

REACTOR PHYSICS ASSESSMENT OF THICK SILICON CARBIDE CLAD PWR FUELS

By

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14. ABSTRACT High temperature tolerance, chemical stability and low neutron affinity make silicon carbide (SiC) a potential fuel cladding material that may improve the economics and safety of light water reactors (LWRs). Thick SiC cladding (0.089 cm) is easier (and thus more economical) to manufacture than SiC of conventional Zircaloy (Zr) cladding thickness (0.057 cm). Five fuel and clad combinations are analyzed: Zr with solid UO₂ pellets, reduced fuel fraction thick SiC (Thick SiC) with annular UO₂ pellets, Thick SiC with solid UO₂/BeO pellets, reduced coolant fraction annular fuel with thick SiC (Thick SiC RCF), and Thick SiC with solid PuO₂/ThO₂ pellets. CASMO-4E and SIMULATE-3 have been utilized to model the above in a 193 assembly, 4-loop Westinghouse pressurized water reactor (PWR). A new program, CSpy, has been written to use CASMO/SIMULATE to conduct optimization searches of burnable poison layouts and core reload patterns. All fuel/clad combinations have been modeled using 84 assembly reloads, and Thick SiC clad annular UO₂ has been modeled using both 84 and 64 assembly reloads. Dual Binary Swap (DBS) optimization via three Objective Functions (OFs) has been applied to each clad/fuel/reload # case to produce a single reload enrichment equilibrium core reload map. The OFs have the goals of: minimal peaking, balancing lower peaking with longer cycle length, or maximal cycle length. Results display the tradeoff between minimized peaking and maximized cycle length for each clad/fuel/reload # case. The presented Zr reference cases and Thick SiC RCF cases operate for an 18 month cycle at 3587 MWth using 4.3% and 4.8% enrichment, respectively. A 90% capacity factor was applied to all SiC cladding cases to reflect the challenge to introduction of a new fuel. The Thick SiC clad annular UO₂ (84 reload cores) and Thick SiC UO₂/BeO exhibit similar reactor physics performance but require higher enrichments than 5%. The Thick SiC RCF annular UO₂ fuel cases provide the required cycle length with less than 5% enrichment. The Thick SiC clad PuO₂/ThO₂ cores can operate with a Pu% of heavy metal of about 12%, however they may have unacceptable shutdown margins without altering the control rod materials.		

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by

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ABSTRACT

High temperature tolerance, chemical stability and low neutron affinity make silicon carbide (SiC) a potential fuel cladding material that may improve the economics and safety of light water reactors (LWRs). “Thick” SiC cladding (0.089 cm) is easier (and thus more economical) to manufacture than SiC of conventional Zircaloy (**Zr**) cladding thickness (0.057 cm). Five fuel and clad combinations are analyzed: **Zr** with solid UO₂ pellets, reduced fuel fraction “thick” SiC (**Thick SiC**) with annular UO₂ pellets, Thick SiC with solid UO₂/BeO pellets, reduced coolant fraction annular fuel with “thick” SiC (**Thick SiC RCF**), and Thick SiC with solid PuO₂/ThO₂ pellets.

CASMO-4E and SIMULATE-3 have been utilized to model the above in a 193 assembly, 4-loop Westinghouse pressurized water reactor (PWR). A new program, CSpy, has been written to use CASMO/SIMULATE to conduct optimization searches of burnable poison layouts and core reload patterns. All fuel/clad combinations have been modeled using 84 assembly reloads, and **Thick SiC** clad annular UO₂ has been modeled using both 84 and 64 assembly reloads.

Dual Binary Swap (DBS) optimization via three Objective Functions (OFs) has been applied to each clad/fuel/reload # case to produce a single reload enrichment equilibrium core reload map. The OFs have the goals of: minimal peaking, balancing lower peaking with longer cycle length, or maximal cycle length. Results display the tradeoff between minimized peaking and maximized cycle length for each clad/fuel/reload # case.

The presented **Zr** reference cases and **Thick SiC RCF** cases operate for an 18 month cycle at 3587 MW_{th} using 4.3% and 4.8% enrichment, respectively. A 90% capacity factor was applied to all SiC cladding cases to reflect the challenge to introduction of a new fuel. The **Thick SiC** clad annular UO₂ (84 reload cores) and **Thick SiC** UO₂/BeO exhibit similar reactor physics performance but require higher enrichments than 5%. The **Thick SiC RCF** annular UO₂ fuel cases provide the required cycle length with less than 5% enrichment. The **Thick SiC** clad PuO₂/ThO₂ cores can operate with a Pu% of heavy metal of about 12%, however they may have unacceptable shutdown margins without altering the control rod materials.

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Nomenclature

B_c	Cycle Burnup	IHM	Initial Heavy Metal
B_d	Discharge Burnup	ITC	Isothermal Temperature
BOC	Beginning of Cycle		Coefficient
BOL	Beginning of Life	kg	kilogram
cm	centimeter	kgIHM	kilogram Initial Heavy Metal
CTP	Ceramic Tubular Products	kW	kiloWatt
CVD	Chemical Vapor Deposition	LOCA	Loss of Coolant Accident
DBS	Dual Binary Swap	LWR	Light Water Reactor
DNB	Departure from Nucleate Boiling	MOX	Mixed Oxide Fuel
		MTC	Moderator Temperature
dpa	Displacements per Atom		Coefficient
EDBS	Exhaustive Dual Binary Swap	MWd/kgIHM	Megawatt days per kilogram of initial heavy metal
EFPD	Effective Full Power Days	MWth	Megawatts thermal
EOC	End of Cycle	NRC	Nuclear Regulatory Commission
EOFPL	End of Full Power Life		
EOL	End of Life	NSE	Nuclear Science and Engineering
$F_{\Delta h}$	Maximum Channel Enthalpy Rise	OF	Objective Function
FHR	Fluoride Salt Cooled High-Temperature Reactor	PCMI	Pellet-Clad Mechanical Interaction
F_q	Maximum Local Power	PkExp	Peak Pin Exposure
H/HM	Hydrogen to Heavy Metal Ratio	PWR	Pressurized Water Reactor
		RGDBS	Random Greedy Dual Binary Swap
HFP	Hot Full Power		
HIP	Hot Isostatic Pressing	RPV	Reactor Pressure Vessel
HZP	Hot Zero Power	SDB	Shutdown Margin at
IFBA	Integral Fuel Burnable Absorber		Beginning of Cycle

SDE	Shutdown Margin at End of Cycle	Thick SiC RCF	Thick SiC Reduced Coolant Fraction Geometry Case
SDM	Shutdown Margin		
SiC	Silicon Carbide	Thin SiC	Thin SiC Geometry Case
SNF	Spent Nuclear Fuel	WABA	Wet Annular Burnable Absorber
Thick SiC	Thick SiC Geometry Case	Zr	Zircaloy

1 Introduction

1.1 Statement of Purpose

Previous work has examined the potential use of SiC as a fuel cladding material in a PWR environment. However the economic viability of implementing SiC cladding material using the same dimensions as existing Zr cladding is not clear. Thicker SiC cladding has been proposed because it is easier to manufacture, and hence improves the economic viability of SiC cladding. The purpose of this thesis is to model and evaluate the neutronic performance of three thick SiC clad fuels in PWR cores: annular UO_2 fuel pellets, UO_2/BeO fuel, and $\text{PuO}_2/\text{ThO}_2$ fuel.

In the case of annular UO_2 and UO_2/BeO fuels it is desired to understand if one or the other is preferable in terms of extending the maximum burnup of the fuel. Furthermore, three annular UO_2 cases are examined: reduced fuel fraction with 64 assembly reloads per cycle, reduced fuel fraction with 84 assembly reloads per cycle, and reduced coolant fraction with 84 assembly reloads per cycle. In the reduced fuel fraction cases, the clad outer radius matches the conventional fuel used today and volume to accommodate the extra thickness of the cladding is taken from the fuel volume. In the case of reduced coolant fraction, the fuel pellets' outer radius matches the conventional pellets used today and the volume to accommodate the extra thickness of the cladding is taken from the coolant volume.

In the case of $\text{PuO}_2/\text{ThO}_2$ fuel there are two parameters of primary interest: initial loading of plutonium required in order to meet cycle length, and plutonium remaining in discharged fuel.

1.2 Background

1.2.1 Early experimental reactors

The earliest attempts at creating critical nuclear chain reactions were experimental and so novel at the time that no idea was outside the realm of consideration. The Chicago Pile 1 was a graphite-moderated criticality experiment and had no cooling or shielding whatsoever, and yet this experiment was done in a densely populated area. The third nuclear reactor ever built, LOPO, was a homogeneous aqueous reactor that went critical using water as the moderator and the shield in May of 1944. [1],[2]

The scope of consideration for cladding material was equally broad. For example, in 1944, the B-Reactor at Hanford in the United States used aluminum clad uranium metal fuel to produce plutonium for the Manhattan Project. The British weapons plutonium production also used aluminum cladding, for example at Windscale. British CO₂-cooled MAGNOX reactors used fuel clad in a “non-oxidizing” magnesium alloy.

Austenitic stainless steels and ferritic/martensitic stainless steels have also been used, particularly in fast reactors.

1.2.2 Commercial Reactors

Stainless steel fuel cladding was utilized in the first privately owned, large-scale commercial PWR at Yankee Rowe. **Zr** cladding was adopted by the vast majority of the commercial nuclear power industry after the first few cores due to its reduced neutron absorption and acceptable corrosion resistance. **Zr** cladding service life is primarily limited by corrosion and irradiation embrittlement. While **Zr** is acceptable for normal operations, its performance in accident scenarios has proven problematic—and avoidance of **Zr** failure is a primary goal of nuclear reactor safety engineering and analysis that must be performed to license a reactor.

1.2.3 Chernobyl, TMI, Fukushima

The accident at Three Mile Island (TMI) on March 28th, 1979 is the worst commercial nuclear power generation accident in the history of the United States. Coolant from the primary coolant system leaked resulting in a significant quantity of fuel rods failing. Fuel failure included rupture of the **Zr** cladding and melting of the UO₂ fuel. [NRC site] The nuclear industry in the United States saw new plant construction cease for over thirty years as a result of this partial core melt. It also galvanized anti-nuclear sentiment among significant elements of the voting populace, however the actual release of radionuclides was negligible.

By far the most catastrophic accident in the history of commercial nuclear power occurred on April 26th, 1986 at the then Soviet Chernobyl Nuclear Power Plant in what is now the Ukraine. The reactor at Chernobyl was an RBMK type reactor, which is graphite moderated and light water cooled. Under hot full power conditions this design has a negative moderator temperature coefficient. However, that day the reactor was operated in a low power regime where the moderator temperature coefficient and void coefficient were strongly positive. [ref]

This led to an uncontrollable power transient that almost instantly boiled the coolant inventory and over-pressurized the reactor vessel to the extent that it exploded. The explosion was a steam explosion, not a nuclear explosion. However, the reactor core continued to heat up, lighting the graphite moderator on fire—which carried away in the smoke fission products and other material released from ruptured fuel rods. The confinement design for the RBMK was completely inadequate and significant radionuclide release into the environment occurred. This nuclear accident infuriated Europe, which was directly downwind of this unprecedented radioactive nuclide release. The world has not forgotten Chernobyl, and the official Russian and IAEA total number of deaths, cancers, and other deleterious health effects from this disaster are at times disputed. The only possible benefit to come from this experience has been that the radiation health physics community now has more data to analyze concerning the effects of exposure to fission products.

The accident at Fukushima Daiichi on March 11th, 2011 was the result of a very high wave tsunami which followed a strong earthquake, and caused the failure all but one of the plant's emergency diesel generators and several switchboards connecting individual reactor buildings to the local power grid. Lacking the power at the pumps needed to circulate the water and cool the reactor, catastrophic fuel heat up and failure occurred, including the **Zr** cladding reaching such high temperatures so as to undergo exothermic hydrogen producing reaction with H₂O. Hydrogen escaped from the path provided for its release and explosions destroyed the top floors of three reactor buildings, and significant amounts of radiation were released into the atmosphere and Pacific Ocean. Germany has claimed that it will permanently phase out nuclear energy in response to this accident, and many other countries now question their commitments to nuclear energy as well. [3]

1.2.4 Silicon Carbide (SiC)

SiC is a ceramic material with a high elastic modulus, high ultimate tensile strength, and low fracture toughness. Its melting point is over 2700°C, and it is chemically stable in liquid H₂O and high temperature steam representative of Loss Of Coolant Accident (LOCA) conditions.

SiC's tolerance of high temperature and chemical stability in aqueous environments is vastly superior to conventional **Zr** fuel cladding, which undergoes a strongly exothermic

hydrogen producing reaction above $\sim 1200^{\circ}\text{C}$. SiC is also not susceptible to hydrogen embrittlement.

SiC may also be a candidate cladding material for the Generation IV Fluoride Salt-Cooled High-Temperature Reactor (FHR), since high temperature reactors tend to be limited by degradation of materials performance at high temperature. Zr cladding is not stable in 700°C Li_2BeF_4 eutectic molten salt and therefore unacceptable for the FHR—while SiC may enable the use of rod-type fuel assemblies with conventional low-enriched UO_2 . This would be an alternative to TRISO particle fuel which must be enriched to $\sim 20\%$.

SiC clad fuel also dramatically improves the safety of Spent Nuclear Fuel (SNF) wet storage, dry cask storage, and repository disposal. The temperature limit of Zr cladding is an engineering constraint that the entire SNF waste management industry currently designs around. SiC cladding would allow for more efficient storage and disposal of SNF by allowing waste management engineers to pack more assemblies into waste packages without overheating the cladding and releasing fission products into the waste package.

The potential safety and economic benefits of SiC fuel cladding may allow for a far-reaching re-evaluation of many aspects of nuclear engineering from fuel performance and reactor physics to fuel cycle and waste management.

However, many questions regarding the *in situ* performance of SiC fuel cladding under irradiation remain unanswered or controversial. How does thermal conductivity degrade with fluence? Does SiC's polymorphism lead to phase instability at high fluence and high displacements per atom (dpa) rates? Are the mechanical and thermal properties and their evolution with fluence particularly sensitive to the manufacturing process and initial microstructure? These questions are beyond the scope of this thesis, yet are critically relevant to nuclear fuel cladding applications of SiC.

1.3 Scope

The results presented in this thesis will focus on designing nuclear reactor cores to operate within the desired limiting parameters of particular interest to electrical power generation utilities and the United States Nuclear Regulatory Commission (NRC). Peaking factors, soluble boron concentration, neutron leakage, reactivity coefficients, and shutdown margin calculations have been performed for all cores and are the primary metrics by which they be evaluated.

Assembly burnable pin layouts and core reload maps have been produced via optimization algorithms. In each batch only a single enrichment assembly is used. This methodology has produced a **Zr** clad reference case competitive with more heterogeneous core designs sold by major vendors.

A total of 18 cores have been designed; one core per OF has been designed for each of six fuel and cladding combinations. An OF is the means by which to quantify the relative value of a given system configuration in an optimization algorithm. The three OFs have been chosen to elucidate the dynamic range of performance achievable by each fuel and clad combination—using extremes of design criteria valuations from peaking only optimization to cycle length only optimization.

A software suite, CSpY, has been written to facilitate this design work. The development of this software is essential to studies of this type since it integrates and organizes many different functions such as initial sensitivity studies using lattice depletions, optimization at both the assembly and full-core levels, and automated generation of plots, tables, and full reports summarizing core physics performance.

2 PWR Core Parameters and Parameter Limitations

2.1 Geometry

Since the fuel-clad gap in SiC clad fuel does not close as rapidly as in the case of **Zr** clad fuel, fuel temperatures will be higher in SiC fuel. To compensate for this, the fuel pellets must be altered. One option is to make the pellet annular with an inner hole of about 10% volume—an option based on FRAPCON results by D. Carpenter. [4] Another option is to add a high conductivity constituent in the fuel, which in this study was chosen to be BeO.

In order to preserve the thermal hydraulics of conventional 17x17 PWR assemblies, **Thick SiC** clad fuel is modeled in most cases as having the same cladding outer radius as conventional fuel. [5] Thus, the outer radius of the fuel has been decreased (while maintaining an equivalent fuel/clad gap), but the thermal hydraulics of the core remain unaltered.

In the case of **Thick SiC 2**, the thermal hydraulics are altered by increasing the cladding outer radius and keeping the pellet outer radius constant. The likely thermal hydraulic compensation for this reduction in coolant volume will be an increase in coolant velocity in order to preserve the total coolant mass flow rate through the core. The larger surface area will reduce the heat flux at the outer surface of the cladding, which together with the higher mass flux in the core will improve the margin to departure from nucleate boiling (DNB). The downside to this change is the increase in the required pumping power. Another downside to this change could be that the reduction in the space between the rods could result in coolant flow blockage and increased flow velocity will increase the vibrational amplitude and result in increased risk of Grid To Rod Fretting and other fuel failures. Detailed thermal-hydraulic analysis of **Thick SiC 2** is considered beyond the scope of this thesis and left as future work.

Table 1 describes the fuel rod geometry for each case. All dimensions are in **cm**. The asterisk for **Thick SiC** indicates that the fuel inner radius is case dependent—0.1290 cm in the case of annular UO₂, and 0.0 cm in the UO₂/BeO and PuO₂/ThO₂ cases.

Table 1: Fuel Pin Dimensions in Centimeters

	Zircaloy	Thin SiC	Thick SiC	Thick SiC 2
Clad Outer Radius (R_{co})	0.4750	0.4750	0.4750	0.5069
Clad Inner Radius (R_{ci})	0.4180	0.4180	0.3861	0.4180

Fuel Outer Radius (R_{fo})	0.4096	0.4096	0.3777	0.4096
Fuel Inner Radius (R_{ci})	0.0000	0.1290	*	0.1290
Clad Thickness (δ_c)	0.0570	0.0570	0.0889	0.0889
Gap Thickness (δ_g)	0.0084	0.0084	0.0084	0.0084
% Vol. of PWR Fuel	100.00	90.08	*	90.08

Thick SiC rods contain the following fraction of fuel present in **Thin SiC** rods:

$$\frac{\pi(0.3777^2 - 0.1290^2)}{\pi(0.4096^2 - 0.1290^2)} = 83.382 \%$$

$L = 365.76$	Heated length
$P = 1.26$	Rod-to-rod pitch
$l = 21.50$	Assembly pitch

2.2 Material Densities

Material densities utilized in this work are shown below in Table 2.

Table 2: Material Densities

Material	Density (g/cc)	Comments
Zircaloy-4	6.55	
Triplex SiC	2.85	Manufacturer's Spec
UO ₂	10.47	95.5% TD
BeO	2.85	
PuO ₂	10.925	95.5% TD
ThO ₂	9.158	95.5% TD

The BeO content of the proposed UO₂/BeO fuel is specified as 10% by volume. Calculations in Appendix A provide values for use in specifying the isotopic composition of the homogeneous UO₂/BeO fuel in CAMSO. UO₂/BeO is modeled as having no ²³⁴U content, while CASMO's default ²³⁴U content is used for UO₂ fuel (both annular and solid).

Fuel density in the PuO₂/ThO₂ core is a function of the weight percent of plutonium metal. Calculations for PuO₂/ThO₂ fuel density and isotopics' weight percent are also presented in Appendix A.

Previous work used a triplex SiC density of 2.39 g/cc. [6] However, we found no reference as to why this value was used. The sensitivity of core design parameters to SiC density has not been investigated in detail, however it is only reasonable to imagine that underestimation of cladding density and thus neutron absorption may produce non-conservative results, particularly for enrichment requirements to meet cycle length. The Triplex SiC cladding density specified in Table 2 was provided by Ceramic Tubular Products (CTP). [private comm Herb, date]

Recent literature from Oak Ridge National Laboratory (ORNL) lists SiC monolith density as 3.215-3.219 g/cc depending on polytype. [7] 3.20 g/cc and 3.21 g/cc have been reported for SiC produced by chemical vapor deposition (CVD) and hot isostatic pressing (HIP), respectively. [8] Density of SiC fiber has been reported to vary from 2.55-3.1 g/cc. [9]

Cladding volume per rod in **Thick SiC** fuel is considerably larger than in **Zr** or **Thin SiC** rods. Fuel clad in **Thick SiC 2** has even more cladding volume per rod. The calculations in Table 2 assume a fuel rod heated length of 365.76 cm, and a fuel density of 10.47 g/cc (for UO₂):

Table 3: Fuel Rod Masses for Different Clads

Quantities Per Rod	Zircaloy	Thin SiC	Thick SiC	Thick SiC 2
Clad Vol (cc)	58.49	58.49	87.96	94.49
Fuel Vol (cc)	192.8	173.7	144.8	173.7
Clad Mass (g)	383.1	166.7	250.7	269.3
Fuel Mass (g)	2018	1818	1516	1818
Clad + Fuel Mass (g)	2401.1	1984.7	1766.7	2087.7

The increase in fuel cladding volume for **Thick SiC** decreases the fuel volume and increases the neutron absorption by the cladding. **Thick SiC 2** has the same fuel volume as the **Thin SiC**, however it has the highest cladding volume of all cases presented here.

2.3 Fuel Mass (Core Total)

The total mass of the fuel and the Initial Heavy Metal (IHM) loadings vary considerably among the conventional case and the new conceptual designs as illustrated in Table 3. For the PuO₂/ThO₂ fueled core the fuel mass is dependent on the Pu wt% and will vary from design to design, whereas the variation of fuel mass as a function of enrichment of UO₂ is insignificant.

Table 4: Core Clad, Fuel, and IHM Masses in kg

	Zircaloy	Thn SiC UO₂ Annular	Thk SiC UO₂ Annular	Thk SiC UO₂/ BeO	Thk SiC PuO₂/ ThO₂	ThkSiC2 UO₂ Annular
Clad Mass (kg)	19522	8494	12775	12775	12775	13721
Fuel Mass (kg)	102850	92652	77255	81092	78095	92652
IHM Mass (kg)	90661	81667	68095	69379	68662	81667
Fuel+Clad (kg)	122380	101146	90030	93867	90869	106373

2.4 Enrichment: Main Length, Axial Blankets, and Overall

In order to improve neutron economy and axial power shape, the axial ends of the fuel rods had lower enrichments than the bulk of the fuel. The following enrichment zones were used. When Integral Fuel Burnable Absorber (IFBA) is used, it is present only in the main heated length of the fuel.

Table 5: Axial Enrichment Zones for All Core Designs

Segment	Length	84 Zr4 UO₂ (w/o)	64 SiC UO₂ (w/o)	84 SiC UO₂ (w/o)	84 SiC2 UO₂ (w/o)	84 SiC UO₂/ BeO	84 SiC PuO₂/ ThO₂
Top Outer	6"	2.00	3.20	3.60	2.60	3.39	6.82
Top Inner	6"	4.50	6.90	5.60	5.00	5.49	12.51
Main Length	10"	4.50	6.90	5.60	5.00	5.49	12.51
Bottom Inner	6"	4.50	6.90	5.60	5.00	5.49	12.51
Bottom Outer	6"	2.00	3.20	3.60	2.60	3.39	6.82
Average		4.292	6.592	5.433	4.800	5.325	12.037

The percentage reported in Table 5 for plutonium content in the fuel is the plutonium weight percent of IHM, excluding all oxygen bound in the fuel matrix.

The enrichment needs for the nominal Zr4 and the 84 SiC2 case shown in Table 5 do not exceed the current enrichment limit (5%) for PWRs in the US, significantly simplifying and reducing the cost of implementation of these designs.

No attempt was made to further flatten axial power shapes by slightly reducing enrichment in the bottom two axial blanket zones. This may be considered in future work.

The isotopic compositions for the outer blanket regions were chosen to provide the correct cycle length, and to be roughly half the enrichment or plutonium content of the main length. Since axial power peaking is not particularly sensitive to the enrichment or plutonium composition of this outer blanket region, this method has produced results sufficient to provide evidence that designs with the above desired materials are viable.

More refinements in enrichment and plutonium specification will allow for finer control of cycle length via adjustment of the composition of the fuel's main length while also allowing precise specification of the outer blanket composition. In such a case the outer blanket composition could be specified as a function of the main length composition. This approach is left to future investigators, in addition to analysis of the impact of axial power on DNB calculations.

2.5 Plutonium Vector

The plutonium vector used in this work is typical of discharged fuel from current PWR practice and is as indicated in the following Table 6:

Table 6: Plutonium Vector

Isotope	Wt%
²³⁸ Pu	3.18
²³⁹ Pu	56.35
²⁴⁰ Pu	26.62
²⁴¹ Pu	8.02
²⁴² Pu	5.83

Americium and other higher actinides are not present in the fuel modeled in this thesis. These conditions would represent loading of fuel that had been recently reprocessed and fabricated in a manner sufficiently rapid so that decay of ²⁴¹Pu produces only negligible quantities of ²⁴¹Am.

The plutonium vector utilized is characteristic of LWR SNF that has been discharged at approximately 50 MWd/kg (based on CASMO output of a typical PWR assembly). This plutonium vector is not favorable for utilization as fissile material in thermal spectrum reactors; the fissile content is less than 65 wt%. The even mass number Pu isotopes fission more readily as the neutron spectrum hardens, or as ²³⁸Pu and ²⁴⁰Pu transmute via neutron absorption, reducing the reactivity penalty for non-fissile content.

Other sources of plutonium will provide different isotopic compositions. Low burnup LWR SNF (previous modi operandorum were 30 MWd/kg) would be significantly higher in ^{239}Pu . Plutonium extracted from fast reactor fuel would also be significantly higher in ^{239}Pu . These high-fissile content plutonium vectors are more reactive and capable of achieving higher burnup than low-fissile content plutonium. In thermal spectrum reactors the initial vector will gradually accumulate higher proportions of even numbered Pu isotopes.

In practice, core designers may specify a desired plutonium vector for delivery from the reprocessor to the fuel fabricator. In the event that the reprocessor is unable to deliver fuel utilizing the desired plutonium vector, the core must be redesigned according to the specific plutonium vector supplied in the fuel as delivered from the fuel fabricator.

2.6 Clad Isotopic Composition

For triplex silicon carbide clad, an isotopic composition of 70 wt% Si, 30 wt% C is used. This is approximately stoichiometric, with the carbon composition rounded up very slightly to reflect the presence of residual carbon from the manufacturing process. The manufacturer Ceramic Tubular Industries has specified that these conditions are accurate and applicable to their product.

Previous work used a value of 62 wt% Si, 37 wt% C, and 1 wt% O. A reference as to where these values come from has not been found. However, SiC monolith manufacture can be accomplished via deposition over a graphite rod and SiC fiber manufacture entails the use of a graphite lubricant. These facts may have led to the assumption of high carbon content used in previous modeling of the neutronic performance of SiC cladding.

Previous work used SiC instrumentation and control rod guide tubes of conventional thickness. The inner radius of these tubes might not be easily changeable (without redesign of the control rods), therefore it may be required to use **Thin SiC** or even **Zr** for them because using a thicker clad would change an assembly's thermal hydraulics. In this analysis **Zr** has remained as the material of the guide tubes since the guide tube thickness is smaller than that of fuel cladding (in all cases).

2.7 Burnable Poison

IFBA is a thin layer of ZrB_2 painted onto the outer curved surface of fuel pellets. It is now the most common burnable poison used in Westinghouse PWRs and the only burnable poison utilized in this analysis.

All cores designed in this work use 156 1.0x IFBA rods per assembly, with the exception of the $\text{PuO}_2/\text{ThO}_2$ core which uses 156 1.5x IFBA rods per assembly. Further optimization may require using different numbers of burnable poison rods to achieve desired reactor physics parameters.

Table 7: IFBA Composition

IFBA Type	$\text{mg}^{10}\text{B}/\text{cm}$	$\text{mg}^{10}\text{B}/\text{inch}$
1.0x	0.618	1.570
1.5x	0.927	2.355

2.8 State Parameters

The following state parameters are used:

Table 8: State Parameters

Parameter	Value	Units
Power Density	109.9	kW/L
Reactor Pressure	155.1	bar
Core Inlet Temp	558.6	K

These conditions are representative of Westinghouse 4-loop PWRs, and in particular are modeled after Seabrook's Stretch Power Uprate of 2004. [10]

2.9 Fuel Temperature Relations

A relation defining nodal average fuel temperature in terms of nodal relative power fraction and nodal burnup is required in order to faithfully model core physics performance. These correlations must be specified by the user in SIMULATE. Yanin Sukjai and Dr. Koroush Shirvan have performed a FRAPCON analysis and provided a curve fit for the results to be used in this work.

The form of the temperature relation for nodal average fuel temperature is given below.

$$T_{AVE} = T_{MOD} + c_0 + [c_1 + b]P + c_2P^2$$

This primary form is further modified by burnup dependent modification of the linear term (**b**).

Table 9 presents the coefficients of the correlations used below.

Table 9: SIMULATE Temperature Relation Coefficients

	Zircaloy	Thn SiC UO₂ Annular	Thk SiC UO₂ Annular	ThkSiC2 UO₂ Annular	Thk SiC UO₂/ BeO	Thk SiC PuO₂/ ThO₂
c₀	0.0	0.0	0.0	0.0	0.0	0.0
c₁	316.25	470.5	335.18	335.18	361.81	397.28
c₂	-12.33	-27.359	-19.31	-19.31	-3.414	-31.17
Source	Shirvan & Sukjai	Carpenter	Shirvan & Sukjai	Shirvan & Sukjai	Shirvan & Sukjai	Shirvan & Sukjai

In addition to the above table, a table of values for **b** as a function of burnup exists in SIMULATE for each fuel and cladding combination. Values of **b** were used for all temperature correlations produced by Dr. Shirvan and Yanin Sukjai.

The temperature correlation used for **ThickSiC2** case is the same as for **ThickSiC**. Future work may consider using an updated temperature correlation, however the assumption of this work is that the temperature correlations for the two cases will not be significantly different.

2.10 Specific Power

Specific power is the ratio of a core's rated thermal power to its IHM mass. It is typically expressed as kW/kgIHM. Multiplication of this power by the time interval of one day is equivalent to the energy produced in one day per kgIHM—i.e. the daily burnup. Since the core thermal power and cycle length are the same for all cases considered herein—yet the core IHM loadings vary, it is reasonably expected that designs with less IHM will be associated with higher specific power and higher burnup. The higher specific power reduces SNF production. The higher specific power also implies that the fuel cost may be reduced as less Uranium is utilized. However, for total fuel cycle cost analysis, the enrichment level has to also be considered.

Table 10 shows the specific power for each core designed in this thesis.

Table 10: Specific Powers For Fuel/Clad Combinations

	Zircaloy	Thn SiC UO ₂ Annular	Thk SiC UO ₂ Annular	Thk SiC UO ₂ / BeO	Thk SiC PuO ₂ / ThO ₂	ThkSiC2 UO ₂ Annular
Thermal Power (MW _{th})	3587	3587	3587	3587	3587	3587
IHM Mass (kg)	90661	81667	68095	69379	68662	81667
Specific Power (kW/kg)	39.57	43.92	52.68	51.70	52.24	43.92

Thick SiC Annular UO₂ and **Thick SiC** PuO₂/ThO₂ have the highest specific powers. Thick SiC UO₂/BeO is less than the previous two, but not significantly different. **Thick SiC 2** has the same specific power as **Thin SiC**, and all cases considered have higher specific powers than the **Zr** clad case.

2.11 Cycle Length

The target cycle length for all cores designed in this study is 469 Effective Full Power Days (EFPD) at a power level of 3587 MW_{th} with a 90% capacity factor between refuelings. This capacity factor is more likely to be representative of implementation of new technology, in this case SiC cladding, than the conventional 95% capacity factor. The **Zr** reference cores were also designed with a capacity factor of 90% to allow for direct comparison of the SiC cores to the reference cores.

Burnup increases appreciably for cores that have a smaller IHM loading. This effect is unavoidable, since burnup is energy produced per unit mass IHM. By demanding the same (or higher) quantity of energy from a core before a reload while reducing the fuel mass burnup must increase.

Table 11 shows Linear Reactivity Model (LRM) burnup predictions for equilibrium cores loading 84 fresh assemblies per reload. [11] The values presented are core averaged for End of Full Power Life (EOFPL), and discharge burnup is the batch average for the discharged assemblies. These values are calculated from the IHM mass and specific power—and are not results from full-core modeling. All burnup units are in MWd/kgIHM, and each core will be referred to by the fuel type except for **Zr** clad UO₂ and **Thin SiC** clad UO₂.

Table 11: 84 Assembly per Reload Core Burnups, LRM Calculation

	EFPD	Zircaloy	Thn SiC	ThkSiC UO ₂ Annular	ThkSiC2 UO ₂ Annular	ThkSiC UO ₂ / BeO	ThkSiC PuO ₂ / ThO ₂
Cycle	469	18.5	20.5	24.6	20.5	24.2	24.4
EOFPL	773	30.5	33.8	40.6	33.8	39.8	40.2
Discharge	1078	42.5	47.2	56.6	47.2	55.5	56.1

Table 12 shows Linear Reactivity Model (LRM) burnup predictions for cores loading 64 fresh assemblies per reload:

Table 12: 64 Assembly per Reload Core Burnups, LRM Calculation

	EFPD	Zircaloy	Thn SiC	ThkSiC UO ₂ Annular	ThkSiC2 UO ₂ Annular	ThkSiC UO ₂ / BeO	ThkSiC PuO ₂ / ThO ₂
Cycle	469	18.5	20.5	24.6	20.5	24.2	24.4
EOFPL	938	37.0	41.1	49.2	41.1	48.3	48.8
Discharge	1407	55.5	61.6	73.4	61.6	72.5	73.3

A detailed procedure for the calculation of these values is presented in Appendix A.

2.12 Core Performance Evaluation Criteria

2.12.1 Design-Limiting Performance Parameters

Peaking factors, soluble boron concentration, moderator temperature coefficient (MTC), peak pin burnup, and shutdown margin (SDM) are the primary design considerations. Typical targets are shown below:

Table 13: Design-Limiting Performance Factors

Parameter	Target Value
$F_{\Delta h}$	< 1.55
F_q	< 2.00
Maximum boron concentration (ppm)	< 1700
MTC (pcm/°F) @ HFP	< 0.0
Peak pin burnup (SiC)	< 100 MWd/KgU

Peak pin burnup (Zr)	< 62 MWd/KgU
SDM	> 1.3% or 1300 pcm

Values for these parameters with the exception of shutdown margin have been calculated for all cores. Minor violations of these guidelines are present in the current designs, however the current designs do provide a clear picture of the capability to effectively utilize the desired clad/fuel combinations. Further optimization is expected to provide superior conformity with the complete set of above guidelines.

Further, the results achieved in this work utilize only a single enrichment for a given reload. While CSpy does allow for multiple assembly types to be utilized in a single reload pattern, this feature has not been utilized in order to reduce the number of parameters that must be investigated throughout the course of optimization. Multiple assembly types used in a single reload batch may allow for core performance superior to the designs presented in this work. However, since this study is meant to show the comparative performance of each design, a single assembly type is advantageous in decoupling specific core reload loading pattern designs from the physics of each specific design that result in differences in performance.

2.12.2 Maximum Channel Enthalpy Rise ($F_{\Delta h}$)

$F_{\Delta h}$ is the ratio of the maximum value of axially integrated power for a single fuel rod to the core-average pin power (the core's total power divided by the total number of fuel rods). It is one of the primary criteria of interest for the NRC when evaluating license approval for design, construction, and operation of commercial reactors. The NRC does not directly limit $F_{\Delta h}$ but requires it to be such as to preclude DNB in normal operation or in Anticipated Operational Occurrences. [12]. The higher the value of $F_{\Delta h}$, the more likely an unanticipated power transient is to cause DNB; for a fixed coolant mass flow rate increasing $F_{\Delta h}$ reduces margin to DNB. The value of 1.55 is a typical value found in commercial reactors.

2.12.3 Maximum Local Power (F_q)

F_q is the ratio of the peak to core average linear power. This value is particularly relevant in the determination of the minimum critical heat flux ratio for a PWR.

The SIMULATE output parameter that reports F_q is “4PIN.” This differs from “3PIN” in that “3PIN” reports the peak node-averaged relative power fraction—whereas “4PIN” reports the

actual intra-node peak value of relative power fraction. In SIMULATE, a node is modeled as quarter of an assembly in the core and so “4PIN” is therefore more conservative, and thus the parameter reported in this thesis. It is worth noting however that others may opt to report “3PIN” or similar such spatially-averaged peak values of relative power fraction which do not correspond to the true peak value.

2.12.4 Soluble Boron

Boric acid is injected into the primary coolant loop of PWRs to control long term changes in reactivity. Its concentration is easily controlled, and since it is soluble in the coolant it provides a reactivity control effect that is homogeneous—unlike control rods which can significantly alter the power distribution in a reactor’s core.

Soluble boron concentration is not limited by the NRC, however soluble boron concentrations more than 2000 ppm are generally considered undesirable since boric acid is corrosive in the PWR primary loop environment. If the soluble boron concentration is high enough, the MTC can become positive (which is unacceptable in a LWR). In today’s operational reactors, the desired concentration of boric acid is even lower (~1200 ppm) as it will reduce the risk for inducing axial offset anomalies. [13]

2.12.5 Moderator Temperature Coefficient (MTC)

The MTC is the change in the core’s reactivity resulting from a permutation in moderator temperature of one degree (typically K or °F).

This value is of particular interest in plant power level maneuvering and in preventing uncontrollable over-power transients. A negative hot-full-power (HFP) MTC causes a reactor power level to drop in response to an increase in moderator temperature. This builds into the reactor a level of inherent safety in handling power and temperature transients. The NRC requires the MTC at rated power to be non-positive.

A highly negative MTC can be a hindrance however in the event of reactor shutdown and anticipated decrease in coolant temperature transients such as steam generator tube rupture, since the core’s reactivity will increase as the temperature drops (due to the increase in number density of the coolant which is also the fuel’s moderator). This can sometimes require an increase in shutdown margin.

The isothermal temperature coefficient (ITC) is the change in the core's reactivity resulting from a permutation in both moderator and fuel temperature of one degree (typically K or °F).

2.12.6 Peak Pin Burnup

Peak fuel pin burnup is a major criterion of interest from a fuel performance point of view. Material limitations in terms of dpa, plenum pressure, corrosion, and Pellet-Clad Mechanical Interaction (PCMI) all play a role in determining the level of material damage a clad can sustain without suffering an unacceptable increase in the probability of cladding failure.

Radiation damage to **Zr** causes degradation of its mechanical properties. Thermal stress, vibration, fatigue, fretting wear, oxidation, and hydrogen embrittlement are all factors that increase the probability of cladding failure. All of these effects are damaging to **Zr**'s mechanical properties even in the absence of radiation, however radiation increases the severity of these effects—and the effect of radiation accumulates with continued exposure.

For **Zr** cladding, the NRC currently limits peak rod burnup to 62 MWd/kg.

2.12.7 Shutdown Margin (SDM)

There is a large difference in reactivity between HFP and hot zero power (HZIP). The density of the moderator increases as power is reduced, therefore the reactivity worth of the control rod system must be sufficient to overcome this difference.

A conservative calculation includes the assumed failure of the control rod with the highest reactivity worth, and an assumed level of insertion of control rods. The calculation of SDM proceeds as follows:

Table 14: Shutdown Margin Calculation Terms

Symbol	Reactivity Difference
Δk_1	HFP to Control Rods 30% In
Δk_2	HFP to HZIP
Δk_3	HFP to All Rods In (ARI)
Δk_4	HFP to Most Effective Rod In
$SDM = (\Delta k_1 + \Delta k_2) + 0.9(\Delta k_3 + \Delta k_4)$	

Equations for the above parameters are included in Appendix A.

2.12.8 Additional Criteria

Various additional criteria are considered in evaluating the value of a particular core design. Leakage, fast fluence to the reactor pressure vessel (RPV), boron worth, fast to thermal neutronic flux ratio, breeding ratios and other parameters may be considered. Fuel performance consequences must be evaluated such as peak centerline temperature and End Of Life (EOL) plenum pressure.

Leakage is a measure of neutron economy, and reducing leakage tends to increase cycle length or alternatively reduce the enrichment required. Leakage also results in neutron absorption by materials outside the core, including PWR baffles, heat shields, and RPVs. Transmutation of structural materials via neutron absorption tends to lead to degradation of mechanical properties via formation of elements not present in the as manufactured alloy, helium production, and hydrogen production. [14] Fast neutron dose to the RPV also embrittles it by elevating the nil ductility transition temperature, degrading the RPV performance during accidents involving thermal shock and hindering the extending of the plant's operating lifetime.

3 Methodology of Fuel Management

Two primary tools were used to conduct this analysis: Studsvik Core Management software, and CSpy. It should be noted that a few particular phenomena are not accurately captured by the Studsvik Core Management software since it was designed to be a commercial production code for utilities working only with UO_2 and UO_2/PuO_2 mixed oxide (MOX) fuels.

3.1 Studsvik Core Management Software

CASMO-4E and SIMULATE-3 are the primary computational tools utilized in this thesis.

3.1.1 CASMO-4E

CASMO is an industry standard assembly level depletion code for *in silico* analysis and modeling of LWR reactor physics performance. The version used to collect the data in this report is CASMO-4E.

It uses a 2D method of characteristics algorithm to solve the neutron transport equation for single assemblies or groups of assemblies.

The primary results of interest from CASMO assembly calculations are reactivity and intra-assembly pin peaking as a function of burnup. CASMO also produces cross section data which can then be used in SIMULATE, to simulate the operation of a full core in 3D. Myriad other parameters are produced by CASMO including fuel elemental and isotopic composition, and fast (>0.625 eV) and thermal (<0.625 eV) group neutron fluxes.

The following is a map of k_{∞} as a function of burnup. It contains data from 78 CASMO runs. Each “series” ranges in enrichment from 5% to 7.5%, in 0.1% increments. Unpoisoned, 1x IFBA, and 1.5x IFBA cases are presented.

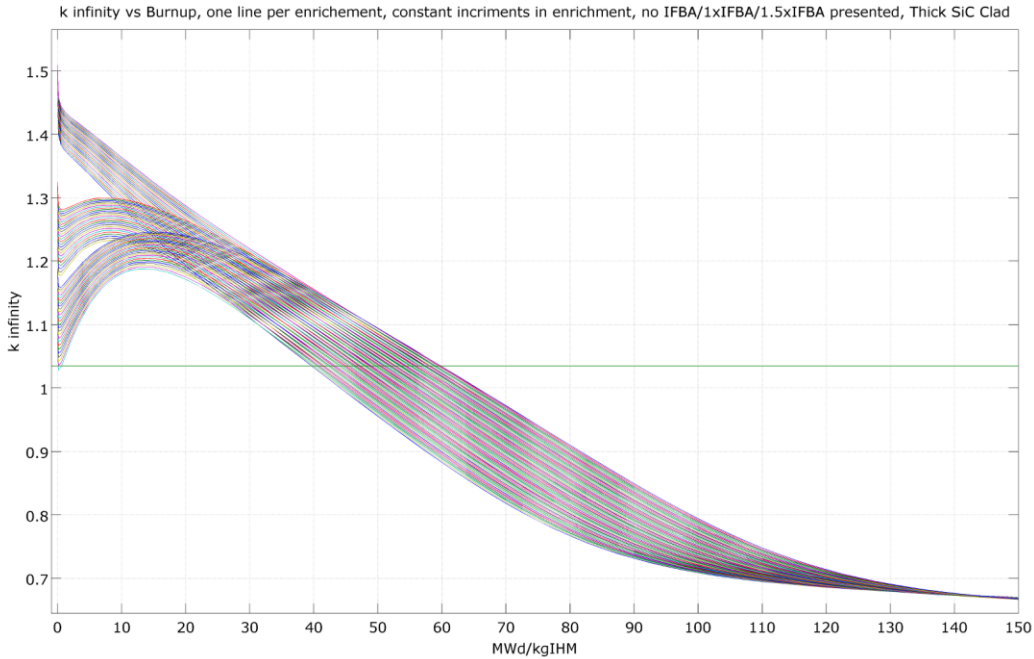


Figure 1: Thick SiC Clad Annular UO_2 : CASMO k_∞ vs Burnup with Varied IFBA Content

3.1.2 SIMULATE-3

SIMULATE-3 is an industry standard tool for simulation of core performance. It uses a three dimensional two-group nodal method capable of pin-power reconstruction. SIMULATE-3 has been benchmarked against various other numerical methods and also experimental data.

3.2 CSpy

CSpy is a software suite written to efficiently utilize CASMO and SIMULATE to analyze potential fuel and cladding configurations on the assembly level and as implemented in a 193 assembly Westinghouse 4-loop PWR core. CSpy generates input files for CASMO according to a range of parameters of interest that may be varied in a specified manner so as to conduct sensitivity studies and optimization. CSpy also generates CASMO input files for the purpose of constructing a cross section library for use in full-core simulations by SIMULATE. SIMULATE input files are also generated by CSpy for 193 assembly cores using either 64 or 84 reloads per cycle. CASMO and SIMULATE output files are parsed by CSpy which uses output results in optimization schema, writing CSpy's own succinct report files, and plotting of results.

3.3 Design Process

The core design process is an iterative one, since the range of input parameters includes several factors and the design criteria satisfied by one iteration might not be satisfied by the next. Nevertheless, the process itself consists of a specific set of steps:

1. Choose the cladding material.
2. Choose the cladding geometry.
3. Choose the fuel compound(s). If plutonium is present in the as loaded fuel then the plutonium vector must be specified.
4. Choose the fuel geometry. If the fuel is annular, what criteria determine the inner radius?
5. Choose the composition of other materials, such as the control rod guide tubes and instrumentation tubes, control rods, and stainless steel support structures.
6. Choose the core reflector geometry.
7. Choose the number of reloads per cycle.
8. Choose a concentration of IFBA: 1.0x, or 1.5x.
9. Choose a burnable poison pin layout. Optimize burnable poison layout to minimize intra-assembly peaking.
10. Choose a core reload pattern.
11. Determine an average fuel temperature correlation as a function of nodal relative power fraction and burnup.
12. Optimize the core reload pattern according to the desired design criteria.

Several steps could be added to this process in the future. For example, the cycle length could be chosen to be other than the cycle length of 469 EFPD used in this study. Power uprated cores could be designed using a different volumetric power density. Different numbers of assemblies could be used, for example if one wished to design a core for a 157 assembly AP1000. Assemblies with different control rod positions could be used, or assemblies other than standard 17 x 17 PWR assemblies. Different burnable poisons could be used, such as gadolinium, Wet Annular Burnable Absorber (WABA), erbium, or hafnium. Combinations of burnable absorbers could be investigated.

Fuel performance parameters can be entered into the design process, either as threshold limits to disqualify prospective designs or as parameters that enter the optimization algorithm's OF.

Even within the narrow guidelines defining the core design work in this work, the potential search space for a core design is massive. There exist multiple levels of optimization, each one dependent on a great abundance of preceding parameter selections. Similarly, the design work possible depends on the computing power available and the flexibility afforded by the basic tools used in the analysis.

The end result of the design process in this case is an "equilibrium core." The properties of the equilibrium core are the theoretical core performance results if an operational cycle and reload pattern are repeated until core performance artifacts from the initial configuration are negligible. For example, a cycle that begins using fresh assemblies for each location (but varying enrichment) will behave differently compared to a cycle that begins using assemblies that have been depleted during a previous cycle.

4 Optimization Schema

Optimization schema have been implemented to produce burnable poison pin layouts and quarter core, rotationally symmetric reload maps. Optimization schema in general are comprised of two mechanisms: a means by which to permute system parameters, and a means by which to evaluate new permutations. Both mechanisms must have unambiguous, explicit, quantitative or procedural definitions.

4.1 Objective Functions (OFs)

The optimization designer must ask, “what exactly do I wish to optimize?” Equivalently, the designer may ask, “what are the properties of an optimal system?” Trade-offs between parameters influencing overall system behavior and value must be considered.

An OF must be defined in order to compare new optimizer results with the best results to date. The OF of an optimization algorithm can be as simple as a single parameter—or exceedingly complex in an attempt to address non-linearities and idiosyncratic behavior near saddle points.

Once an OF has been defined in terms of quantitative system performance parameters, the OF result from a new system permutation can be compared with historical results. Comparison and acceptance criteria may be as simple as selecting the system configuration with the higher OF result. Any mathematical comparator may be utilized, and equality of certain parameters may be acceptable (particularly if the number of significant figures input into the OF are limited). The historical best OF result may be used as the reference for comparison and acceptance of new permutations, or more sophisticated comparisons against multiple historical OF results and other parameters may also be used.

In this work the ideal assembly burnable poison layout has maximal burnup when reactivity reaches an arbitrary endpoint (when reactivity letdown reaches 1.035 or 0.95 or another arbitrary value) and minimal peaking (pin power, pin exposure).

In this work the ideal nuclear reactor core has maximal cycle length, and minimal peaking ($F_{\Delta h}$, F_q , peak pin exposure). Shutdown margin, soluble boron, and leakage must be within specified limits. Specific details of OFs used in this work will be explained in detail in the sections introducing their context.

4.2 Permutation Algorithms

There exist many algorithms by which to permute system properties in search of an optimal configuration. Before beginning to construct any such algorithmic process, a set of quantitative and/or logical conditions must completely define the system. In the case of burnable poison layouts or core reload maps a vector whose elements represent each pin or assembly is sufficient. Element values represent the possible occupants, and the number of element values is not necessarily related to the number of elements in the vector. For example, in the burnable poison layouts presented in this work every pin is either poisoned or unpoisoned. Completely defining the burnable poison layout then is a vector with one element for each fuel pin in an octant where each pin is either a 1 (unpoisoned) or a 2 (poisoned). (Poison type and loading are preselected.) The numbers are arbitrary labels in this case. The following is a vector defining the burnable poison pin layout for a 17 x 17 Westinghouse assembly using octant symmetry.

VECTOR=[1, 1, 1, 2, 2, 1, 1, 1, 2, 1, 1, 1, 2, 2, 1, 1, 1, 1, 1, 1, 1, 2, 1, 2, 2, 2, 2, 1, 2, 2, 1, 2, 1, 2, 1]

Permutation of this vector can occur by a variety of processes, so long as the number of 1's and 2's are conserved. In the case of burnable poison layouts, some elements lie on the diagonal of the octant and count for a different number of burnable poison pins than those in the interior of the octant. Phenomena of this nature must be carefully accounted for, the number of burnable poison pins is to be conserved by the permutation process.

A binary swap is the interchange of two elements. This is the simplest permutation possible. There is however no upward limit to the complexity of possible permutations.

4.2.1 Genetic Algorithm

The "Genetic Algorithm" starts with the creation of a group of independent and unique configurations of a given system. Applied to nuclear reactor core reload map optimization the starting point would be a group of different maps.

The algorithm would then create a "generation" of new maps by combining pieces of existing maps. These maps would then be tested and their value computed via an OF. A group of new maps is then chosen from the best valued maps to form the basis for the next generation.

[15]

4.2.2 Simulated Annealing

Simulated Annealing is an optimization algorithm that allows acceptance of system configurations that produce OF results worse than the reference OF value. By allowing this to occur, the algorithm is less constrained by local extrema. As the number of iterations of a Simulated Annealing algorithm increases, generally the tolerance of worse OF results decreases. This tolerance is compared to the temperature in an annealing process, where the temperature initially is high (to allow the greatest possibility of escaping local extrema) and is gradually reduced (to hone in on the value of the closest extremum). [16]

4.2.3 Dual Binary Swap (DBS)

The primary algorithm used to produce new configurations and while attempting to avoid local extrema in the search space is the DBS. The DBS is the execution of two binary swaps at the same time. Any map or layout element involved in one of the swaps may not be involved in the other; for each DBS four elements are moved. The DBS has been implemented as a random walk to generate core reload maps. Figure 2 below illustrates an example of the DBS process.

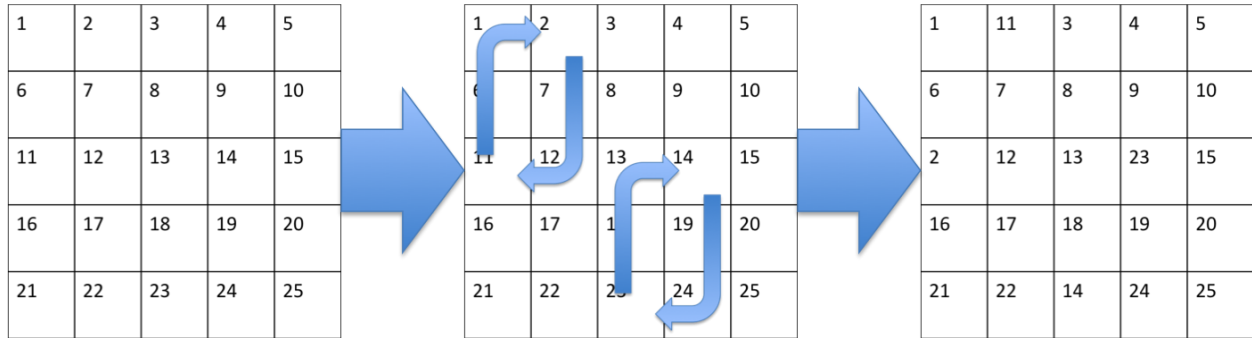


Figure 2: DBS Process: Before (left), Swap (center), After (right)

4.2.4 Exhaustive Dual Binary Swap (EDBS)

An EDBS is a collection of all DBSs possible given a specified initial condition. An Exhaustive Dual Binary Swap (EDBS) algorithm has been implemented to produce burnable poison layouts.

4.2.5 Random Greedy Dual Binary Swap (RGDBS)

While the EDBS performs an exhaustive sweep of the possible permutations of a system via DBS and compares the best result from that analysis to the historical best result, an RGDBS

explores the permutation space of a given configuration until any improvement whatsoever is found.

This is a fundamentally different process since it cannot be guaranteed that the best possible new permutation is chosen at each step. The RGDBS is a stochastic process, and a significantly greater variation in end states produced from a given initial condition is possible if there exists a high density of local extrema in the search space.

4.3 CASMO Burnable Poison Layout Optimization

The EDBS has been implemented for the optimization of burnable poison pin layouts using lifetime peak intra-assembly power peaking as the OF. Several iterations of the EDBS process are required before further EDBSs no longer produce improvement. In the case of burnable poison pin layouts, EDBS has consistently reached the same maximum lifetime intra-assembly peaking factor for a given enrichment and number of burnable poison pins. For example, if 5.0% UO_2 and 156 1.0x IFBA rods were specified, the final result was invariant with respect to the initial burnable poison pin layout. For 156 burnable poison pins per assembly, a single EDBS iteration consists of 11,898 individual layouts that must be run in CASMO and the results must be parsed to find the best resulting layout. This was typically accomplished in about 10 hours by running multiple instances of CASMO in parallel via CSpy. The optimal maximum intra-assembly peaking factor was achieved by many different layouts, on the order of hundreds of layouts. A maximum of three iterations of EDBS were required to reach an end-state intra-assembly peaking value in all cases investigated throughout the course of this work.

It was also found that burnable poison layouts were transferrable to fuels and enrichments other than those for which they were originally intended. Some layouts were found to be optimal for multiple fuel types at the same enrichment, and for multiple values of enrichment for each fuel. For example, the burnable poison layout for 6.7% enriched Thick SiC clad annular UO_2 was also optimal (as tested by EDBS) for several neighboring enrichments. The burnable poison map utilized in all 1.0x IFBA cases was exactly the same through the first generation of SIMULATE reload map optimization. Optimization via EDBS of a map that has been applied to a fuel or geometry different from its original parameters tended to produce no improvement or an improvement of intra-assembly peaking by 0.001.

2D and 3D histograms of occurrences of cycle burnup vs peaking, and peaking vs enrichment plots have been constructed describing the CASMO burnable poison layout optimization process.

Figure 3 below shows an EDBS result for 4.5% enriched **Zr** clad UO_2 . These results are from the re-optimization effort described below in Section 5.1. It is particularly noteworthy that over 5% of the DBSs in the exhaustive sweep produced the optimal value of maximum lifetime intra-assembly peaking. Even more noteworthy is that over 7% of the DBSs were 0.001 higher than the optimal value. Over 12% of the results are at or near the optimal OF result.

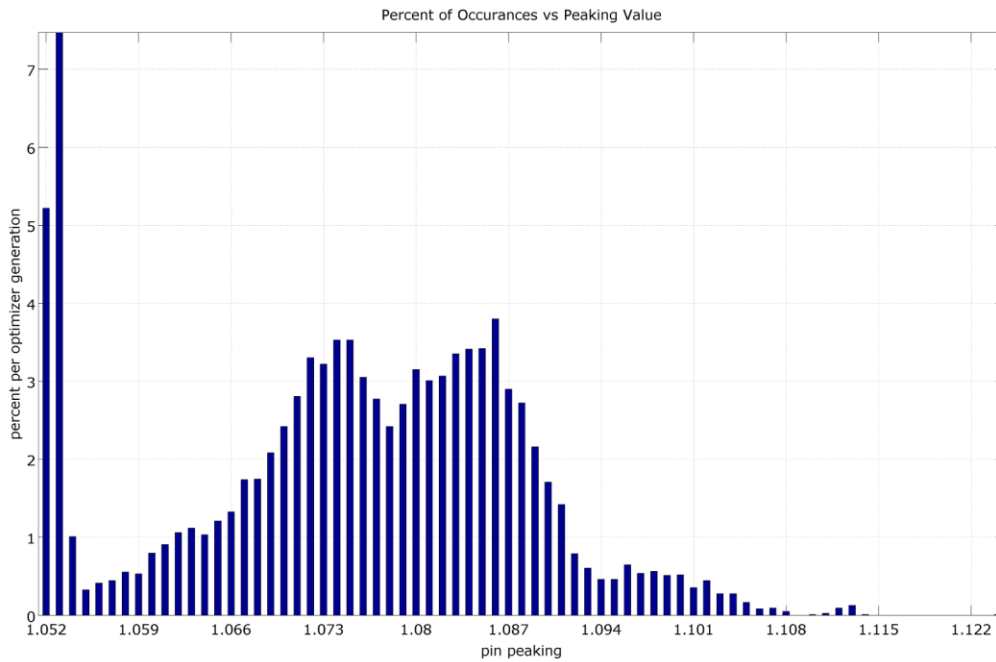


Figure 3: EDBS, % Occurrences vs. Peaking Value

Figure 4 shows the number of occurrences for each pairing of: the point at which the reactivity curve of an assembly crosses 1.035 (B_1), and maximum lifetime intra-assembly peaking.

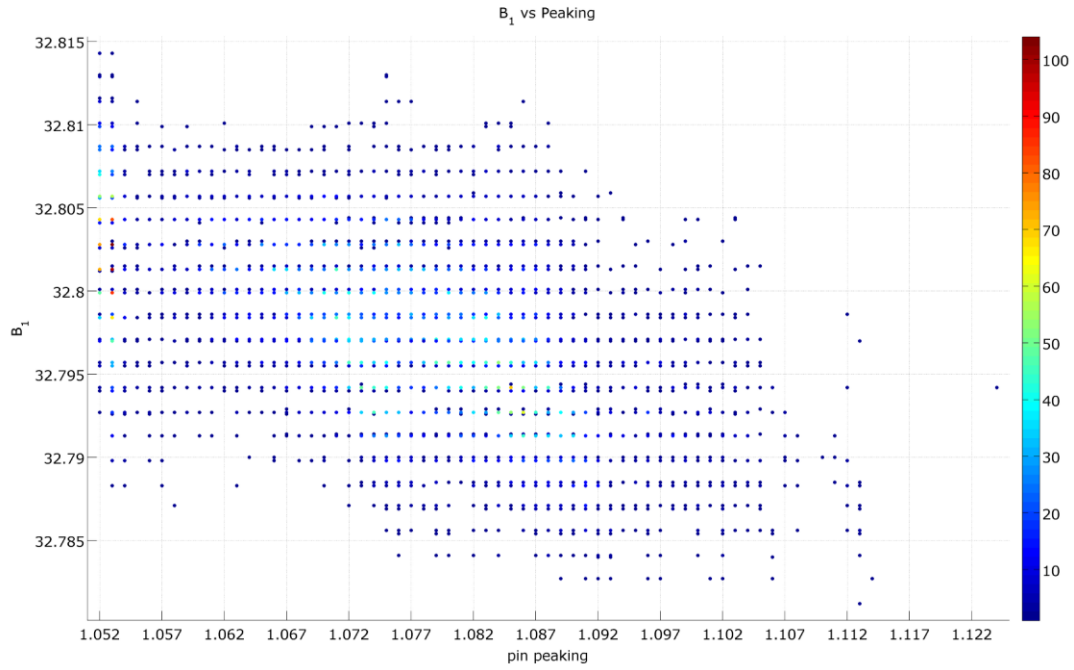


Figure 4: EDBS, B_1 vs Peaking, Occurrences by Color (2D)

Figure 5 shows the same data as Figure 4, however by using a 3D plot the data is easier to interpret.

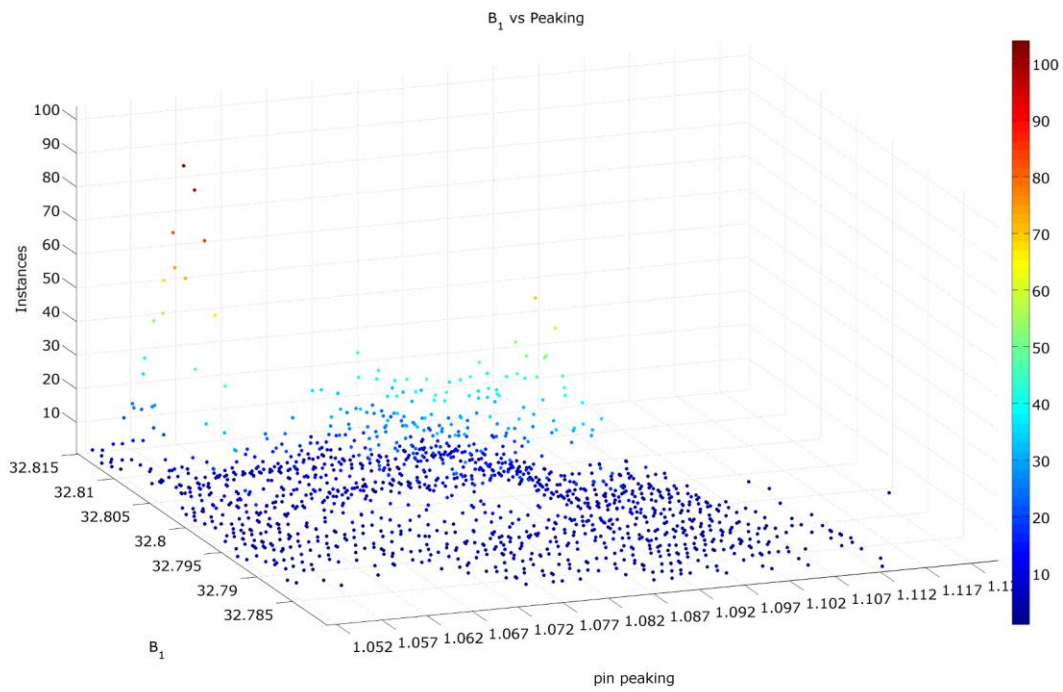


Figure 5: EDBS, B_1 vs Peaking, Occurrences by Color (3D)

Considerable variation exists in the results of an EDBS, and the regions of high occurrence show the most probable results using stochastic DBSs.

4.3.1 CASMO Burnable Poison Layout Optimization OFs

The OF utilized for burnable poison layout optimization was lifetime peak intra-assembly pin power peaking factor.

More sophisticated OFs may include: lifetime peak intra-assembly power peaking, lifetime averaged intra-assembly peaking, and B_1 .

Heuristics could be applied to reject layouts containing time steps in which the peak power pin occurs in peripheral locations. It has been observed that SIMULATE results using the exact same core reload pattern can be significantly altered by changing the burnable poison layout of the assemblies used. OFs for burnable poison maps could therefore also include parameters from full-core implementation. Iteration between CASMO and SIMULATE could involve OFs that interact with each other.

4.4 SIMULATE Core Reload Map Optimization

Implementation of EDBS for core reload maps in SIMULATE involves over an order of magnitude more combinations of DBSs to run and parse and to date has not been implemented. Optimization of SIMULATE core reload maps instead relies on the RGDBS, in which a new map is constructed by a randomly generated DBS and if the new result is superior to the previous best result then the new map is accepted as the new best result.

SIMULATE is capable of performing core physics calculations at various levels of precision, reducing calculation time while reducing accuracy. This effect was utilized to accelerate optimization. The first layer of optimization using SIMULATE was using a single axial node to model core performance, i.e solving only a 2-dimensionoal problem. These calculations were exceedingly fast (~10 seconds per complete equilibrium core calculation). The second layer of optimization of a core reload pattern used 12 axial nodes, and thus represented the 3 dimensions. The final layer of optimization used 24 axial nodes—the same number used in the full calculation of all parameters presented herein. Typically, when transitioning from one axial node count to the next the performance parameters would change; the single axial node calculations tended to over-predict cycle length and under-predict peaking. 12 axial node

calculation results would also differ from 24 axial nodes, however this time over-predicting both peaking and cycle length.

The starting point for the first core reload maps was a conventional checkerboard pattern with very high peaking. When starting a new core design for a new fuel and clad combination, either an existing map could be adapted and re-optimized for the new configuration or a pattern could be found using the checkerboard baseline starting point.

A heuristic is applied to the map generation algorithm that rejects any map containing one or more fresh fuel assemblies on the periphery of the core. Additional heuristics for SIMULATE core reload map generation have been proposed but not implemented, including requiring that most twice burnt fuel be loaded on the periphery. In the case of 84 reloads per cycle there would not be enough twice burnt fuel to completely fill the peripheral assembly locations and some once burnt assemblies would also be present.

4.4.1 Peaking Factor OFs

4.4.1.1 OF 0.1

The first OF utilized was $F_{\Delta h}$.

$$F_{\Delta h_{New}} < F_{\Delta h_{Best}}$$

Without any other constraint, implementation of this OF resulted in the optimization algorithm placing fresh fuel at the periphery of the core. While $F_{\Delta h}$ was reduced, the cycle length was significantly diminished. Leakage was also increased.

The heuristic rejecting DBSs that placed fresh fuel on the periphery significantly improved results. Core reload maps thus generated looked similar to “ring of fire” cores in which the highest concentration of fresh fuel assemblies was near the periphery. The core interiors were mostly checkerboard-like patterns.

This simple OF was used to ensure that all considered fuel and clad combinations were capable of satisfying the core physics parameter limitations. While this end was achieved, several resultant cores had a high, rapidly decreasing Beginning of Cycle (BOC) F_q indicative of over poisoning.

4.4.1.2 OF 0.2

Experience running optimization with this OF led to the observation that tens of thousands of DBS permutations may be checked between finding new improvements. A new OF was implemented in order to reduce this average interval between finding new improvements, speculating that increasing overall activity may be preferable to a more stagnant situation. The new OF also only considered $F_{\Delta h}$.

$$F_{\Delta h_{New}} \leq F_{\Delta h_{Best}}$$

4.4.1.3 OF 0.4

This was producing results that were not significantly different from the previous algorithm. It was then decided to optimize considering both $F_{\Delta h}$ and cycle peak soluble boron. The logic for this system was to accept new maps with a lower $F_{\Delta h}$ and accept maps with an equal $F_{\Delta h}$ but lower cycle peak soluble boron.

$$\{F_{\Delta h_{New}} < F_{\Delta h_{Best}}\} \text{ or } \{F_{\Delta h_{New}} = F_{\Delta h_{Best}} \text{ and } [B]_{New} < [B]_{Best}\}$$

This OF was observed to increase core leakage and often negatively affected cycle burnup, however this effect on cycle burnup was inconsistent.

4.4.1.4 OF 0.5

Given that OF 0.2 increased leakage and often reduced cycle length, it was logical to try the reverse—accepting new maps if they had higher cycle peak soluble boron.

$$\{F_{\Delta h_{New}} < F_{\Delta h_{Best}}\} \text{ or } \{F_{\Delta h_{New}} = F_{\Delta h_{Best}} \text{ and } [B]_{New} > [B]_{Best}\}$$

This OF was observed to decrease core leakage and its effect on cycle length was also inconsistent.

4.4.1.5 OF 0.6

While the above OFs were useful investigations, the first set of optimizations had produced several cores whose BOC F_q was significantly higher than at any other period in the cycle. This high initial F_q would also drop off quickly, indicating a potentially over-poisoned condition. It was therefore attempted to reduce BOC F_q via reshuffling of the core reload map.

$$\{F_{\Delta h_{New}} < F_{\Delta h_{Best}}\} \text{ or } \{F_{\Delta h_{New}} = F_{\Delta h_{Best}} \text{ and } F_{q_{New}} \leq F_{q_{Best}}\}$$

This OF was observed to reduce F_q .

4.4.1.6 OF 0.7

As in OF 0.6, OF 0.7 is also an attempt to reduce F_q . The only difference between 0.6 and 0.7 is that 0.7 does not accept maps with both an equal $F_{\Delta h}$ and F_q .

$$\{F_{\Delta h_{New}} < F_{\Delta h_{Best}}\} \text{ or } \{F_{\Delta h_{New}} = F_{\Delta h_{Best}} \text{ and } F_{q_{New}} < F_{q_{Best}}\}$$

This OF was also observed to reduce F_q and not observed to be significantly different from OF 0.6.

4.4.2 Exposure to Peaking Ratio OFs

The peaking factor OFs accomplished their intended purpose of showing that acceptable peaking factors can be achieved for the fuel and clad combinations presented herein. However, it was noticed that cycle length was affected negatively upon application of OF 0.7. Therefore it was speculated that an OF involving cycle burnup and peaking factors may extend cycle length without compromising peaking factor minimization.

4.4.2.1 OF 1.0

OF 1.0 was constructed to allow for small changes in output results to lead to the acceptance of new maps with the following trends.

1. If cycle burnup (B_c) increases and everything else stays the same then the new map should be accepted.
2. If $F_{\Delta h}$ decreases and everything else stays the same then the new map should be accepted.
3. If F_q decreases and everything else stays the same then the new map should be accepted.

These three criteria lead to the construction of OF 1.0.

$$OBJ_{1.0} = \frac{B_c}{F_{\Delta h} F_q}$$

It was noticed that if the product of $F_{\Delta h}$ and F_q remain constant while cycle burnup increases then the new map will also be accepted.

As implemented, this OF was able to reduce the BOC F_q that was so problematic with earlier OFs. It appeared to be less susceptible to becoming trapped in local extrema, and gradually extended cycle length while essentially maintaining the low peaking achieved using the 0.x series of OFs.

Many of the new maps would be accepted with a completely new combination of B_c , $F_{\Delta h}$ and F_q . Generally, lower values of peaking might cut cycle length—but then cycle length would again be extended.

4.4.2.2 OF 1.1

OF 1.0, despite its effectiveness in extending cycle length in practice, heavily weights the peaking factors in its determination of a given reload maps objective value. The following OF is the first variation of OF 1.0 attempting to extend cycle length while retaining an appropriate level of peaking factor minimization.

$$OBJ_{1.1} = \frac{EXP}{\sqrt[n]{F_{\Delta h} F_q}}$$

By setting $n > 1$ and reducing the importance of the peaking factors this OF acts somewhat differently, however the overall results are similar to OF 1.0.

4.4.3 Threshold Dependent OFs

Since cycle length is the primary parameter of interest when considering the economic value of nuclear fuel to the utility, it was decided to explore optimization that was constrained within the safety limits of core physics parameters.

4.4.3.1 OF 2.0

What if peaking were allowed to take any value $F_{\Delta h} < 1.55$ and $F_q < 2.00$, and the OF was solely the cycle length?

$$B_{c_{New}} > B_{c_{Best}}$$

4.4.4 Other OFs

A vast quantity of parameters may be considered in the design of OFs for the purpose of reactor core optimization. Peaking factors and cycle length may be common factors to take into account, however the dynamics of core physics can be exposed in a variety of ways by optimizing according to combinations of parameters.

For example, leakage could be investigated using rational OFs as above. Cycle length divided by leakage could be an OF that may be relevant to a designer attempting to reduce RPV fluence.

4.4.4.1 Peak Pin Burnup

Peak pin burnup is another parameter that may be incorporated into an OF. A rational OF with peak pin burnup in the denominator (perhaps raised to a power less than 1) may assist in optimization motivated from a fuel performance point of view.

4.4.4.2 Combinations of OFs and Thresholds

Future OFs may include flow charts where different regimes of optimization are entered when specific parameters are reached. For example, before applying OF 2.0, either OF 0.7 or OF 1.0 could be applied to reduce peaking to within the threshold limits of OF 2.0. However, what would be the effect of changing the transition from 0.7 to 2.0 from the threshold of 2.0 to a lower limit (either defined in absolute terms or by a number of optimization trials)?

5 Results for UO₂ Fueled Cores

Six fuel and clad combinations have been evaluated. The first is a reference case, using conventional **Zr** clad, solid UO₂ fuel pellets and 84 reloads per cycle. It is the benchmark against which all other results will be compared since this core most closely resembles current industry practice.

Four additional fuel and clad combinations have been evaluated using **Thick SiC** cladding. Two reload numbers per cycle have been evaluated utilizing annular **Thick SiC** clad UO₂ fuel pellets: 64 reloads per cycle and 84 reloads per cycle. All remaining combinations have been evaluated using 84 reloads per cycle. The urania/beryllia and plutonia/thoria fuels are both mixed homogeneously, as opposed to being modeled as duplex pellets.

Lastly, **Thick SiC RCF** has been evaluated using annular UO₂ fuel pellets. This clad represents a departure from conventional 17x17 PWR thermal hydraulics and is included to assess the effect of taking the extra cladding volume from the coolant fraction as opposed to the fuel fraction (as in all other cases).

For each fuel and cladding combination there are three core designs—one design produced via the action of each optimization OF: 0.7, 1.0, and 2.0. These results range from a peaking-minimization only approach to a cycle length only approach (utilizing peaking acceptability thresholds). The middle ground between these two extremes is OF 1.0, which considers cycle length and peaking.

One fact to consider in interpreting the results produced via OF 0.7 is that the temperature correlation used by SIMULATE was updated after the optimization algorithm was run. Therefore the performance of those cores is slightly degraded. An addendum may include an updated set of OF 0.7 optimized cores.

5.1 Zr Clad UO₂ 84 Reload Cores

The reference core for this work is solid UO₂ fuel clad in **Zr**, utilizing 84 reloads per cycle. This core is intended to resemble commercial cores, although it is acknowledged that the use of a single assembly type is a departure from commercial designs. Nevertheless, in order to compare cladding material and fuel combinations the reference core was designed using the same methodology as other cores.

Figure 6 shows the peaking factors and soluble boron letdown curves of the **Zr** clad reference cases. The peaking factors are considerably higher for the case produced via OF 2.0.

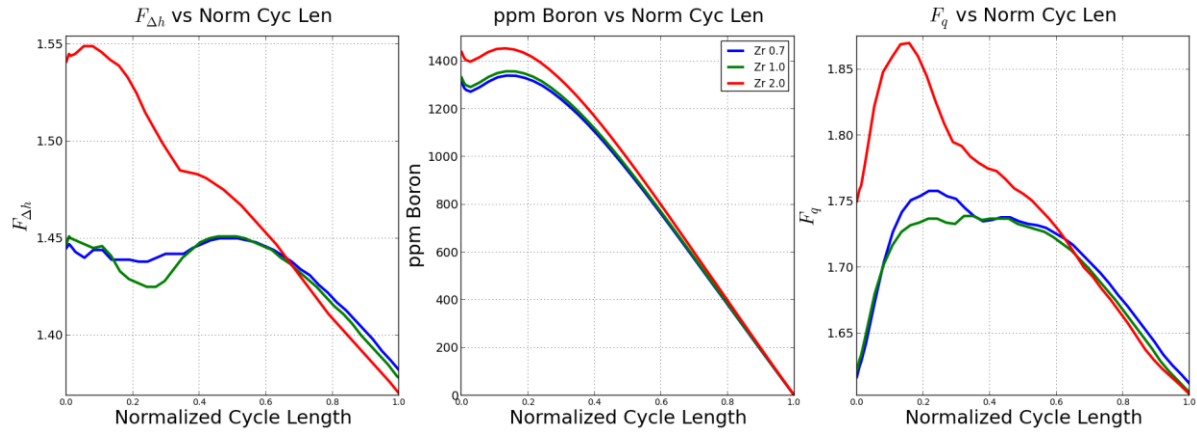


Figure 6: Zr Clad UO₂ 84 Reload Cores, Peaking Factors and Soluble Boron

Figure 7 shows reactivity coefficient results for the **Zr** clad reference cases.

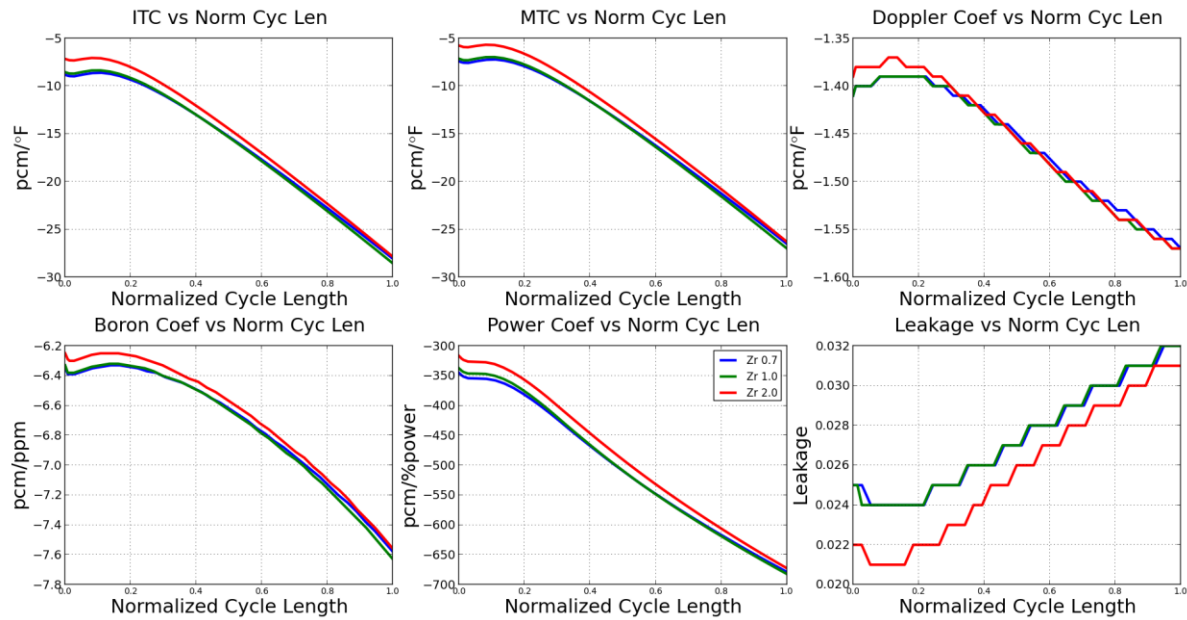


Figure 7: Zr Clad UO₂ 84 Reload Cores, Coefficient Calculations

Figure 8 shows the core reload maps utilized in the **Zr** clad reference cases.

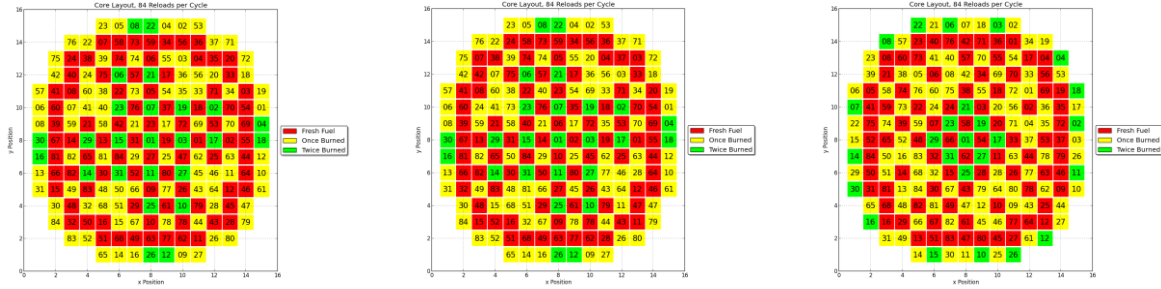


Figure 8: Zr Clad UO₂ 84 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 15 summarizes core geometry, material densities, and mass for the **Zr** clad reference cases. The hydrogen atom to heavy metal atom (H/HM) ratio is reported below as “**H/HM.**”

Table 15: Zr Clad UO₂ 84 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.4750	0.4180	0.4096	0	10.47	6.55	3.35	90661

Table 16 summarizes physics performance values for the **Zr** clad reference cases. In Table 16, “SDB” and “SDE” refer to shutdown margin at BOC and End of Cycle (EOC), respectively. Also in Table 16, “PkExp” refers to peak pin exposure.

Table 16: Zr Clad UO₂ 84 Reload Physics Summary

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Ah}	F _q	PkExp	SDB	SDE
0.7	4.29	466.5	18.46	42.78	1340	1.450	1.758	71.6	-2090	-1610
1.0	4.29	470.8	18.63	42.21	1358	1.451	1.739	71.1	-2074	-1601
2.0	4.29	481.3	19.04	41.68	1454	1.549	1.870	67.5	-2055	-1645

During the design of these cores many generations of optimization were executed. The burnable poison layouts used in the CAMSO lattice calculations for **Zr** were adopted without modification from the initial optimization work on burnable poison layouts developed for **Thick SiC** annular UO₂ fuel. EDBS determined that 3.8% enriched fuel clad in **Zr** already had a fully optimized burnable poison layout. Therefore, optimization of the SIMULATE reload map began.

The optimization occurred at many levels of resolution, starting with a single axial node, then 12 axial nodes, then all 24 axial nodes of the standard case. SIMULATE optimization produced a result that proved difficult to improve upon. This result was an end-point arrived at after more than ten re-initializations of the optimization process from the initial checkerboard

pattern (returning to the initial checkerboard to start optimization again hoping to avoid undesirable local minima).

Once the correct fuel main length enrichment was found, CASMO burnable poison layout optimization was re-conducted on the layout applied to the main length enrichment. Intra-assembly peaking in the 2D infinite lattice case dropped from 1.053 to 1.052. In the interest of further depressing the core peaking factors, the CASMO library used by SIMULATE was updated with the new map—just for the main length enrichment.

The result of this modification was a strong de-optimization of the core physics parameters. Both peaking factors developed a spike early in the cycle that was not present prior to this modification. Cycle length was also diminished. The critical observation is that burnable poison configurations can strongly affect core reload pattern performance. To state this phenomenon in another way, core reload pattern performance can be sensitive to burnable poison layouts.

Switching back to the original burnable poison layout, further optimization of the SIMULATE reload map also reduced cycle length while reducing $F_{\Delta h}$. This experience contributed to the motivation to explore alternate OFs for more complete and dynamic optimization.

The difference in EFPD observed between the OF 0.7 and the OF 2.0 cases is 3.4%. More detailed discussion of the differences in results from the use of different OFs will be presented in Chapter 7.

The **Zr** cases have the lowest cycle burnup, discharge burnup, peaking factors, and peak pin burnup of all cases presented herein.

Comparison of the **Zr** reference cores produced in this work to the 84 reload **Zr** case in previous work by Dobisesky is presented in Table 17. LRM has been used to match EFPD values across all designs. **B_c**, **B_d**, and w/o% have been adjusted as well. Details of these calculations are presented in Appendix A. The remaining values have not been altered and may or may not reflect actual performance. Further modeling would be required to produce directly comparable cores using the methodology developed herein.

Table 17: Comparison of Zr Reference Cores to Previous Work

Obj Fcn	w/o	EFPD	B_c	B_d	BOR	F_{Δh}	F_q	PkExp	SDB	SDE
0.7	4.50	492	19.47	45.11	1340	1.450	1.758	71.6	-2090	-1610

1.0	4.46	492	19.47	44.10	1358	1.451	1.739	71.1	-2074	-1601
2.0	4.37	492	19.47	42.61	1454	1.549	1.870	67.5	-2055	-1645
Dobisesky	4.52	492	19.45	44.7	1477	1.53	1.80	66.8	-2737	-1928

The superior performance of the **Zr** cases of this work clearly demonstrate the efficacy of the methodology developed herein. Dobisesky's **Zr** case uses three different types of assemblies for each batch. The peaking factors of Dobisesky's **Zr** case are not much less than those of the OF 2.0 **Zr** case, and are not likely to change much pending design of the **Zr** cores of this work for a longer cycle. The extra enrichment of Dobisesky's **Zr** case does not yield a significant extension of cycle length.

5.2 Thick SiC Clad Annular UO₂ 64 Reload Cores

Figure 9 shows the peaking factors and soluble boron letdown curves of the 64 reload **Thick SiC** clad annular UO₂ cases.

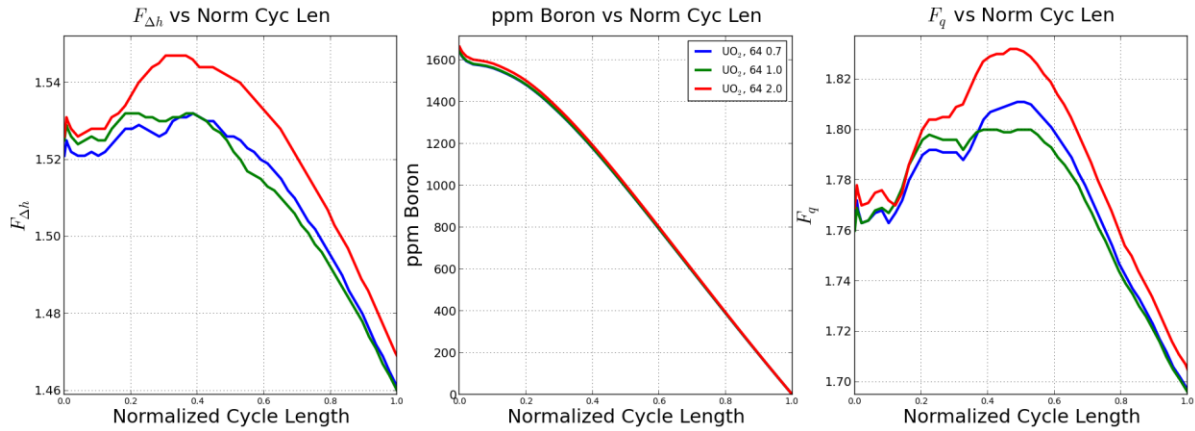


Figure 9: Thick SiC Clad Annular UO₂ 64 Reload Cores, Peaking Factors and Soluble Boron

Figure 10 shows reactivity coefficient results for the 64 reload **Thick SiC** clad annular UO₂ cases.

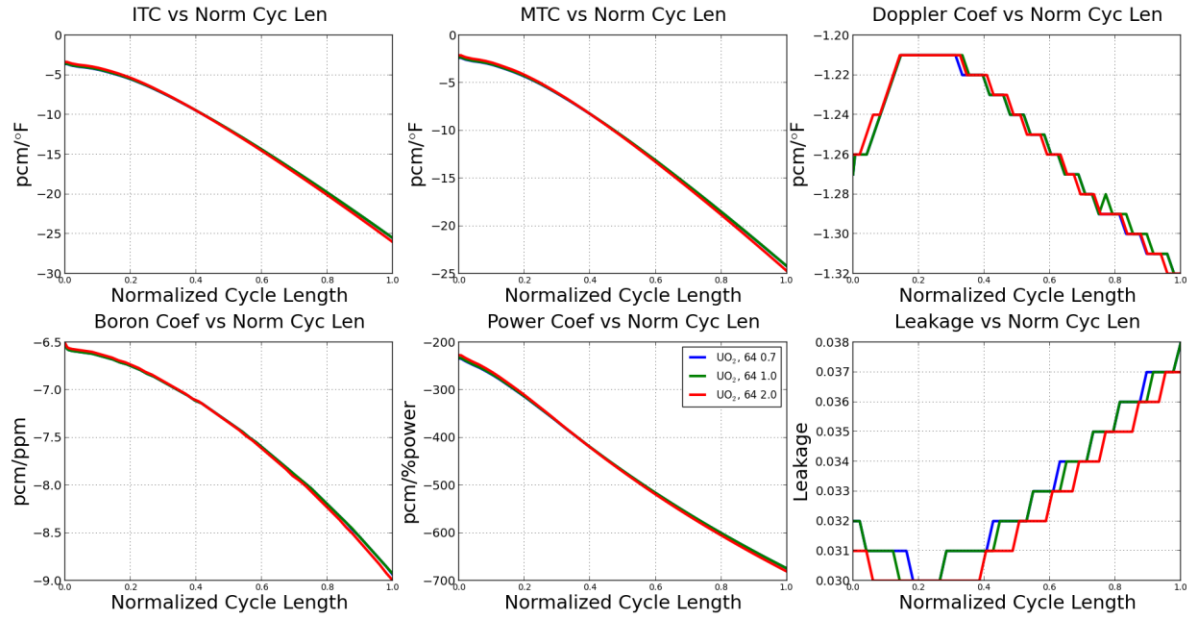


Figure 10: Thick SiC Clad Annular UO₂ 64 Reload Cores, Coefficient Calculations

Figure 11 shows the core reload maps utilized in the 64 reload **Thick SiC** clad annular UO₂ cases.

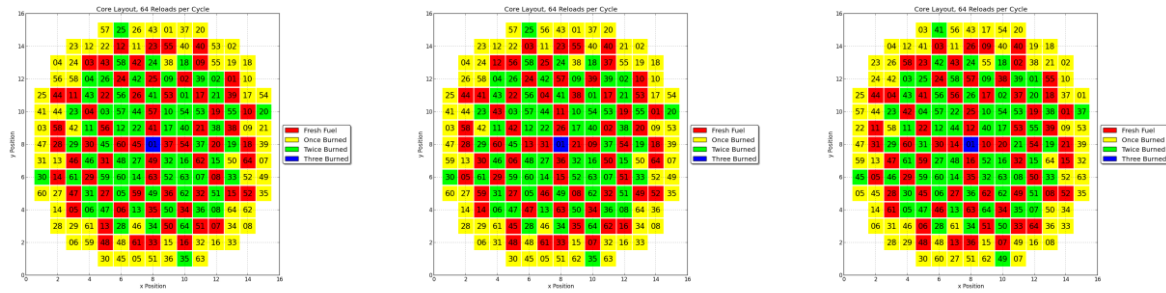


Figure 11: Thick SiC Clad Annular UO₂ 64 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 18 summarizes core geometry, material densities, and mass for the 64 reload **Thick SiC** clad annular UO₂ cases.

Table 18: Thick SiC Clad Annular UO₂ 64 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.475	0.3861	0.3777	0.129	10.47	2.85	4.47	68094

Table 19 summarizes physics performance values for the 64 reload **Thick SiC** clad annular UO₂ cases.

Table 19: Thick SiC Clad Annular UO₂ 64 Reload Physics Summary

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
0.7	6.59	466.3	24.57	74.06	1641	1.532	1.811	102.6	-2897	-2458
1.0	6.59	466.5	24.57	74.07	1643	1.532	1.800	101.8	-2900	-2458
2.0	6.59	468.0	24.65	74.20	1664	1.547	1.832	98.7	-2895	-2449

The 64 reload **Thick SiC** clad annular UO₂ fueled core designs represent the least adaptable situation. Peaking cannot be suppressed to anywhere near the reference case levels. The high peaking results from the high enrichment and high burnup which increases the reactivity differences between the assemblies of different batches. Peak pin burnup is beyond the guideline outlined in Section 2.12.1.

Negligible variation in results are observed for each OF. Cycle length ranges from 466.3 to 468.0 EFPD—a variation of less than 0.4%. In this fuel/clad combination both cycle burnup and discharge burnup increased with optimization via OF 2.0—contrary to the trend observed with all other fuel/clad combinations where cycle burnup increases and discharge burnup decreases with optimization via OF 2.0.

These results demonstrate the viability of 3 batch **Thick SiC** clad annular UO₂ fueled cores.

Comparison of the 64 reload **Thick SiC** clad annular UO₂ cores produced in this work to the 64 reload **Thin SiC** clad annular UO₂ case in previous work by Dobisesky is presented in Table 20. The presented **Thick SiC** and **Thin SiC** cases exhibit similar performance in terms of peaking factors and soluble boron. Enrichment requirements are higher in **Thick SiC**, and peak pin exposure is lower in **Thin SiC**. However, the methodology used in the previous work by Dobisesky is significantly different and it may be reasonable to speculate that superior performance may be obtained via the application of the methodology developed herein.

Comparison of the 64 reload **Thick SiC** clad annular UO₂ cores produced in this work to the 64 reload **Thin SiC** clad annular UO₂ case in previous work by Dobisesky is presented in Table 20. LRM has been used to match EFPD values across all designs.

Table 20: Comparison of 64 Reload Thick SiC Annular UO₂ to Thin SiC of Previous Work

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
0.7	6.93	492	25.92	78.12	1641	1.532	1.811	102.6	-2897	-2458

1.0	6.93	492	25.92	78.13	1643	1.532	1.800	101.8	-2900	-2458
2.0	6.90	492	25.92	78.01	1664	1.547	1.832	98.7	-2895	-2449
Dobisesky	5.74	495	21.70	65.5	1654	1.55	1.81	81.3	-2889	-1776

The significantly lower fuel fraction of the 64 reload **Thick SiC** clad annular UO_2 cores requires higher cycle burnup and higher enrichment. The higher H/HM ratio of the 64 reload **Thick SiC** clad annular UO_2 cores may mitigate this slightly, but not enough to bring the enrichment down to values near previous work for **Thin SiC**.

5.3 Thick SiC Clad Annular UO_2 84 Reload Cores

Figure 12 shows the peaking factors and soluble boron letdown curves of the 84 reload **Thick SiC** clad annular UO_2 cases. The peaking factors are considerably higher for the case produced via OF 2.0.

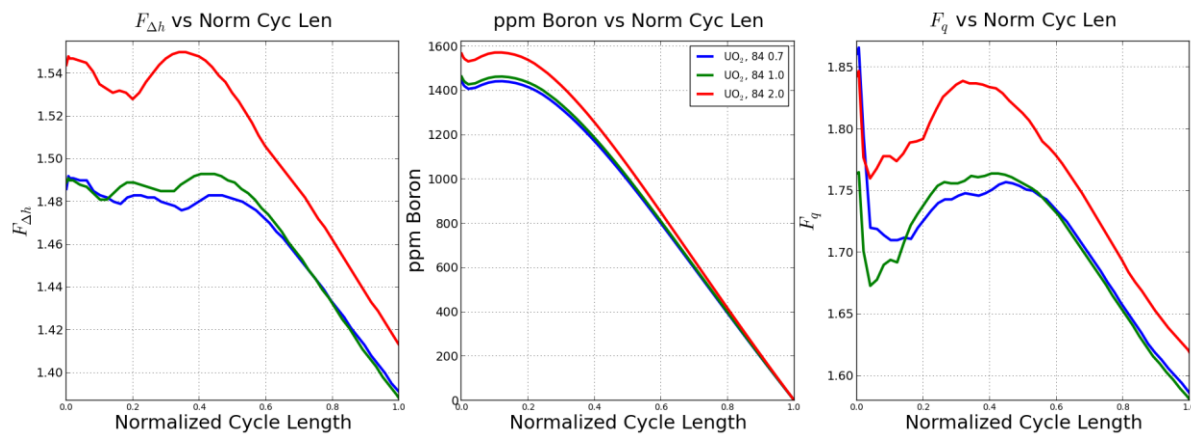


Figure 12: Thick SiC Clad Annular UO_2 84 Reload Cores, Peaking Factors and Soluble Boron

Figure 13 shows reactivity coefficient results for the 84 reload **Thick SiC** clad annular UO_2 cases.

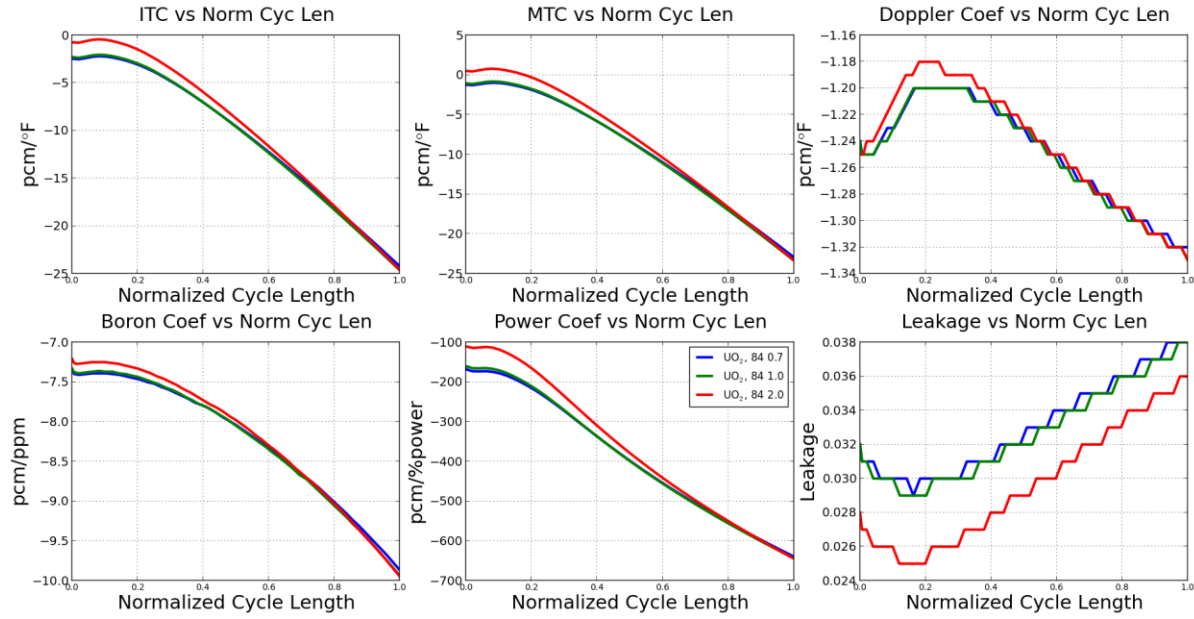


Figure 13: Thick SiC Clad Annular UO₂ 84 Reload Cores, Coefficient Calculations

Figure 14 shows the core reload maps utilized in the 84 reload **Thick SiC** clad annular UO₂ cases.

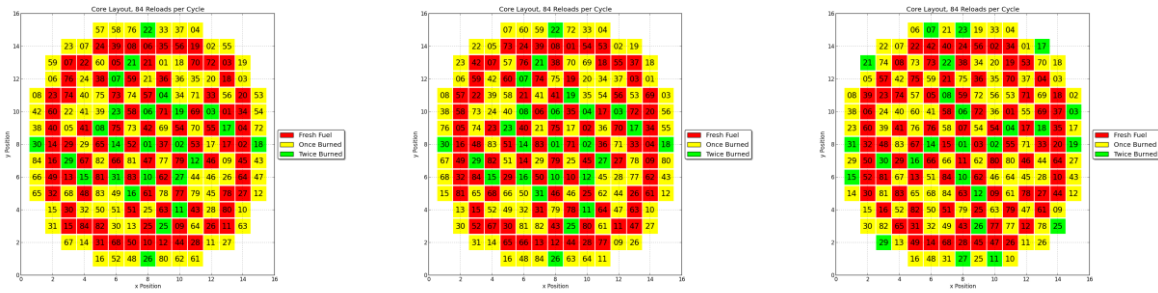


Figure 14: Thick SiC Clad Annular UO₂ 84 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 21 summarizes core geometry, material densities, and mass for the 84 reload Thick SiC clad annular UO₂ cases.

Table 21: Thick SiC Clad Annular UO₂ 84 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.475	0.3861	0.3777	0.129	10.47	2.85	4.47	68096

Table 22 summarizes physics performance values for the 84 reload **Thick SiC** clad annular UO₂ cases.

Table 22: Thick SiC Clad Annular UO₂ 84 Reload Physics Summary

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
0.7	5.43	466.3	24.56	55.65	1444	1.492	1.866	90.9	-2637	-2434
1.0	5.43	469.3	24.72	55.35	1464	1.493	1.765	88.7	-2711	-2416
2.0	5.43	476.7	25.11	54.69	1573	1.550	1.847	80.6	-2713	-2575

There is a significant problem with the OF 2.0 optimized 84 reload **Thick SiC** clad annular UO₂ case—it has a positive MTC for the first ~20% of the cycle. The **Thick SiC** clad annular UO₂ cases all have a high soluble boron worth and small negative MTC, so that an increase of soluble boron concentration of less than 10% is enough to push the MTC positive. This difficulty could be probably be alleviated via the use of 1.5x IFBA as opposed to 1.0xIFBA.

These observations imply that H/HM for the **Thick SiC** clad annular UO₂ cases may be too high, particularly given the loss of self-shielding due to pellet annularization. Being too high on the moderation curve would explain the positive MTC and high soluble boron worth for the OF 2.0 case.

Comparison of the 84 reload **Thick SiC** clad annular UO₂ cores produced in this work to the 64 reload **Thin SiC** clad annular UO₂ case in previous work by Dobisesky is presented in Table 23. The presented **Thick SiC** and **Thin SiC** cases again exhibit similar performance in terms of peaking factors and soluble boron. Also, enrichment requirements are again higher in **Thick SiC**, and peak pin exposure is lower in **Thin SiC**. Again, it may be reasonable to speculate that superior **Thin SiC** performance may be obtained via the application of the methodology developed herein.

Comparison of the 84 reload **Thick SiC** clad annular UO₂ cores produced in this work to the 84 reload **Thin SiC** clad annular UO₂ case in previous work by Dobisesky is presented in Table 23. LRM has been used to match EFPD values across all designs.

Table 23: Comparison of 84 Reload Thick SiC Annular UO₂ to Thin SiC of Previous Work

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
0.7	5.71	492	25.92	58.72	1444	1.492	1.866	90.9	-2637	-2434
1.0	5.67	492	25.92	58.03	1464	1.493	1.765	88.7	-2711	-2416
2.0	5.59	492	25.92	56.45	1573	1.550	1.847	80.6	-2713	-2575
Dobisesky	4.79	492	21.56	49.6	1509	1.50	1.76	74.7	-2784	-2203

The significantly lower fuel fraction of the 84 reload **Thick SiC** clad annular UO_2 cores also necessitates higher cycle burnup and higher enrichment. The higher H/HM ratio of the 84 reload **Thick SiC** clad annular UO_2 cores also helps mitigate this slightly, but again—not enough to bring enrichment down to values near previous work for **Thin SiC**.

5.4 Thick SiC RCF Clad Annular UO_2 84 Reload Cores

Figure 15 shows the peaking factors and soluble boron letdown curves of the 84 reload **Thick SiC RCF** clad annular UO_2 cases. The peaking factors are considerably higher for the case produced via OF 2.0.

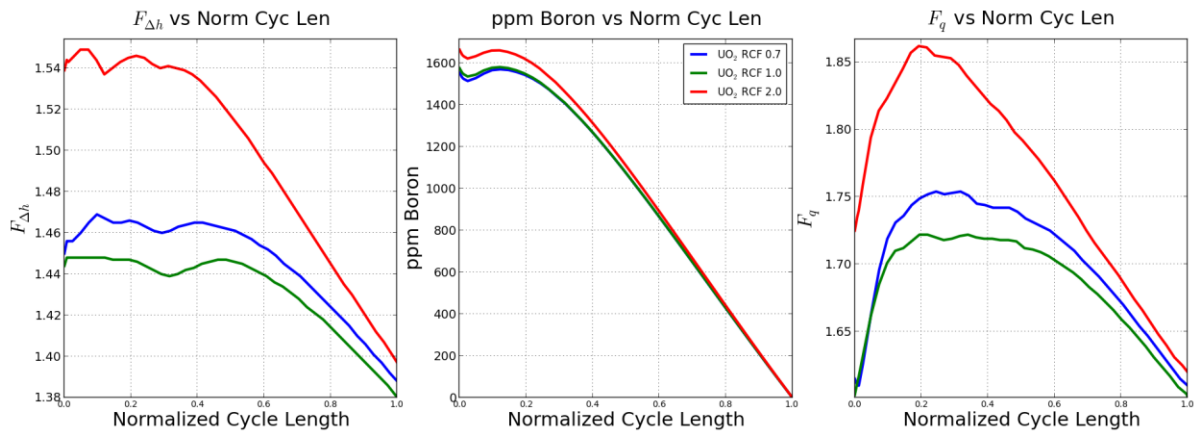


Figure 15: Thick SiC RCF Clad Annular UO_2 84 Reload Cores, Peaking Factors and Soluble Boron

Figure 16 shows reactivity coefficient results for the 84 reload **Thick SiC RCF** clad annular UO_2 cases.

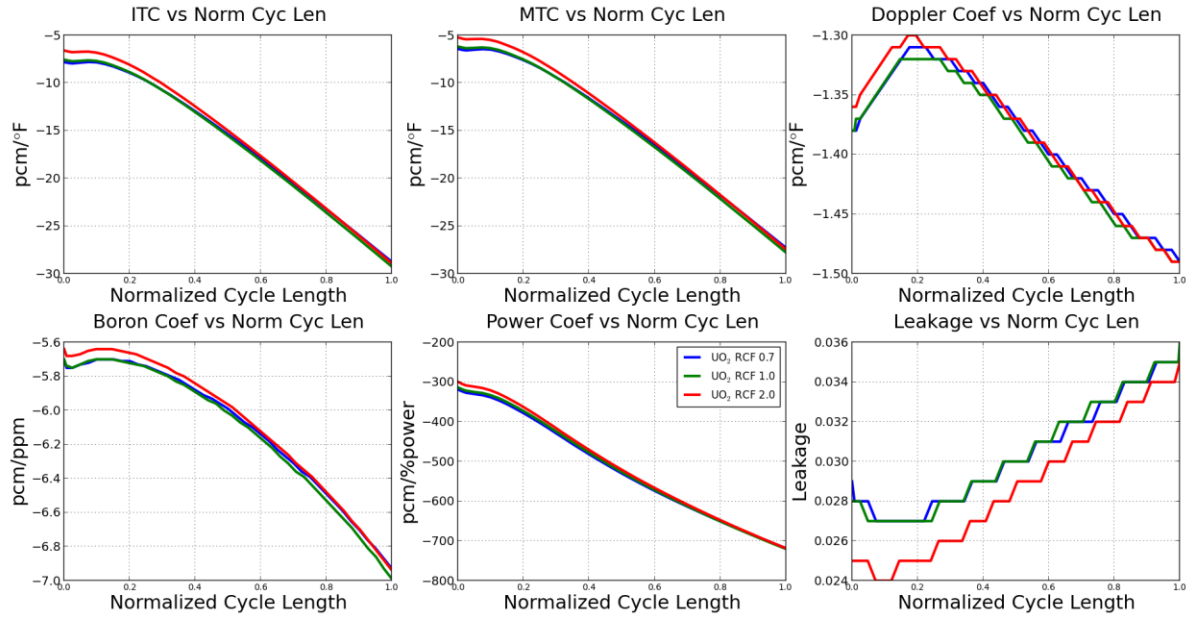


Figure 16: Thick SiC RCF Clad Annular UO₂ 84 Reload Cores, Coefficient Calculations

Figure 17 shows the core reload maps utilized in the 84 reload **Thick SiC RCF** clad annular UO₂ cases.

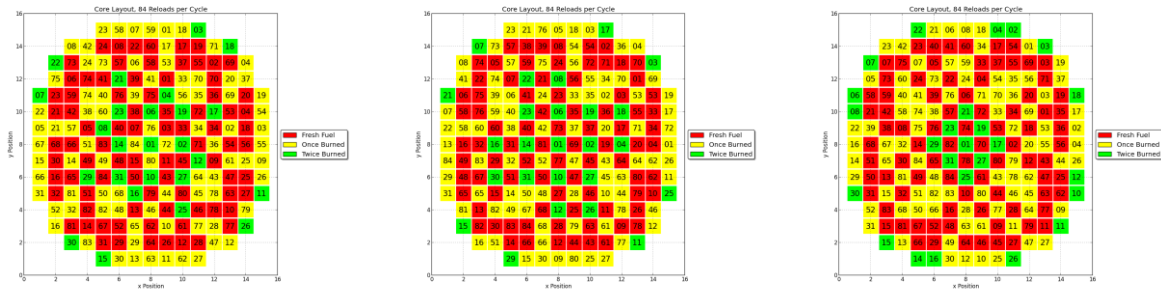


Figure 17: Thick SiC RCF Clad Annular UO₂ 84 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 24 summarizes core geometry, material densities, and mass for the 84 reload Thick SiC RCF clad annular UO₂ cases.

Table 24: Thick SiC RCF Clad Annular UO₂ 84 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.5069	0.4180	0.4096	0.129	10.47	2.85	3.31	81668

Table 25 summarizes physics performance values for the 84 reload **Thick SiC RCF** clad annular UO₂ cases.

Table 25: Thick SiC RCF Clad Annular UO₂ 84 Reload Physics Summary

Obj Fcn	w/o	EFPD	B_c	B_d	BOR	F_{Δh}	F_q	PkExp	SDB	SDE
0.7	4.80	465.8	20.46	45.55	1571	1.469	1.754	79.5	-2275	-1433
1.0	4.80	468.7	20.59	45.64	1582	1.448	1.722	76.8	-2173	-1379
2.0	4.80	474.3	20.83	45.64	1665	1.549	1.862	72.0	-2038	-1414

The most significant and useful observation relating to the 84 reload **Thick SiC RCF** clad annular UO₂ cases is that they require no more than 5.00% enrichment—which is the current limit of licensed operational fuel fabrication facilities. Therefore, the licensing and implementation considerations for this set of core designs are fundamentally different from all of the rest. It is however not without qualification, since a full thermal-hydraulic analysis and other elements of a feasibility study must be conducted in order to confirm the viability of cores of this type. Regardless, this result establishes a meaningful basis for further work.

The physics performances of these SiC cores are actually very similar to those of the **Zr** clad reference case. Chapter 7 contains comparative plots to illustrate this similarity which will be discussed there in more detail. Here however, the physics behind the similarity warrant further discussion.

In the above 84 reload **Thick SiC** clad annular UO₂ cases reactivity was simply too high because of the significant alteration of the H/HM ratio and large loss of self-shielding. In the **Thick SiC RCF** clad cases hydrogen is removed concurrently with removal of fuel—resulting in an H/HM ratio similar to a conventionally fueled LWR. The annular region in the **Thick SiC RCF** clad cases constitutes a smaller fraction of the area inside the clad than in the **Thick SiC** clad cases—resulting in less loss of self-shielding than in the **Thick SiC RCF** clad annular UO₂ fueled cases.

The 84 reload **Thick SiC RCF** clad annular UO₂ cases exhibit the best physics performance of the **SiC** cores due to their similarity to the conventional **Zr** cases—in particular their ability to power a 469 EFPD cycle at 3587 MW_{th} using 5.0% or less.

Comparison of the 84 reload **Thick SiC RCF** clad annular UO₂ cores produced in this work to the 84 reload **Thin SiC** clad annular UO₂ case in previous work by Dobisesky is presented in Table 26. LRM has been used to match EFPD values across all designs.

Table 26: Comparison of 84 Reload Thick SiC RCF Annular UO₂ to Thin SiC of Previous Work

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
0.7	5.03	492	21.61	48.11	1571	1.469	1.754	79.5	-2275	-1433
1.0	5.00	492	21.61	47.90	1582	1.448	1.722	76.8	-2173	-1379
2.0	4.95	492	21.61	47.35	1665	1.549	1.862	72.0	-2038	-1414
Dobisesky	4.79	492	21.56	49.6	1509	1.50	1.76	74.7	-2784	-2203

The reactivity of the 84 reload **Thick SiC RCF** clad annular UO₂ cores is reduced by the lower H/HM ratio and thus requires a higher enrichment than the 84 reload **Thin SiC** clad annular UO₂ case of previous work.

5.5 Thick SiC Clad UO₂/BeO 84 Reload Cores

Figure 18 shows the peaking factors and soluble boron letdown curves of the 84 reload **Thick SiC** clad UO₂/BeO cases. The peaking factors are considerably higher for the case produced via OF 2.0.

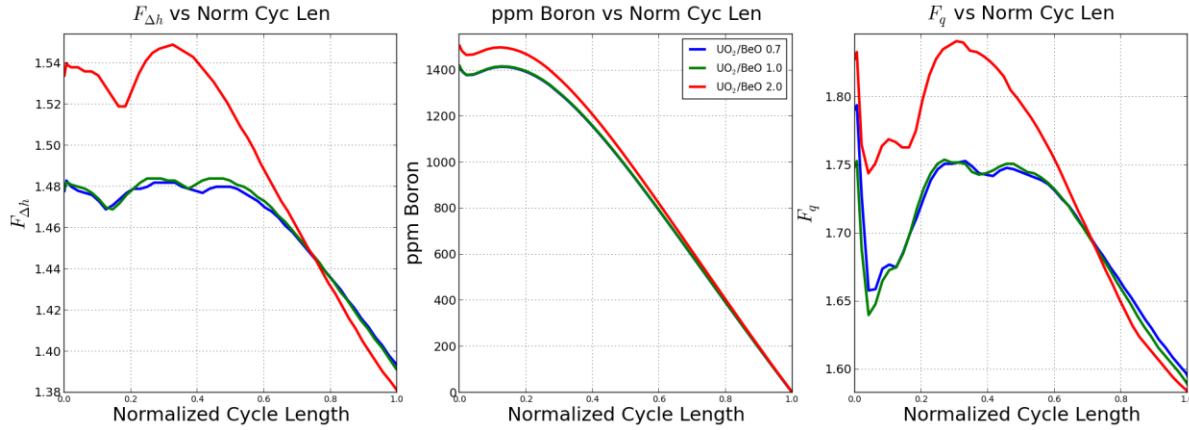


Figure 18: Thick SiC Clad UO₂/BeO 84 Reload Cores, Peaking Factors and Soluble Boron

Figure 19 shows reactivity coefficient results for the 84 reload **Thick SiC** clad UO₂/BeO cases.

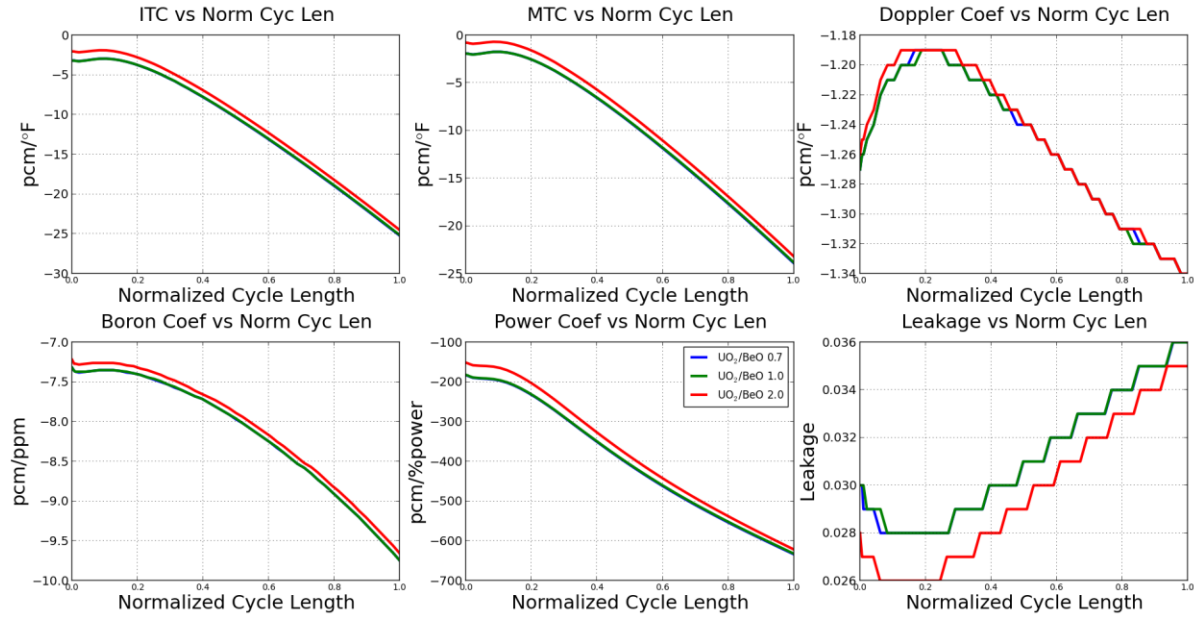


Figure 19: Thick SiC Clad UO₂/BeO 84 Reload Cores, Coefficient Calculations

Figure 20 shows the core reload maps utilized in the 84 reload **Thick SiC** clad UO₂/BeO cases.

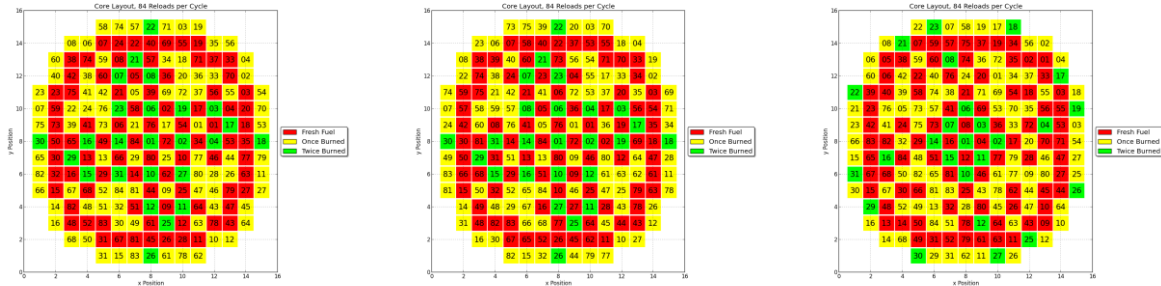


Figure 20: Thick SiC Clad UO₂/BeO 84 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 27 summarizes core geometry, material densities, and mass for the 84 reload Thick SiC clad UO₂/BeO cases.

Table 27: Thick SiC Clad UO₂/BeO 84 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.475	0.3861	0.3777	0	9.71	2.85	4.38	69380

Table 28 summarizes physics performance values for the 84 reload **Thick SiC** clad UO₂/BeO cases.

Table 28: Thick SiC Clad UO₂/BeO 84 Reload Physics Summary

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
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0.7	5.32	465.9	24.09	54.53	1417	1.483	1.794	85.4	-2214	-2034
1.0	5.32	466.6	24.12	54.31	1419	1.484	1.754	87.5	-2242	-2020
2.0	5.32	475.0	24.56	53.62	1506	1.549	1.841	79.7	-2418	-2227

The initial loading of heavy metal in the 84 reload **Thick SiC** clad UO_2/BeO cores is greater than in the 84 reload **Thick SiC** clad annular UO_2 cores. Therefore the H/HM ratio is lower for the UO_2/BeO cores, which reduces reactivity.

In addition to this, the **Thick SiC** clad UO_2/BeO cores use solid fuel pellets, while the **Thick SiC** clad annular UO_2 cores use annular pellets. This results in an effectively reduced self-shielding effect per ^{238}U atom in the **Thick SiC** clad UO_2/BeO cores—but an overall increase in ^{238}U absorption that reduces the reactivity of the **Thick SiC** clad UO_2/BeO cores.

The combined effect of these reactivity reductions is that the **Thick SiC** clad UO_2/BeO cores are farther away from the over-moderation seen in the 84 reload **Thick SiC** clad annular UO_2 OF 2.0 core. To state it another way, the **Thick SiC** clad UO_2/BeO cores are essentially at a lower point on the moderation curve than the 84 reload **Thick SiC** clad annular UO_2 cores.

6 Results for Thorium Hosted Plutonium

6.1 Thick SiC Clad $\text{PuO}_2/\text{ThO}_2$ 84 Reload Cores

Figure 21 shows the peaking factors and soluble boron letdown curves of the 84 reload **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ cases. The peaking factors are considerably higher for the case produced via OF 2.0.

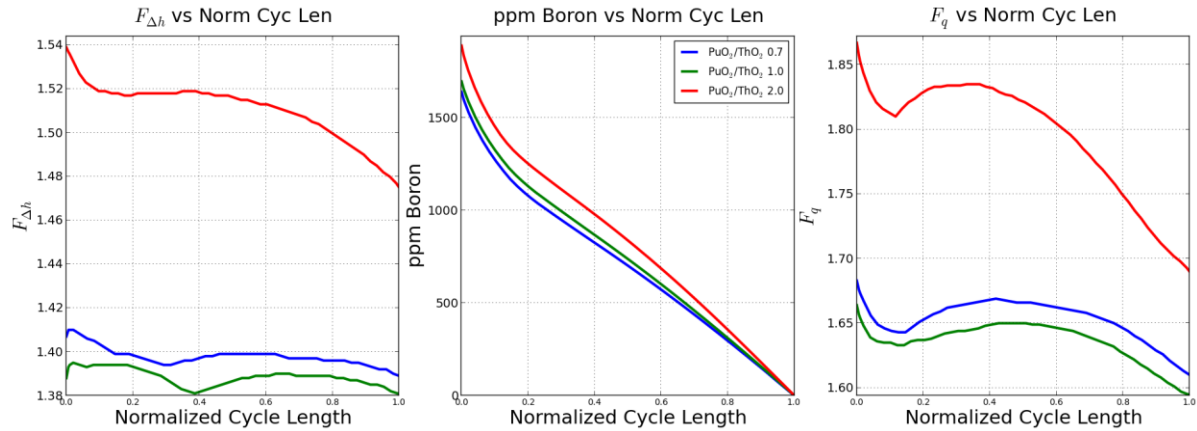


Figure 21: Thick SiC Clad $\text{PuO}_2/\text{ThO}_2$ 84 Reload Cores, Peaking Factors and Soluble Boron

Figure 22 shows reactivity coefficient results for the 84 reload **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ cases.

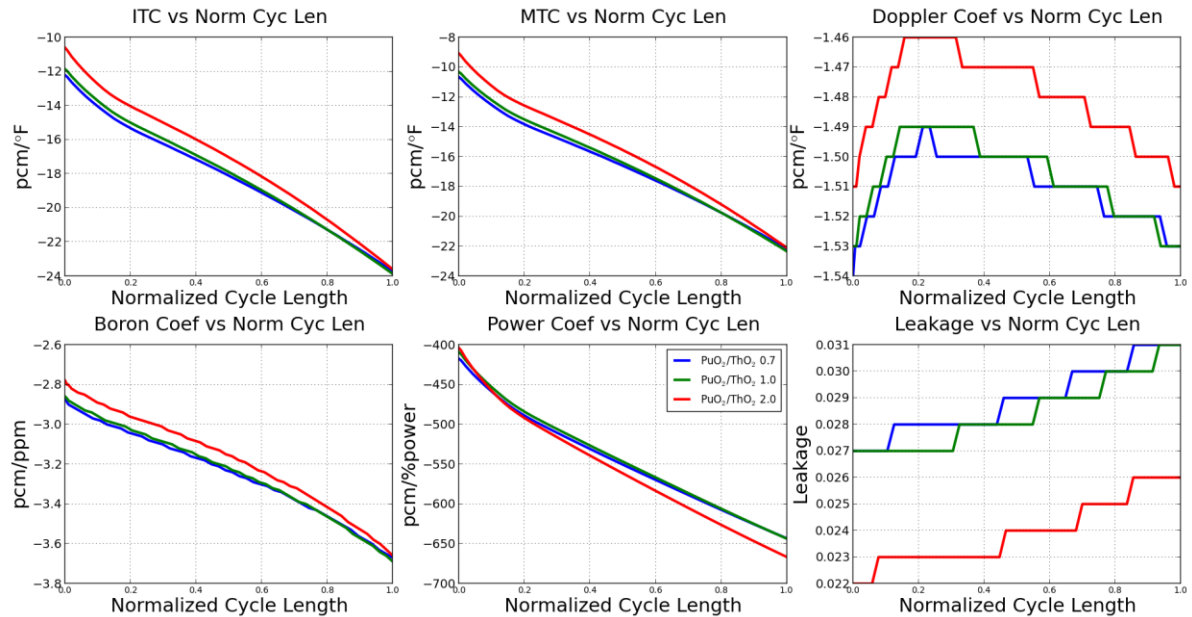


Figure 22: Thick SiC Clad $\text{PuO}_2/\text{ThO}_2$ 84 Reload Cores, Coefficient Calculations

Figure 23 shows the core reload maps utilized in the 84 reload **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ cases.

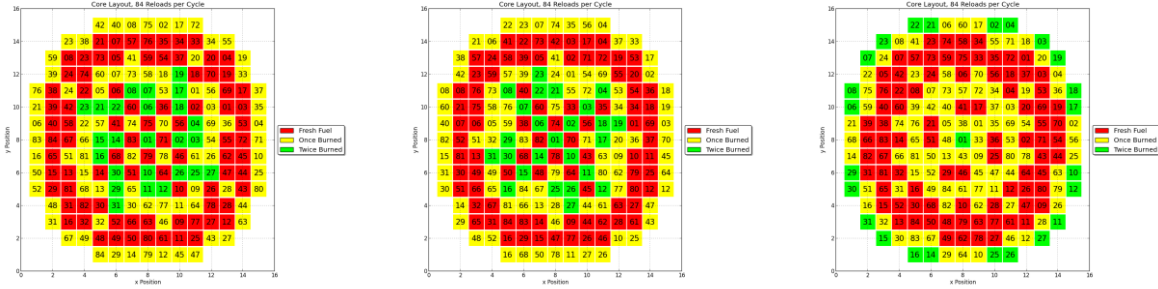


Figure 23: Thick SiC Clad PuO₂/ThO₂ 84 Reload Cores, Reload Maps. (Left - 0.7 / Center - 1.0 / Right - 2.0)

Table 29 summarizes core geometry, material densities, and mass for the 84 reload Thick SiC clad PuO₂/ThO₂ cases.

Table 29: Thick SiC Clad PuO₂/ThO₂ 84 Reload Geometry, Material Density, and Mass

R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
0.475	0.3861	0.3777	0	9.35	2.85	4.34	68662

Table 30 summarizes physics performance values for the 84 reload **Thick SiC** clad PuO₂/ThO₂ cases.

Table 30: Thick SiC Clad PuO₂/ThO₂ 84 Reload Physics Summary

Obj Fcn	w/o	EFPD	B _c	B _d	BOR	F _{Ah}	F _q	PkExp	SDB	SDE
0.7	12.04	458.0	23.93	54.08	1640	1.410	1.683	101.8	-779	-209
1.0	12.04	471.4	24.63	53.89	1697	1.395	1.664	102.2	-781	-235
2.0	12.04	492.6	25.73	57.69	1890	1.539	1.867	97.9	-614	43

The 84 reload **Thick SiC** clad PuO₂/ThO₂ cases exhibit the greatest variation in cycle length from the application of different OFs. The reactivity differences between fresh and burned assemblies are less here than in any other fuel and clad combination presented herein.

The soluble boron worth is very low in these cases, and the shutdown margins are unacceptable—indicating low control rod worth. The shutdown margin is positive for optimization via OF 2.0. The highly negative MTC, combined with the notably low soluble boron worth suggests extreme under-moderation indicative of a neutron spectrum harder than typical LWR spectra.

Despite the high fast to thermal neutron flux ratio and low soluble boron worth, these cores probably do not present an increased fast fluence hazard to the RPV. Since the core nominal power is fixed in all cases presented herein, the fission rates of each case are roughly the

same (to first order, fission energy is the same for all fissioning isotopes present in this work). Given nearly identical fission rates and moderator fractions between $\text{PuO}_2/\text{ThO}_2$ and other **Thick SiC** clad fuel cases, there is no reason for fast flux leakage to be significantly altered. The differences in the ^{238}U and ^{232}Th fast neutron capture cross sections are relatively minor, with slightly higher fast neutron absorption exhibited by ^{232}Th . Thus, it is reasonable to conclude that RPV fast fluence is not significantly altered—and if it is altered it is likely reduced.

The 300K fission and neutron capture cross sections for ^{238}U and ^{232}Th are shown below in Figure 24. The green and red lines are ^{238}U capture and fission, respectively. The purple and blue lines are ^{232}Th capture and fission, respectively.

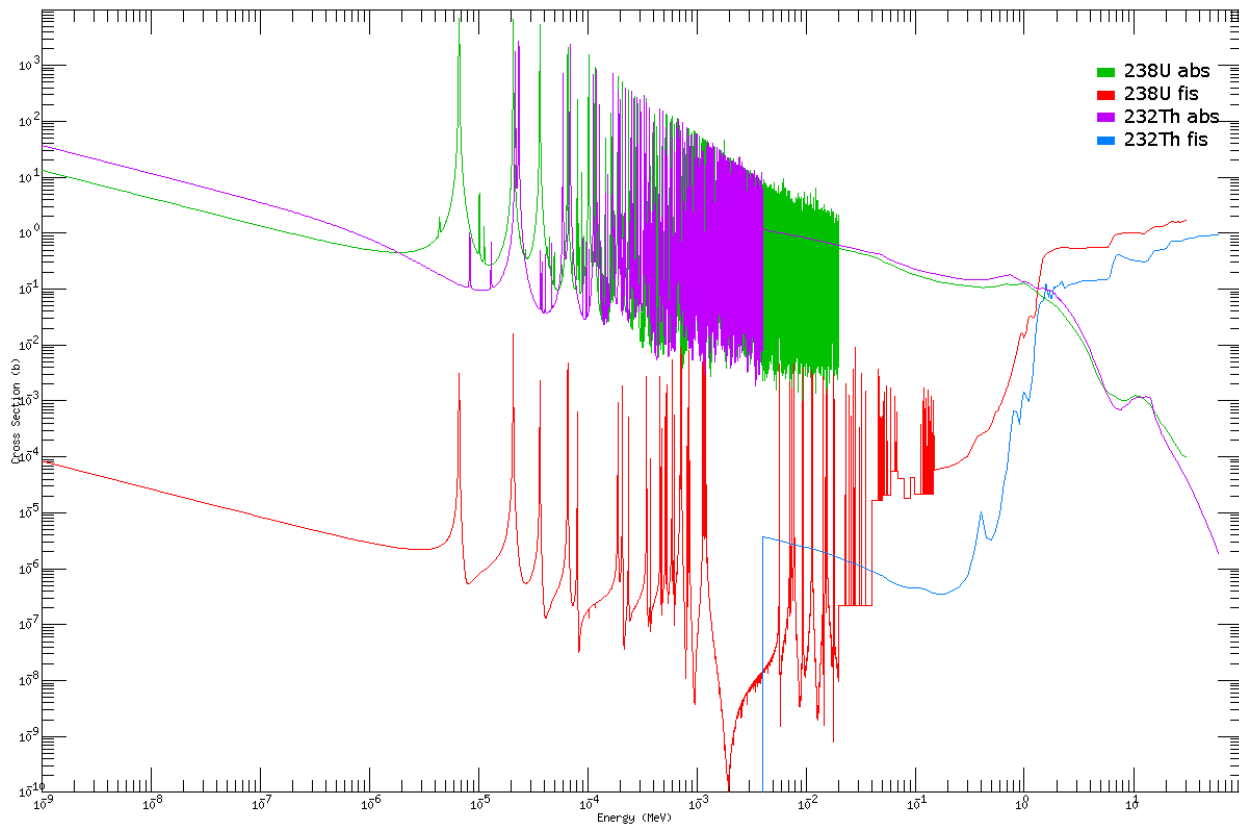


Figure 24: ^{238}U and ^{232}Th Fission and Capture Cross Sections [17]

6.2 Plutonium Content as a Function of Burnup

CASMO depletion modeling has been conducted for the above fuel and clad combination for a series of conditions defined in terms of Pu wt% of IHM. There are 11 cases, and in each case the CASMO 2D depletion is conducted at the power density specified in Section 2.8.

These plots predict the quantity of plutonium in an assembly at a given burnup. For example, given a specific Pu loading in terms of wt% IHM, the plot can be used to determine the Pu content (as wt% of IHM) at 60 MWd/kg. The difference between the initial and discharge plutonium content is the quantity of plutonium that has been consumed.

Figure 25 below shows the total and fissile plutonium content and k_{∞} as a function of burnup for 11 cases relevant to this work. Each separate case is defined by its initial quantity of plutonium as read at the 0 MWd/kg intercepts.

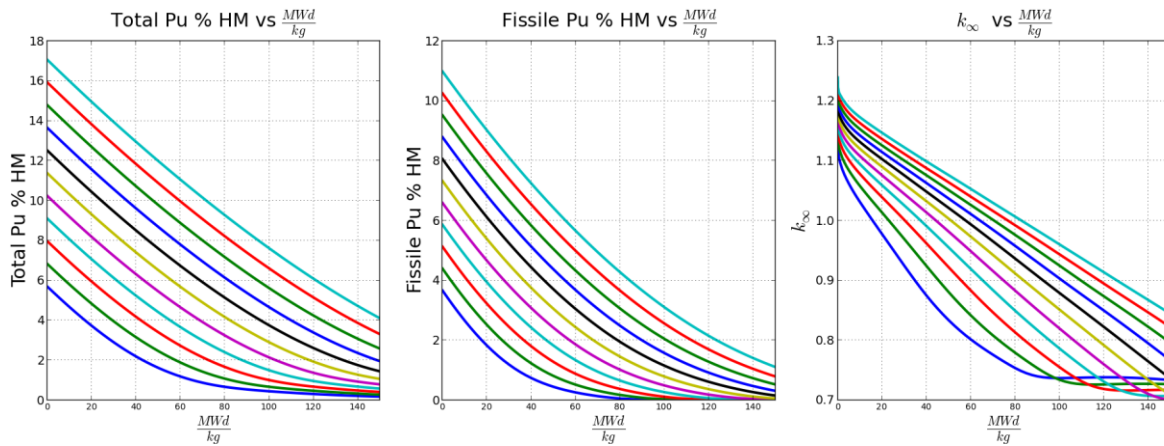


Figure 25: Pu Content and k_{∞} as a Function of Burnup For Different Pu wt% IHM

Using the total Pu 12.5 wt% IHM (black) line in the above figure it can be estimated that at 60 MWd/kg the total Pu wt% will be 6.7 wt% of initial heavy metal. The fissile Pu wt% at the same burnup will be 3.5 wt%. This indicates that to a first approximation the $\text{PuO}_2/\text{ThO}_2$ cores designed above burn roughly 46% of total Pu and 57% of fissile Pu.

While more precise calculations derived from full-core modeling produce more specific results, the above plot serves as a general guide to plutonium consumption with depletion for assemblies of this type. A similar set of curves can be generated for any assembly type corresponding to different material, geometry, temperature, and power density conditions.

For example, if one were to decide that one wished to reduce fissile plutonium by 75%, these plots will tell you how much burnup is required for a given initial loading—or vice versa. If a 40 MWd/kg exposure was desired, then using this plutonium vector, fissile Pu at EOL will be 75% of Beginning of Life (BOL) fissile Pu for an initial fissile Pu wt% IHM of ~3.8%. Conversely, if it was desirable to consume 75% of fissile Pu when the initial fissile Pu wt% IHM was ~10%, the EOL burnup required is ~100 MWd/kg.

7 Results Reviewed Via OF

7.1 Geometry, Material Density, and Mass Summary for All Cores

The performance of annular UO_2 pellets and BeO enhanced UO_2 pellets in thick SiC cladding have been analyzed. Also, the burning of Pu in ThO_2 with thick SiC cladding has been analyzed. Table 31 summarizes the geometry, material densities, and heavy metal mass for all cores analyzed.

Table 31: Geometry, Material Density, and Mass Summary, All Cores

Fuel/Clad/Reloads	R_{co}	R_{ci}	R_{fo}	R_{fi}	ρ_f	ρ_c	H/HM	m_{HM} (kg)
Zr UO_2 , 84	0.475	0.418	0.4096	0	10.47	6.55	3.35	90661
ThkSiC Ann. UO_2 , 64	0.475	0.3861	0.3777	0.129	10.47	2.85	4.47	68094
ThkSiC Ann. UO_2 , 84	0.475	0.3861	0.3777	0.129	10.47	2.85	4.47	68096
ThkSiC2 Ann. UO_2 , 84	0.5069	0.418	0.4096	0.129	10.47	2.85	3.31	81668
ThkSiC UO_2/BeO , 84	0.475	0.3861	0.3777	0	9.71	2.85	4.38	69380
ThkSiC $\text{PuO}_2/\text{ThO}_2$, 84	0.475	0.3861	0.3777	0	9.35	2.85	4.34	68662

7.2 OF 0.7, All Fuel/Clad Combinations

All cores had the same total power (3587 MW_{th}). The core physics performance was optimized under constraints for peaking factors, boron concentration, MTC, peak pin burnup, and shutdown margin. Three OFs were considered for the optimization: OF 0.7, OF 1.0, and OF 2.0. Figure 26 shows the peaking factors and soluble boron letdown curves of all cases optimized using OF 0.7.

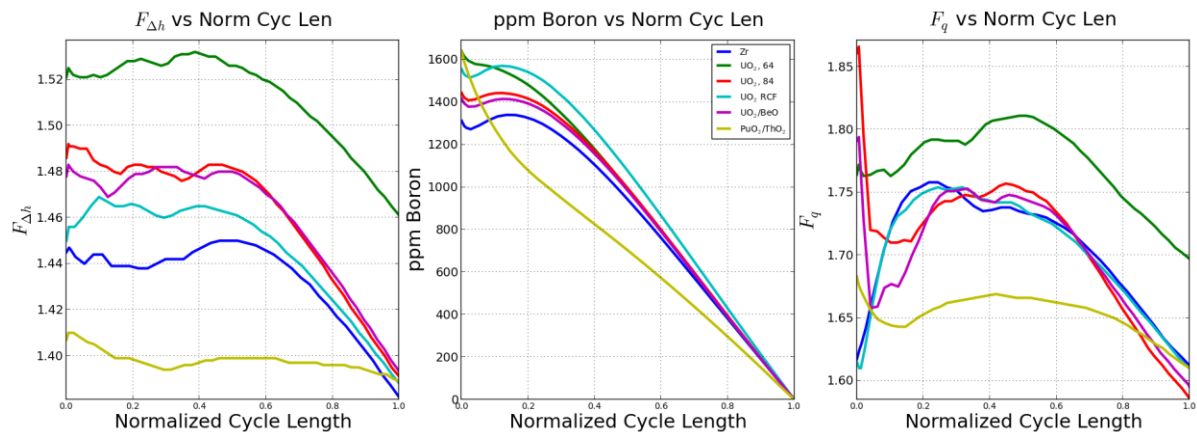


Figure 26: OF 0.7, Peaking Factors and Soluble Boron, All Cores

Figure 27 shows reactivity coefficient results for all cases optimized using OF 0.7.

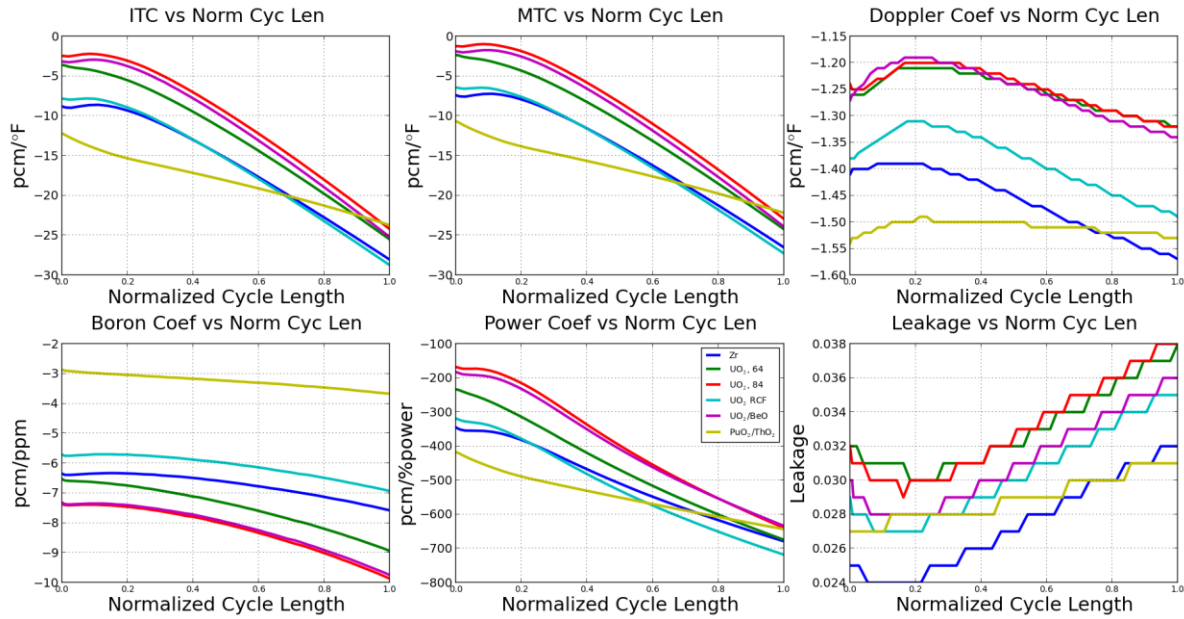


Figure 27: OF 0.7, Coefficient Calculations, All Cores

Table 32 summarizes physics performance values for all cases optimized using OF 0.7.

Table 32: OF 0.7, Physics Summary, All Cores

Fuel/Clad/Rlds	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
Zr U 64	4.29	466.5	18.46	42.78	1340	1.450	1.758	71.6	-2090	-1610
TkSiC U 64	6.59	466.3	24.57	74.06	1641	1.532	1.811	102.6	-2897	-2458
TkSiC U 84	5.43	466.3	24.56	55.65	1444	1.492	1.866	90.9	-2637	-2434
TkSiC2 U 84	4.80	465.8	20.46	45.55	1571	1.469	1.754	79.5	-2275	-1433
TkSiC UBe 84	5.32	465.9	24.09	54.53	1417	1.483	1.794	85.4	-2214	-2034
TkSiC PuTh 84	12.04	458.0	23.93	54.08	1640	1.410	1.683	101.8	-779	-209

The cores optimized using OF 0.7 were the first set of cores constructed. Their optimization was conducted before the final update of the SIMULATE temperature correlation inputs, resulting in a slight degradation of their performance. Nevertheless, this set of cores provides an example of optimization according to peaking factors alone.

Compared to the other sets of cores optimized according to the other OFs, this set has the lowest cycle lengths and some very significant BOC peaks in F_q.

The **Zr** and **Thick SiC RCF** cases meet cycle length requirements using no more than 5.0% enrichment. They have very similar characteristics: their peaking, ITC, MTC, and power coefficient plots all track together. They also have the lowest peaking of the UO_2 fueled cores (including UO_2/BeO).

Similarly, the **Thick SiC** UO_2 and UO_2/BeO cores' peaking, ITC, MTC, boron coefficient, power coefficient, and Doppler coefficient track together.

The cycle length of the OF 0.7 cores are the lowest in comparison to the cycle lengths achieved via the other OFs. Also, the OF 0.7 cores have the highest values of peak pin burnup for each fuel and cladding combination.

7.3 OF 1.0, All Fuel/Clad Combinations

Figure 28 shows the peaking factors and soluble boron letdown curves of all cases optimized using OF 1.0.

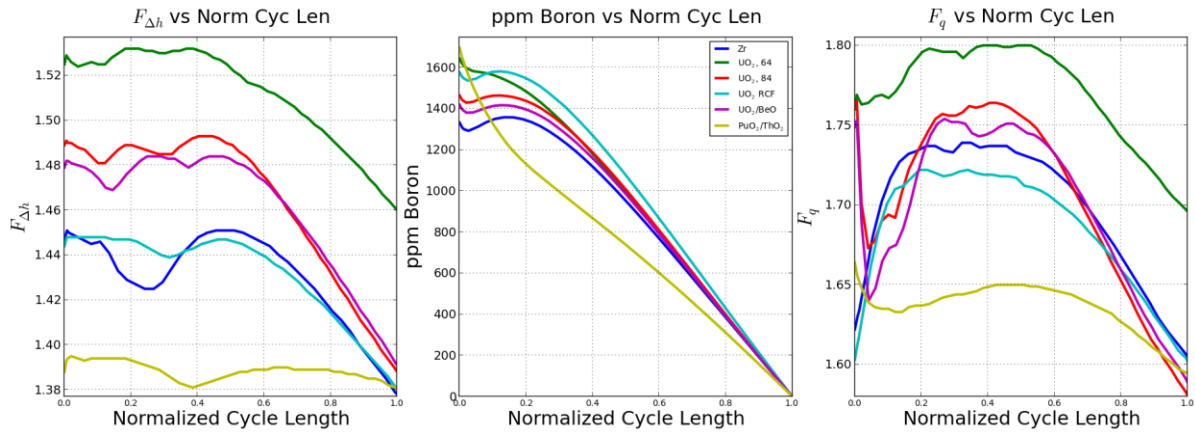


Figure 28: OF 1.0, Peaking Factors and Soluble Boron, All Cores

Figure 29 shows reactivity coefficient results for all cases optimized using OF 1.0.

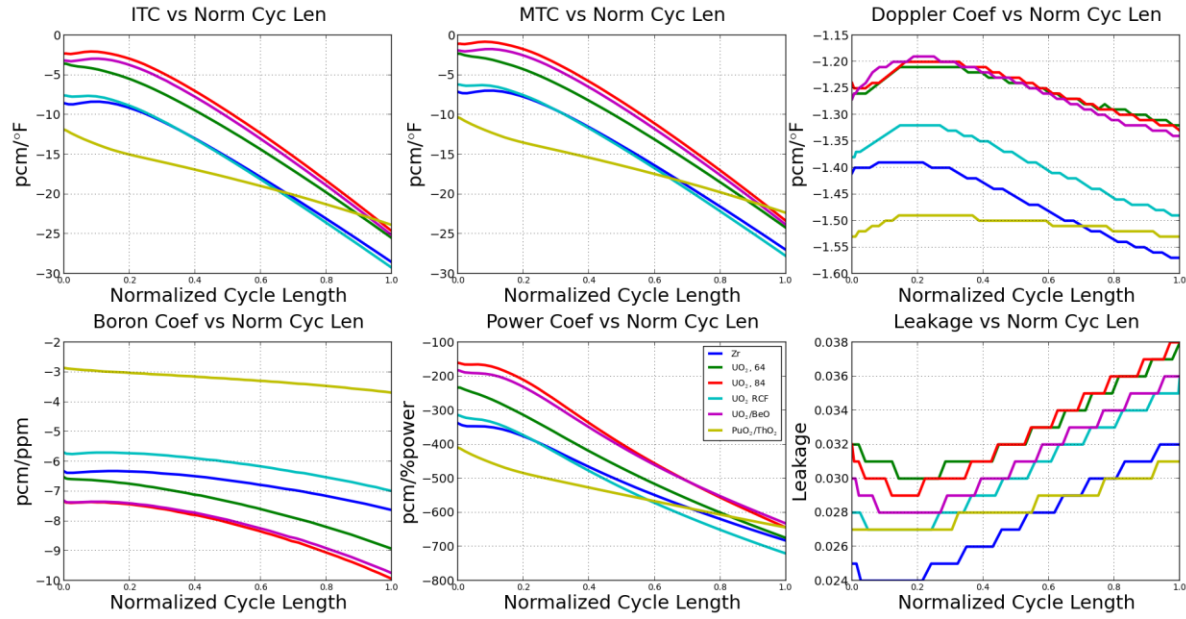


Figure 29: OF 1.0, Coefficient Calculations, All Cores

Table 33 summarizes physics performance values for all cases optimized using OF 1.0.

Table 33: OF 1.0, Physics Summary, All Cores

Fuel/Clad/Rlds	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
Zr U 64	4.29	470.8	18.63	42.21	1358	1.451	1.739	71.1	-2074	-1601
TkSiC U 64	6.59	466.5	24.57	74.07	1643	1.532	1.800	101.8	-2900	-2458
TkSiC U 84	5.43	469.3	24.72	55.35	1464	1.493	1.765	88.7	-2711	-2416
TkSiC2 U 84	4.80	468.7	20.59	45.64	1582	1.448	1.722	76.8	-2173	-1379
TkSiC UBe 84	5.32	466.6	24.12	54.31	1419	1.484	1.754	87.5	-2242	-2020
TkSiC PuTh 84	12.04	471.4	24.63	53.89	1697	1.395	1.664	102.2	-781	-235

OF 1.0 was effective in extending cycle length while simultaneously lowering peaking factors, and managed to balance BOC F_q peaks with intra-cycle F_q peaks.

The optimization algorithm would frequently extend cycle length in small increments and then make large jumps when a map with a lower product of $F_{\Delta h}$ and F_q was found. These large jumps often coincided with a shortening of cycle length. Then at the new peaking values the algorithm would again extend cycle length, often beyond the previous level.

OF 1.0 was also more active in accepting new maps than OF 0.7. The higher frequency of accepting new maps appeared to allow OF 1.0 to optimize core reload maps more quickly than OF 0.7.

The **Zr** and **Thick SiC RCF** cores again displayed similar performance. This was also true of the **Thick SiC** UO₂ and UO₂/BeO cores' performance.

Optimization via OF 1.0 increased cycle length for all fuel and clad combinations. The OF 1.1 presented in Section 4.4.2 exhibited behavior similar to OF 1.0, however optimization results from OF 1.1 are left to be included as an addendum or for future work.

7.4 OF 2.0, All Fuel/Clad Combinations

Figure 30 shows the peaking factors and soluble boron letdown curves of all cases optimized using OF 2.0.

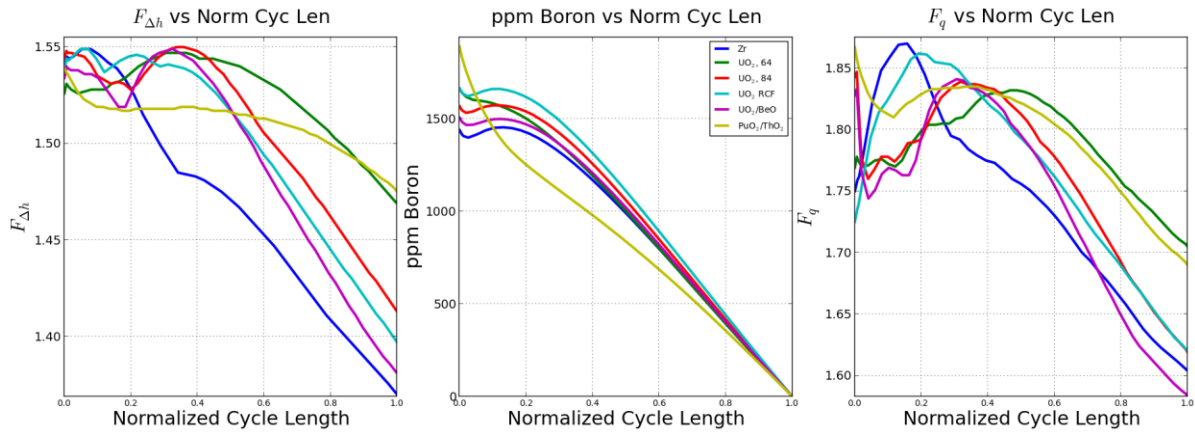


Figure 30: OF 2.0, Peaking Factors and Soluble Boron, All Cores

Figure 31 shows reactivity coefficient results for all cases optimized using OF 2.0.

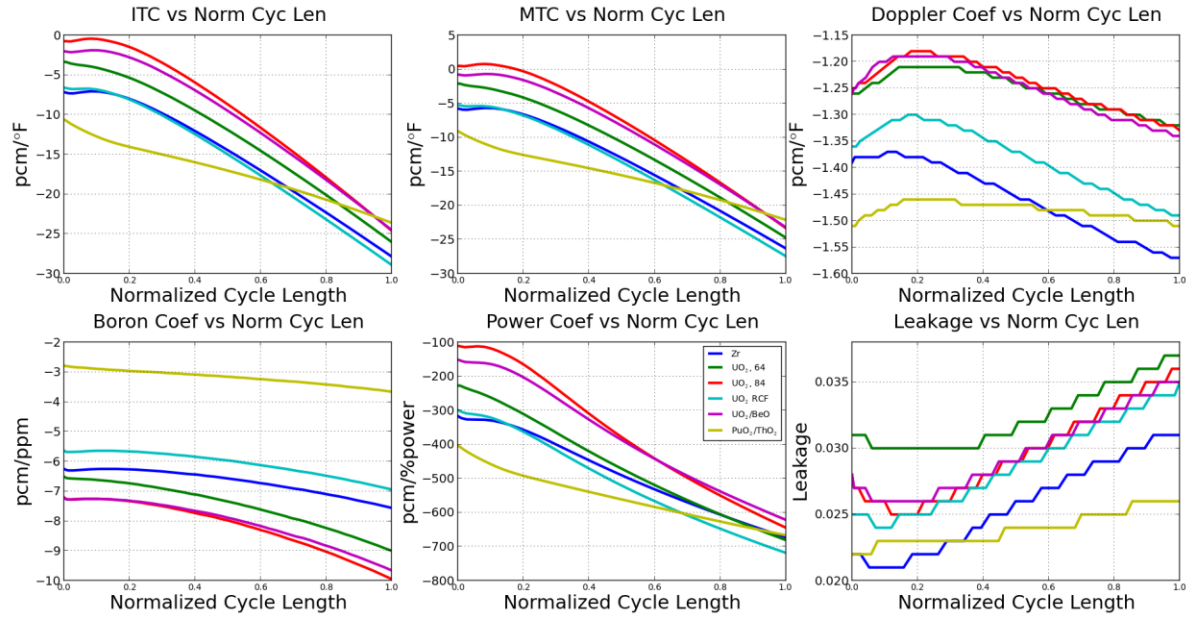


Figure 31: OF 2.0, Coefficient Calculations, All Cores

Table 34 summarizes physics performance values for all cases optimized using OF 2.0.

Table 34: OF 2.0, Physics Summary, All Cores

Fuel/Clad/Rlds	w/o	EFPD	B _c	B _d	BOR	F _{Δh}	F _q	PkExp	SDB	SDE
Zr U 64	4.29	481.3	19.04	41.68	1454	1.549	1.870	67.5	-2055	-1645
TkSiC U 64	6.59	468.0	24.65	74.20	1664	1.547	1.832	98.7	-2895	-2449
TkSiC U 84	5.43	476.7	25.11	54.69	1573	1.550	1.847	80.6	-2713	-2575
TkSiC2 U 84	4.80	474.3	20.83	45.64	1665	1.549	1.862	72.0	-2038	-1414
TkSiC UBe 84	5.32	475.0	24.56	53.62	1506	1.549	1.841	79.7	-2418	-2227
TkSiC PuTh 84	12.04	492.6	25.73	57.69	1890	1.539	1.867	97.9	-614	43

Optimization using OF 2.0 demonstrates the competitive relationship between cycle length and peaking factors. In each case, cycle length was extended beyond the values achieved by either of the other two OFs—and at the same time peaking factors were not given any weight in determining a map’s value. Only cycle length was considered for any map whose peaking factors were below the limits outlined in Section 2.12.1, and the peaking factors rose to very near those limits in all cases. Leakage dropped in all cases.

The **Zr** and **Thick SiC RCF** cores again displayed similar performance, as in the cases of optimization via OF 0.7 and OF 1.0. This was also again true of the **Thick SiC** UO₂ and UO₂/BeO cores’ performance.

8 Remarks on Uncertainties

8.1 Uncertainty in CASMO/SIMULATE

Validity of the core simulation codes is well established for PWRs using the current fuel materials and geometry. Predictions of PWR reactor physics made by CASMO-4 and SIMULATE-3 have been compared to measurements obtained *in situ* from operating large scale reactors. Predictions by CASMO-4 and SIMULATE-3 have been validated for: assembly power, soluble boron letdown, control rod worth, ITC, peak pin exposure, and other parameters. Results have been shown to be accurate and with low uncertainties. [18] As an industry standard tool, it has been used by utilities to perform their own Fuel Management analyses to support licensing with the NRC. It is also noted that while MIT does not have access to the most up-to-date versions of CASMO/SIMULATE, the deficiencies in the versions used in this work are expected to cancel out when comparing various designs to each other.

8.2 Depletion of Be in UO₂/BeO Fuel

CASMO-4E does not deplete beryllium present in fuel. Therefore, since beryllium does deplete via various mechanisms, it is reasonable to ask to what extent does beryllium deplete and what reactivity effect does this depletion have?

Depletion of Be was modeled in SERPENT; the depletion of Be at 60 MWd/kg in 5.5% ²³⁵U enriched fuel was negligible as the difference between the SERPENT predicted eigenvalue vs. CASMO-4E remained constant over the fuel burnup [K. Shirvan, private communication, 2013]. This validates the CASMO-4E calculations with constant presence of BeO in the UO₂/BeO fuel over the interval of interest to this work.

8.3 Plutonium and Thorium Cross Sections in ENDF-VI

There are inaccuracies associated with the ENDF-VI cross section library that is used by CASMO-4E to generate the two group cross sections used by SIMULATE in the evaluation of core physics performance.

Comparison of ENDF-VI based CASMO results with ENDF-VII based SERPENT results for $\text{PuO}_2/\text{ThO}_2$ cases was performed and found to be within 300 pcm [K. Shirvan, private communication, 2013].

8.4 Annularization of Fuel

Figure 32 shows CASMO 2D, assembly-level depletion simulation results for a series of fuel geometries and compositions where the initial loading of ^{235}U per fuel rod is fixed. The annular plenum radius is therefore determined as a function of enrichment or vice-versa—as more ^{238}U is removed there is less fuel volume and the fuel that remains exists as an annular fuel pellet.

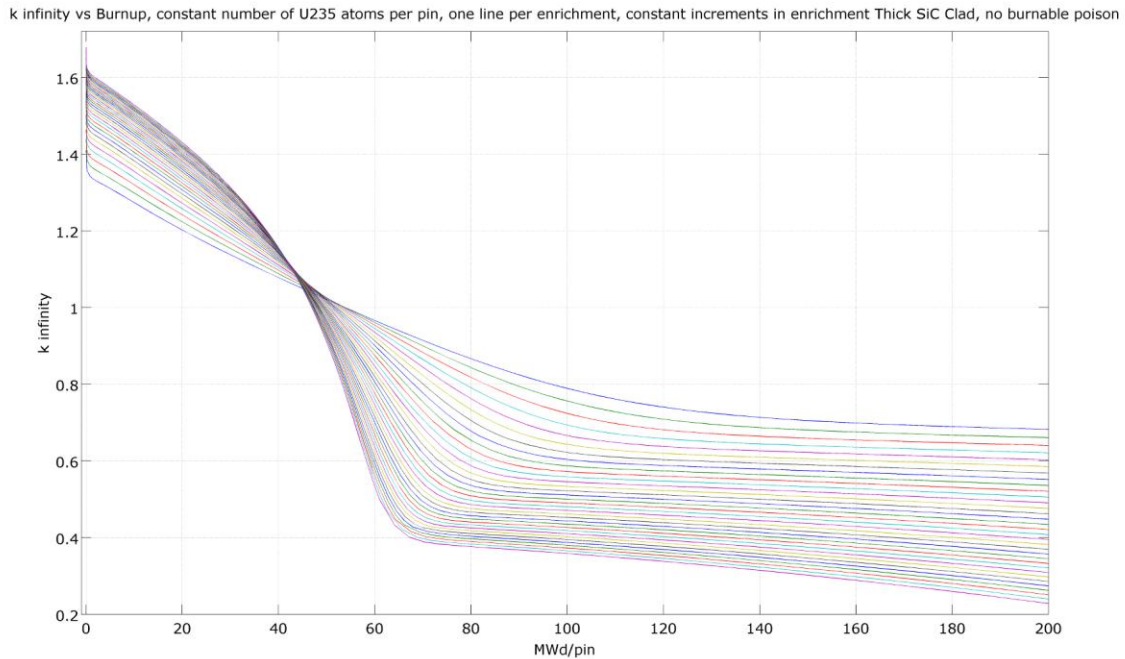


Figure 32: Effect of Increasing Annularization With Constant ^{235}U Content

It is observed via this sensitivity study that the annularization of fuel increases the slope of the reactivity curve as a function of energy released per fuel rod (or equivalently burnup per unit mass if initial ^{235}U loading, since that is the same for all cases). The smoothest curve will be that of the solid pellet, and it is reasonably expected that this will be true for all fuels.

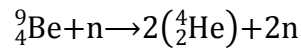
Neutron capture in ^{238}U is when the fuel is annularized. Absorption per ^{238}U atom is increased, which competes with the effect of reduced ^{238}U content. Overall reduced rates of neutron capture in ^{238}U result in significantly higher initial reactivity and less breeding of new

fissile material throughout the cycle. These effects are the primary causes of the steepening of the reactivity curves with increasing annularization.

Steeper reactivity curves complicate core design and necessarily imply higher peaking factors, $F_{\Delta h}$ and F_q . This elevation of peaking reduces the dynamic range of performance available to core designers.

8.5 Homogeneous Fissile Oxide/BeO Mixtures

The primary motivation to add BeO to nuclear reactor fuel is to reduce the average and peak fuel temperatures. This addition also slightly improves neutron moderation and neutron multiplication in the fuel. BeO presence in the fuel introduces the following nuclear reaction:



However, this reduction in fuel temperature does not come without a cost. The additional helium production, increases EOL plenum pressure and partially offsets the reduced fission gas release due to the lower fuel temperature.

Further, thermal conductivity data for UO_2/BeO is not as plentiful as for UO_2 . It is certainly possible that thermal conductivity of UO_2/BeO is sensitive to manufacturing processes and burnup in ways that are not currently understood or accurately modeled. Therefore, the fuel temperature correlation used in this work may require revision and thus obscure the true performance of homogeneous UO_2/BeO mixtures.

9 Conclusion and Future Work

9.1 Conclusion

The core design and modeling work presented herein demonstrates the neutronic feasibility of annular UO_2 and UO_2/BeO fuels clad in **Thick SiC** and annular UO_2 clad in **Thick SiC RCF**. The most notable observation in this work is that the **Thick SiC RCF** cases allow for fuel enrichment of not more than 5.0%.

The **Zr** and **Thick SiC RCF** cases are very similar in the time evolution of their performance, enrichment utilization of 5.0% or less, and low peak pin burnup values.

The **Thick SiC** annular UO_2 and UO_2/BeO cases are also very similar in the time evolution of their performance. The differences in their performance is readily accounted for by the additional initial heavy metal mass of the UO_2/BeO cases.

The OF 2.0 84 assembly reload **Thick SiC** clad annular UO_2 core has a positive MTC early in life which may be overcome via the use of additional burnable poison.

The $\text{PuO}_2/\text{ThO}_2$ cores all have unacceptable shutdown margins, including a positive shutdown margin at EOC for the OF 2.0 **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ core. Increasing control rod worth may improve the shutdown margins of the $\text{PuO}_2/\text{ThO}_2$ cores.

Previous work by Dobisesky shows that **Thin SiC** requires less enrichment than **Thick SiC** to achieve 492 EFPD at 3587 MW_{th} . However, the methodology developed herein may further reduce the enrichment requirements of the **Thin SiC** cases.

9.2 Recommendations for Future Work

While significant effort has been invested in the development of CSpy and the results presented in this thesis, there remains considerable additional work to be done in order to reveal a more complete picture of the potential of Thick SiC Clad fuels in a PWR environment.

9.2.1 Core Power Upgrades or Longer Fuel Cycle

Increasing the core power represents a significant gain in the electrical power production capacity of a nuclear power plant. Extending the fuel cycle length also increases the plant capacity factor and could lead to cheaper fuel cycle cost. Detailed core physics models of uprated or extended

cycle scenarios may provide impetus for further consideration of plant power uprates. These may involve other plant modifications which affect the lifetime average capital costs, including earlier steam generator replacement or modification, potential reduction in reactor pressure vessel life, increased rates of corrosion in piping due to off-design temperatures of operation, turbine replacement(s), pumping upgrades and other modifications requiring sophisticated engineering analyses.

9.2.2 Variation of Burnable Poison Rod Number

Variation of the number of burnable poison rods per assembly is a key feature of a truly general core physics optimization code and study. In this thesis this parameter was fixed in order to simplify the optimization search space and to simplify coding of CSpY, however expansion of CSpY to include this capability is essential to its development as a general code for optimization of PWR core physics.

In particular, three cores presented in this work may benefit from fewer burnable poison rods used in their assemblies: both 84 and 64 reload number **Thick SiC** clad annular UO_2 cores, and the **Thick SiC** clad UO_2/BeO 84 reload cores. All three cases have OF 0.7 results where BOC F_q values are in excess of a subsequent local F_q maximum at higher burnup. This indicates presence of excessive burnable poison. Correcting this should bring the OF 0.7 cycle peak F_q for all three of the above mentioned cases in line with the **Zr** clad reference cores—however the soluble boron required to hold down reactivity throughout the cycle will rise as less IFBA is used.

9.2.3 Split Enrichment Feed

The work presented in this thesis relies heavily on optimization schema to produce core designs utilizing loading only a single assembly type at each reload. However, it may be possible to achieve superior core physics performance and fuel economy by loading more than one type of assembly at each reload.

The design process would then be expanded to include the number of assembly types, and then the clad type, fuel type, enrichment, burnable poison type, and number of burnable poison rods for each assembly type to be loaded.

The first relevant case expanding upon the work of this thesis would be to develop a two-assembly **Zr** clad UO_2 reference core. Initial inquiry should start with 20 assemblies of higher enrichment than the bulk, leaving all other parameters equal.

9.2.4 Twice Burned Fuel on the Periphery

By loading twice burned fuel on the periphery of a given core, it may be possible to extend cycle length and reduce leakage. Optimization via OF 2.0 resulted in placement of more twice burned fuel on the core periphery than via the other OFs, however a heuristic requirement may another way to investigate core design and physics performance using twice burned fuel on the periphery.

Heuristic implementation requires that most twice burned fuel assemblies occupy peripheral assembly locations in the case of 84 reloads per cycle, or that most peripheral assembly locations be occupied by twice burned fuel in the case of 64 reloads per cycle.

9.2.5 Extraction of Pin Power Profiles

Axial power profiles for peak power and peak burnup fuel rods are required inputs to fuel performance codes, which currently rely on conservative assumptions that may prove too limiting in the analysis of the viability of Thick SiC clad fuels. Detailed axial power shapes as functions of burnup for all rods that are the peak power rod for any given time step during the first cycle would be valuable data for realistic simulation of fuel performance. Alternatively, one could also use peak power assemblies of each batch to construct power profiles for fuel performance simulations.

9.2.6 Further Development and Utilization of Optimization Schema

Speculation as to which OF is most appropriate for a given situation is a topic that receives much attention and is debated by experienced professionals. The true test of an OF is its efficacy in producing the desired results. As such, further investigation into optimization schema will include further development of and experimentation with new OFs.

It may also be beneficial to expand CSpY to include a Genetic Algorithm and/or a Simulated Annealing Algorithm to provide additional means by which to permute assembly burnable poison layouts and core reload map configurations.

9.2.7 Fuel Performance Oriented Optimization

I envision an iterative process in which FRAPCON fuel performance limits can be used as optimization criteria for SIMULATE core reload map optimization. When a new core reload map is found via SIMULATE optimization, the new core's peak pin power history is to be automatically extracted and input into a new FRAPCON simulation. This new FRAPCON simulation defines new fuel performance limitations which can then be used to update the optimization criteria for SIMULATE core reload map optimization.

This iterative process may find an integrated balance between fuel performance and neutronics that is superior to conventional methodologies today.

9.2.8 Definition of Outer Axial Blanket Composition as a Function of Main Length Composition

Outer axial blankets affect both core neutron leakage and axial power shape. Higher outer blanket enrichment is associated with higher leakage, and lower outer blanket enrichment is associated with greater heterogeneity of the axial power shape. Future work may consider specifying outer axial blanket enrichment as a fraction of the enrichment of the main heated length.

9.2.9 Variation of Reload Assembly Number

One additional means to reduce enrichment requirements is to use more reload assemblies. For cores using enrichments above 5.0%, it may prove valuable to find the number of reload assemblies required to keep the maximum enrichment used to no more than 5.0%. This information may better guide industry consideration of new fuels and claddings.

9.2.10 Improving the Thick SiC Clad $\text{PuO}_2/\text{ThO}_2$ Shutdown Margin

Shutdown margin must be improved significantly before cores using **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ can be considered viable. Alternate control rod materials, increasing coolant fraction at the expense of fuel fraction, or other means may be investigated to improve the shutdown margin of **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ cores.

9.2.11 Thermal Hydraulic Safety Analysis

The thermal hydraulic safety analysis must be performed for all cases presented herein. DNB margins, fretting wear, sliding wear, pressure drop, and other parameters must be modeled in anticipated and unanticipated transient scenarios.

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Appendix A: Fuel Composition and Cycle Burnup Calculations

UO₂/BeO Fuel Composition

The BeO content of the proposed UO₂/BeO fuel is specified as 10% by volume. Calculations in Appendix XX provide values for use in specifying the isotopic composition of the homogeneous UO₂/BeO fuel in CAMSO. The fuel is assumed to have no ²³⁴U content.

First, the molar masses of uranium and uranium dioxide must be calculated.

$$a = \frac{e}{e + \frac{M_{235U}}{M_{238U}}(1 - e)}$$

$$M_U = a \cdot M_{235U} + (1 - a)M_{238U}$$

$$M_{UO_2} = M_U + 2M_O$$

The quantity of BeO present in the fuel is specified as 10% by volume. This quantity must be converted to a BeO mass fraction of the total mass, thus specifying each oxide's mass fraction of the total fuel mass.

$$\rho_m = v\%_{BeO} \cdot \rho_{BeO} + v\%_{UO_2} \cdot \rho_{UO_2}$$

$$wt_T\%_{BeO} = \frac{v\%_{BeO} \cdot \rho_{BeO}}{\rho_m}$$

$$wt_T\%_{UO_2} = \frac{v\%_{UO_2} \cdot \rho_{UO_2}}{\rho_m}$$

Knowing the oxide mass fractions and molar masses, element mass fractions can be determined.

$$wt_T\%_{Be} = wt_T\%_{BeO} \cdot \frac{M_{Be}}{M_{BeO}}$$

$$wt_T\%_U = wt_T\%_{UO_2} \cdot \frac{M_U}{M_{UO_2}}$$

$$wt_T\%_O = 100\% - wt_T\%_U - wt_T\%_{Be}$$

Finally, using the enrichment and uranium mass fraction, the isotopic mass fractions can be determined.

$$wt_T\%_{0235U} = wt_T\%_U \cdot wt_{HM}\%_{0235U} = wt_T\%_U \cdot e$$

$$wt_T\%_{0238U} = wt_T\%_U \cdot (1 - e)$$

The isotopic mass fractions are then converted to percentages of total fuel mass which are used to specify fuel composition in CASMO.

PuO₂/ThO₂ Fuel Composition

Determining the weight percent of total mass for each isotope in PuO₂/ThO₂ starts by specifying the heavy metal mass fraction of plutonium. Derivation of the necessary relations begins by using mass balances.

$$m_{Pu} \frac{M_{PuO_2}}{M_{Pu}} + m_{Th} \frac{M_{ThO_2}}{M_{Th}} = m_{PuO_2} + m_{ThO_2} = m_{Total}$$

$$m_{Pu} + m_{Th} = m_{HM}$$

Using the definition of percent of heavy metal, the relation between heavy metal mass and total mass can be obtained.

$$\frac{m_{Pu}}{m_{HM}} \frac{M_{PuO_2}}{M_{Pu}} + \frac{m_{Th}}{m_{HM}} \frac{M_{ThO_2}}{M_{Th}} = wt_{HM}\%_{PuO_2} \frac{M_{PuO_2}}{M_{Pu}} + (1 - wt_{HM}\%_{PuO_2}) \frac{M_{ThO_2}}{M_{Th}} = \frac{m_{Total}}{m_{HM}}$$

Multiplication by the ratio of heavy metal mass to total mass provides the necessary values to specify percent of total weight for each isotope present in the PuO₂/ThO₂ fuel.

$$wt_{HM}\%_{PuO_2} \cdot \frac{m_{HM}}{m_{Total}} = \frac{m_{Pu}}{m_{Pu} + m_{Th}} \cdot \frac{m_{Pu} + m_{Th}}{m_{PuO_2} + m_{ThO_2}} = wt_T\%_{PuO_2}$$

$$wt_{HM}\%_{ThO_2} \cdot \frac{m_{HM}}{m_{Total}} = \frac{m_{Th}}{m_{Pu} + m_{Th}} \cdot \frac{m_{Pu} + m_{Th}}{m_{PuO_2} + m_{ThO_2}} = wt_T\%_{ThO_2}$$

Similarly, given a known plutonium percent of total mass one can determine the plutonium percent of heavy metal.

$$wt_{HM}\%_{PuO_2} = \frac{\frac{M_{ThO_2}}{M_{Th}}}{\frac{1}{wt_T\%_{PuO_2}} - \frac{M_{PuO_2}}{M_{Pu}} + \frac{M_{ThO_2}}{M_{Th}}}$$

Cycle Burnup Calculations

First, the fuel volume is calculated.

$$V_f = \#rods \text{ per assay} \cdot \#assys \cdot \pi(R_{fo}^2 - R_{fi}^2) \cdot L$$

In the case of annular UO₂:

$$m_{HM} = V_f \rho_f \frac{M_U}{M_{UO_2}}$$

In the case of homogeneous UO₂/BeO:

$$m_{HM} = vol\%_{UO_2} \cdot V_f \rho_f \frac{M_U}{M_{UO_2}}$$

The EFPD target is calculated as follows:

$$((30.5 \times 18) - 28) \times 0.90 = 468.9 \sim 469$$

Cycle burnup targets are calculated as follows:

$$B_c = \frac{\text{EFPD} \cdot MW_{th}}{m_{HM}}$$

The cycle burnup is recalculated for comparisons with previous work using 492 EFPD.

LRM Calculations

LRM cycle and discharge burnup calculations for 84 reload cores:

$$EOFPL = \frac{1 + \frac{193}{84}}{2} B_c$$

$$B_d = \frac{193}{84} B_c$$

LRM cycle and discharge burnup calculations for 64 reload cores:

$$EOFPL = \frac{1 + \frac{193}{64}}{2} B_c$$

$$B_d = \frac{193}{64} B_c$$

LRM prediction for required enrichment to achieve off-design cycle length:

$$\Delta \text{enrichment} \propto \Delta \left(\frac{B_c + B_d}{2} \right)$$

The ratio of B_c/B_d is assumed to be invariant when making LRM predictions for off-design cycle lengths.

SDM Calculations

In the following equation for Δk_1 the value of k_{eff} comes from the HFP to HZP calculation.

$$\Delta k_1 = (k_{eff} - 1) \times 10^5$$

In the following equation for Δk_2 the value of k_{eff} comes from the HFP to 30% rods in calculation.

$$\Delta k_2 = (1 - k_{eff}) \times 10^5$$

In the following equation for Δk_3 the value of k_{eff} comes from the HFP to HZP calculation.

$$\Delta k_3 = (k_{eff} - 1) \times 10^5$$

The values of Δk_4 are read directly from the SIMULATE output for the HFP to most effective rod in calculation.

Calculation of H/HM

The ratio of hydrogen to heavy metal is calculated as shown below:

$$\frac{H}{HM} = \frac{mol_H}{mol_{HM}} = \frac{2 * V_H * \rho_{H_2O}}{mm_{H_2O} * mol_{HM}}$$

Appendix B: Burnable Poison Maps

The burnable poison layout shown below in Figure 33 was used in all 156 1.0x IFBA rod assemblies. This pattern was produced via EDBS optimization. Once the fuel composition was finalized for all fuel and clad combinations, re-optimization via EDBS showed that the pattern below was either optimal or differed in peak lifetime intra-assembly peaking by 0.001. Future optimization schema may include additional parameters for the optimization of burnable poison layouts.

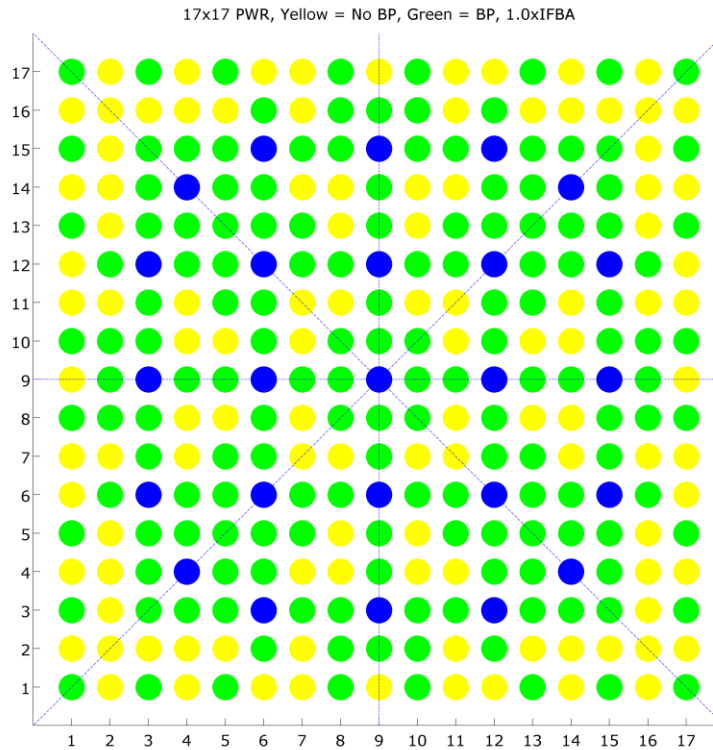


Figure 33: 156 1.0x IFBA Rod Assembly Layout

The burnable poison layout shown below in Figure 34 used in the 156 1.5x IFBA rod assemblies. Only the **Thick SiC** clad $\text{PuO}_2/\text{ThO}_2$ cases utilized 1.5x IFBA.

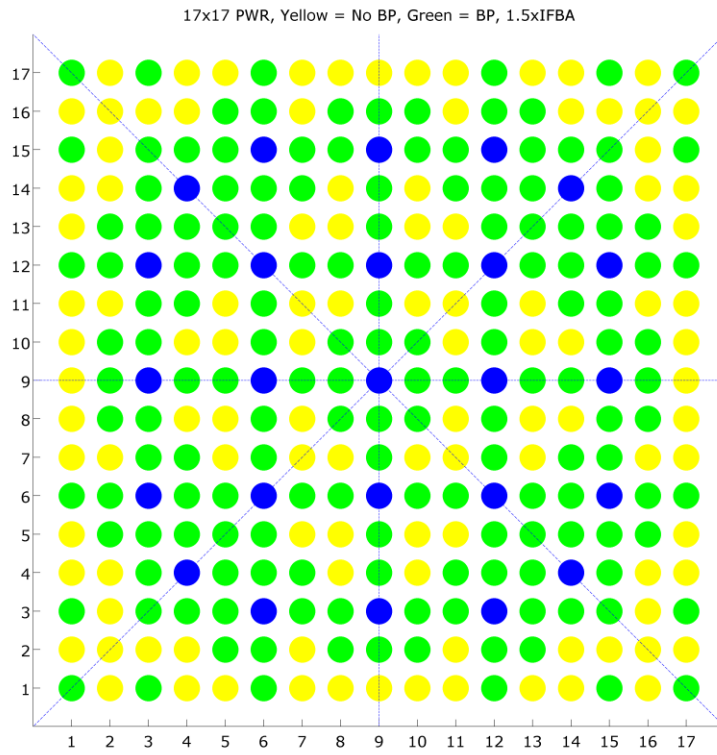


Figure 34: 156 1.5x IFBA Rod Assembly Layout

Appendix C: Example CASMO/SIMULATE Input Files

The following is a sample CASMO-4E input file.

```
TTL * K0F1R4096E0450B0P1 Python

* State Parameters
PDE 109.926
PRE 155.130
TFU 810
TMO 585
BOR 600
VOI 000

* Assembly Geometry Parameters
PWR 17.00 1.26 21.50

* Pin Geometry Parameters
PIN 1 0.4096 0.4180 0.4750 /'1' 'MI1' 'CAN'
PIN 2 0.4096 0.4180 0.4750 /'1' 'MI1' 'CAN'
PIN 3 0.5690 0.6147 /'MOD' 'BOX'
PIN 4 0.5690 0.6147 /'MOD' 'BOX'
PIN 4 0.4331 0.4369 0.4839 0.5690 0.6147
      /'AIC' 'AIR' 'CRS' 'MOD' 'BOX'
      //1 'RCC' 'ROD'

* Fuel Composition Parameters
FUE 1 10.47 / 04.50

* Material Composition Parameters
CAN 6.55 / 304=100.0
MI1 1.159E-03 / 2003=1.3E-05
SPA 10.81934 1.800E-05 ,, 8.154 / 718=84.59 347=15.41

* Pin Layout Map
LPI
3
1 1
1 1 1
4 1 1 4
1 1 1 1 1
1 1 1 1 1 4
4 1 1 4 1 1 1
1 1 1 1 1 1 1
1 1 1 1 1 1 1 1

* Depletion and Execute Statement
DEP , -100
SIM , 'K0F1R4096E0450B0P1'
S3C
STA
END
```

The following is a sample SIMULATE-3 input file.

```
'DIM.PWR' 15/
'DIM.CAL' 24 2 2/
'DIM.DEP' 'EXP' 'SAM' 'HTMO' 'HBOR' 'HTFU' 'PIN' 'EBP'/

'TIT.PRO' 'Zircaloy-4 Clad UO2 Fuel'/
'TIT.RUN' 'Solid Pellet,156 1.0xIFBA'/
'TIT.CAS' 'Cycle 01'/

'LIB' '/home/dbloore/LIB/K0F1R0P1.lib'/

'COR.SYM' 'ROT'/
'COR.DAT' 21.5 365.76 109.926 751.53/
'COR.STM' 0/

'PWR.OPT' 'ON'/
'PWR.CTP' 0 25 50 75 100/
'PWR.TIN' 557 557.4 557.8 558.2 558.6/

'REF.LIB' , 01 'K0F1REFBOT'/
          , 02 'K0F1REFRAD'/
          , 03 'K0F1REFTOP'/
'SEG.LIB' , 04 'K0F1R4096E0200B0P1'/
```

```

, 05 'K0F1R4096E0360B0P1'/
, 06 'K0F1R4096E0370B0P1'/
, 07 'K0F1R4096E0380B0P1'/
, 08 'K0F1R4096E0390B0P1'/
, 09 'K0F1R4096E0400B0P1'/
, 10 'K0F1R4096E0410B0P1'/
, 11 'K0F1R4096E0420B0P1'/
, 12 'K0F1R4096E0430B0P1'/
, 13 'K0F1R4096E0440B0P1'/
, 14 'K0F1R4096E0450B0P1'/
, 15 'K0F1R4096E0200B1P1'/
, 16 'K0F1R4096E0360B1P1'/
, 17 'K0F1R4096E0370B1P1'/
, 18 'K0F1R4096E0380B1P1'/
, 19 'K0F1R4096E0390B1P1'/
, 20 'K0F1R4096E0400B1P1'/
, 21 'K0F1R4096E0410B1P1'/
, 22 'K0F1R4096E0420B1P1'/
, 23 'K0F1R4096E0430B1P1'/
, 24 'K0F1R4096E0440B1P1'/
, 25 'K0F1R4096E0450B1P1'/

'SEG.TFU' 0 0 347.38 -5.3799/

'FUE.ZON' , 01 1 'K0F1REFRAD' 01 0.0 02 365.76 03/
, 02 1 'K0F1R4096E0450B1P1' 01 0.00 04 15.24 14 30.48 25 335.28 14 350.52 04 365.76 03/
, 03 1 'K0F1R4096E0450B1P1' 01 0.00 04 15.24 14 30.48 25 335.28 14 350.52 04 365.76 03/
, 04 1 'K0F1R4096E0450B1P1' 01 0.00 04 15.24 14 30.48 25 335.28 14 350.52 04 365.76 03/
, 05 1 'K0F1R4096E0450B1P1' 01 0.00 04 15.24 14 30.48 25 335.28 14 350.52 04 365.76 03/
, 06 1 'K0F1R4096E0450B1P1' 01 0.00 04 15.24 14 30.48 25 335.28 14 350.52 04 365.76 03/
'FUE.GRD' 'ON' 2.82 3.36 'INC'
64.87 3.36 'INC'
117.07 3.36 'INC'
169.27 3.36 'INC'
221.46 3.36 'INC'
273.66 3.36 'INC'
325.86 3.36 'INC'/

'FUE.TYP' 1
2 2 2 2 2 2 2 2 1
2 2 2 2 2 2 2 2 1
2 2 2 2 2 2 2 2 1
2 2 2 2 2 2 2 2 1
2 2 2 2 2 2 2 1 1
2 2 2 2 2 2 2 1 0
2 2 2 2 2 2 1 1 0
2 2 2 2 1 1 1 0 0
1 1 1 1 1 0 0 0 0/

'FUE.NEW' 'TYPE01' 'A01' 16 02,,,,,20 24
1 24*36 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'A17' 16 03,,,,,20 24
1 24*36 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'A33' 20 04,,,,,20 24
1 24*36 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'A53' 16 05,,,,,20 24
1 24*36 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'A69' 16 06,,,,,20 24
1 24*36 7 24*0.704 9 24*600/

'FUE.NEW' 'TYPE01' 'B01' 16 02,,,,,20 24
1 24*18 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'B17' 16 03,,,,,20 24
1 24*18 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'B33' 20 04,,,,,20 24
1 24*18 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'B53' 16 05,,,,,20 24
1 24*18 7 24*0.704 9 24*600/
'FUE.NEW' 'TYPE01' 'B69' 16 06,,,,,20 24
1 24*18 7 24*0.704 9 24*600/

'FUE.NEW' 'TYPE01' 'C01' 16 02/
'FUE.NEW' 'TYPE01' 'C17' 16 03/
'FUE.NEW' 'TYPE01' 'C33' 20 04/
'FUE.NEW' 'TYPE01' 'C53' 16 05/
'FUE.NEW' 'TYPE01' 'C69' 16 06/

'FUE.SER' 4/
01 1 B48 B52 A16 A30 B05 B08 B40
02 1 B31 B68 C32 C83 C16 C84 C39 C60 C41 B06 B59
03 1 B67 C15 C30 B49 C50 B82 C29 B76 B07 C58 C73 C07 B23
04 1 B14 C81 B32 C82 A14 C65 A29 C05 B41 B75 B24 C22 B60

```

```

05 1 B50 C51 C66 B83 B30 C31 B65 C52 B58 B73 B22 C74 B39 C24 B38
06 1 B16 C68 B15 B51 B81 A31 C48 A15 C06 A23 C23 A06 C40 C75 B42
07 1 B13 C49 B84 C13 B66 C14 B29 C67 B21 C38 B57 C57 B74 C08 A08
08 1 A26 C80 C25 A25 C47 A11 C63 A01 C59 A07 C42 A21 C21 C76 A22
09 1 A12 C12 B78 C61 B61 C43 B25 C55 B17 C02 B54 C01 B72 C34 B01
10 1 B47 C79 C45 A10 C27 A27 C10 A03 C33 A19 B69 B36 B03 C56 B04
11 1 B43 C28 B44 C78 B26 B77 B62 C37 B53 C19 B18 B71 C54 C36 B35
12 1 B64 C26 B28 B79 B46 C09 A17 C53 A02 C70 B20 C69 B02
13 1 B27 C11 C77 C62 B11 B80 C17 B70 C35 B34 C18 C03 B55
14 1 B63 B10 C46 C64 C44 C72 C04 C71 C20 B56 B19
15 1 B45 B12 B09 A18 A04 B37 B33
0 0

```

'RES' 'NEWFUEL' /

'HYD.ITE' /

'BAT.EDT' 'OFF' /

'ITE.BOR' 1500 /

'ITE.SRC' 'SET' 'EOLEXP',,0.001,,,'KEF' 1.000 0.00001 'MINBOR' /

'DEP.CYC' 'CYCLE01' 0.0 01 /

'DEP.STA' 'AVE' 0.0 0.15 0.25 0.5 -0.5 20 /

'PRI.STA' '2EXP' '2RPF' /

'SUM' '/home/dbloore/SIMA2RL2E25P1_01.sum' /

'WRE' '/home/dbloore/SIMA2RL2E25P1_01.res' 20000 /

'STA' /

'END' /

'DIM.PWR' 15 /

'DIM.CAL' 24 2 2 /

'DIM.DEP' 'EXP' 'SAM' 'HTMO' 'HBOR' 'HTFU' 'PIN' 'EBP' /

'TIT.CAS' 'Cycle 02' /

'FUE.NEW' 'TYPE01' 'D01' 16 02 /

'FUE.NEW' 'TYPE01' 'D17' 16 03 /

'FUE.NEW' 'TYPE01' 'D33' 20 04 /

'FUE.NEW' 'TYPE01' 'D53' 16 05 /

'FUE.NEW' 'TYPE01' 'D69' 16 06 /

'FUE.SER' 4 /

```

01 1 C48 C52 B16 B30 C05 C08 C40
02 1 C31 C68 D32 D83 D16 D84 D39 D60 D41 C06 C59
03 1 C67 D15 D30 C49 D50 C82 D29 C76 C07 D58 D73 D07 C23
04 1 C14 D81 C32 D82 B14 D65 B29 D05 C41 C75 C24 D22 C60
05 1 C50 D51 D66 C83 C30 D31 C65 D52 C58 C73 C22 D74 C39 D24 C38
06 1 C16 D68 C15 C51 C81 B31 D48 B15 D06 B23 D23 B06 D40 D75 C42
07 1 C13 D49 C84 D13 C66 D14 C29 D67 C21 D38 C57 D57 C74 D08 B08
08 1 B26 D80 D25 B25 D47 B11 D63 B01 D59 B07 D42 B21 D21 D76 B22
09 1 B12 D12 C78 D61 C61 D43 C25 D55 C17 D02 C54 D01 C72 D34 C01
10 1 C47 D79 D45 B10 D27 B27 D10 B03 D33 B19 C69 C36 C03 D56 C04
11 1 C43 D28 C44 D78 C26 C77 C62 D37 C53 D19 C18 C71 D54 D36 C35
12 1 C64 D26 C28 C79 C46 D09 B17 D53 B02 D70 C20 D69 C02
13 1 C27 D11 D77 D62 C11 C80 D17 C70 D35 C34 D18 D03 C55
14 1 C63 C10 D46 D64 D44 D72 D04 D71 D20 C56 C19
15 1 C45 C12 C09 B18 B04 C37 C33
0 0

```

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'ITE.BOR' 1500 /

'ITE.SRC' 'SET' 'EOLEXP',,0.001,,,'KEF' 1.000 0.00001 'MINBOR' /

'DEP.CYC' 'CYCLE02' 0.0 02 /

'DEP.STA' 'AVE' 0.0 0.15 0.25 0.5 -0.5 20 /

'PRI.STA' '2EXP' '2RPF' /

'SUM' '/home/dbloore/SIMA2RL2E25P1_02.sum' /

'WRE' '/home/dbloore/SIMA2RL2E25P1_02.res' 20000 /

'STA' /

'END' /

'DIM.PWR' 15 /

'DIM.CAL' 24 2 2 /

'DIM.DEP' 'EXP' 'SAM' 'HTMO' 'HBOR' 'HTFU' 'PIN' 'EBP' /

'TIT.CAS' 'Cycle 03' /

```

'FUE.NEW' 'TYPE01' 'E01' 16 02/
'FUE.NEW' 'TYPE01' 'E17' 16 03/
'FUE.NEW' 'TYPE01' 'E33' 20 04/
'FUE.NEW' 'TYPE01' 'E53' 16 05/
'FUE.NEW' 'TYPE01' 'E69' 16 06/

'FUE.SER' 4/
01 1
02 1      D31 D68 E32 E83 E16 E84 E39 E60 E41 D06 D59
03 1      D67 E15 E30 D49 E50 D82 E29 D76 D07 E58 E73 E07 D23
04 1      D14 E81 D32 E82 C14 E65 C29 E05 D41 D75 D24 E22 D60
05 1 D50 E51 E66 D83 D30 E31 D65 E52 D58 D73 D22 E74 D39 E24 D38
06 1 D16 E68 D15 D51 D81 C31 E48 C15 E06 C23 E23 C06 E40 E75 D42
07 1 D13 E49 D84 E13 D66 E14 D29 E67 D21 E38 D57 E57 D74 E08 C08
08 1 C26 E80 E25 C25 E47 C11 E63 C01 E59 C07 E42 C21 E21 E76 C22
09 1 C12 E12 D78 E61 D61 E43 D25 E55 D17 E02 D54 E01 D72 E34 D01
10 1 D47 E79 E45 C10 E27 C27 E10 C03 E33 C19 D69 D36 D03 E56 D04
11 1 D43 E28 D44 E78 D26 D77 D62 E37 D53 E19 D18 D71 E54 E36 D35
12 1      D64 E26 D28 D79 D46 E09 C17 E53 C02 E70 D20 E69 D02
13 1      D27 E11 E77 E62 D11 D80 E17 D70 E35 D34 E18 E03 D55
14 1      D63 D10 E46 E64 E44 E72 E04 E71 E20 D56 D19
15 1      D45 D12 D09 C18 C04 D37 D33
0 0

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'ITE.BOR' 1500/
'ITE.SRC' 'SET' 'EOLEXP',,0.001,,,'KEF' 1.000 0.00001 'MINBOR'/

'DEP.CYC' 'CYCLE03' 0.0 03/
'DEP.STA' 'AVE' 0.0 0.15 0.25 0.5 -0.5 20/
'PRI.STA' '2EXP' '2RPF'/
'SUM' '/home/dbloore/SIMA2RL2E25P1_03.sum'/
'WRE' '/home/dbloore/SIMA2RL2E25P1_03.res' 20000/

'STA'/
'END'/

'DIM.PWR' 15/
'DIM.CAL' 24 2 2/
'DIM.DEP' 'EXP' 'SAM' 'HTMO' 'HBOR' 'HTFU' 'PIN' 'EBP'/

'TIT.CAS' 'Cycle 04'/

'FUE.NEW' 'TYPE01' 'F01' 16 02/
'FUE.NEW' 'TYPE01' 'F17' 16 03/
'FUE.NEW' 'TYPE01' 'F33' 20 04/
'FUE.NEW' 'TYPE01' 'F53' 16 05/
'FUE.NEW' 'TYPE01' 'F69' 16 06/

'FUE.SER' 4/
01 1
02 1      E31 E68 F32 F83 F16 F84 F39 F60 F41 E06 E59
03 1      E67 F15 F30 E49 F50 E82 F29 E76 E07 F58 F73 F07 E23
04 1      E14 F81 E32 F82 D14 F65 D29 F05 E41 E75 E24 F22 E60
05 1 E50 F51 F66 E83 E30 F31 E65 F52 E58 E73 E22 F74 E39 F24 E38
06 1 E16 F68 E15 E51 E81 D31 F48 D15 F06 D23 F23 D06 F40 F75 E42
07 1 E13 F49 E84 F13 E66 F14 E29 F67 E21 F38 E57 F57 E74 F08 D08
08 1 D26 F80 F25 D25 F47 D11 F63 D01 F59 D07 F42 D21 F21 F76 D22
09 1 D12 F12 E78 F61 E61 F43 E25 F55 E17 F02 E54 F01 E72 F34 E01
10 1 E47 F79 F45 D10 F27 D27 F10 D03 F33 D19 E69 E36 E03 F56 E04
11 1 E43 F28 E44 F78 E26 E77 E62 F37 E53 F19 E18 E71 F54 F36 E35
12 1      E64 F26 E28 E79 E46 F09 D17 F53 D02 F70 E20 F69 E02
13 1      E27 F11 F77 F62 E11 E80 F17 E70 F35 E34 F18 F03 E55
14 1      E63 E10 F46 F64 F44 F72 F04 F71 F20 E56 E19
15 1      E45 E12 E09 D18 D04 E37 E33
0 0

'RES' '/home/dbloore/SIMA2RL2E25P1_03.res' 20000/

'ITE.BOR' 1500/
'ITE.SRC' 'SET' 'EOLEXP',,0.001,,,'KEF' 1.000 0.00001 'MINBOR'/

'DEP.CYC' 'CYCLE04' 0.0 04/
'DEP.STA' 'AVE' 0.0 0.15 0.25 0.5 -0.5 20/
'PRI.STA' '2EXP' '2RPF'/
'SUM' '/home/dbloore/SIMA2RL2E25P1_04.sum'/
'WRE' '/home/dbloore/SIMA2RL2E25P1_04.res' 20000/

'STA'/
'END'/

```

```

'DIM.PWR' 15/
'DIM.CAL' 24 2 2/
'DIM.DEP' 'EXP' 'SAM' 'HTMO' 'HBOR' 'HTFU' 'PIN' 'EBP'/

'TIT.CAS' 'Cycle 05'/

'FUE.NEW' 'TYPE01' 'G01' 16 02/
'FUE.NEW' 'TYPE01' 'G17' 16 03/
'FUE.NEW' 'TYPE01' 'G33' 20 04/
'FUE.NEW' 'TYPE01' 'G53' 16 05/
'FUE.NEW' 'TYPE01' 'G69' 16 06/

'FUE.SER' 4/
01 1          F48 F52 E16 E30 F05 F08 F40
02 1          F31 F68 G32 G83 G16 G84 G39 G60 G41 F06 F59
03 1          F67 G15 G30 F49 G50 F82 G29 F76 F07 G58 G73 G07 F23
04 1          F14 G81 F32 G82 E14 G65 E29 G05 F41 F75 F24 G22 F60
05 1 F50 G51 G66 F83 F30 G31 F65 G52 F58 F73 F22 G74 F39 G24 F38
06 1 F16 G68 F15 F51 F81 E31 G48 E15 G06 E23 G23 E06 G40 G75 F42
07 1 F13 G49 F84 G13 F66 G14 F29 G67 F21 G38 F57 G57 F74 G08 E08
08 1 E26 G80 G25 E25 G47 E11 G63 E01 G59 E07 G42 E21 G21 G76 E22
09 1 E12 G12 F78 G61 F61 G43 F25 G55 F17 G02 F54 G01 F72 G34 F01
10 1 F47 G79 G45 E10 G27 E27 G10 E03 G33 E19 F69 F36 F03 G56 F04
11 1 F43 G28 F44 G78 F26 F77 F62 G37 F53 G19 F18 F71 G54 G36 F35
12 1          F64 G26 F28 F79 F46 G09 E17 G53 E02 G70 F20 G69 F02
13 1          F27 G11 G77 G62 F11 F80 G17 F70 G35 F34 G18 G03 F55
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'FUE.NEW' 'TYPE01' 'H69' 16 06/

'FUE.SER' 4/
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02 1          G31 G68 H32 H83 H16 H84 H39 H60 H41 G06 G59
03 1          G67 H15 H30 G49 H50 G82 H29 G76 G07 H58 H73 H07 G23
04 1          G14 H81 G32 H82 F14 H65 F29 H05 G41 G75 G24 H22 G60
05 1 G50 H51 H66 G83 G30 H31 G65 H52 G58 G73 G22 H74 G39 H24 G38
06 1 G16 H68 G15 G51 G81 F31 H48 F15 H06 F23 H23 F06 H40 H75 G42
07 1 G13 H49 G84 H13 G66 H14 G29 H67 G21 H38 G57 H57 G74 H08 F08
08 1 F26 H80 H25 F25 H47 F11 H63 F01 H59 F07 H42 F21 H21 H76 F22
09 1 F12 H12 G78 H61 G61 H43 G25 H55 G17 H02 G54 H01 G72 H34 G01
10 1 G47 H79 H45 F10 H27 F27 H10 F03 H33 F19 G69 G36 G03 H56 G04
11 1 G43 H28 G44 H78 G26 G77 G62 H37 G53 H19 G18 G71 H54 H36 G35
12 1          G64 H26 G28 G79 G46 H09 F17 H53 F02 H70 G20 H69 G02
13 1          G27 H11 H77 H62 G11 G80 H17 G70 H35 G34 H18 H03 G55
14 1          G63 G10 H46 H64 H44 H72 H04 H71 H20 G56 G19
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'FUE.NEW' 'TYPE01' 'J53' 16 05/
'FUE.NEW' 'TYPE01' 'J69' 16 06/

'FUE.SER' 4/
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04 1 H14 J81 H32 J82 G14 J65 G29 J05 H41 H75 H24 J22 H60
05 1 H50 J51 J66 H83 H30 J31 H65 J52 H58 H73 H22 J74 H39 J24 H38
06 1 H16 J68 H15 H51 H81 G31 J48 G15 J06 G23 J23 G06 J40 J75 H42
07 1 H13 J49 H84 J13 H66 J14 H29 J67 H21 J38 H57 J57 H74 J08 G08
08 1 G26 J80 J25 G25 J47 G11 J63 G01 J59 G07 J42 G21 J21 J76 G22
09 1 G12 J12 H78 J61 H61 J43 H25 J55 H17 J02 H54 J01 H72 J34 H01
10 1 H47 J79 J45 G10 J27 G27 J10 G03 J33 G19 H69 H36 H03 J56 H04
11 1 H43 J28 H44 J78 H26 H77 H62 J37 H53 J19 H18 H71 J54 J36 H35
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13 1 H27 J11 J77 J62 H11 H80 J17 H70 J35 H34 J18 J03 H55
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'END'/

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'FUE.NEW' 'TYPE01' 'K53' 16 05/
'FUE.NEW' 'TYPE01' 'K69' 16 06/

'FUE.SER' 4/
01 1
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04 1 J14 K81 J32 K82 H14 K65 H29 K05 J41 J75 J24 K22 J60
05 1 J50 K51 K66 J83 J30 K31 J65 K52 J58 J73 J22 K74 J39 K24 J38
06 1 J16 K68 J15 J51 J81 H31 K48 H15 K06 H23 K23 H06 K40 K75 J42
07 1 J13 K49 J84 K13 J66 K14 J29 K67 J21 K38 J57 K57 J74 K08 H08
08 1 H26 K80 K25 H25 K47 H11 K63 H01 K59 H07 K42 H21 K21 K76 H22
09 1 H12 K12 J78 K61 J61 K43 J25 K55 J17 K02 J54 K01 J72 K34 J01
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'FUE.NEW' 'TYPE01' 'L53' 16 05/
'FUE.NEW' 'TYPE01' 'L69' 16 06/

'FUE.SER' 4/
01 1 K48 K52 J16 J30 K05 K08 K40
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06 1 K16 L68 K15 K51 K81 J31 L48 J15 L06 J23 L23 J06 L40 L75 K42
07 1 K13 L49 K84 L13 K66 L14 K29 L67 K21 L38 K57 L57 K74 L08 J08
08 1 J26 L80 L25 J25 L47 J11 L63 J01 L59 J07 L42 J21 L21 L76 J22
09 1 J12 L12 K78 L61 K61 L43 K25 L55 K17 L02 K54 L01 K72 L34 K01
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'FUE.NEW' 'TYPE01' 'M53' 16 05/
'FUE.NEW' 'TYPE01' 'M69' 16 06/

'FUE.SER' 4/
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02 1 L31 L68 M32 M83 M16 M84 M39 M60 M41 L06 L59
03 1 L67 M15 M30 L49 M50 L82 M29 L76 L07 M58 M73 M07 L23
04 1 L14 M81 L32 M82 K14 M65 K29 M05 L41 L75 L24 M22 L60
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