic MCNP Input File

```
ORR Fuel Assembly
c Matthew Sternat 8/11/2010
c
c
c sideplates-------------------------------------------------------------------
1    5 -2.7268  ((-24  23):(19 -20)) 3 -4 -18 31                          imp:n=1
3    5 -2.7268  ((-24  23):(19 -20)) 3 -4 -32 17                          imp:n=1
c water
5    1 -0.988 33 -34 31 -32 3 -4 (219:24:-19) (-101:24:-19) #1  #3        imp:n=1
c cladding for plates----------------------------------------------------------
11   5 -2.7268 20 -23 3 -4 ((101 -201):(119 -219)) #31                    imp:n=1
12   5 -2.9546 20 -23 11 -12 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #32                                                    imp:n=1
c fuel meat--------------------------------------------------------------------
31   3 -3.396 5 -6  7  -8  ((121 -221):(139 -239))                       imp:n=1
32   3 -3.396 13 -14 15 -16 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32   imp:n=1
c coolant channels-------------------------------------------------------------
51   1 -0.988 20 -23 ((-102 201) : (-103 202) : (-104 203) : (-105 204) : &
     (-106 205) : (-107 206) : (-108 207) : (-109 208) : (-110 209) : &
     (-111 210) : (-112 211) : (-113 212) : (-114 213) : (-115 214) : &
     (-116 215) : (-117 216) : (-118 217) : (-119 218) : (-141 210) : &
     (220 -111)) 31 -32 3 -4                                              imp:n=1
c    water above/below
72   1 -0.988 20 -23  12 -4 ((102 -202):(103 -203) : (104 -204) : (105 -205) : &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32             imp:n=1
91   1 -0.988 20 -23 -11  3 ((102 -202):(103 -203) : (104 -204) : (105 -205) : &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32             imp:n=1
c void and upper/lower water
901  1 -0.988 -3  35 31 -32 33 -34                                         imp:n=1
902  1 -0.988  4 -36 31 -32 33 -34                                         imp:n=1
999  0 (-35:36:-31:32:-33:34)                                              imp:n=0

c surface descriptions
c plate dimensions (outer)
3    pz -34.4488
4    pz  34.4488
c fuel meat (outer)
5    px  -3.138805
6    px   3.138805
7    pz -29.90215
8    pz  29.90215
c surface descriptions
c plate dimensions (inner)
11   pz -31.2738
12   pz  31.2738
c fuel meat (inner)
13   px  -3.140075
14   px   3.140075
15   pz -29.89199
16   pz  29.89199
c side plates (left)
17   py  3.7575
18   py  3.70593
19   px -3.65857
20   px -3.49477
c (Right)
23   px 3.49477
24   px 3.65857
c outer shell
32   -32 py 8.100001
31   -31 py 0.000001
c 33   -34 px -3.7
c 34   -33 px 3.7
33   -34 px -3.85445
34   -33 px 3.85445
35   pz -150
36   pz  150
c curvature for plates and spacing (note starts from bottom)
c centered at 0
c 100 series "lower" side 200 series "upper" side of plate
101  c/z 0.0 -09.7054 13.97
102  c/z 0.0 -09.2431 13.97
```

```
103  c/z 0.0 -08.8215 13.97
104  c/z 0.0 -08.3998 13.97
105  c/z 0.0 -07.9782 13.97
106  c/z 0.0 -07.5566 13.97
107  c/z 0.0 -07.1349 13.97
108  c/z 0.0 -06.7133 13.97
109  c/z 0.0 -06.2916 13.97
110  c/z 0.0 -05.8700 13.97
111  c/z 0.0 -13.5484 13.97
112  c/z 0.0 -13.1267 13.97
113  c/z 0.0 -12.7051 13.97
114  c/z 0.0 -12.2834 13.97
115  c/z 0.0 -11.8618 13.97
116  c/z 0.0 -11.4402 13.97
117  c/z 0.0 -11.0185 13.97
118  c/z 0.0 -10.5969 13.97
119  c/z 0.0 -10.1752 13.97
c
c added two
120  c/z 0.0 -13.9700 13.97
141  c/z 0.0 -5.44840 13.97
c upper
201  c/z 0.0 -09.5416 13.97
202  c/z 0.0 -09.1156 13.97
203  c/z 0.0 -08.6940 13.97
204  c/z 0.0 -08.2723 13.97
205  c/z 0.0 -07.8507 13.97
206  c/z 0.0 -07.4291 13.97
207  c/z 0.0 -07.0074 13.97
208  c/z 0.0 -06.5858 13.97
209  c/z 0.0 -06.1641 13.97
210  c/z 0.0 -05.7425 13.97
211  c/z 0.0 -13.4209 13.97
212  c/z 0.0 -12.9992 13.97
213  c/z 0.0 -12.5776 13.97
214  c/z 0.0 -12.1559 13.97
215  c/z 0.0 -11.7343 13.97
216  c/z 0.0 -11.3127 13.97
217  c/z 0.0 -10.8910 13.97
218  c/z 0.0 -10.4694 13.97
219  c/z 0.0 -10.0114 13.97
c
c added one
220  c/z 0.0 -13.8425 13.97
c fuel meat 121-139 lower
121  c/z 0.0 -09.64890 13.97
122  c/z 0.0 -09.20477 13.97
123  c/z 0.0 -08.78313 13.97
124  c/z 0.0 -08.36149 13.97
125  c/z 0.0 -07.93985 13.97
126  c/z 0.0 -07.51821 13.97
127  c/z 0.0 -07.09657 13.97
128  c/z 0.0 -06.67493 13.97
129  c/z 0.0 -06.25329 13.97
130  c/z 0.0 -05.83165 13.97
131  c/z 0.0 -13.51001 13.97
132  c/z 0.0 -13.08837 13.97
133  c/z 0.0 -12.66673 13.97
134  c/z 0.0 -12.24509 13.97
135  c/z 0.0 -11.82345 13.97
136  c/z 0.0 -11.40181 13.97
137  c/z 0.0 -10.98017 13.97
138  c/z 0.0 -10.55853 13.97
139  c/z 0.0 -10.11870 13.97
c
c added one
140  c/z 0.0 -13.93165 13.97
c  fuel meat 221-239 upper
221  c/z 0.0 -09.598100 13.97
222  c/z 0.0 -09.153962 13.97
223  c/z 0.0 -08.732322 13.97
224  c/z 0.0 -08.310682 13.97
225  c/z 0.0 -07.889042 13.97
226  c/z 0.0 -07.467402 13.97
227  c/z 0.0 -07.045762 13.97
228  c/z 0.0 -06.624122 13.97
229  c/z 0.0 -06.202482 13.97
230  c/z 0.0 -05.780842 13.97
231  c/z 0.0 -13.459202 13.97
232  c/z 0.0 -13.037562 13.97
233  c/z 0.0 -12.615922 13.97
234  c/z 0.0 -12.194282 13.97
235  c/z 0.0 -11.772642 13.97
236  c/z 0.0 -11.351002 13.97
237  c/z 0.0 -10.929362 13.97
238  c/z 0.0 -10.507722 13.97
239  c/z 0.0 -10.067900 13.97
```

```
c
c added one
240  c/z 0.0 -13.880842 13.97

c materials
m1   1001 2
     8016 1
     nlib=70c
mt1  lwtr.64t
c fuel meat-----------------------------------------------------------------------
m3   92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
c m4   92235 -0.231552976
c      92238 -0.017061798
c       8016 -0.045191829
c      13027 -0.706193397
c      nlib=70c
c aluminum------------------------------------------------------------------------
m5   13027 1
     nlib=70c
c source--------------------------------------------------------------------------
print
kcode 2500 1 50 500
ksrc 0 3.88 0  0 3.88 12  0 3.88 24  0 3.88 -12  0 3.88 -24
     0 6.47  28   0 1.32  28   0 4.35  28
     0 6.47  24   0 1.32  24   0 4.35  24
     0 6.47  21   0 1.32  21   0 4.35  21
     0 6.47  15   0 1.32  15   0 4.35  15
     0 6.47  12   0 1.32  12   0 4.35  12
     0 6.47  09   0 1.32  09   0 4.35  09
     0 6.47  03   0 1.32  03   0 4.35  03
     0 6.47  00   0 1.32  00   0 4.35  00
     0 6.47 -28   0 1.32 -28   0 4.35 -28
     0 6.47 -24   0 1.32 -24   0 4.35 -24
     0 6.47 -21   0 1.32 -21   0 4.35 -21
     0 6.47 -15   0 1.32 -15   0 4.35 -15
     0 6.47 -12   0 1.32 -12   0 4.35 -12
     0 6.47 -09   0 1.32 -09   0 4.35 -09
     0 6.47 -03   0 1.32 -03   0 4.35 -03
```

A.2.3 Basic Feed Input File

```
Time   Days   Power MBMat Feed Begin&EndRates Remov. Fraction F.P.Removed
 Step Burned  Fract.  #   #      grams/day    Group#
   1    0.50  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   2    1.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   3    2.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   4    8.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   5   10.28  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   6  217.82  0.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   7    0.50  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   8    1.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   9    2.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  10    8.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  11   10.28  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  12  217.82  0.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  13    0.50  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  14    1.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  15    2.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  16    8.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  17   10.28  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  18  217.82  0.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  19    0.50  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  20    1.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  21    2.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  22    8.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  23   10.28  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  24  217.82  0.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  25    0.50  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  26    1.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  27    2.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  28    8.00  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  29   10.28  1.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
  30 8799.82  0.000   1   0      0.0      0.0     0    0.000  0 0.0 0 0.0
   0                            ! # of feed specs
```

```
0                              ! # of removal groups
```

A.3 Detailed MONTEBURNS ORR Model

A.3.1 Detailed MONTEBURNS Input File

```
ORR 35 mat
UNSU        ! Type of operating system
35          ! Number of MCNP materials to burn
11          ! MCNP material number #01 (must be less than 100)
12          ! MCNP material number #02 (must be less than 100)
13          ! MCNP material number #03 (must be less than 100)
14          ! MCNP material number #04 (must be less than 100)
15          ! MCNP material number #05 (must be less than 100)
16          ! MCNP material number #06 (must be less than 100)
17          ! MCNP material number #07 (must be less than 100)
18          ! MCNP material number #08 (must be less than 100)
19          ! MCNP material number #09 (must be less than 100)
20          ! MCNP material number #10 (must be less than 100)
21          ! MCNP material number #11 (must be less than 100)
22          ! MCNP material number #12 (must be less than 100)
23          ! MCNP material number #13 (must be less than 100)
24          ! MCNP material number #14 (must be less than 100)
25          ! MCNP material number #15 (must be less than 100)
26          ! MCNP material number #16 (must be less than 100)
27          ! MCNP material number #17 (must be less than 100)
28          ! MCNP material number #18 (must be less than 100)
29          ! MCNP material number #19 (must be less than 100)
30          ! MCNP material number #20 (must be less than 100)
31          ! MCNP material number #21 (must be less than 100)
32          ! MCNP material number #22 (must be less than 100)
33          ! MCNP material number #23 (must be less than 100)
34          ! MCNP material number #24 (must be less than 100)
35          ! MCNP material number #25 (must be less than 100)
36          ! MCNP material number #26 (must be less than 100)
37          ! MCNP material number #27 (must be less than 100)
38          ! MCNP material number #28 (must be less than 100)
39          ! MCNP material number #29 (must be less than 100)
40          ! MCNP material number #30 (must be less than 100)
41          ! MCNP material number #31 (must be less than 100)
42          ! MCNP material number #32 (must be less than 100)
43          ! MCNP material number #33 (must be less than 100)
44          ! MCNP material number #34 (must be less than 100)
45          ! MCNP material number #35 (must be less than 100)
3.49648     ! Material #01 volume (cc), input 0 to use mcnp value (if exists)
0.59938     ! Material #02 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #03 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #04 volume (cc), input 0 to use mcnp value (if exists)
0.59938     ! Material #05 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #06 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #07 volume (cc), input 0 to use mcnp value (if exists)
0.59938     ! Material #08 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #09 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #10 volume (cc), input 0 to use mcnp value (if exists)
0.59938     ! Material #11 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #12 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #13 volume (cc), input 0 to use mcnp value (if exists)
0.59938     ! Material #14 volume (cc), input 0 to use mcnp value (if exists)
3.49648     ! Material #15 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #16 volume (cc), input 0 to use mcnp value (if exists)
5.40401     ! Material #17 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #18 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #19 volume (cc), input 0 to use mcnp value (if exists)
5.40401     ! Material #20 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #21 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #22 volume (cc), input 0 to use mcnp value (if exists)
5.40401     ! Material #23 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #24 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #25 volume (cc), input 0 to use mcnp value (if exists)
5.40401     ! Material #26 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #27 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #28 volume (cc), input 0 to use mcnp value (if exists)
5.40401     ! Material #29 volume (cc), input 0 to use mcnp value (if exists)
29.7221     ! Material #30 volume (cc), input 0 to use mcnp value (if exists)
0.03634     ! Material #31 volume (cc), input 0 to use mcnp value (if exists)
0.03634     ! Material #32 volume (cc), input 0 to use mcnp value (if exists)
0.03634     ! Material #33 volume (cc), input 0 to use mcnp value (if exists)
0.03634     ! Material #34 volume (cc), input 0 to use mcnp value (if exists)
```

```
0.03634    ! Material #35 volume (cc), input 0 to use mcnp value (if exists)
1.11       ! Power in MWt (for the entire system modeled in mcnp deck)
-200.      ! Recov. energy/fis (MeV); if negative use for U235, ratio other isos
0          ! Total number of days burned (used if no feed)
30         ! Number of outer burn steps
50         ! Number of internal burn steps (multiple of 10)
1          ! Number of predictor steps (+1 on first step), 1 usually sufficient
0          ! Step number to restart after (0=beginning)
thermal    ! number of default origen2 lib - next line is origen2 lib location
/scratch/msternat
.0001      ! fractional importance (track isos with abs,fis,atom,mass fraction)
1          ! Intermediate keff calc. 0) No 1) Yes
143        ! Number of automatic tally isotopes, followed by list. #1
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
```

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55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #2
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
```

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39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
```

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62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #3
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
```

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48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
```

```
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #4
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
```

```
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #5
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
```

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40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
```

```
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #6
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
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49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
```

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95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #7
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
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57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #8
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
```

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40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
```

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63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #9
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
```

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50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
```

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96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #10
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
```

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58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #11
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
```

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42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
```

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63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #12
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
```

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50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
```

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143         ! Number of automatic tally isotopes, followed by list. #13
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
```

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58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #14
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
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42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
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64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #15
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
```

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51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #16
8016.70c
13027.70c
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34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
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60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #17
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
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44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
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66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #18
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
```

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52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #19
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
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34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
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60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #20
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
```

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44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
```

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91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #21
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
```

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53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #22
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
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36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
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60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #23
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
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45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
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92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #24
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
```

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54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #25
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
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37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
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61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #26
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
```

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46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
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92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #27
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
```

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54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #28
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
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38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
```

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62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #29
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
```

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47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
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94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #30
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
```

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55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #31
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
```

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39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
```

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62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #32
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
```

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48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
```

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94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #33
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
```

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56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #34
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
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40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
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62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
143         ! Number of automatic tally isotopes, followed by list. #35
8016.70c
13027.70c
34077.70c
34078.70c
34079.70c
34080.70c
34082.70c
35081.70c
36083.70c
36084.70c
36085.70c
37085.70c
37087.70c
38088.70c
38089.70c
38090.70c
39089.70c
39091.70c
40091.70c
40092.70c
40093.70c
40094.70c
40095.70c
40096.70c
41095.70c
42095.70c
42097.70c
42098.70c
42099.70c
42100.70c
43099.70c
44100.70c
44101.70c
44102.70c
44103.70c
44104.70c
44106.70c
45103.70c
45105.70c
46105.70c
46106.70c
46107.70c
46108.70c
46110.70c
47109.70c
47111.70c
48111.70c
48112.70c
48113.70c
48114.70c
```

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49115.70c
50117.70c
50118.70c
50119.70c
50120.70c
50124.70c
50126.70c
51121.70c
51123.70c
51125.70c
52128.70c
52130.70c
52132.70c
53127.70c
53129.70c
53131.70c
53135.70c
54131.70c
54132.70c
54133.70c
54134.70c
54135.70c
54136.70c
55133.70c
55134.70c
55135.70c
55137.70c
56137.70c
56138.70c
56140.70c
57139.70c
57140.70c
58140.70c
58141.70c
58142.70c
58143.70c
58144.70c
59141.70c
59143.70c
60143.70c
60144.70c
60145.70c
60146.70c
60147.70c
60148.70c
60150.70c
61147.70c
61148.70c
61149.70c
61151.70c
62147.70c
62148.70c
62149.70c
62150.70c
62151.70c
62152.70c
62153.70c
62154.70c
63151.70c
63152.70c
63153.70c
63154.70c
63155.70c
63156.70c
64155.70c
64156.70c
64157.70c
65159.70c
66162.70c
66164.70c
90230.70c
90232.70c
91231.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
93237.70c
94238.70c
94239.70c
94240.70c
94241.70c
94242.70c
94244.70c
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95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
```

A.3.2 Detailed MCNP Input File

```
ORR Fuel Assembly
c Matthew Sternat
c
c
c sideplates-------------------------------------------------------------------
01   5 -2.73 ((-24  23):(19 -20)) 3 -4 -18 31                              imp:n=1
03   5 -2.73 ((-24  23):(19 -20)) 3 -4 -32 17                              imp:n=1
c water------------------------------------------------------------------------
05   1 -0.988 33 -34 31 -32 3 -4 (219:24:-19) (-101:24:-19) #1  #3         imp:n=1
c cladding for plates----------------------------------------------------------
11   5 -2.73 20 -23 3 -4 ((101 -201):(119 -219)) #31 #32 #33 #34 #35 #36 &
     #37 #38 #39 #40 #41 #42 #43 #44 #45 #71 #72 #73 #74 #75               imp:n=1
12   5 -2.73 20 -23 11 -506 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #58 #59 #60 #61 #62 #63 #64 #65                         imp:n=1
13   5 -2.73 20 -23 506 -12 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #51 #52 #53 #54 #55 #56 #57                             imp:n=1
c fuel meat--------------------------------------------------------------------
31   11 -3.396 5 -6  500    -8  ((121 -221):(139 -239))                    imp:n=1
32   12 -3.396 5 -6  501  -500  ((121 -221):(139 -239)) #71                 imp:n=1
33   13 -3.396 5 -6  502  -501  ((121 -221):(139 -239))                    imp:n=1
34   14 -3.396 5 -6  503  -502  ((121 -221):(139 -239))                    imp:n=1
35   15 -3.396 5 -6  504  -503  ((121 -221):(139 -239)) #72                 imp:n=1
36   16 -3.396 5 -6  505  -504  ((121 -221):(139 -239))                    imp:n=1
37   17 -3.396 5 -6  506  -505  ((121 -221):(139 -239))                    imp:n=1
38   18 -3.396 5 -6  507  -506  ((121 -221):(139 -239)) #73                 imp:n=1
39   19 -3.396 5 -6  508  -507  ((121 -221):(139 -239))                    imp:n=1
40   20 -3.396 5 -6  509  -508  ((121 -221):(139 -239))                    imp:n=1
41   21 -3.396 5 -6  510  -509  ((121 -221):(139 -239)) #74                 imp:n=1
42   22 -3.396 5 -6  511  -510  ((121 -221):(139 -239))                    imp:n=1
43   23 -3.396 5 -6  512  -511  ((121 -221):(139 -239))                    imp:n=1
44   24 -3.396 5 -6  513  -512  ((121 -221):(139 -239)) #75                 imp:n=1
45   25 -3.396 5 -6    7  -513  ((121 -221):(139 -239))                    imp:n=1
51   26 -3.396 13 -14 500 -16 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
52   27 -3.396 13 -14 501 -500 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
53   28 -3.396 13 -14 502 -501 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
54   29 -3.396 13 -14 503 -502 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
55   30 -3.396 13 -14 504 -503 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
56   31 -3.396 13 -14 505 -504 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
57   32 -3.396 13 -14 506 -505 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
58   33 -3.396 13 -14 507 -506 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32      imp:n=1
59   34 -3.396 13 -14 508 -507 ((122 -222) : (123 -223) : (124 -224) : &
```

```
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
60   35 -3.396 13 -14 509 -508 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
61   36 -3.396 13 -14 510 -509 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
62   37 -3.396 13 -14 511 -510 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
63   38 -3.396 13 -14 512 -511 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
64   39 -3.396 13 -14 513 -512 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
65   40 -3.396 13 -14 15 -513 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32    imp:n=1
71   41 -3.396 -601 139 -239                                             imp:n=1
72   42 -3.396 -602 139 -239                                             imp:n=1
73   43 -3.396 -603 139 -239                                             imp:n=1
74   44 -3.396 -604 139 -239                                             imp:n=1
75   45 -3.396 -605 139 -239                                             imp:n=1
c coolant channels-------------------------------------------------------------
91   1 -0.988 20 -23 ((-102 201) : (-103 202) : (-104 203) : (-105 204) : &
     (-106 205) : (-107 206) : (-108 207) : (-109 208) : (-110 209) : &
     (-111 210) : (-112 211) : (-113 212) : (-114 213) : (-115 214) : &
     (-116 215) : (-117 216) : (-118 217) : (-119 218) : (-141 210) : &
     (220 -111)) 31 -32 3 -4                                             imp:n=1
c water above/below------------------------------------------------------------
92   1 -0.988 20 -23  12 -4 ((102 -202) : (103 -203) : (104 -204): (105 -205): &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32               imp:n=1
93   1 -0.988 20 -23 -11  3 ((102 -202) : (103 -203) : (104 -204): (105 -205): &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32               imp:n=1
c void and upper/lower water---------------------------------------------------
901  1 -0.988 -3  35 31 -32 33 -34                                       imp:n=1
902  1 -0.988  4 -36 31 -32 33 -34                                       imp:n=1
999  0 (-35:36:-31:32:-33:34)                                            imp:n=0

c plate dimensions (outer)
3    pz -34.4488
4    pz  34.4488
c fuel meat (outer)
5    px  -3.138805
6    px   3.138805
7    pz -29.90215
8    pz  29.90215
c plate dimensions (inner)
11   pz -31.2738
12   pz  31.2738
c fuel meat (inner)
13   px  -3.140075
14   px   3.140075
15   pz -29.89199
16   pz  29.89199
c side plates
17   py  3.7575
18   py  3.70593
19   px -3.65857
20   px -3.49477
23   px 3.49477
24   px 3.65857
c outer shell
32   -31 py 8.100001
31   -32 py 0.000001
c 33   -34 px -3.7
c 34   -33 px 3.7
33   -34 px -3.85445
34   -33 px 3.85445
35   pz -150
36   pz  150
c
101  c/z 0.0 -09.7054 13.97
102  c/z 0.0 -09.2431 13.97
```

```
103   c/z 0.0 -08.8215 13.97
104   c/z 0.0 -08.3998 13.97
105   c/z 0.0 -07.9782 13.97
106   c/z 0.0 -07.5566 13.97
107   c/z 0.0 -07.1349 13.97
108   c/z 0.0 -06.7133 13.97
109   c/z 0.0 -06.2916 13.97
110   c/z 0.0 -05.8700 13.97
111   c/z 0.0 -13.5484 13.97
112   c/z 0.0 -13.1267 13.97
113   c/z 0.0 -12.7051 13.97
114   c/z 0.0 -12.2834 13.97
115   c/z 0.0 -11.8618 13.97
116   c/z 0.0 -11.4402 13.97
117   c/z 0.0 -11.0185 13.97
118   c/z 0.0 -10.5969 13.97
119   c/z 0.0 -10.1752 13.97
120   c/z 0.0 -13.9700 13.97
141   c/z 0.0 -5.44840 13.97
c
201   c/z 0.0 -09.5416 13.97
202   c/z 0.0 -09.1156 13.97
203   c/z 0.0 -08.6940 13.97
204   c/z 0.0 -08.2723 13.97
205   c/z 0.0 -07.8507 13.97
206   c/z 0.0 -07.4291 13.97
207   c/z 0.0 -07.0074 13.97
208   c/z 0.0 -06.5858 13.97
209   c/z 0.0 -06.1641 13.97
210   c/z 0.0 -05.7425 13.97
211   c/z 0.0 -13.4209 13.97
212   c/z 0.0 -12.9992 13.97
213   c/z 0.0 -12.5776 13.97
214   c/z 0.0 -12.1559 13.97
215   c/z 0.0 -11.7343 13.97
216   c/z 0.0 -11.3127 13.97
217   c/z 0.0 -10.8910 13.97
218   c/z 0.0 -10.4694 13.97
219   c/z 0.0 -10.0114 13.97
220   c/z 0.0 -13.8425 13.97
c
121   c/z 0.0 -09.64890 13.97
122   c/z 0.0 -09.20477 13.97
123   c/z 0.0 -08.78313 13.97
124   c/z 0.0 -08.36149 13.97
125   c/z 0.0 -07.93985 13.97
126   c/z 0.0 -07.51821 13.97
127   c/z 0.0 -07.09657 13.97
128   c/z 0.0 -06.67493 13.97
129   c/z 0.0 -06.25329 13.97
130   c/z 0.0 -05.83165 13.97
131   c/z 0.0 -13.51001 13.97
132   c/z 0.0 -13.08837 13.97
133   c/z 0.0 -12.66673 13.97
134   c/z 0.0 -12.24509 13.97
135   c/z 0.0 -11.82345 13.97
136   c/z 0.0 -11.40181 13.97
137   c/z 0.0 -10.98017 13.97
138   c/z 0.0 -10.55853 13.97
139   c/z 0.0 -10.11870 13.97
140   c/z 0.0 -13.93165 13.97
c
221   c/z 0.0 -09.598100 13.97
222   c/z 0.0 -09.153962 13.97
223   c/z 0.0 -08.732322 13.97
224   c/z 0.0 -08.310682 13.97
225   c/z 0.0 -07.889042 13.97
226   c/z 0.0 -07.467402 13.97
227   c/z 0.0 -07.045762 13.97
228   c/z 0.0 -06.624122 13.97
229   c/z 0.0 -06.202482 13.97
230   c/z 0.0 -05.780842 13.97
231   c/z 0.0 -13.459202 13.97
232   c/z 0.0 -13.037562 13.97
233   c/z 0.0 -12.615922 13.97
234   c/z 0.0 -12.194282 13.97
235   c/z 0.0 -11.772642 13.97
236   c/z 0.0 -11.351002 13.97
237   c/z 0.0 -10.929362 13.97
238   c/z 0.0 -10.507722 13.97
239   c/z 0.0 -10.067900 13.97
240   c/z 0.0 -13.880842 13.97
c
c divider lines
500   pz  24.5
501   pz  23.5
502   pz  18.0
```

```
503  pz  12.5
504  pz  11.5
505  pz   6.0
506  pz   0.5
507  pz  -0.5
508  pz  -6.0
509  pz -11.5
510  pz -12.5
511  pz -18.0
512  pz -23.5
513  pz -24.5
c
c punch cylinders
601  c/y 0  24 0.47625
602  c/y 0  12 0.47625
603  c/y 0   0 0.47625
604  c/y 0 -12 0.47625
605  c/y 0 -24 0.47625

c materials
m1   1001 2
     8016 1
     nlib=70c
mt1  lwtr.61t
c fuel meat-----------------------------------------------------------------------
m11  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m12  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m13  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m14  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m15  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m16  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m17  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m18  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m19  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
```

```
     nlib=70c
m20  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m21  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m22  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m23  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m24  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m25  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m26  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m27  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m28  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m29  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m30  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m31  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
m32  92234 -0.002489399
     92235 -0.231647947
```

```
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m33   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m34   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m35   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m36   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m37   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m38   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m39   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m40   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m41   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m42   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m43   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
      13027 -0.706217375
      nlib=70c
m44   92234 -0.002489399
      92235 -0.231647947
      92236 -0.00107687
      92238 -0.013474275
      8016  -0.045094134
```

```
     13027 -0.706217375
     nlib=70c
m45  92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
c alminum-------------------------------------------------------------------------
m5   13027 1
     nlib=70c
c source--------------------------------------------------------------------------
print
kcode 8000 1 100 800
ksrc 0 3.88 0  0 3.88 12  0 3.88 24  0 3.88 -12  0 3.88 -24
     0 6.47  28   0 1.32  28   0 4.35  28
     0 6.47  24   0 1.32  24   0 4.35  24
     0 6.47  21   0 1.32  21   0 4.35  21
     0 6.47  15   0 1.32  15   0 4.35  15
     0 6.47  12   0 1.32  12   0 4.35  12
     0 6.47  09   0 1.32  09   0 4.35  09
     0 6.47  03   0 1.32  03   0 4.35  03
     0 6.47  00   0 1.32  00   0 4.35  00
     0 6.47 -28   0 1.32 -28   0 4.35 -28
     0 6.47 -24   0 1.32 -24   0 4.35 -24
     0 6.47 -21   0 1.32 -21   0 4.35 -21
     0 6.47 -15   0 1.32 -15   0 4.35 -15
     0 6.47 -12   0 1.32 -12   0 4.35 -12
     0 6.47 -09   0 1.32 -09   0 4.35 -09
     0 6.47 -03   0 1.32 -03   0 4.35 -03
```

A.3.3 Detailed Feed Input File

```
Time   Days   Power MBMat Feed Begin&EndRates Remov. Fraction F.P.Removed
 Step Burned  Fract.  #   #   grams/day    Group#
   1  00.500  1.000   1   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      2   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      3   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      4   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      5   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      6   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      7   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      8   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      9   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      10  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      11  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      12  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      13  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      14  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      15  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      16  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      17  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      18  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      19  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      20  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      21  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      22  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      23  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      24  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      25  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      26  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      27  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      28  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      29  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      30  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      31  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      32  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      33  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      34  0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      35  0  0.0      0.0    0    1.000  0 0.0 0 0.0
   2  01.000  1.000   1   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      2   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      3   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      4   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      5   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      6   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      7   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      8   0  0.0      0.0    0    1.000  0 0.0 0 0.0
                      9   0  0.0      0.0    0    1.000  0 0.0 0 0.0
```

```
                    10  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0     1.000  0 0.0 0 0.0
3  02.000  1.000     1  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     2  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     3  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     4  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     5  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     6  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     7  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     8  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     9  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0     1.000  0 0.0 0 0.0
4  08.000  1.000     1  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     2  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     3  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     4  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     5  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     6  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     7  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     8  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                     9  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0     1.000  0 0.0 0 0.0
```

			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
5	10.280	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
6	217.82	0.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
7	00.500	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
8	01.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
9	02.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
10	08.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
11	10.280	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
12	217.82	0.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0

```
                    8   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    9   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0    1.000  0 0.0 0 0.0
13  00.500  1.000   1   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    2   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    3   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    4   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    5   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    6   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    7   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    8   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    9   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0    1.000  0 0.0 0 0.0
14  01.000  1.000   1   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    2   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    3   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    4   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    5   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    6   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    7   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    8   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    9   0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0    1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0    1.000  0 0.0 0 0.0
```

			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
15	02.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
16	08.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
17	10.280	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
18	217.82	0.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
19	00.500	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
20	01.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
21	02.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
22	08.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
23	10.280	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
24	217.82	0.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0

			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
25	00.500	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
26	01.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			5	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			6	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			7	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			8	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			9	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			10	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			11	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			12	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			13	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			14	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			15	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			16	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			17	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			18	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			19	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			20	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			21	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			22	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			23	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			24	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			25	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			26	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			27	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			28	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			29	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			30	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			31	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			32	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			33	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			34	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			35	0	0.0	0.0	0	1.000	0	0.0	0	0.0
27	02.000	1.000	1	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			2	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			3	0	0.0	0.0	0	1.000	0	0.0	0	0.0
			4	0	0.0	0.0	0	1.000	0	0.0	0	0.0

```
                        5   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        6   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        7   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        8   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        9   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        10  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        11  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        12  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        13  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        14  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        15  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        16  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        17  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        18  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        19  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        20  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        21  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        22  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        23  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        24  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        25  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        26  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        27  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        28  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        29  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        30  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        31  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        32  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        33  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        34  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        35  0  0.0      0.0     0    1.000   0 0.0 0 0.0
28  08.000  1.000       1   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        2   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        3   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        4   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        5   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        6   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        7   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        8   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        9   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        10  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        11  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        12  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        13  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        14  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        15  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        16  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        17  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        18  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        19  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        20  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        21  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        22  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        23  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        24  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        25  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        26  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        27  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        28  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        29  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        30  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        31  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        32  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        33  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        34  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        35  0  0.0      0.0     0    1.000   0 0.0 0 0.0
29  10.280  1.000       1   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        2   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        3   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        4   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        5   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        6   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        7   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        8   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        9   0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        10  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        11  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        12  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        13  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        14  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        15  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        16  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        17  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        18  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        19  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        20  0  0.0      0.0     0    1.000   0 0.0 0 0.0
                        21  0  0.0      0.0     0    1.000   0 0.0 0 0.0
```

```
                    22  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0     1.000  0 0.0 0 0.0
  30  8799.82 0.000   1   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    2   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    3   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    4   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    5   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    6   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    7   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    8   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    9   0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    10  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    11  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    12  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    13  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    14  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    15  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    16  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    17  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    18  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    19  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    20  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    21  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    22  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    23  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    24  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    25  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    26  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    27  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    28  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    29  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    30  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    31  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    32  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    33  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    34  0  0.0      0.0     0     1.000  0 0.0 0 0.0
                    35  0  0.0      0.0     0     1.000  0 0.0 0 0.0
  0                          ! # of feed specs
  0                          ! # of removal groups
```

A.4 Basic MCNPX/CINDER Input File

```
ORR Fuel Assembly
c Matthew Sternat 8/11/2010
c
c
c sideplates-------------------------------------------------------------------
1    5 -2.7268  ((-24  23):(19 -20)) 3 -4 -18 31                          imp:n=1
3    5 -2.7268  ((-24  23):(19 -20)) 3 -4 -32 17                          imp:n=1
c water
5    1 -0.988 33 -34 31 -32 3 -4 (219:24:-19) (-101:24:-19) #1  #3        imp:n=1
c cladding for plates----------------------------------------------------------
11   5 -2.7268 20 -23 3 -4 ((101 -201):(119 -219)) #31                    imp:n=1
12   5 -2.9546 20 -23 11 -12 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #32                                                    imp:n=1
c fuel meat--------------------------------------------------------------------
31   3 -3.396 5 -6  7  -8  ((121 -221):(139 -239))  vol=38.143            imp:n=1
32   3 -3.396 13 -14 15 -16 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=324.240                                                          imp:n=1
c coolant channels-------------------------------------------------------------
51   1 -0.988 20 -23 ((-102 201) : (-103 202) : (-104 203) : (-105 204) : &
     (-106 205) : (-107 206) : (-108 207) : (-109 208) : (-110 209) : &
```

```
     (-111 210) : (-112 211) : (-113 212) : (-114 213) : (-115 214) : &
     (-116 215) : (-117 216) : (-118 217) : (-119 218) : (-141 210) : &
     (220 -111)) 31 -32 3 -4                                          imp:n=1
c    water above/below
72   1 -0.988 20 -23  12 -4 ((102 -202):(103 -203) : (104 -204) : (105 -205) : &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32            imp:n=1
91   1 -0.988 20 -23 -11  3 ((102 -202):(103 -203) : (104 -204) : (105 -205) : &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32            imp:n=1
c void and upper/lower water
901  1 -0.988 -3  35 31 -32 33 -34                                     imp:n=1
902  1 -0.988  4 -36 31 -32 33 -34                                     imp:n=1
999  0 (-35:36:-31:32:-33:34)                                          imp:n=0

c surface descriptions
c plate dimensions (outer)
3    pz -34.4488
4    pz  34.4488
c fuel meat (outer)
5    px  -3.138805
6    px   3.138805
7    pz -29.90215
8    pz  29.90215
c surface descriptions
c plate dimensions (inner)
11   pz -31.2738
12   pz  31.2738
c fuel meat (inner)
13   px  -3.140075
14   px   3.140075
15   pz -29.89199
16   pz  29.89199
c side plates (left)
17   py  3.7575
18   py  3.70593
19   px -3.65857
20   px -3.49477
c (Right)
23   px 3.49477
24   px 3.65857
c outer shell
32   -32 py 8.100001
31   -31 py 0.000001
c 33   -34 px -3.7
c 34   -33 px 3.7
33   -34 px -3.85445
34   -33 px 3.85445
35   pz -150
36   pz  150
c curvature for plates and spacing (note starts from bottom)
c centered at 0
c 100 series "lower" side 200 series "upper" side of plate
101  c/z 0.0 -09.7054 13.97
102  c/z 0.0 -09.2431 13.97
103  c/z 0.0 -08.8215 13.97
104  c/z 0.0 -08.3998 13.97
105  c/z 0.0 -07.9782 13.97
106  c/z 0.0 -07.5566 13.97
107  c/z 0.0 -07.1349 13.97
108  c/z 0.0 -06.7133 13.97
109  c/z 0.0 -06.2916 13.97
110  c/z 0.0 -05.8700 13.97
111  c/z 0.0 -13.5484 13.97
112  c/z 0.0 -13.1267 13.97
113  c/z 0.0 -12.7051 13.97
114  c/z 0.0 -12.2834 13.97
115  c/z 0.0 -11.8618 13.97
116  c/z 0.0 -11.4402 13.97
117  c/z 0.0 -11.0185 13.97
118  c/z 0.0 -10.5969 13.97
119  c/z 0.0 -10.1752 13.97
c
c added two
120  c/z 0.0 -13.9700 13.97
141  c/z 0.0 -5.44840 13.97
c upper
201  c/z 0.0 -09.5416 13.97
202  c/z 0.0 -09.1156 13.97
203  c/z 0.0 -08.6940 13.97
204  c/z 0.0 -08.2723 13.97
205  c/z 0.0 -07.8507 13.97
206  c/z 0.0 -07.4291 13.97
207  c/z 0.0 -07.0074 13.97
208  c/z 0.0 -06.5858 13.97
```

```
209  c/z 0.0 -06.1641 13.97
210  c/z 0.0 -05.7425 13.97
211  c/z 0.0 -13.4209 13.97
212  c/z 0.0 -12.9992 13.97
213  c/z 0.0 -12.5776 13.97
214  c/z 0.0 -12.1559 13.97
215  c/z 0.0 -11.7343 13.97
216  c/z 0.0 -11.3127 13.97
217  c/z 0.0 -10.8910 13.97
218  c/z 0.0 -10.4694 13.97
219  c/z 0.0 -10.0114 13.97
c
c added one
220  c/z 0.0 -13.8425 13.97
c fuel meat 121-139 lower
121  c/z 0.0 -09.64890 13.97
122  c/z 0.0 -09.20477 13.97
123  c/z 0.0 -08.78313 13.97
124  c/z 0.0 -08.36149 13.97
125  c/z 0.0 -07.93985 13.97
126  c/z 0.0 -07.51821 13.97
127  c/z 0.0 -07.09657 13.97
128  c/z 0.0 -06.67493 13.97
129  c/z 0.0 -06.25329 13.97
130  c/z 0.0 -05.83165 13.97
131  c/z 0.0 -13.51001 13.97
132  c/z 0.0 -13.08837 13.97
133  c/z 0.0 -12.66673 13.97
134  c/z 0.0 -12.24509 13.97
135  c/z 0.0 -11.82345 13.97
136  c/z 0.0 -11.40181 13.97
137  c/z 0.0 -10.98017 13.97
138  c/z 0.0 -10.55853 13.97
139  c/z 0.0 -10.11870 13.97
c
c added one
140  c/z 0.0 -13.93165 13.97
c  fuel meat 221-239 upper
221  c/z 0.0 -09.598100 13.97
222  c/z 0.0 -09.153962 13.97
223  c/z 0.0 -08.732322 13.97
224  c/z 0.0 -08.310682 13.97
225  c/z 0.0 -07.889042 13.97
226  c/z 0.0 -07.467402 13.97
227  c/z 0.0 -07.045762 13.97
228  c/z 0.0 -06.624122 13.97
229  c/z 0.0 -06.202482 13.97
230  c/z 0.0 -05.780842 13.97
231  c/z 0.0 -13.459202 13.97
232  c/z 0.0 -13.037562 13.97
233  c/z 0.0 -12.615922 13.97
234  c/z 0.0 -12.194282 13.97
235  c/z 0.0 -11.772642 13.97
236  c/z 0.0 -11.351002 13.97
237  c/z 0.0 -10.929362 13.97
238  c/z 0.0 -10.507722 13.97
239  c/z 0.0 -10.067900 13.97
c
c added one
240  c/z 0.0 -13.880842 13.97

c burn card
burn time=0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 8799.82
     pfrac=1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
     mat=3
     power=1.11
     bopt=1 14 1
c materials
m1   1001 2
     8016 1
     nlib=70c
mt1  lwtr.64t
c fuel meat-------------------------------------------------------------------
m3   8016  -4.5094E-02
     13027 -7.0622E-01
     34077 -1.00E-30
     34078 -1.00E-30
     34079 -1.00E-30
     34080 -1.00E-30
```

```
34082 -1.00E-30
35081 -1.00E-30
36083 -1.00E-30
36084 -1.00E-30
36085 -1.00E-30
37085 -1.00E-30
37087 -1.00E-30
38088 -1.00E-30
38089 -1.00E-30
38090 -1.00E-30
39089 -1.00E-30
39091 -1.00E-30
40091 -1.00E-30
40092 -1.00E-30
40093 -1.00E-30
40094 -1.00E-30
40095 -1.00E-30
40096 -1.00E-30
41095 -1.00E-30
42095 -1.00E-30
42097 -1.00E-30
42098 -1.00E-30
42099 -1.00E-30
42100 -1.00E-30
43099 -1.00E-30
44100 -1.00E-30
44101 -1.00E-30
44102 -1.00E-30
44103 -1.00E-30
44104 -1.00E-30
44106 -1.00E-30
45103 -1.00E-30
45105 -1.00E-30
46105 -1.00E-30
46106 -1.00E-30
46107 -1.00E-30
46108 -1.00E-30
46110 -1.00E-30
47109 -1.00E-30
47111 -1.00E-30
48111 -1.00E-30
48112 -1.00E-30
48113 -1.00E-30
48114 -1.00E-30
49115 -1.00E-30
50117 -1.00E-30
50118 -1.00E-30
50119 -1.00E-30
50120 -1.00E-30
50124 -1.00E-30
50126 -1.00E-30
51121 -1.00E-30
51123 -1.00E-30
51125 -1.00E-30
52128 -1.00E-30
52130 -1.00E-30
52132 -1.00E-30
53127 -1.00E-30
53129 -1.00E-30
53131 -1.00E-30
53135 -1.00E-30
54131 -1.00E-30
54132 -1.00E-30
54133 -1.00E-30
54134 -1.00E-30
54135 -1.00E-30
54136 -1.00E-30
55133 -1.00E-30
55134 -1.00E-30
55135 -1.00E-30
55137 -1.00E-30
56137 -1.00E-30
56138 -1.00E-30
56140 -1.00E-30
57139 -1.00E-30
57140 -1.00E-30
58140 -1.00E-30
58141 -1.00E-30
58142 -1.00E-30
58143 -1.00E-30
58144 -1.00E-30
59141 -1.00E-30
59143 -1.00E-30
60143 -1.00E-30
60144 -1.00E-30
60145 -1.00E-30
60146 -1.00E-30
```

```
     60147 -1.00E-30
     60148 -1.00E-30
     60150 -1.00E-30
     61147 -1.00E-30
     61148 -1.00E-30
     61149 -1.00E-30
     61151 -1.00E-30
     62147 -1.00E-30
     62148 -1.00E-30
     62149 -1.00E-30
     62150 -1.00E-30
     62151 -1.00E-30
     62152 -1.00E-30
     62153 -1.00E-30
     62154 -1.00E-30
     63151 -1.00E-30
     63152 -1.00E-30
     63153 -1.00E-30
     63154 -1.00E-30
     63155 -1.00E-30
     63156 -1.00E-30
     64155 -1.00E-30
     64156 -1.00E-30
     64157 -1.00E-30
     65159 -1.00E-30
     66162 -1.00E-30
     66164 -1.00E-30
     90230 -1.00E-30
     90232 -1.00E-30
     91231 -1.00E-30
     92232 -1.00E-30
     92233 -1.00E-30
     92234 -2.4894E-03
     92235 -2.3165E-01
     92236 -1.0769E-03
     92237 -1.00E-30
     92238 -1.3474E-02
     93237 -1.00E-30
     94238 -1.00E-30
     94239 -1.00E-30
     94240 -1.00E-30
     94241 -1.00E-30
     94242 -1.00E-30
     94244 -1.00E-30
     95241 -1.00E-30
     95242 -1.00E-30
     95243 -1.00E-30
     96242 -1.00E-30
     96243 -1.00E-30
     96244 -1.00E-30
     nlib=70c
c m4   92235 -0.231552976
c      92238 -0.017061798
c       8016 -0.045191829
c      13027 -0.706193397
c      nlib=70c
c aluminum-------------------------------------------------------------------------
m5   13027 1
     nlib=70c
c source---------------------------------------------------------------------------
print
kcode 900 1 25 125
ksrc 0 3.88 0  0 3.88 12  0 3.88 24  0 3.88 -12  0 3.88 -24
     0 6.47  28   0 1.32  28   0 4.35  28
     0 6.47  24   0 1.32  24   0 4.35  24
     0 6.47  21   0 1.32  21   0 4.35  21
     0 6.47  15   0 1.32  15   0 4.35  15
     0 6.47  12   0 1.32  12   0 4.35  12
     0 6.47  09   0 1.32  09   0 4.35  09
     0 6.47  03   0 1.32  03   0 4.35  03
     0 6.47  00   0 1.32  00   0 4.35  00
     0 6.47 -28   0 1.32 -28   0 4.35 -28
     0 6.47 -24   0 1.32 -24   0 4.35 -24
     0 6.47 -21   0 1.32 -21   0 4.35 -21
     0 6.47 -15   0 1.32 -15   0 4.35 -15
     0 6.47 -12   0 1.32 -12   0 4.35 -12
     0 6.47 -09   0 1.32 -09   0 4.35 -09
     0 6.47 -03   0 1.32 -03   0 4.35 -03
PRDMP   3j  5
```

A.5 Detailed MCNPX/CINDER Input File

```
ORR Fuel Assembly MCNPX 35 material model
c Matthew Sternat
c
c
c sideplates-------------------------------------------------------------------
01   5 -2.73 ((-24  23):(19 -20)) 3 -4 -18 31                              imp:n=1
03   5 -2.73 ((-24  23):(19 -20)) 3 -4 -32 17                              imp:n=1
c water------------------------------------------------------------------------
05   1 -0.988 33 -34 31 -32 3 -4 (219:24:-19) (-101:24:-19) #1  #3         imp:n=1
c cladding for plates----------------------------------------------------------
11   5 -2.73 20 -23 3 -4 ((101 -201):(119 -219)) #31 #32 #33 #34 #35 #36 &
     #37 #38 #39 #40 #41 #42 #43 #44 #45 #71 #72 #73 #74 #75               imp:n=1
12   5 -2.73 20 -23 11 -506 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #58 #59 #60 #61 #62 #63 #64 #65                         imp:n=1
13   5 -2.73 20 -23 506 -12 ((102 -202) : (103 -203) : (104 -204) : &
     (105 -205) : (106 -206) : (107 -207) : (108 -208) : (109 -209) : &
     (110 -210) : (111 -211) : (112 -212) : (113 -213) : (114 -214) : &
     (115 -215) : (116 -216) : (117 -217) : (118 -218) : (120 -220) : &
     (141)) 31 -32 #51 #52 #53 #54 #55 #56 #57                             imp:n=1
c fuel meat--------------------------------------------------------------------
31   11 -3.396 5 -6  500    -8  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
32   12 -3.396 5 -6  501  -500  ((121 -221):(139 -239)) #71 vol=0.59938  imp:n=1
33   13 -3.396 5 -6  502  -501  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
34   14 -3.396 5 -6  503  -502  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
35   15 -3.396 5 -6  504  -503  ((121 -221):(139 -239)) #72 vol=0.59938  imp:n=1
36   16 -3.396 5 -6  505  -504  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
37   17 -3.396 5 -6  506  -505  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
38   18 -3.396 5 -6  507  -506  ((121 -221):(139 -239)) #73 vol=0.59938  imp:n=1
39   19 -3.396 5 -6  508  -507  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
40   20 -3.396 5 -6  509  -508  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
41   21 -3.396 5 -6  510  -509  ((121 -221):(139 -239)) #74 vol=0.59938  imp:n=1
42   22 -3.396 5 -6  511  -510  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
43   23 -3.396 5 -6  512  -511  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
44   24 -3.396 5 -6  513  -512  ((121 -221):(139 -239)) #75 vol=0.59938  imp:n=1
45   25 -3.396 5 -6    7  -513  ((121 -221):(139 -239))     vol=3.49648  imp:n=1
51   26 -3.396 13 -14 500 -16 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                           imp:n=1
52   27 -3.396 13 -14 501 -500 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=5.40401                                                           imp:n=1
53   28 -3.396 13 -14 502 -501 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                           imp:n=1
54   29 -3.396 13 -14 503 -502 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                           imp:n=1
55   30 -3.396 13 -14 504 -503 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=5.40401                                                           imp:n=1
56   31 -3.396 13 -14 505 -504 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                           imp:n=1
57   32 -3.396 13 -14 506 -505 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                           imp:n=1
58   33 -3.396 13 -14 507 -506 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=5.40401                                                           imp:n=1
59   34 -3.396 13 -14 508 -507 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
```

```
     vol=29.7221                                                          imp:n=1
60   35 -3.396 13 -14 509 -508 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                          imp:n=1
61   36 -3.396 13 -14 510 -509 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=5.40401                                                          imp:n=1
62   37 -3.396 13 -14 511 -510 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                          imp:n=1
63   38 -3.396 13 -14 512 -511 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                          imp:n=1
64   39 -3.396 13 -14 513 -512 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=5.40401                                                          imp:n=1
65   40 -3.396 13 -14 15 -513 ((122 -222) : (123 -223) : (124 -224) : &
     (125 -225) : (126 -226) : (127 -227) : (128 -228) : (129 -229) : &
     (130 -230) : (131 -231) : (132 -232) : (133 -233) : (134 -234) : &
     (135 -235) : (136 -236):(137 -237):(138 -238):(140 -240)) 31 -32 &
     vol=29.7221                                                          imp:n=1
71   41 -3.396 -601 139 -239  vol=0.03634                                 imp:n=1
72   42 -3.396 -602 139 -239  vol=0.03634                                 imp:n=1
73   43 -3.396 -603 139 -239  vol=0.03634                                 imp:n=1
74   44 -3.396 -604 139 -239  vol=0.03634                                 imp:n=1
75   45 -3.396 -605 139 -239  vol=0.03634                                 imp:n=1
c coolant channels-------------------------------------------------------------
91   1 -0.988 20 -23 ((-102 201) : (-103 202) : (-104 203) : (-105 204) : &
     (-106 205) : (-107 206) : (-108 207) : (-109 208) : (-110 209) : &
     (-111 210) : (-112 211) : (-113 212) : (-114 213) : (-115 214) : &
     (-116 215) : (-117 216) : (-118 217) : (-119 218) : (-141 210) : &
     (220 -111)) 31 -32 3 -4                                              imp:n=1
c water above/below------------------------------------------------------------
92   1 -0.988 20 -23  12 -4 ((102 -202) : (103 -203) : (104 -204): (105 -205): &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32                imp:n=1
93   1 -0.988 20 -23 -11  3 ((102 -202) : (103 -203) : (104 -204): (105 -205): &
     (106 -206) : (107 -207) : (108 -208) : (109 -209) : (110 -210 -32) : &
     (111 -211 31) : (112 -212) : (113 -213) : (114 -214) : (115 -215) : &
     (116 -216) : (117 -217) : (118 -218):-220:141) 31 -32                imp:n=1
c void and upper/lower water---------------------------------------------------
901  1 -0.988 -3  35 31 -32 33 -34                                        imp:n=1
902  1 -0.988  4 -36 31 -32 33 -34                                        imp:n=1
999  0 (-35:36:-31:32:-33:34)                                             imp:n=0

c plate dimensions (outer)
3    pz -34.4488
4    pz  34.4488
c fuel meat (outer)
5    px  -3.138805
6    px   3.138805
7    pz -29.90215
8    pz  29.90215
c plate dimensions (inner)
11   pz -31.2738
12   pz  31.2738
c fuel meat (inner)
13   px  -3.140075
14   px   3.140075
15   pz -29.89199
16   pz  29.89199
c side plates
17   py  3.7575
18   py  3.70593
19   px -3.65857
20   px -3.49477
23   px 3.49477
24   px 3.65857
c outer shell
32   -31 py 8.100001
31   -32 py 0.000001
c 33   -34 px -3.7   $ old pitch do not use
c 34   -33 px 3.7
33   -34 px -3.85445
34   -33 px 3.85445
35   pz -150
```

```
36   pz  150
c
101  c/z 0.0 -09.7054 13.97
102  c/z 0.0 -09.2431 13.97
103  c/z 0.0 -08.8215 13.97
104  c/z 0.0 -08.3998 13.97
105  c/z 0.0 -07.9782 13.97
106  c/z 0.0 -07.5566 13.97
107  c/z 0.0 -07.1349 13.97
108  c/z 0.0 -06.7133 13.97
109  c/z 0.0 -06.2916 13.97
110  c/z 0.0 -05.8700 13.97
111  c/z 0.0 -13.5484 13.97
112  c/z 0.0 -13.1267 13.97
113  c/z 0.0 -12.7051 13.97
114  c/z 0.0 -12.2834 13.97
115  c/z 0.0 -11.8618 13.97
116  c/z 0.0 -11.4402 13.97
117  c/z 0.0 -11.0185 13.97
118  c/z 0.0 -10.5969 13.97
119  c/z 0.0 -10.1752 13.97
120  c/z 0.0 -13.9700 13.97
141  c/z 0.0 -5.44840 13.97
c
201  c/z 0.0 -09.5416 13.97
202  c/z 0.0 -09.1156 13.97
203  c/z 0.0 -08.6940 13.97
204  c/z 0.0 -08.2723 13.97
205  c/z 0.0 -07.8507 13.97
206  c/z 0.0 -07.4291 13.97
207  c/z 0.0 -07.0074 13.97
208  c/z 0.0 -06.5858 13.97
209  c/z 0.0 -06.1641 13.97
210  c/z 0.0 -05.7425 13.97
211  c/z 0.0 -13.4209 13.97
212  c/z 0.0 -12.9992 13.97
213  c/z 0.0 -12.5776 13.97
214  c/z 0.0 -12.1559 13.97
215  c/z 0.0 -11.7343 13.97
216  c/z 0.0 -11.3127 13.97
217  c/z 0.0 -10.8910 13.97
218  c/z 0.0 -10.4694 13.97
219  c/z 0.0 -10.0114 13.97
220  c/z 0.0 -13.8425 13.97
c
121  c/z 0.0 -09.64890 13.97
122  c/z 0.0 -09.20477 13.97
123  c/z 0.0 -08.78313 13.97
124  c/z 0.0 -08.36149 13.97
125  c/z 0.0 -07.93985 13.97
126  c/z 0.0 -07.51821 13.97
127  c/z 0.0 -07.09657 13.97
128  c/z 0.0 -06.67493 13.97
129  c/z 0.0 -06.25329 13.97
130  c/z 0.0 -05.83165 13.97
131  c/z 0.0 -13.51001 13.97
132  c/z 0.0 -13.08837 13.97
133  c/z 0.0 -12.66673 13.97
134  c/z 0.0 -12.24509 13.97
135  c/z 0.0 -11.82345 13.97
136  c/z 0.0 -11.40181 13.97
137  c/z 0.0 -10.98017 13.97
138  c/z 0.0 -10.55853 13.97
139  c/z 0.0 -10.11870 13.97
140  c/z 0.0 -13.93165 13.97
c
221  c/z 0.0 -09.598100 13.97
222  c/z 0.0 -09.153962 13.97
223  c/z 0.0 -08.732322 13.97
224  c/z 0.0 -08.310682 13.97
225  c/z 0.0 -07.889042 13.97
226  c/z 0.0 -07.467402 13.97
227  c/z 0.0 -07.045762 13.97
228  c/z 0.0 -06.624122 13.97
229  c/z 0.0 -06.202482 13.97
230  c/z 0.0 -05.780842 13.97
231  c/z 0.0 -13.459202 13.97
232  c/z 0.0 -13.037562 13.97
233  c/z 0.0 -12.615922 13.97
234  c/z 0.0 -12.194282 13.97
235  c/z 0.0 -11.772642 13.97
236  c/z 0.0 -11.351002 13.97
237  c/z 0.0 -10.929362 13.97
238  c/z 0.0 -10.507722 13.97
239  c/z 0.0 -10.067900 13.97
240  c/z 0.0 -13.880842 13.97
c
```

```
c divider lines
500  pz  24.5
501  pz  23.5
502  pz  18.0
503  pz  12.5
504  pz  11.5
505  pz   6.0
506  pz   0.5
507  pz  -0.5
508  pz  -6.0
509  pz -11.5
510  pz -12.5
511  pz -18.0
512  pz -23.5
513  pz -24.5
c
c punch cylinders
601  c/y 0  24 0.47625
602  c/y 0  12 0.47625
603  c/y 0   0 0.47625
604  c/y 0 -12 0.47625
605  c/y 0 -24 0.47625

c burn card
burn time=0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 217.82
          0.5 1 2 8 10.280 8799.82
     pfrac=1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
           1 1 1 1 1 0
     mat=11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
         33 34 35 36 37 38 39 40 41 42 43 44 45
     power=1.11
     bopt=1 14 1
c materials
m1   1001 2
     8016 1
     nlib=70c
mt1  lwtr.61t
c fuel meat-------------------------------------------------------------------
m11  8016  -4.5094E-02
     13027 -7.0622E-01
     34077 -1.00E-30
     34078 -1.00E-30
     34079 -1.00E-30
     34080 -1.00E-30
     34082 -1.00E-30
     35081 -1.00E-30
     36083 -1.00E-30
     36084 -1.00E-30
     36085 -1.00E-30
     37085 -1.00E-30
     37087 -1.00E-30
     38088 -1.00E-30
     38089 -1.00E-30
     38090 -1.00E-30
     39089 -1.00E-30
     39091 -1.00E-30
     40091 -1.00E-30
     40092 -1.00E-30
     40093 -1.00E-30
     40094 -1.00E-30
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     42098 -1.00E-30
     42099 -1.00E-30
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     46105 -1.00E-30
     46106 -1.00E-30
     46107 -1.00E-30
     46108 -1.00E-30
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66164 -1.00E-30
90230 -1.00E-30
90232 -1.00E-30
91231 -1.00E-30
92232 -1.00E-30
92233 -1.00E-30
92234 -2.4894E-03
92235 -2.3165E-01
92236 -1.0769E-03
92237 -1.00E-30
92238 -1.3474E-02
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      96244 -1.00E-30
      nlib=70c
m12   8016  -4.5094E-02
      13027 -7.0622E-01
      34077 -1.00E-30
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      66164 -1.00E-30
      90230 -1.00E-30
      90232 -1.00E-30
      91231 -1.00E-30
      92232 -1.00E-30
      92233 -1.00E-30
      92234 -2.4894E-03
      92235 -2.3165E-01
      92236 -1.0769E-03
      92237 -1.00E-30
      92238 -1.3474E-02
      93237 -1.00E-30
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      13027 -7.0622E-01
      34077 -1.00E-30
      34078 -1.00E-30
      34079 -1.00E-30
      34080 -1.00E-30
      34082 -1.00E-30
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      38089 -1.00E-30
      38090 -1.00E-30
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61149 -1.00E-30
61151 -1.00E-30
62147 -1.00E-30
62148 -1.00E-30
62149 -1.00E-30
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      62151 -1.00E-30
      62152 -1.00E-30
      62153 -1.00E-30
      62154 -1.00E-30
      63151 -1.00E-30
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      66164 -1.00E-30
      90230 -1.00E-30
      90232 -1.00E-30
      91231 -1.00E-30
      92232 -1.00E-30
      92233 -1.00E-30
      92234 -2.4894E-03
      92235 -2.3165E-01
      92236 -1.0769E-03
      92237 -1.00E-30
      92238 -1.3474E-02
      93237 -1.00E-30
      94238 -1.00E-30
      94239 -1.00E-30
      94240 -1.00E-30
      94241 -1.00E-30
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      95243 -1.00E-30
      96242 -1.00E-30
      96243 -1.00E-30
      96244 -1.00E-30
      nlib=70c
m43   8016  -4.5094E-02
      13027 -7.0622E-01
      34077 -1.00E-30
      34078 -1.00E-30
      34079 -1.00E-30
      34080 -1.00E-30
      34082 -1.00E-30
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      47111 -1.00E-30
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92233 -1.00E-30
92234 -2.4894E-03
92235 -2.3165E-01
92236 -1.0769E-03
92237 -1.00E-30
92238 -1.3474E-02
93237 -1.00E-30
94238 -1.00E-30
94239 -1.00E-30
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      96242 -1.00E-30
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      96244 -1.00E-30
      nlib=70c
m44   8016  -4.5094E-02
      13027 -7.0622E-01
      34077 -1.00E-30
      34078 -1.00E-30
      34079 -1.00E-30
      34080 -1.00E-30
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      92232 -1.00E-30
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      92234 -2.4894E-03
      92235 -2.3165E-01
      92236 -1.0769E-03
      92237 -1.00E-30
      92238 -1.3474E-02
      93237 -1.00E-30
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      13027 -7.0622E-01
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      38090 -1.00E-30
      39089 -1.00E-30
      39091 -1.00E-30
      40091 -1.00E-30
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58143 -1.00E-30
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59141 -1.00E-30
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62148 -1.00E-30
62149 -1.00E-30
62150 -1.00E-30
62151 -1.00E-30
62152 -1.00E-30
```

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     62153 -1.00E-30
     62154 -1.00E-30
     63151 -1.00E-30
     63152 -1.00E-30
     63153 -1.00E-30
     63154 -1.00E-30
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     65159 -1.00E-30
     66162 -1.00E-30
     66164 -1.00E-30
     90230 -1.00E-30
     90232 -1.00E-30
     91231 -1.00E-30
     92232 -1.00E-30
     92233 -1.00E-30
     92234 -2.4894E-03
     92235 -2.3165E-01
     92236 -1.0769E-03
     92237 -1.00E-30
     92238 -1.3474E-02
     93237 -1.00E-30
     94238 -1.00E-30
     94239 -1.00E-30
     94240 -1.00E-30
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     96242 -1.00E-30
     96243 -1.00E-30
     96244 -1.00E-30
     nlib=70c
c alminum-------------------------------------------------------------------------
m5   13027 1
     nlib=70c
c source--------------------------------------------------------------------------
kcode 2500 1 50 500
ksrc 0 3.88 0  0 3.88 12  0 3.88 24  0 3.88 -12  0 3.88 -24
     0 6.47  28   0 1.32  28   0 4.35  28
     0 6.47  24   0 1.32  24   0 4.35  24
     0 6.47  21   0 1.32  21   0 4.35  21
     0 6.47  15   0 1.32  15   0 4.35  15
     0 6.47  12   0 1.32  12   0 4.35  12
     0 6.47  09   0 1.32  09   0 4.35  09
     0 6.47  03   0 1.32  03   0 4.35  03
     0 6.47  00   0 1.32  00   0 4.35  00
     0 6.47 -28   0 1.32 -28   0 4.35 -28
     0 6.47 -24   0 1.32 -24   0 4.35 -24
     0 6.47 -21   0 1.32 -21   0 4.35 -21
     0 6.47 -15   0 1.32 -15   0 4.35 -15
     0 6.47 -12   0 1.32 -12   0 4.35 -12
     0 6.47 -09   0 1.32 -09   0 4.35 -09
     0 6.47 -03   0 1.32 -03   0 4.35 -03
PRDMP   3j  5
```

A.6 MONTEBURNS Full Core Model

A.6.1 Full Core MONTEBURNS Input File

```
Full Core Model
PC          ! Type of operating system
1           ! Number of MCNP materials to burn
3           ! MCNP material number #1 (must be less than 100)
9784.449    ! Material #1  volume (cc), input 0 to use mcnp value (if exists)
29.65       ! Power in MWt (for the entire system modeled in mcnp deck)
-200.       ! Recov. energy/fis (MeV); if negative use for U235, ratio other isos
0           ! Total number of days burned (used if no feed)
30          ! Number of outer burn steps
50          ! Number of internal burn steps (multiple of 10)
1           ! Number of predictor steps (+1 on first step), 1 usually sufficient
0           ! Step number to restart after (0=beginning)
FFTFC       ! number of default origen2 lib - next line is origen2 lib location
```

```
c:/mb/origen22/libs
.000000001 ! fractional importance (track isos with abs,fis,atom,mass fraction)
1          ! Intermediate keff calc. 0) No 1) Yes
102        ! Number of automatic tally isotopes, followed by list.
1003.70c
2004.70c
3007.70c
8016.70c
13027.70c
33075.70c
35081.70c
36080.70c
36082.70c
36083.70c
36084.70c
36086.70c
37085.70c
37087.70c
39089.70c
40093.70c
42095.70c
43099.70c
44101.70c
44103.70c
45103.70c
45105.70c
46105.70c
46108.70c
47109.70c
53127.70c
53129.70c
53135.70c
54131.70c
54134.70c
54135.70c
55133.70c
55134.70c
55135.70c
55136.70c
55137.70c
56138.70c
59141.70c
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60145.70c
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63153.70c
63154.70c
63155.70c
64152.70c
64154.70c
64155.70c
64156.70c
64157.70c
64158.70c
64160.70c
67165.70c
90232.70c
91233.70c
92232.70c
92233.70c
92234.70c
92235.70c
92236.70c
92237.70c
92238.70c
92239.70c
92240.70c
93236.70c
93237.70c
93238.70c
93239.70c
94236.70c
94237.70c
94238.70c
94239.70c
94240.70c
```

```
94241.70c
94242.70c
94243.70c
94244.70c
95241.70c
95242.70c
95243.70c
96242.70c
96243.70c
96244.70c
96245.70c
96246.70c
96247.70c
96248.70c
97249.70c
98249.70c
98250.70c
98251.70c
98252.70c
```

A.6.2 Full Core MCNP Input File

```
ORR full core
c
c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c
c                                                                     c
c    fuel map:                                                        c
c       co - corner assembly                                          c
c       ba - beryllium assembly                                       c
c       ea - experimental assembly                                    c
c       xe - xenon exp assembly                                       c
c       ir - irridium exp assembly                                    c
c       ca - control assembly                                         c
c       ## - regular assembly (## = number of cycles burned)          c
c                                                                     c
c                                                                     c
c        01 02 03  04 05 06  07 08 09                                 c
c                                                                     c
c    g)  ba fa fa  fa fa fa  fa fa ba                                 c
c    f)  ba ba fa  sr fa sr  fa xe ba                                 c
c    e)  ba fa ea  fa fa fa  ea fa ba                                 c
c    d)  ba fa fa  sr fa sr  fa fa ba                                 c
c    c)  ba fa ea  fa ir fa  ir fa ba                                 c
c    b)  ba ba fa  sr fa sr  fa ba ba                                 c
c    a)  ba ba ba  ba ba ba  ba ba ba                                 c
c                                                                     c
c                                                                     c
c                                                                     c
c        01 02 03  04 05 06  07 08 09                                 c
c                                                                     c
c    g)  70 01 02  03 04 05  06 07 90                                 c
c    f)  71 91 08  50 09 51  10 xe 89                                 c
c    e)  72 11 ea  12 13 14  ea 15 88                                 c
c    d)  73 16 17  52 00 53  18 19 87                                 c
c    c)  74 20 ea  21 ir 22  ir 23 86                                 c
c    b)  75 92 24  54 25 55  26 93 85                                 c
c    a)  76 77 78  79 80 81  82 83 84                                 c
c                                                                     c
c                                                                     c
c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c c
c
c    fuel assemblies
c    center
100  0 39 -40((19 -20 17 -18):(23 -24 17 -18):(20 -23 101 -219)) &
     trcl=100 fill=1 imp:n=1
c    row 1
101  like 100 but trcl=101                              imp:n=1
102  like 100 but trcl=102                              imp:n=1
103  like 100 but trcl=103                              imp:n=1
104  like 100 but trcl=104                              imp:n=1
105  like 100 but trcl=105                              imp:n=1
106  like 100 but trcl=106                              imp:n=1
107  like 100 but trcl=107                              imp:n=1
c    row 2
108  like 100 but trcl=108                              imp:n=1
109  like 100 but trcl=109                              imp:n=1
110  like 100 but trcl=110                              imp:n=1
c    row 3
111  like 100 but trcl=111                              imp:n=1
112  like 100 but trcl=112                              imp:n=1
```

```
113  like 100 but trcl=113                                imp:n=1
114  like 100 but trcl=114                                imp:n=1
115  like 100 but trcl=115                                imp:n=1
c    row 4
116  like 100 but trcl=116                                imp:n=1
117  like 100 but trcl=117                                imp:n=1
118  like 100 but trcl=118                                imp:n=1
119  like 100 but trcl=119                                imp:n=1
c    row 5
120  like 100 but trcl=120                                imp:n=1
121  like 100 but trcl=121                                imp:n=1
122  like 100 but trcl=122                                imp:n=1
123  like 100 but trcl=123                                imp:n=1
c    row 6
124  like 100 but trcl=124                                imp:n=1
125  like 100 but trcl=125                                imp:n=1
126  like 100 but trcl=126                                imp:n=1
c
c
c    control assemblies
150  0 39 -40((800 -801 804 -805):(802 -803 804 -805): &
     (801 -802 806 -807)) trcl=150 fill=8 imp:n=1
151  like 150 but trcl=151                                 imp:n=1
152  like 150 but trcl=152                                 imp:n=1
153  like 150 but trcl=153                                 imp:n=1
154  like 150 but trcl=154                                 imp:n=1
155  like 150 but trcl=155                                 imp:n=1
c    be assemblies
170  9 -1.85 3 -4 19 -24 101 -219 trcl=170                 imp:n=1
171  like 170 but trcl=171                              imp:n=1
172  like 170 but trcl=172                              imp:n=1
173  like 170 but trcl=173                              imp:n=1
174  like 170 but trcl=174                              imp:n=1
175  like 170 but trcl=175                              imp:n=1
176  like 170 but trcl=176                              imp:n=1
177  like 170 but trcl=177                              imp:n=1
178  like 170 but trcl=178                              imp:n=1
179  like 170 but trcl=179                              imp:n=1
180  like 170 but trcl=180                              imp:n=1
181  like 170 but trcl=181                              imp:n=1
182  like 170 but trcl=182                              imp:n=1
183  like 170 but trcl=183                              imp:n=1
184  like 170 but trcl=184                              imp:n=1
185  like 170 but trcl=185                              imp:n=1
186  like 170 but trcl=186                              imp:n=1
187  like 170 but trcl=187                              imp:n=1
188  like 170 but trcl=188                              imp:n=1
189  like 170 but trcl=189                              imp:n=1
190  like 170 but trcl=190                              imp:n=1
191  like 170 but trcl=191                              imp:n=1
192  like 170 but trcl=192                              imp:n=1
193  like 170 but trcl=193                              imp:n=1
c
c
c
c -------------------------------------------------------------------------------
c -------------------------------------------------------------------------------
c    fuel assembly cells
c -------------------------------------------------------------------------------
c -------------------------------------------------------------------------------
c
c
c    sideplates-----------------------------------------------------------------
1011 5 -2.7268 3 -4 (-20:23)                                    u=1 imp:n=1
c    sideplates-----------------------------------------------------------------
c
c    plates
c    bottom outer plate
c    cladding for plates--------------------------------------------------------
1013 5 -2.7268 20 -23 3 -4 (-201:119) #1016                     u=1 imp:n=1
1014 5 -2.9546 20 -23 11 -12 ((102 -202):(103 -203):(104 -204):(105 -205): &
     (106 -206):(107 -207):(108 -208):(109 -209):(110 -210):(111 -211): &
     (112 -212):(113 -213):(114 -214):(115 -215):(116 -216):(117 -217): &
     (118 -218)) #1015                                          u=1 imp:n=1
c    cladding for plates--------------------------------------------------------
c
c    fuel meat------------------------------------------------------------------
1015 3 -3.396 13 -14 15 -16 ((122 -222):(123 -223):(124 -224):(125 -225): &
     (126 -226):(127 -227):(128 -228):(129 -229):(130 -230):(131 -231): &
     (132 -232):(133 -233):(134 -234):(135 -235):(136 -236):(137 -237): &
     (138 -238))                                                u=1 imp:n=1
1016 3 -3.396 5 -6  7  -8 (( 121 -221):(139 -239))              u=1 imp:n=1
c    fuel meat------------------------------------------------------------------
c
c    coolant channels-----------------------------------------------------------
1017 1 -1 20 -23 3 -4 ((-102 201):(-103 202):(-104 203):(-105 204):(-106 205): &
     (-107 206):(-108 207):(-109 208):(-110 209):(-111 210):(-112 211): &
```

```
     (-113 212):(-114 213):(-115 214):(-116 215):(-117 216):(-118 217): &
     (-119 218))                                                    u=1 imp:n=1
c    coolant channels-----------------------------------------------------------
c
c    water above/below fuel plates---------------------------------------------
1018 1 -1 20 -23 12 -4 ((102 -202):(103 -203):(104 -204):(105 -205): &
     (106 -206):(107 -207):(108 -208):(109 -209):(110 -210):(111 -211): &
     (112 -212):(113 -213):(114 -214):(115 -215):(116 -216):(117 -217): &
     (118 -218)) u=1                                                  imp:n=1
c
1019 1 -1 20 -23 -11 3 ((102 -202):(103 -203):(104 -204):(105 -205): &
     (106 -206):(107 -207):(108 -208):(109 -209):(110 -210):(111 -211): &
     (112 -212):(113 -213):(114 -214):(115 -215): (116 -216):(117 -217): &
     (118 -218)) u=1                                                  imp:n=1
c
c    water above/below assembly------------------------------------------------
1020 1 -1 -3                                                        u=1 imp:n=1
1021 1 -1  4                                                        u=1 imp:n=1
c
c
c
c ---------------------------------------------------------------------------
c ---------------------------------------------------------------------------
c ---------------------------------------------------------------------------
c
c
c
c    control assembly
c    sideplates-----------------------------------------------------------------
811  5 -2.7268 3 -12 (-20:23) trcl=(-7.7089 16.2 0)                 u=8 imp:n=1
c    sideplates-----------------------------------------------------------------
c
c    plates
c    bottom outer plate
c    cladding for plates--------------------------------------------------------
813  5 -2.7268 20 -23 3 -12 (-201:119) #816 trcl=(-7.7089 16.2 0)    u=8 imp:n=1
814  5 -2.9546 20 -23 11 -12 ((102 -202):(103 -203):(104 -204):(105 -205): &
     (106 -206):(107 -207):(108 -208):(109 -209):(110 -210):(111 -211): &
     (112 -212):(113 -213):(114 -214):(115 -215):(116 -216):(117 -217): &
     (118 -218)) #815 trcl=(-7.7089 16.2 0)                        u=8 imp:n=1
c    cladding for plates--------------------------------------------------------
c
c    fuel meat------------------------------------------------------------------
815  3 -3.396 13 -14 15 -16 ((122 -222):(123 -223):(124 -224):(125 -225): &
     (126 -226):(127 -227):(128 -228):(129 -229):(130 -230):(131 -231): &
     (132 -232):(133 -233):(134 -234):(135 -235):(136 -236):(137 -237): &
     (138 -238)) trcl=(-7.7089 16.2 0)                              u=8 imp:n=1
816  3 -3.396 5 -6  7  -8 (( 121 -221):(139 -239)) trcl=(-7.7089 16.2 0) &
     u=8                                                            imp:n=1
c    fuel meat------------------------------------------------------------------
c
c    coolant channels-----------------------------------------------------------
817  1 -1 20 -23 3 -12((-102 201):(-103 202):(-104 203):(-105 204):(-106 205): &
     (-107 206):(-108 207):(-109 208):(-110 209):(-111 210):(-112 211): &
     (-113 212):(-114 213):(-115 214):(-116 215):(-117 216):(-118 217): &
     (-119 218)) trcl=(-7.7089 16.2 0)                              u=8 imp:n=1
c    coolant channels-----------------------------------------------------------
c
c    water below fuel plates----------------------------------------------
819  1 -1 20 -23 -11 3 ((102 -202):(103 -203):(104 -204):(105 -205): &
     (106 -206):(107 -207):(108 -208):(109 -209):(110 -210):(111 -211): &
     (112 -212):(113 -213):(114 -214):(115 -215): (116 -216):(117 -217): &
     (118 -218)) trcl=(-7.7089 16.2 0)                              u=8 imp:n=1
c    absorber material
820  8 -8.65 12 -45                                                 u=8 imp:n=1
c
c    water above/below assembly------------------------------------------------
821 1 -1 -3                                                         u=8 imp:n=1
822 1 -1  45                                                        u=8 imp:n=1
c
c
c
c ---------------------------------------------------------------------------
c ---------------------------------------------------------------------------
c    end assembly level cells
c ---------------------------------------------------------------------------
c ---------------------------------------------------------------------------
c
c
c
c    begin outer structures ----------------------------------------------------
900  1 -1 35 -36 -37 46 48 -49 &
     #101 #102 #108 #111 #116 #117 #120 #124 &
     #170 #171 #172 #173 #174 #175 #176 #177 #178 #191 #192          imp:n=1
901  1 -1 35 -36 37 -38 48 -49 &
     #103 #104 #105 #109 #112 #113 #114 #100 #121 #122 #125 &
     #150 #151 #152 #153 #154 #155 &
```

```
     #179 #180 #181                                                          imp:n=1
902  1 -1 35 -36 38 -47 48 -49 &
     #106 #107 #110 #115 #118 #119 #123 #126 &
     #182 #183 #184 #185 #186 #187 #188 #189 #190 #193                       imp:n=1
903  5 -2.70 41 -42 35 -36                                                   imp:n=1
904  1 -1 (44 -43 31 -32 33 -34) (42:-35:36)                                 imp:n=1
905  1 -1 -41 35 -36 (-46:47:-48:49) #906                                    imp:n=1
906  5 -2.7 3 -4 50 -51 52 -53 (-46:47:-48:49)                               imp:n=1
999  0 (-44:43:-31:32:-33:34)                                                imp:n=0
c
c
c
c ------------------------------------------------------------------------------
c ------------------------------------------------------------------------------
c ------------------------------------------------------------------------------

c    surface descriptions-------------------------------------------------------
c    outer plate dimensions
3    pz -34.4488
4    pz  34.4488
c    outer fuel meat
5    px  -3.138805
6    px   3.138805
7    pz -29.90215
8    pz  29.90215
c    inner plate dimensions
11   pz -31.2738
12   pz  31.2738
c    inner fuel meat
13   px  -3.140075
14   px   3.140075
15   pz -29.89199
16   pz  29.89199
c    side plates
17   py -4.3425
18   py  3.70593
19   px -3.65857
20   px -3.49477
23   px  3.49477
24   px  3.65857
c    outer shell
32   py  250
31   py -250
33   px -250
34   px  250
35   pz -225.552
36   pz  225.552
37   px -11.5
38   px  11.5
43   pz  350
44   pz -350
c    upper and lower water boundaries
39   pz -140
40   pz  140
c    reactor vessel surfaces
41   c/z 0.0 0.0 161.544
42   c/z 0.0 0.0 164.719
c    top of control absorber material
45   pz 108.74
c    core box
46   px -35
47   px  35
48   py -29
49   py  29
50   px -38
51   px  38
52   py -32
53   py  32
c    clad lower
101  c/z 0.0 -17.8054 13.97
102  c/z 0.0 -17.3431 13.97
103  c/z 0.0 -16.9215 13.97
104  c/z 0.0 -16.4998 13.97
105  c/z 0.0 -16.0782 13.97
106  c/z 0.0 -15.6566 13.97
107  c/z 0.0 -15.2349 13.97
108  c/z 0.0 -14.8133 13.97
109  c/z 0.0 -14.3916 13.97
110  c/z 0.0 -13.9700 13.97
111  c/z 0.0 -13.5484 13.97
112  c/z 0.0 -13.1267 13.97
113  c/z 0.0 -12.7051 13.97
114  c/z 0.0 -12.2834 13.97
115  c/z 0.0 -11.8618 13.97
116  c/z 0.0 -11.4402 13.97
117  c/z 0.0 -11.0185 13.97
118  c/z 0.0 -10.5969 13.97
```

```
119   c/z 0.0 -10.1752 13.97
c     clad upper
201   c/z 0.0 -17.6416 13.97
202   c/z 0.0 -17.2156 13.97
203   c/z 0.0 -16.7940 13.97
204   c/z 0.0 -16.3723 13.97
205   c/z 0.0 -15.9507 13.97
206   c/z 0.0 -15.5291 13.97
207   c/z 0.0 -15.1074 13.97
208   c/z 0.0 -14.6858 13.97
209   c/z 0.0 -14.2641 13.97
210   c/z 0.0 -13.8425 13.97
211   c/z 0.0 -13.4209 13.97
212   c/z 0.0 -12.9992 13.97
213   c/z 0.0 -12.5776 13.97
214   c/z 0.0 -12.1559 13.97
215   c/z 0.0 -11.7343 13.97
216   c/z 0.0 -11.3127 13.97
217   c/z 0.0 -10.8910 13.97
218   c/z 0.0 -10.4694 13.97
219   c/z 0.0 -10.0114 13.97
c
c     fuel meat 121-139 lower
121   c/z 0.0 -17.74890 13.97
122   c/z 0.0 -17.30477 13.97
123   c/z 0.0 -16.88313 13.97
124   c/z 0.0 -16.46149 13.97
125   c/z 0.0 -16.03985 13.97
126   c/z 0.0 -15.61821 13.97
127   c/z 0.0 -15.19657 13.97
128   c/z 0.0 -14.77493 13.97
129   c/z 0.0 -14.35329 13.97
130   c/z 0.0 -13.93165 13.97
131   c/z 0.0 -13.51001 13.97
132   c/z 0.0 -13.08837 13.97
133   c/z 0.0 -12.66673 13.97
134   c/z 0.0 -12.24509 13.97
135   c/z 0.0 -11.82345 13.97
136   c/z 0.0 -11.40181 13.97
137   c/z 0.0 -10.98017 13.97
138   c/z 0.0 -10.55853 13.97
139   c/z 0.0 -10.11870 13.97
c
c     fuel meat 221-239 upper
221   c/z 0.0 -17.6981   13.97
222   c/z 0.0 -17.253962 13.97
223   c/z 0.0 -16.832322 13.97
224   c/z 0.0 -16.410682 13.97
225   c/z 0.0 -15.989042 13.97
226   c/z 0.0 -15.567402 13.97
227   c/z 0.0 -15.145762 13.97
228   c/z 0.0 -14.724122 13.97
229   c/z 0.0 -14.302482 13.97
230   c/z 0.0 -13.880842 13.97
231   c/z 0.0 -13.459202 13.97
232   c/z 0.0 -13.037562 13.97
233   c/z 0.0 -12.615922 13.97
234   c/z 0.0 -12.194282 13.97
235   c/z 0.0 -11.772642 13.97
236   c/z 0.0 -11.351002 13.97
237   c/z 0.0 -10.929362 13.97
238   c/z 0.0 -10.507722 13.97
239   c/z 0.0 -10.0679   13.97
c
c     control assembly shell
800   px   -11.36747
801   px   -11.20367
802   px   -4.21413
803   px   -4.05033
804   py   11.8575
805   py   19.90593
806   c/z -07.7089 -1.6054 13.97
807   c/z -07.7089 6.1886 13.97

c ------------------------------------------------------------------------------
c ------------------------------------------------------------------------------
c ------------------------------------------------------------------------------
c
c
c
c     materials-------------------------------------------------------------
c     water
m1    1001 2
      8016 1
      nlib=70c
mt1   lwtr.64t
c     fuel meat
```

```
m3   92234 -0.002489399
     92235 -0.231647947
     92236 -0.00107687
     92238 -0.013474275
     8016  -0.045094134
     13027 -0.706217375
     nlib=70c
c    aluminum
m5   13027 1
     nlib=70c
c    be reflector material
m9   4009 1
     nlib=70c
c Cadmium control element
m8   48106 0.0125
     48108 0.0089
     48110 0.1249
     48111 0.1280
     48112 0.2413
     48113 0.1222
     48114 0.2873
     48116 0.0749
     nlib=70c
c
c    assembly translations
tr100   0.0000   0.0 0 -1 0 0 0 -1 0 0 0 1
tr101 -23.1267  24.3 0 -1 0 0 0 -1 0 0 0 1
tr102 -15.4178  24.3 0 -1 0 0 0 -1 0 0 0 1
tr103 -07.7089  24.3 0 -1 0 0 0 -1 0 0 0 1
tr104  00.0000  24.3 0 -1 0 0 0 -1 0 0 0 1
tr105  07.7089  24.3 0 -1 0 0 0 -1 0 0 0 1
tr106  15.4178  24.3 0 -1 0 0 0 -1 0 0 0 1
tr107  23.1267  24.3 0 -1 0 0 0 -1 0 0 0 1
tr108 -15.4178  16.2 0 -1 0 0 0 -1 0 0 0 1
tr109  00.0000  16.2 0 -1 0 0 0 -1 0 0 0 1
tr110  15.4178  16.2 0 -1 0 0 0 -1 0 0 0 1
tr111 -23.1267  08.1 0 -1 0 0 0 -1 0 0 0 1
tr112 -07.7089  08.1 0 -1 0 0 0 -1 0 0 0 1
tr113  00.0000  08.1 0 -1 0 0 0 -1 0 0 0 1
tr114  07.7089  08.1 0 -1 0 0 0 -1 0 0 0 1
tr115  23.1267  08.1 0 -1 0 0 0 -1 0 0 0 1
tr116 -23.1267  00.0 0 -1 0 0 0 -1 0 0 0 1
tr117 -15.4178  00.0 0 -1 0 0 0 -1 0 0 0 1
tr118  15.4178  00.0 0 -1 0 0 0 -1 0 0 0 1
tr119  23.1267  00.0 0 -1 0 0 0 -1 0 0 0 1
tr120 -23.1267 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr121 -07.7089 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr122  07.7089 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr123  23.1267 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr124 -15.4178 -16.2 0 -1 0 0 0 -1 0 0 0 1
tr125  00.0000 -16.2 0 -1 0 0 0 -1 0 0 0 1
tr126  15.4178 -16.2 0 -1 0 0 0 -1 0 0 0 1
c    control element translations
tr150 -15.4178 32.4 0  -1 0 0 0 -1 0 0 0 1
tr151 0 32.4 0      -1 0 0 0 -1 0 0 0 1
tr152 -15.4178 16.2 0        -1 0 0 0 -1 0 0 0 1
tr153 0 16.2 0  -1 0 0 0 -1 0 0 0 1
tr154 -15.4178 0 0        -1 0 0 0 -1 0 0 0 1
tr155 0 0 0  -1 0 0 0 -1 0 0 0 1
c    reflector translations
tr170 -30.8356  24.3 0 -1 0 0 0 -1 0 0 0 1
tr171 -30.8356  16.2 0 -1 0 0 0 -1 0 0 0 1
tr172 -30.8356  08.1 0 -1 0 0 0 -1 0 0 0 1
tr173 -30.8356  00.0 0 -1 0 0 0 -1 0 0 0 1
tr174 -30.8356 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr175 -30.8356 -16.2 0 -1 0 0 0 -1 0 0 0 1
tr176 -30.8356 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr177 -23.1267 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr178 -15.4178 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr179 -07.7089 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr180  00.0000 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr181  07.7089 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr182  15.4178 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr183  23.1267 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr184  30.8356 -24.3 0 -1 0 0 0 -1 0 0 0 1
tr185  30.8356 -16.2 0 -1 0 0 0 -1 0 0 0 1
tr186  30.8356 -08.1 0 -1 0 0 0 -1 0 0 0 1
tr187  30.8356  00.0 0 -1 0 0 0 -1 0 0 0 1
tr188  30.8356  08.1 0 -1 0 0 0 -1 0 0 0 1
tr189  30.8356  16.2 0 -1 0 0 0 -1 0 0 0 1
tr190  30.8356  24.3 0 -1 0 0 0 -1 0 0 0 1
tr191 -23.1267  16.2 0 -1 0 0 0 -1 0 0 0 1
tr192 -23.1267 -16.2 0 -1 0 0 0 -1 0 0 0 1
tr193  23.1267 -16.2 0 -1 0 0 0 -1 0 0 0 1
mode n
kcode 12000 1 50 250
ksrc 23 -24.23 0  7.7 -7.18 0  38.5 -7.18 0  7.7 -40.85 0  38.5 -40.85 0
```

A.6.3 Full Core Feed Input File

```
Time    Days    Power MBMat Feed Begin&EndRates Remov. Fraction F.P.Removed
 Step Burned   Fract.   #    #       grams/day    Group#
   1    0.50  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   2    1.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   3    2.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   4    8.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   5   10.28  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   6  217.82  0.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   7    0.50  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   8    1.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   9    2.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  10    8.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  11   10.28  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  12  217.82  0.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  13    0.50  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  14    1.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  15    2.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  16    8.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  17   10.28  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  18  217.82  0.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  19    0.50  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  20    1.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  21    2.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  22    8.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  23   10.28  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  24  217.82  0.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  25    0.50  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  26    1.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  27    2.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  28    8.00  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  29   10.28  1.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
  30 8799.82  0.000    1    0      0.0      0.0     0    0.000  0 0.0 0 0.0
   0                           ! # of feed specs
   0                           ! # of removal groups
```

APPENDIX B: NUCLEAR FORENSIC CODES DEVELOPED

B.1 Nuclear Forensic Signature Predictor Code

```
#! C:\mb\perl\bin
#  Matthew Sternat - Texas A&M University
#  Perl script to calculate 148 mass bin isotopics using ORIGEN
#  Version 1 November 2011
use File::Copy;
use File::Path;
use FIle::Find;
use IO::Select;
use POSIX;

chomp ($inputfile = $ARGV[0]);
chomp ($XSfile = $ARGV[1]);
$XSorigen= join ('',$XSfile,'.LIB');

print "\nRead input file named $inputfile\n    and cross section file $XSorigen\n";

# read burnup and initial enrichment from input file
open (input,$inputfile);  $lines = <input>;
read input, $BUtimemax, 8; $lines = <input>;
$BUtimemax = $BUtimemax +0;
read input, $DECtimemax, 8; $lines = <input>;
$DECtimemax = $DECtimemax +0;
read input, $BUtimemin, 8; $lines = <input>;
$BUtimemin = $BUtimemin +0;
read input, $DECtimemin, 8; $lines = <input>;
$BUtimemin = $BUtimemin +0;
read input, $BUsteps, 8; $lines = <input>;
read input, $DECsteps, 8; $lines = <input>;
read input, $burnup, 8; $lines = <input>;
$burnup = $burnup +0;
read input, $pwrdensity, 8; $lines = <input>;
$pwrdensity = $pwrdensity +0;
read input, $finaldecay, 8; $lines = <input>;
$finaldecay = $finaldecay + 0;
read input, $U234, 8; $lines = <input>;
read input, $U235, 8; $lines = <input>;
read input, $U236, 8; $lines = <input>;
read input, $U238, 8;
close (input);


  # print "$BUtimemax\n$DECtimemax\n$BUtimemin\n$DECtimemin\n$BUsteps\n$DECsteps\n$burnup\n$pwrdensity\n$finaldecay\n\n\n";

$burnupstep = $BUtimemin +0;
$decaystep = $DECtimemin +0;

$buinc = ($BUtimemax - $BUtimemin)/$BUsteps +0;
$decinc= ($DECtimemax - $DECtimemin)/$DECsteps+0;

print "\n\n\n$buinc\n$decinc\n\n\n";

$burnuptime = $burnup/$pwrdensity+0;
print "Burntime = $burnuptime\n";

open (output,">output.txt");

for ($bu = 1; $bu<=$BUsteps; $bu++){
  for ($dec = 1; $dec<$DECsteps; $dec++){

    $steps = $burnuptime/$burnupstep;
    $steps1 = ($steps - floor($steps))*$burnupstep;
    # select(STDOUT);
    # print "Burnup step length = $steps\n Fractional final step length = $steps1\n\n\n";
    $steps = floor($steps);

    @times=();
    $i=1;
    while ($i<$steps+1) {
      $times[2*$i-1]= $burnupstep*$i + $decaystep*($i-1);
      $i=$i+1;
    }
    $i=1;
    while ($i<$steps) {
      $times[2*$i]= $burnupstep*$i + $decaystep*($i);
      $i=$i+1;
    }

    $i=1;
    # while ($i<2*$steps) {
```

```
      # print "$times[$i]\n";
      # $i=$i+1;
    # }

    system ("del tape* origenoutput.txt" >nul);
    &origen_execution;

    $file="origenoutput.txt";
    open (origen, $file);

    while ($lines = <origen>) {
      read origen, $isotope, 11;
      if ($isotope eq "SM148      "){
        # print "$isotope\n";
        read origen, $SM148m, 9;
        $SM148m = $SM148m+0;
        # print "The $isotope mass is $SM148m\n";
        last;
      } elsif ($isotope eq "ND148      "){
        # print "$isotope\n";
        read origen, $ND148m, 9;
        $ND148m = $ND148m+0;
        # print "The $isotope mass is $ND148m\n";
      } elsif ($isotope eq " U238      "){
        # print "$isotope\n";
        read origen, $U238m, 9;
        $U238m = $U238m+0;
        # print "The $isotope mass is $U238m\n";
      } elsif ($isotope eq "TOT BURNUP "){
        # print "$isotope\n";
        read origen, $totburn, 9;
        # $totburn = $totburn+0;
        print "$isotope  $totburn\n";
      }
    }
    close (origen);

    select(output);
    # $m148ratio[$bu][$dec] = ($SM148+$ND148)/$U238;
    $m148ratio = ($SM148m+$ND148m)/$U238m*238/148;
    printf "%.5f     ", $m148ratio;

    $decaystep = $decaystep + $decinc;
  }
  print "\n";
  $burnupstep = $burnupstep + $buinc;
}

# for ($bu = 1; $bu<=$BUsteps; $bu++){
  # for ($dec = 1; $dec<$DECsteps; $dec++){
    # print "$m148ratio[$bu][$dec]   ";
  # }
  # print "\n";
# }

sub origen_execution {
     open (tape5, ">tape5.inp");
     select(tape5);

     print "-1\n";
     print "-1\n";
     print "-1\n";
     print "  LIB  0  1 2 3  201 202 203  9 50 0 1 0\n";
     print "  PHO     101 102 103  10\n";
     print "  INP  1   1  -1  -1   1   1\n";
     print "  BUP\n";
     $j=1;
     while ($j<2*$steps) {
       printf "  IRP %3.2f %2.2f 1 1 4 0\n", $times[$j],$pwrdensity;
       if ($j<2*$steps-1){
         printf "  DEC %3.2f      1 1 4 0\n", $times[$j+1];
       }
       $JJ = ($j+1)%50;
       if ($JJ==0){
         print "  BUP\n  RDA    blank line hit 50 step limit\n  BUP\n";
       }
       # if ($j==49){
         # print "  BUP\n  RDA\n  BUP\n";
       # } elsif ($j==99) {
         # print "  BUP\n  RDA\n  BUP\n";
       # } elsif ($j==149) {
         # print "  BUP\n  RDA\n  BUP\n";
       # } elsif ($j==199) {
         # print "  BUP\n  RDA\n  BUP\n";
       # } elsif ($j==249) {
         # print "  BUP\n  RDA\n  BUP\n";
       # } elsif ($j==299) {
```

```
        # print "  BUP\n  RDA\n  BUP\n";
      # } elsif ($j==349) {
        # print "  BUP\n  RDA\n  BUP\n";
      # } elsif ($j==399) {
        # print "  BUP\n  RDA\n  BUP\n";
      # }
      $j=$j+2;
    }
    if ($steps1 > 0){
      $secondlastdecay = $times[-1]+$decaystep;
      print "  DEC $secondlastdecay 1 1 4 0\n";
      $finalburn = $secondlastdecay+$steps1;
      print "  IRP $finalburn $pwrdensity 1 1 4 0\n";
      $decaytime = $finalburn+$finaldecay;
      print "  DEC $decaytime 1 1 4 0\n";
    } else {
      $decaytime = $times[-1]+$finaldecay;
      print "  DEC $decaytime 1 1 4 0\n";
    }
    print "  BUP\n";
    print "  OPTL 8 8 8 8 8 8 8 8 8 18*8 8 8 8\n";
    print "  OPTA 8 8 8 8 5 8 8 8 8 18*8 8 8 8\n";
    print "  OPTF 8 8 8 8 5 8 8 8 8 18*8 8 8 8\n";
    print "  OUT     1   1  -1   0\n";
    print "  END\n";
    print "1 80160  181.32 130270 2839.76 0 0 0 0\n";
    printf "2 922340 %.1f 922350 %.1f 922360 %.1f 922380 %.1f \n", $U234, $U235, $U236, $U238;
    print "0\n";
    print "\n";
    print "\n";
    select(STDOUT);
    close (tape5);

    # # Execute ORIGEN2.2
    copy("$XSorigen","tape999.inp");
    system "copy decay.lib+tape999.inp tape9.inp >nul";
    system ("copy gxuo2brm.lib tape10.inp >nul");
    system ("origen2.2 1>nul 2>nul");
    system ("copy TAPE6.out origenoutput.txt >nul");
    # system ("del tape* >nul");
}
```

B.2 Nuclear Forensic Signature Predictor Code Input Example

```
Input parameters
25                      ! Burn axis max [d]
100                     ! Decay axis max [d]
10                      ! Burn axis min [d]
1.0                     ! Decay axis min [d]
25                      ! Burn axis steps [d]
25                      ! Decay axis steps [d]
425.7                   ! Total Burnup [GWd/MTHM]
3.3                     ! Power density [MW/MTHM]
8000                    ! Decay time after final burn step [d]
10                      ! U234
930                     ! U235
10                      ! U236
50                      ! U238
```

B.3 Spent Fuel Forensics Code

```
#! C:\mb\perl\bin
#  Matthew Sternat - Texas A&M University
#  Perl script to converge initial enrichment and burnup values using ORIGEN
#  Version 1 November 2011
use File::Copy;
use File::Path;
use FIle::Find;
use IO::Select;

chomp ($inputfile = $ARGV[0]);
print "\nRead input file named $inputfile\n\n";
chomp ($XSfile = $ARGV[1]);
```

```
$XSfiles = join ('',$XSfile,'.txt');
$XSorigen= join ('',$XSfile,'.LIB');

# read burnup and initial enrichment from input file
open (input,$inputfile);  $lines = <input>;
read input, $U234meas, 9; $lines = <input>;
read input, $U234meas_un, 9; $lines = <input>;
read input, $U235meas, 9; $lines = <input>;
read input, $U235meas_un, 9; $lines = <input>;
read input, $U236meas, 9; $lines = <input>;
read input, $U236meas_un, 9; $lines = <input>;
read input, $U238meas, 9; $lines = <input>;
read input, $U238meas_un, 9; $lines = <input>;
read input, $Pu239meas, 9; $lines = <input>;
read input, $Pu239meas_un, 9; $lines = <input>;
read input, $Pu240meas, 9; $lines = <input>;
read input, $Pu240meas_un, 9; $lines = <input>;
read input, $Pu241meas, 9; $lines = <input>;
read input, $Pu241meas_un, 9; $lines = <input>;
read input, $Cs137meas, 9; $lines = <input>;
read input, $Cs137meas_un, 9; $lines = <input>;
read input, $Nd148meas, 9; $lines = <input>;
read input, $Nd148meas_un, 9; $lines = <input>;
read input, $mass137meas, 9; $lines = <input>;
read input, $mass137meas_un, 9; $lines = <input>;
read input, $burnsteps, 9; $lines = <input>;
read input, $burnup_method, 5; $lines = <input>;
read input, $pwrdensity, 9; $lines = <input>;
read input, $units, 1;
close (input);
open (XSinput,$XSfiles); $lines = <XSinput>;
read XSinput, $XS234c, 10; $lines = <XSinput>;
read XSinput, $XS234f, 10; $lines = <XSinput>;
read XSinput, $XS235c, 10; $lines = <XSinput>;
read XSinput, $XS235f, 10; $lines = <XSinput>;
read XSinput, $XS236c, 10; $lines = <XSinput>;
read XSinput, $XS236f, 10; $lines = <XSinput>;
read XSinput, $XS238c, 10; $lines = <XSinput>;
read XSinput, $XS238f, 10; $lines = <XSinput>;
read XSinput, $XS239c, 10; $lines = <XSinput>;
read XSinput, $XS239f, 10; $lines = <XSinput>;
read XSinput, $XS240c, 10; $lines = <XSinput>;
read XSinput, $XS240f, 10; $lines = <XSinput>;
read XSinput, $XS241c, 10; $lines = <XSinput>;
read XSinput, $XS241f, 10; $lines = <XSinput>;
close (XSinput);
print "Burnup Method is $burnup_method\n\n";
# Constants
$avag = 6.022*10**23; # Avagadro's number
$Er   = 3.7037E-25;   # Recoverable energy per fission [GWd]
$Cs137amass= 136.9070;
$Nd148amass= 147.9169;
$U234amass = 234.0409;
$U235amass = 235.0439;
$U236amass = 236.0455;
$U238amass = 238.0507;
$Pu239amass= 239.0521;
$Pu240amass= 240.0538;
$Pu241amass= 241.0568;
$Nd148yield = 0.0167165;
$Cs137yield = 0.0627;
$XS234a=$XS234c+$XS234f;
$XS235a=$XS235c+$XS235f;
$XS236a=$XS236c+$XS236f;
$XS238a=$XS238c+$XS238f;
$XS239a=$XS239c+$XS239f;
$XS240a=$XS240c+$XS240f;
$XS241a=$XS241c+$XS241f;
$HL_Cs137=30.07; # (in years)

$MoU=($U234meas+$U235meas+$U236meas+$U238meas)/($U234meas/$U234amass+$U235meas/$U235amass+$U236meas/$U236amass+$U238meas/$U238amass)/(
# print "$XS234a\n$XS235a\n$XS236a\n$XS238a\n$XS239a\n$XS240a\n$XS241a\n";

# Convert input concentrations to atomic if given in mass
if ($units==1){
  $Cs137meas=$Cs137meas*$avag/$Cs137amass;
  $mass137meas=$mass137meas*$avag/$Cs137amass;
  $Nd148meas=$Nd148meas*$avag/$Nd148amass;
  $U234meas=$U234meas*$avag/$U234amass;
  $U235meas=$U235meas*$avag/$U235amass;
  $U236meas=$U236meas*$avag/$U236amass;
  $U238meas=$U238meas*$avag/$U238amass;
  $Pu239meas=$Pu239meas*$avag/$Pu239amass;
  $Pu240meas=$Pu240meas*$avag/$Pu240amass;
  $Pu241meas=$Pu241meas*$avag/$Pu241amass;
}
# Calculate burnup from isotopic parameters
```

```
$ep1=999;
$burnup=0;
$burnup_un=0.00000000001;
$burnup_iterations=0;
$MoU=($U234meas+$U235meas+$U236meas+$U238meas)/($U234meas/$U234amass+$U235meas/$U235amass+$U236meas/$U236amass+$U238meas/$U238amass)/(
# # print "$MoU\n";
if ($burnup_method eq "Nd148"){
  $burnup_monitor=$Nd148meas;
  $burnup_monitor_un=$Nd148meas_un;
  $burnup_yield=$Nd148yield;
} elsif ($burnup_method eq "Cs137") {
  $burnup_monitor=$mass137meas;
  $burnup_monitor_un=$mass137meas_un;
  $burnup_yield=$Cs137yield;
}

while ($ep1>0.000001){
  $NU_U238=($U234meas/$U238meas+$U235meas/$U238meas+$U236meas/$U238meas+1+$Pu239meas/$U238meas+$Pu240meas/$U238meas+$Pu241meas/$U238me
  $NU_U238_un=sqrt((sqrt((sqrt(($U234meas*$U234meas_un)**2+($U235meas*$U235meas_un)**2+($U236meas*$U236meas_un)**2+($U238meas*$U238mea
  # print "$NU_U238_un\n";
  $burnup2=$burnup_monitor/$U238meas*1/$NU_U238*$avag*$Er/$burnup_yield/$MoU;
  $burnup_un=sqrt((sqrt($burnup_monitor_un**2+$U238meas_un**2))**2+($NU_U238_un/100)**2)*100;
  # print "$burnup_un\n";
  $ep1=abs($burnup2-$burnup)/$burnup2;
  $burnup=$burnup2;
  $burnup_iterations=$burnup_iterations+1;
}
print "Calculated burnup     = $burnup [GWd/MTHM]\n";
print "   Uncertainty        = $burnup_un [%]\n\n";

print "NU_U238 ratio         = $NU_U238\n";
print "   Uncertainty        = $NU_U238_un [%]\n\n";

print "Burnup Iterations = $burnup_iterations \n\n";

$U238_NU=1/$NU_U238;
$U234_U238=$U234meas/$U238meas;
$U235_U238=$U235meas/$U238meas;
$U236_U238=$U236meas/$U238meas;
$Pu239_U238=$Pu239meas/$U238meas;
$Pu240_U238=$Pu240meas/$U238meas;
$Pu241_U238=$Pu241meas/$U238meas;

$p1=$U238_NU*($U235_U238+$U236_U238)+$MoU*$burnup/$avag/$Er;
$p1_un=sqrt((sqrt((sqrt(($U235meas/$U238meas*sqrt($U235meas_un**2+$U238meas_un**2))**2+($U236meas/$U238meas*sqrt($U236meas_un**2+$U238

$p2=-$XS238f/$XS238a*(1-$U234_U238*$U238_NU-$U238_NU);
$p2_un=$XS238f/$XS238a*sqrt(($NU_U238_un/100*$U238_NU)**2+(($U234_U238*$U238_NU)*sqrt($U234meas_un**2+$U238meas_un**2+($NU_U238_un/100

$p3=-$XS239f/$XS239a*(-$Pu239_U238*$U238_NU+$XS238c/$XS238f*-$p2);
$p3_un=$XS239f/$XS239a*sqrt((($Pu239_U238*$U238_NU)*sqrt($Pu239meas_un**2+$U238meas_un**2+($NU_U238_un/100)**2))**2+($XS238c/$XS238f*-

$p4=-$XS240f/$XS240a*(-$Pu240_U238*$U238_NU+$XS239c/$XS239f*-$p3);
$p4_un=$XS240f/$XS240a*sqrt((($Pu240_U238*$U238_NU)*sqrt($Pu240meas_un**2+$U238meas_un**2+($NU_U238_un/100)**2))**2+($XS239c/$XS239f*-

$p5=-$XS241f/$XS241a*(-$Pu241_U238*$U238_NU+$XS240c/$XS240f*-$p4);
$p5_un=$XS241f/$XS241a*sqrt((($Pu241_U238*$U238_NU)*sqrt($Pu241meas_un**2+$U238meas_un**2+($NU_U238_un/100)**2))**2+($XS240c/$XS240f*-

$p6=$XS238f/$XS238a+$XS238c/$XS238a*$XS239f/$XS239a+$XS238c/$XS238a*$XS239c/$XS239a*$XS240f/$XS240a+$XS238c/$XS238a*$XS239c/$XS239a*$X

# print "$p1_un\n";
# print "$p2_un\n";
# print "$p3_un\n";
# print "$p4_un\n";
# print "$p5_un\n\n";
$enrich=($p1+$p2+$p3+$p4+$p5)/(1-$p6)*100;
$enrich_un=1/(1-$p6)*sqrt(($p1*$p1_un)**2+($p2*$p2_un)**2+($p3*$p3_un)**2+($p4*$p4_un)**2+($p5*$p5_un)**2)/($enrich/100)*100;

# print "$p1\n$p2\n$p3\n$p4\n$p5\n$p6\n\n\n\n";

print "Calculated initial U235 enrichment = $enrich [%]\n";
print "   Relative Uncertainty            = $enrich_un [%%]\n\n\n";
# print "Total burn time is $time days with $steplength days/step.\n";

$enrich236 = ($U236_U238/$NU_U238 - 0.0001987*$burnup)*100;
$enrich236_un = abs( (($U236_U238/$NU_U238*sqrt($U234meas_un^2+$U238meas_un^2+$NU_U238^2))^2+(0.0001987*$burnup*$burnup_un)^2)/$enrich
print "Calculated initial U-236 enrichment = $enrich236 [%]\n";
print "   Relative Uncertainty             = $enrich236_un [%%]\n\n\n";

$correctedenrich = $enrich-$enrich236;
$correctedenrich_un = sqrt(($enrich*$enrich_un)^2+($enrich236*$enrich236_un)^2)/$correctedenrich;

print "Corrected initial U-235 enrichment = $correctedenrich [%]\n";
print "   Relative Uncertainty            = $correctedenrich_un [%%]\n\n\n";

$counter=0;
print "Begin predictor & corrector perturbations\n";
```

```
print "----------------------------------------\n";
# Outer enrichment & burnup purtebation loop

  # Converge U235 enrichment to match final U235 enrichment to measured sample
  # ------------------------------------------------------------------------------
  $ep1=999;
  while($ep1>0.001){
    # calculate fuel isotopics in atomic % (U234 content using TransLAT equations)
    $ep2=999;
    $U235=$enrich/100;
    if ($counter==1){
      $U234a=0.000001;
      $U236a=0.000001;
    }
    $U238=1-$U234a-$U235-$U236a;

    # Calculate and print burn time and step length
    $time = $burnup/$pwrdensity;
    $steplength = $time/$burnsteps;
    # print "$burnup\n";
    # make time step array
    $i=0;
    while ($i<$burnsteps+1) {
      $times[$i]=$i*$steplength;
      $i=$i+1;
    }

    # U234 Predictor on first step
    if ($counter==1){
      while($ep2>0.01){
        $U234b = 0.007731*($U235/$U238)**1.0837*$U238;
        $U238 = 1-$U236a-$U235-$U234b;
        $ep2 = abs($U234a-$U234b)/$U234b;
        $U234a=$U234b;
      }
    }

    # convert back to mass % for ORIGEN input [g/kgHM]
    $MoUinit=$U234a*$U234amass+$U235*$U235amass+$U236a*$U236amass+$U238*$U238amass;
    # print "$MoUinit\n$MoU\n";
    $U234=$U234a*$U234amass/$MoUinit*1000;
    $U235=$U235 *$U235amass/$MoUinit*1000;
    $U236=$U236a*$U236amass/$MoUinit*1000;
    $U238=$U238 *$U238amass/$MoUinit*1000;
    # print "$U234\n $U235\n $U236\n $U238\n";



    # # direct output to create ORIGEN tape5
    system ("del tape* origenoutput.txt" >nul);
    &make_origen_input;

    # Open ORIGEN2.2 output and extract new fuel data
    $file="origenoutput.txt";
    open (origen, $file);

    while ($lines = <origen>) {
      read origen, $isotope, 11;
      if ($isotope eq " U234      "){
        # print "$isotope\n";
        read origen, $U234bu, 9;
        $U234bu = $U234bu+0;
        # print "The $isotope mass is $U238a\n";
      } elsif ($isotope eq " U235      "){
        # print "$isotope\n";
        read origen, $U235bu, 9;
        $U235bu = $U235bu+0;
        # print "The $isotope mass is $U238a\n";
      } elsif ($isotope eq " U236      "){
        # print "$isotope\n";
        read origen, $U236bu, 9;
        $U236bu = $U236bu+0;
        # print "The $isotope mass is $U238a\n";
      } elsif ($isotope eq " U238      "){
        # print "$isotope\n";
        read origen, $U238bu, 9;
        $U238bu = $U238bu+0;
        # print "The $isotope mass is $U238a\n";
      } elsif ($isotope eq "CS137      "){
        # print "$isotope\n";
        read origen, $Cs137bu, 9;
        $Cs137bu = $Cs137bu+0;
        # print "The $isotope mass is $Cs137a\n";
      } elsif ($isotope eq "BA137      "){
        # print "$isotope\n";
        read origen, $Ba137bu, 9;
        $Ba137bu = $Ba137bu+0;
```

```
    # print "The $isotope mass is $Ba137a\n";
  } elsif ($isotope eq "ND148      "){
    # print "$isotope\n";
    read origen, $Nd148bu, 9;
    $Nd148bu = $Nd148bu+0;
    # print "The $isotope mass is $Nd148a\n";
    last;
  }
}
close (origen);



# U235 Convergence
# ------------------------------------------------------------------------
# Calculate final U235 enrichment
$finalenrich1=$U235meas/($U234meas+$U235meas+$U236meas+$U238meas);
$finalenrich2=$U235bu/$U235amass/($U234bu/$U234amass+$U235bu/$U235amass+$U236bu/$U236amass+$U238bu/$U238amass);
# $enrich2=$enrich*(($finalenrich1-$finalenrich2)/(2*$finalenrich1)+1);
$enrich_error = abs($finalenrich1-$finalenrich2)/($finalenrich1);
if ($enrich_error > 0.05) {
  if ($finalenrich1 > $finalenrich2) {
    $enrich2 = $enrich*($enrich_error+1);
  } else {
    $enrich2 = $enrich*exp (-$enrich_error/1.5);
  }
} elsif (($enrich_error < 0.05) && ($enrich_error > 0.00025)) {
  if ($finalenrich1 gt $finalenrich2) {
    $enrich2 = $enrich*($enrich_error/2+1);
  } else {
    $enrich2 = $enrich*(1-$enrich_error/2);
  }
}
# } else {
  # $ep10 = $enrich_error;
# }
# print "Measured burned enrichment is   $finalenrich1\n";
# print "Calculated burned enrichment is $finalenrich2\n\n";
# print "The new final enrichment is $finalenrich2\n\n\n";
# $ep1 = abs($enrich2-$enrich)/$enrich2;
$enrich=$enrich2;



# U234 Convergence
# ------------------------------------------------------------------------
# Calculate final U234 enrichment
$U234finalenrich1=$U234meas/($U234meas+$U235meas+$U236meas+$U238meas);
$U234finalenrich2=$U234bu/$U234amass/($U234bu/$U234amass+$U235bu/$U235amass+$U236bu/$U236amass+$U238bu/$U238amass);
# $U234b=$U234a*(($U234finalenrich1-$U234finalenrich2)/(2*$U234finalenrich1)+1);
$enrich_error2 = abs($U234finalenrich1-$U234finalenrich2)/($U234finalenrich1);
if ($enrich_error2 > 0.05) {
  if ($U234finalenrich1 > $U234finalenrich2) {
    $U234b = $U234a*($enrich_error2+1);
  } else {
    $U234b = $U234a*exp (-$enrich_error2/1.5);
  }
} elsif (($enrich_error2 < 0.05) && ($enrich_error2 > 0.00025)) {
  if ($U234finalenrich1 gt $U234finalenrich2) {
    $U234b = $U234a*($enrich_error2/2+1);
  } else {
    $U234b = $U234a*(1-$enrich_error2/2);
  }
}
# print "New U234 final enrich = $U234finalenrich2\nMeasured U234 final Enrich = $U234finalenrich1\n\n";
# print "Original U234 initial enrich = $U234a\nNew U234 initial enrich = $U234b\n\n";
# $ep1 = abs($U234b-$U234a)/$U234b;
$U234a=$U234b;



# U236 Convergence
# ------------------------------------------------------------------------
# Calculate final U236 enrichment
$U236finalenrich1=$U236meas/($U234meas+$U235meas+$U236meas+$U238meas);
$U236finalenrich2=$U236bu/$U236amass/($U234bu/$U234amass+$U235bu/$U235amass+$U236bu/$U236amass+$U238bu/$U238amass);
# $U236b=$U236a*(($U236finalenrich1-$U236finalenrich2)/(2*$U236finalenrich1)+1);
# print "U236 final enrich old = $U236finalenrich2\n";
# print "U236 final enrich new = $U236finalenrich1\n";
if ($U236a < 0.0000009) {
  $enrich_error3=0;
  $U236b=$U236a;
  print "    U-236 will not converge, consider changing cross section sets\n";
} else {
  $enrich_error3 = abs($U236finalenrich1-$U236finalenrich2)/($U236finalenrich1);
}
```

```
    if ($enrich_error3 > 0.01) {
      if ($U236finalenrich1 > $U236finalenrich2) {
        $U236b = $U236a*(100*$enrich_error3+1);
      } else {
        $U236b = $U236a*exp (-$enrich_error3/1.5);
      }
    } elsif (($enrich_error3 < 0.01) && ($enrich_error3 > 0.00025)) {
      if ($U236finalenrich1 gt $U236finalenrich2) {
        $U236b = $U236a*($enrich_error3+1);
      } else {
        $U236b = $U236a*(1-$enrich_error3/2);
      }
    }
    # print "New U236 final enrich = $U236finalenrich2\nMeasured U236 final Enrich = $U236finalenrich1\n\n";
    # print "New U236 initial enrich = $U236b\n\n";
    # $ep1 = abs($U236b-$U236a)/$U236b;
    $U236a=$U236b;



    # Burnup Convergence
    # -----------------------------------------------------------------
    if ($burnup_method eq "Nd148"){
      $burnup_monitor2=$Nd148bu;
      $burnup_amass=$Nd148amass;
    } elsif ($burnup_method eq "Cs137") {
      $burnup_monitor2=$Cs137bu+$Ba137bu;
      $burnup_amass=$Cs137amass
    }

    # Calculate new burnup
    # $burnup2=$burnup*(($burnup_monitor/$U238meas-($burnup_monitor2/$burnup_amass)/($U238bu/$U238amass))/(2*$burnup_monitor/$U238meas
    $ratio1=$burnup_monitor/$U235meas;
    $ratio2=($burnup_monitor2/$burnup_amass)/($U235bu/$U235amass);
    # print "$ratio2\n";
    $burn_error = abs($ratio1-$ratio2)/$ratio1;
    # print "$burn_error\n";
    if ($burn_error > 0.09) {
      if ($ratio1 > $ratio2) {
        $burnup2 = $burnup*($burn_error+1);
      } else {
        $burnup2 = $burnup*exp (-$burn_error/1.5);
      }
    } elsif (($burn_error > 0.00025) && ($burn_error < 0.09)) {
      if ($ratio1 > $ratio2) {
        $burnup2 = $burnup*($burn_error/3+1);
      } else {
        $burnup2 = $burnup*(1-$burn_error/3);
      }
    }
    # } else {
      # $ep11 = $burn_error;
      # $burnup2 = $burnup;
    # }
    # print "The starting burnup was $burnup\n";
    # print "The new burnup is      $burnup2\n";
    # $ep1 = abs($burnup2-$burnup)/$burnup2;
    $burnup=$burnup2;
    $ep1 = $burn_error+$enrich_error+$enrich_error2+$enrich_error3;
    print "$ep1\n";
    print " $burn_error\n  $enrich_error\n   $enrich_error2\n    $enrich_error3\n\n\n";
    $counter=$counter+1;
  }
  print "U235 Enrichment converged at $enrich.\n";
  print "  Enrichment error         = $enrich_error\n\n";
  print "Burnup converged at          $burnup.\n";
  print "  Burnup error             = $burn_error\n\n";
  print "Iterations =                 $counter.\n";

# print "\n\n\n\n";
system ("del origenoutput.txt >nul");
print "\n\n\nRun complete:\n";
print "Final burnup = $burnup [GWd/MTHM]\n";
$U234percent=$U234b*100;
printf "The converged initial uranium isotopics: U234 %7.4f [%]\n",$U234percent;
printf "                                         U235 %7.4f [%]\n",$enrich;
$U236percent=$U236b*100;
printf "                                         U236 %7.4f [%]\n",$U236percent;
$U238percent=100-$U234percent-$enrich-$U236percent;
printf "                                         U238 %7.4f [%]\n",$U238percent;

print "\n\n\n";

# Calculate Fuel Age (Fuel Cooling Time)
# -----------------------------------------------------------------
```

```
# Run ORIGEN predictor to get end of power cooling time monitor concentrations

# Calculate burn time and step length from final burnup
$time = $burnup/$pwrdensity;
$steplength = $time/$burnsteps;
$i=0;
while ($i<$burnsteps+1) {
  $times[$i]=$i*$steplength;
  $i=$i+1;
}

# convert back to mass % for ORIGEN input [g/kgHM]
$MoUinit=$U234percent/100*$U234amass+$enrich/100*$U235amass+$U236percent/100*$U236amass+$U238percent/100*$U238amass;
$U234=$U234percent/100*$U234amass/$MoUinit*1000;
$U235=$enrich/100*$U235amass/$MoUinit*1000;
$U236=$U236percent/100*$U236amass/$MoUinit*1000;
$U238=$U238percent/100*$U238amass/$MoUinit*1000;

&make_origen_input;

# Open ORIGEN2.2 output and extract new fuel data
$file="origenoutput.txt";
open (origen, $file);

while ($lines = <origen>) {
  read origen, $isotope, 11;
  if ($isotope eq " U238      "){
    # print "$isotope\n";
    read origen, $U238a, 9;
    $U238a = $U238a/$U238amass;
    # print "The $isotope mass is $U238a\n";
  } elsif ($isotope eq "CS137      "){
    # print "$isotope\n";
    read origen, $Cs137, 9;
    $Cs137 = $Cs137/$Cs137amass;
    # print "The $isotope mass is $Nd148a\n";
    last;
  }
}
close (origen);
$fuelage1=-$HL_Cs137/log(2)*log(($Cs137meas/$U238meas)/($Cs137/$U238a));
$fuelage1_un=$HL_Cs137/log(2)*sqrt($U238meas_un**2+$Cs137meas_un**2)/$fuelage1*100;
# print "$U238a\n$Cs137\n";
print "Fuel Age calculated using ORIGEN 2.2 predictor\n";
printf "The Cs-137 reconstructed fuel age = %.2f years\n",$fuelage1;
printf "   Uncertainty                    = %.4f [%]\n\n",$fuelage1_un;


$fuelage2=$HL_Cs137/log(2)*log($mass137meas/$Cs137meas);
$fuelage2_un=$HL_Cs137/log(2)*sqrt($mass137meas_un**2+$Cs137meas_un**2)/$fuelage2*100;
print "Fuel Age calculated using 137 mass bin and gamma spec\n";
printf "The Cs-137 reconstructed fuel age = %.2f years \n",$fuelage2;
printf "   Uncertainty                    = %.4f [%]\n",$fuelage2_un;



sub make_origen_input {
     open (tape5, ">tape5.inp");
     select(tape5);

     print "-1\n";
     print "-1\n";
     print "-1\n";
     print "  LIB  0  1 2 3  201 202 203  9 50 0 1 0\n";
     print "  PHO     101 102 103  10\n";
     print "  INP  1   1  -1  -1   1   1\n";
     print "  BUP\n";
     $j=1;
     while ($j<$burnsteps+1) {
       print "  IRP $times[$j] $pwrdensity 1 1 4 0\n";
       $j=$j+1;
     }
     $decaytime = $time+30;
     print "  DEC $decaytime 1 1 4 0\n";
     print "  BUP\n";
     print "  OPTL 8 8 8 8 8 8 8 8 8 18*8 8 8 8\n";
     print "  OPTA 8 8 8 8 5 8 8 8 8 18*8 8 8 8\n";
     print "  OPTF 8 8 8 8 5 8 8 8 8 18*8 8 8 8\n";
     print "  OUT     1   1  -1   0\n";
     print "  END\n";
     printf "2 922340 %.4f 922350 %.4f 922360 %.4f 922380 %.4f \n", $U234, $U235, $U236, $U238;
     print "0\n";
     print "\n";
     print "\n";
     select(STDOUT);
     close (tape5);
```

```
    # # Execute ORIGEN2.2
    copy("$XSorigen","tape999.inp");
    system "copy decay.lib+tape999.inp tape9.inp >nul";
    system ("copy gxuo2brm.lib tape10.inp >nul");
    system ("origen2.2 1>nul 2>nul");
    system ("copy TAPE6.out origenoutput.txt >nul");
    system ("del tape* >nul");
}
```

B.4 Spent Fuel Forensics Code Isotopic Concentration Input File Example

```
Input file for example
425.6                   !U234 measured signature
22250                   !U235 measured signature
4527                    !U236 measured signature
2766                    !U238 measured signature
53.03                   !Pu239 measured signature
16.40                   !Pu240 measured signature
0.00                    !Pu241 measured signature
481.2                   !Cs137 measured signature
303.7                   !Nd148 measured signature
20                      !Number of burnsteps
3.3                     !Power density [MW/MTHM]
1                       !signatures unit [1=mass, 0=atom densities]
```

B.5 Spent Fuel Forensics Code Cross Section Input File Example

```
One Group Cross Section file MTRHEU
33.3                    !U234 Capture Cross Section
0.457                   !U234 Fission Cross Section
17.7                    !U235 Capture Cross Section
88.5                    !U235 Fission Cross Section
15.9                    !U236 Capture Cross Section
0.384                   !U236 Fission Cross Section
7.09                    !U238 Capture Cross Section
0.0972                  !U238 Fission Cross Section
87.1                    !Pu239 Capture Cross Section
172.                    !Pu239 Fission Cross Section
250                     !Pu240 Capture Cross Section
0.574                   !Pu240 Fission Cross Section
70.6                    !Pu241 Capture Cross Section
200.                    !Pu241 Fission Cross Section
```