TRANSMUTATION OF TRANSURANIC ELEMENTS IN ADVANCED MOX AND IMF FUEL ASSEMBLIES UTILIZING MULTI-RECYCLING STRATEGIES

A Thesis

by

YUNHUANG ZHANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2009

Major Subject: Nuclear Engineering

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Approved by:

Chair of Committee,	Jean C. Ragusa
Committee Members,	Pavel V. Tsvetkov
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ABSTRACT

Transmutation of Transuranic Elements in Advanced MOX and IMF Fuel Assemblies Utilizing Multi-recycling Strategies. (December 2009)

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Chair of Advisory Committee: Dr. Jean C. Ragusa

The accumulation of spent nuclear fuel may be hindering the expansion of nuclear electricity production. However, the reprocessing and recycling of spent fuel may reduce its volume and environmental burden. Although fast spectrum reactors are the preferred modality for transuranic element transmutation, such fast spectrum systems are in very short supply. It is therefore legitimate to investigate the recycling potential of thermal spectrum systems, which constitute the overwhelming majority of nuclear power plants worldwide. To do so efficiently, several new fuel assembly designs are proposed in this Thesis: these include (1) Mixed Oxide Fuel (MOX), (2) MOX fuel with Americium coating, (3) Inert-Matrix Fuel (IMF) with UOX as inner zone, and (4) IMF with MOX as inner zone. All these designs are investigated in a multi-recycling strategy, whereby the spent fuel from a given generation is re-used for the next generation.

Computer simulations in terms of in-reactor fuel depletion and long-term isotopic decay are carried out. Results are summarized and measured in terms of Transuranics mass, long-term radiotoxicity and decay heat after irradiation in reactor. All the results are normalized to per 1TWh-electricity produced.

DEDICATION

This thesis is dedicated to my mother and father, for their selfless love and encouragement.

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The deepest gratitude goes to the Chair of the Advisory Committee, Dr. Ragusa, for his generous support and scrupulous guidance throughout this research.

NOMENCLATURE

AFCI	Advanced Fuel Cycle Initiative
BOC	Beginning of Cycle
CONFU	Combined Non-Fertile and Uranium
cMOX	Americium Coated Mixed Oxide Fuel
DRAGON	DRAGON Lattice Physics Code
EOC	End of Cycle
EU	Enriched Uranium
FP	Fission Product
GWd/tHM	Giga Watt Days per Metric Ton Heavy Metal
IMF	Inert Matrix Fuel
k_∞/k-inf	Infinite Multiplication Factor
M-R	Multi-Recycling
MOX	Mixed Oxide Fuel
ORIGEN	Oak Ridge Isotope Generation and Depletion Code
OTC	Once Through Cycle
PWR	Pressurized Water Reactor
TRU	Transuranic Elements
TWh-e	Tera Watt Hours Electricity
WH	Water Hole
w%	Weight Percentage

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1. INTRODUCTION: THE USED NUCLEAR FUEL ISSUE

Used Nuclear Fuel (spent fuel) has become one of the main obstacles for the expansion of the nuclear energy option, especially when adopting an open fuel cycle policy whereby used nuclear fuel is left un-reprocessed and is bound to be stored in deep underground geological repositories. Not reprocessing the spent fuel increase the volume of waste, the long-term radiotoxicity of waste (i.e., the amount of time before waste becomes innocuous), and the long-term heat load on the repository. The Advanced Fuel Cycle Initiative (AFCI) [1], proposed by the US Department of Energy (DOE), is sponsoring various lines of research regarding the spent fuel issue (reprocessing, fuel forms, storage forms, advanced designs to reduce the amount of waste, etc.). The research presented here focuses on an approach to transmute the most radiotoxic isotopes that reside in spent fuel by designing advanced fuel assembly and multi-recycling strategies that are compatible with current thermal reactors, with the expectation to alleviate the need for an additional repository until the next century.

1.1. Brief Overview of Advanced Fuel Cycle Initiative (AFCI)

In view of the challenge set by energy demand in the twenty-first century and the current spent fuel repository status, the Department of Energy (DOE) has launched an Advanced Fuel Cycle Initiative (AFCI). The objectives of the AFCI are to:

This thesis follows the style of *Nuclear Science and Engineering*.

- Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.
- Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.
- Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.
- Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

To summarize, AFCI investigates several potential fuel cycle strategies what would convert current waste liabilities into energy source assets, trying to minimize the waste, secure the energy source, reduce the proliferation risk, while striving to maintain or even enhance the economics competitiveness of nuclear energy.

1.2. Motivation to Recycle

One of the main issues associated with used nuclear fuel is its long term radiotoxicity. Until now, the bulk of the used commercial nuclear fuel in the U.S. is stored in the spent fuel pools on-site at nuclear power plants, waiting to be packaged for long-term storage in a geologic repository. The repository infrastructure is expected to

hold the waste for thousands of years until the radioactive isotopes have decayed away below an acceptable level. Worldwide some 10,500t heavy metal (HM) of spent fuel are discharged annually from nuclear power plants and the industrial reprocessing capacity is only about one third of this total amount [2]. In the U.S., currently neither a reprocessing plant nor a repository is available. It was proposed that a geologic repository at Yucca Mountain, Nevada to be set up to accommodate the used nuclear fuel (also referred to as nuclear waste, though it must be pointed out that used fuel, discharged from thermal reactors, still contains 96% of its original energy potential and the qualification as waste is a matter of perspective). Though the new Administration may have decided to terminate the Yucca Mountain project in 2009, some alternate solution needs to be found to hold that waste eventually. However, even if the Yucca Mountain Project were to be implemented, its projected capacity (65,000t initial HM) will be filled out roughly by the year 2010. Assuming nuclear energy generation remains the same level as nowadays, about 4 repositories of Yucca Mountain size are needed by the year 2100, see Table 1.1. With a constant market share, up to 9 repositories may be required.

Table 1.1 Impact of Different Fuel Cycle Strategies on Eventual Repository Needs under Different Nuclear Futures through the Year 2100[1]

Nuclear Futures		Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative discharged fuel in the year 2100 (metric ton)		100,000	120,000	250,000	600,000	1,400,000
		Existing Reactors Only ⟷		Existing and New Reactors		
Fuel Management Approach		Number of Repositories Needed at 70,000 Metric Ton Each				
No Recycle	Once-Through	2	2	4	9	20
	Once-Through, High Burnup Fuels	2	2	3	7	17
Reprocess & Recycle	Limited Recycle, High Burnup Fuels	Recycle not Recommended		2	5	10
	Transitional and Sustained Recycle			1	1	1

To alleviate the nuclear waste burden, transuranic elements, responsible for the long-term radiotoxicity and decay heat, could be recycled, thereby reducing the long-term radiotoxicity and postponing the needs for additional repositories into the 22nd century.

Radiotoxicity refers to the adverse biological effects on humans from radioactive material in the spent fuel. As indicated in Figure 1.1, the long-term toxicity is associated with actinides, particularly the Transuranium elements (TRUs) while the short-term risks are due to fission products (FPs) [2].

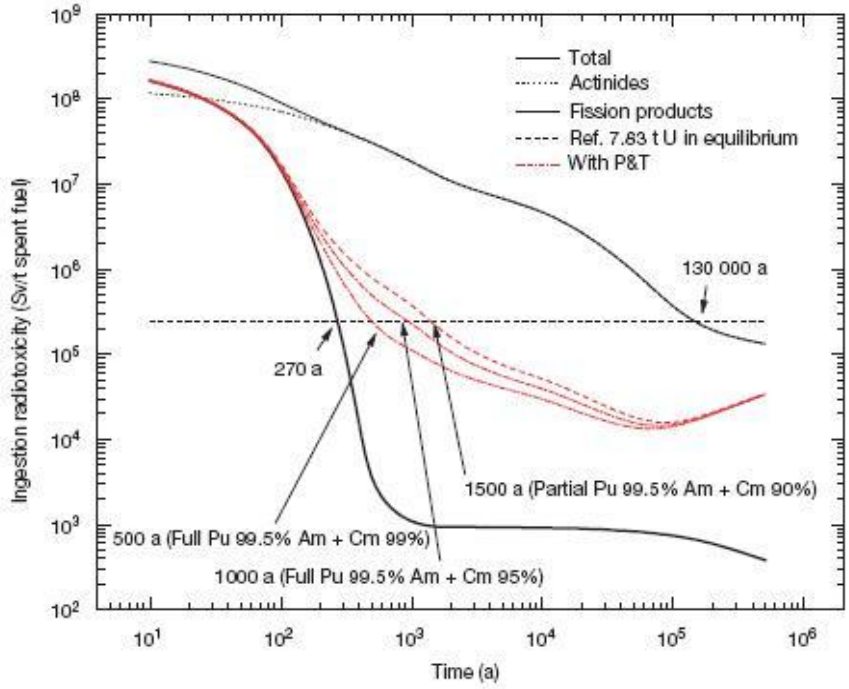


Figure 1.1 Ingestion Radiotoxicity of 1 Ton of Spent Nuclear Fuel [2]

Another key factor that determines the repository capacity is the decay heat released from the spent fuel. Excessive heat can lead to excessive temperatures because of the difficulty of providing for heat removal for long time periods. The tunnel wall temperature and the temperature in the rock between tunnels will affect the integrity of the repository. Additionally, excessive heat load put significant constraints on the design of waste form and waste packaging[3].

2. LITERATURE REVIEW AND GOALS OF THE RESEARCH

Previous research regarding fuel forms and innovative fuel assembly designs for waster transmutation provides foundations and indicates the research direction that this thesis follows. A non-exhaustive summary of these efforts is listed in this section and the goal of this research is drawn at the end.

2.1. Literature Review and Previous Work

As can be seen from Fig 1.1, by removing TRUs from the spent fuel, radiotoxicity can be reduced to the levels of natural uranium ore in about 500 years, which is a great improvement over the 100,000 years required by the unprocessed spent fuel. More importantly, the human civilization as a whole has experience with successful engineering feats with a time scale of a few thousand years, shedding confidence on handling waste for a few millennia [3]. One can go further and remove from the waste short-lived fission products (FPs) such as Cesium-137 and Strontium-90, which dominate toxicity during the first few decades after discharge. But the benefit may be offset by costs for separation recycle and storage system. Further removal of long-lived FPs accomplishes little benefit to the repository [3]. The basic pattern can be observed for decay heat as well. Therefore, the capability of partitioning and transmuting the TRUs is the key to the solution of the spent nuclear fuel.

The partitioning of TRU can be performed through either the PUREX process or the UREX process[4]. Both of them are an aqueous extraction method. With PUREX, U and Pu can be extracted separately. With UREX Np, Pu, Am, and Cm can be extracted or co-extracted depending on the variant of the UREX process. Transmutation of TRUs can be achieved either in future fast reactors or in current thermal reactors, by reloading the discharged TRUs back into reactors for irradiation. Availabilities of both fast and thermal reactors are discussed below.

(1) Fast Reactors

Fast reactors are ideal facilities for TRUs transmutation for two reasons: one is that TRUs tend to have higher fission-to-absorption cross section ratio in a fast neutron spectrum than in a thermal or epithermal spectrum; the other one is that the number of neutrons produced per fission from fissions induced by fast neutrons is larger than that of thermal neutrons, therefore providing additional surplus neutrons to interact with TRUs and transmute them. However, the number of fast reactors worldwide is very limited and most of the facilities are experimental reactors. According to the Generation-IV program, commercial deployment of fast reactors is not scheduled until 2040 at the earliest [1].

(2) Thermal Reactors

Though thermal reactors are not as efficient TRU burners as fast reactors, they are also able to transmute TRUs and are in much greater availability than fast reactors. Current commercial thermal reactors can adopt advanced

fuel assemblies that contain discharged TRUs with the aim to transmute them. Two fuel concepts are investigated in this work. These are the Advanced Mixed-Oxide fuel (AMOX) and the Inert-Matrix Fuel (IMF), respectively.

In order for current and future thermal reactors to be able to transmute TRUs, new fuel assembly designs need to be developed to accommodate these TRU-based fuel in the reactors. The following fuel assemblies (FA) designs are employed in this work:

(1) MOX-EU Fuel Assemblies:

Conventional MOX fuel contains discharged Plutonium from spent UOX fuel and tail Uranium from enrichment plant in dioxide form. MOX fuel has been studied and used in practice for decades. Currently, MOX fuel is employed as a once-through fuel and is not further reprocessed. The discussion here on MOX fuel will concentrate on its potential to multi-recycle spent fuel. In this thesis, we focus on a slightly modified MOX concept, that is, to use slightly enriched Uranium (MOX-EU) to compensate for the fissile content decrease in Pu due to successive recycling[5].

(2) Inert-Matrix Fuel (IMF) Fuel Assemblies:

IMF is a relatively new concept[6]. It contains Plutonium and Minor Actinides (MA) in a fertile-free matrix. By doing this, the possibility of producing new Plutonium from neutron capture on Uranium (e.g., U-238→Pu-239) is excluded, and, therefore, a net consumption of TRUs can be

achieved. The fuel matrix plays a crucial role of diluting the fissile phase to the volumetric concentrations required by reactor control considerations[7]. Some desired properties of the matrix materials are: transparency to neutrons, chemical inert to hot water, and good thermal conductivity[8]. The matrix material proposed include zirconia, silicon carbide, and magnesium oxide [6]. Zirconia is well-known for its resistance to hydration and neutron attack, while Magnesium oxide proved to have superior thermal conductivity[9]. Here, we focus on an MgO-ZrO2 matrix which takes advantages from both of two components. High TRU loading percentage in the IMF fuel may be undesirable due to melting point[10], diphasic phenomena[11], and fuel matrix integrity[12] concerns.

2.2. Goals of the Research and Scope of Work

As suggested by the research above, the work carried out in this research focuses on assessing the TRU destruction potential for a typical PWR employing Westinghouse 17x17 fuel assembly design. The goal of this research is to devise different variations of the MOX and IMF fuel designs and multi-recycling strategies to achieve as high TRU burnup as possible, while 1) trying to match campaign lengths in current thermal power reactors and 2) respecting the safety limits for reactor operation. The target campaign length is set at 60GWd/tHM. The safety concerns that are considered include reactivity void coefficient, linear heating rate (400W/cm), and pin power peaking factor (1.20).

3. CASE DESCRIPTION: FUEL ASSEMBLY DESIGNS AND RECYCLING STRATEGIES

In this section, the various fuel assembly designs and multi-recycling strategies employed in this research are described in detail. Among these are 1) MOX assembly with once-through cycle (OTC) 2) MOX with multi-recycling (M-R), 3) Americium coated MOX assembly with M-R, 4) IMF-UOX assembly with M-R, and 5) IMF-MOX assembly with M-R. Besides, a separate coating thickness study is carried out to evaluate the effectiveness of Am coating on the MOX outer surface.

A modern UOX (4.9w% U-235 enrichment, burned up to 60GWd/tHM) design with OTC is also utilized as the baseline reference case in the current OTC fuel strategy. All these provide a guideline of what constitutes the majority of the work.

3.1 Legacy UOX Fuel

The legacy UOX is the legacy UOX fuel used in past few decades. It is the source for TRUs that are used to fabricate the first generations of advanced TRU-burning fuel assemblies that will be introduced later. They are also the suppliers of additional fresh TRUs in successive advanced fuel recycling if the TRUs directly recycled from previous cycle are not enough to sustain the campaign lengths. The fuel is assumed to be 3.86w% U-235 enriched, burned up to 45GWd/tHM with a power density of 36.05 kW/kg. It is also assumed that the fuel is cooled for 20 years before reprocessed

in order to be representative of current spent fuel stock-pile. The detailed isotopic concentrations (in atoms/(barn cm)) at different burning stage are given in Table 3.1(BOC=beginning of cycle; EOC=end of cycle.):

Table 3.1 Isotopic Concentrations for Legacy UOX Fuel

	BOC	EOC	+20yr Cooling
O16	4.65E-02	4.65E-02	4.65E-02
U234	1.28E-06	7.03E-07	1.71E-06
U235	9.08E-04	1.85E-04	1.85E-04
U236	0.00E+00	1.14E-04	1.14E-04
U238	2.23E-02	2.16E-02	2.16E-02
Np237	0.00E+00	1.53E-05	1.61E-05
Pu238	0.00E+00	6.40E-06	5.93E-06
Pu239	0.00E+00	1.41E-04	1.43E-04
Pu240	0.00E+00	6.39E-05	6.45E-05
Pu241	0.00E+00	3.89E-05	1.49E-05
Pu242	0.00E+00	1.70E-05	1.70E-05
Am241	0.00E+00	1.25E-06	2.48E-05
Am242m	0.00E+00	1.89E-08	1.71E-08
Am243	0.00E+00	3.83E-06	3.83E-06
Cm243	0.00E+00	1.35E-08	8.51E-09
Cm244	0.00E+00	1.53E-06	7.12E-07
Cm245	0.00E+00	9.77E-08	9.75E-08
Cm246	0.00E+00	1.08E-08	1.08E-08

3.2 Fuel Assembly Designs

3.2.1 Lattice Configurations

Both the MOX-EU and IMF designs are initially based on a typical Westinghouse PWR 17x17 assembly. However, some modifications are made to yield the special characteristics of each fuel type.

(1) Homogeneous Assembly for MOX-EU

For the MOX-EU concept, only a homogeneous assembly design is considered, i.e., all of the UOX pins in the assembly are replaced by MOX pins. Geometry and discharge burnup remain unchanged. It has been demonstrated in a reference[13] that homogeneous MOX assembly with Plutonium content of 8w%(HM) is feasible (the U-235 enrichment remains below 5w% and the voiding coefficient is within acceptable range, see Figure 3.1) and the loss of fissile content in Plutonium throughout the multi-recycling process can be compensated by increasing the enrichment of uranium after each cycle.

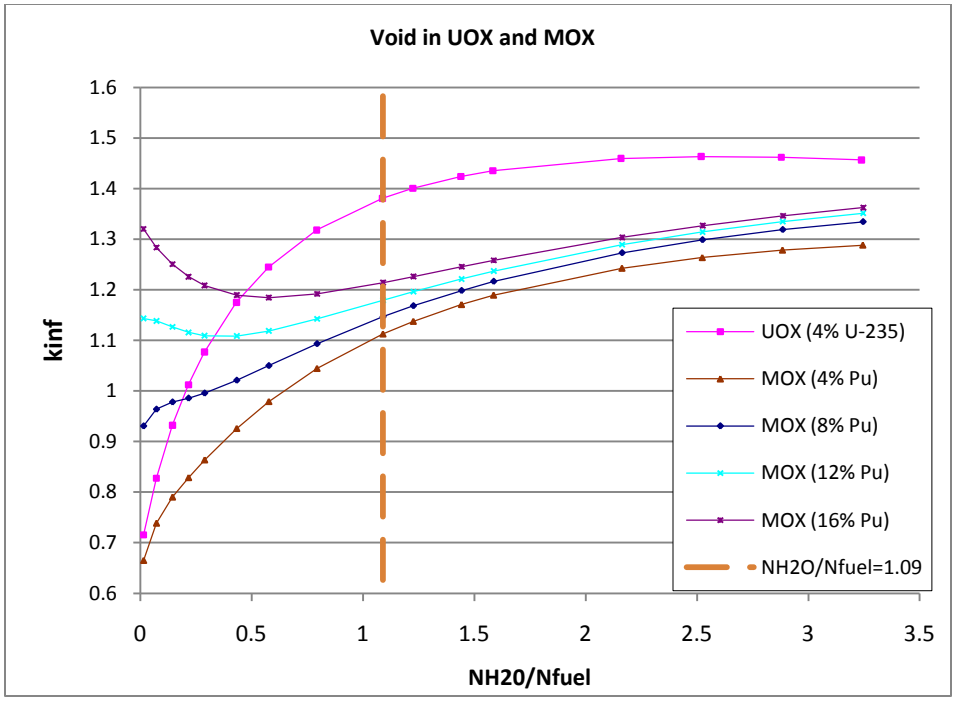


Figure 3.1 Voiding Analyses for Different Pu Percentage in MOX

In this work, a thin coating of Americium (0.002 cm) is applied to the surface of fuel pellet. The purpose of this coating is to burn some Am making use of the thermalized neutrons presented in the coolant. Am-241 is the largest single contributor to heat load of the spent fuel[6] and reducing the Am inventory can greatly benefit the repository performance. Also, the Am coating can serve as burnable poison to manage the excess reactivity at the beginning of cycle.

The specifications for a standard 17x17 Westinghouse PWR fuel assembly are given in the Table 3.2 below,

Table 3.2 17x17 Westinghouse PWR Fuel Assembly Data

Assembly Size	17 x 17
Number of Fuel Pins	264
Number of Guide Tubes (GT)	24
Number of instrumentation Tubes (IT)	1
Fuel Rod Pitch (cm)	1.26
Inter-assembly Gap (cm)	0.08
Fuel Pellet Material	UOX
Fuel Pellet Radius (cm)	0.4096
Clad Inner Radius (cm)	0.4178
Clad Outer Radius (cm)	0.4750
Fuel Density (g/cc)	10.41
Clad Density (g/cc)	6.5522
GT/IT Inner Radius (cm)	0.5715
GT/IT Outer Radius (cm)	0.6121
Discharge Burnup (GWd/MTHM)	60
Fuel Temperature (K)	900.0
Cladding Temperature (K)	581.0
Bulk Coolant Temperature (K)	581.0
Nominal Coolant Density (g/cc)	0.72

Modifications needed for MOX, Am-coated MOX assemblies are as described above and can be applied to this basic model to yield the models that we used in this research as given in Table 3.3 below (The UO2 enrichment is determined along the recycling process by respecting the energy equivalence in between fuel assembly designs. This will be discussed in Section 4.1).

Table 3.3 Case Descriptions for UOX Legacy, Modern UOX, MOX OTC, MOX M-R, and Am-coated MOX M-R

Case Name	Sub-case Name	Am/Pu From	UOX pins	MOX pins	UO_2 enrich(w%)	Pu % in MOX	Power Density (KW/kg)	Days Burned
Legacy	UOX Legacy	--	264	--	3.86	--	36.05	1248
Modern UOX	UOX 4.9	--	264	--	4.90	--	40	1500
MOX OTC	MOX OTC	UOX Legacy	--	264	2.05	8.0	36.05	1664
MOX M-R	MOX - 1	UOX Legacy	--	264	2.05	8.0	36.05	1664
	MOX - 2	MOX-1/Legacy	--	264	3.15	8.0	36.05	1664
	MOX - 3	MOX-2/Legacy	--	264	3.65	8.0	36.05	1664
	MOX - 4	MOX-3/Legacy	--	264	3.85	8.0	36.05	1664
	MOX - 5	MOX-4/Legacy	--	264	4.00	8.0	36.05	1664
	MOX - 6	MOX-5/Legacy	--	264	4.10	8.0	36.05	1664
	MOX - 7	MOX-6/Legacy	--	264	4.15	8.0	36.05	1664
Am-coated MOX M-R	cMOX - 1	UOX Legacy	--	264	2.20	8.0	36.05	1664
	cMOX - 2	cMOX-1/Legacy	--	264	3.30	8.0	36.05	1664
	cMOX - 3	cMOX-2/Legacy	--	264	3.80	8.0	36.05	1664
	cMOX - 4	cMOX-3/Legacy	--	264	4.00	8.0	36.05	1664
	cMOX - 5	cMOX-4/Legacy	--	264	4.15	8.0	36.05	1664
	cMOX - 6	cMOX- 5/Legacy	--	264	4.25	8.0	36.05	1664
	cMOX - 7	cMOX- 6/Legacy	--	264	4.30	8.0	36.05	1664

(2) DUPLEX Assembly for IMF

For the IMF concept, the homogeneous scheme where all pins are IMF pins is not favored because a series of reactor physics criteria is no longer met: the total disappearance of Uranium will result in a significantly hardened neutron spectrum, thus reducing the void coefficient, soluble boron worth, control rod worth, etc[14]. Besides, since no fissile nuclides are created

during burnup, the reactivity of a homogeneous IMF fuel assembly will decrease at a much faster rate than conventional UOX fuel pins. Therefore, a heterogeneous fuel assembly design is considered. Transuranics used in IMF pins come from the same legacy UOX as described above. This time, however, not only Pu, but Np and Am are also recycled. A previous design proposed by MIT , the Combined Non-Fertile and Uranium (CONFU) (2)[15], departs from 17x17 UOX assembly in that 60 UOX pins on the periphery are replaced by IMF pins. As depicted in Figure 3.2 below, 15 pins on each side are replaced by IMF pins[6].

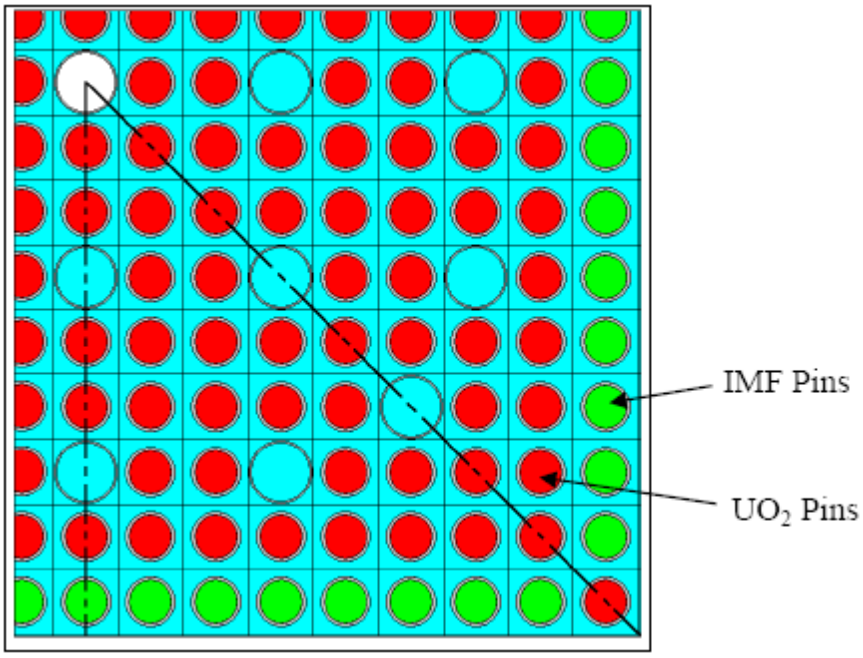
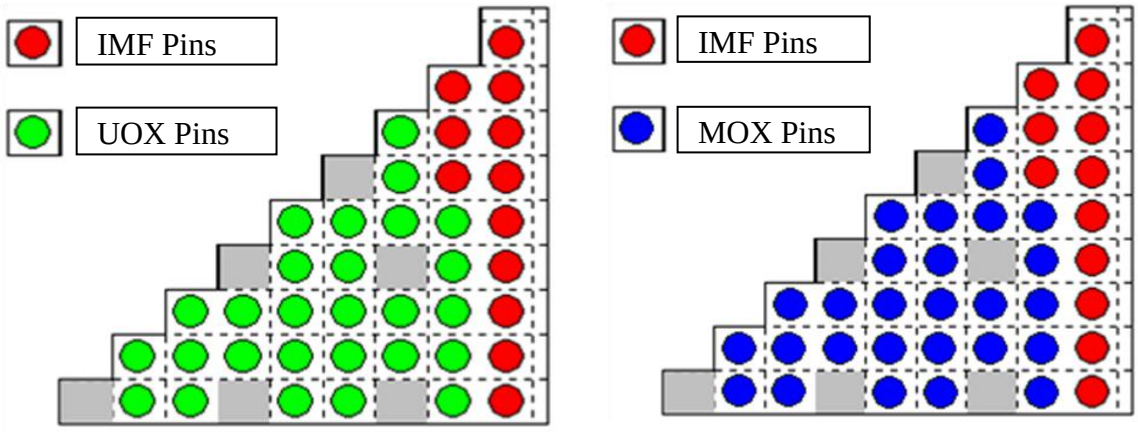


Figure 3.2 CONFU Assembly Design, ¼ Symmetry[6]

Similarly to MOX fuel, after each burn-up cycle, the fissile content in the IMF pins degrades. In order to compensate for that and sustain the required campaign length, one has to either increase the TRU percentage in the IMF pins by blending in fresh TRUs from legacy UOX or increase the U-235 enrichment of the UOX pins located in the inner zone. Our research shows that by only increase the U-235 enrichment in UOX pins (current regulations do not allow the U-235 enrichment to go beyond 5w% for commercial power plants) can we get a reasonably low TRU percentage in IMF pins. A low TRU percentage is preferred because a high TRU percentage, say above 40%, will result in fabrication difficulty. Therefore, our recycling strategy for IMF assembly with UOX inner zone is to fix UOX enrichment at 5% and blend in fresh TRUs in IMF pins between successive cycles.

Unfortunately, our work shows that the CONFU is not suitable for multi-recycling because it has too few IMF pins. Newly blended-in fresh TRUs required to compensate the reactivity lost may push the TRU loading in IMF pins beyond 40% as soon as after 3rd cycle. In the light of a French design, named DUPLEX, where 84 UOX pins are replaced by IMF pins (see Figure 3. 3), we did the multi-recycling simulation and up to 7 recycling cycles have been achieved.



IMF-UOX Assembly IMF-MOX Assembly

Figure 3.3 DUPLEX Assembly Designs, 1/8 Symmetry

A more radical variation for the DUPLEX concept is that the 60 UOX pins be replaced by MOX pins. Such a design will allow more TRUs from the spent fuel stockpile to be transmuted, in both the IMF and MOX pins. However, this modification will sacrifice some controllability to suppress the amount of fresh TRUs required to be blended in IMF pins between successive cycles, due to the hardening of the neutron spectrum by introducing MOX pins.

In addition, the Pu weight percent in the MOX inner pins is chosen to be 4w%, different from what used for MOX homogeneous assemblies. That is because the more Pu is loaded into the MOX pins, the more discharged TRU from the previous cycle is needed to be put in to next cycle IMF pins. With 8w% Pu in the MOX pins. The TRU discharged from a previous cycle will

soon exceed the maximum amount allowed in the IMF pins in the next cycle. The U-235 enrichment in MOX pins are arbitrarily chosen as 3.4w%.

IMF pins radii are slightly changed to achieve maximum TRU destruction (see Section 3.2.2). All the inner pins radii are the same as conventional UOX pins. The assembly power for IMF assemblies is fixed to 16.4MW/Assembly, as suggested in Goldmann's thesis[6]. The cycle length is fixed to 1500 days. The total thermal power generated by this type of IMF assembly is equivalent to that amount generated by UOX assemblies burned to 51GWd/tHM.

3.2.2 Geometry Variations

On top of various lattice patterns, the pin geometry is also varied with the aim of maximizing the TRU net consumption. These variations include increased coating thickness and modified radius, described below.

(1) Increased Coating Thickness

In the Am-coated MOX case cited above, an arbitrary coating thickness (the thickness is measured in diameter, twice as the thickness in radius) is chosen to see the viability of the coating option. In order to further investigate the effectiveness of the coated design, a series of increased thickness coatings are applied to both UOX and MOX OTC. Thicknesses applied for UOX

range from 0 cm to 0.01 cm, while those applied to MOX OTC range from 0 cm to 0.036 cm. We stop at 0.01 cm and 0.036 cm for UOX and MOX assembly respectively because beyond that thickness the required campaign length can no longer be achieved. Figure 3.4 shows an exaggerated illustration of Am-coated Pin cross-section.

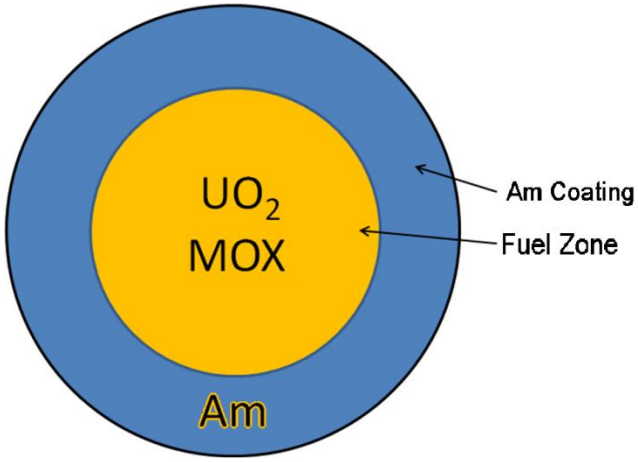


Figure 3.4 Am-coated Pin[13]

As another variation, the Am region can also be chosen to be the inner region while putting the standard fuel region in the outer region. The motivation for doing this is that in the inner region of the fuel, the neutron spectrum will be harder and, with faster neutrons, the TRUs have better chance to undergo fast fissions rather than epithermal absorptions. In this way, the Am will more likely be split into fission products rather than being transmuted into higher actinides. Also, the surplus of fission neutrons may

improve the neutron economy, thereby improving the transmutation efficiency.

(2) Modified Radius

Here the radius refers to the pin outer radius. As can be easily seen in Figure 3.5, modifying the pin radius will change the moderator-to-fuel ratio, thus change the neutron spectrum. The objective is to find the optimized moderation ratio that would facilitate TRU transmutation (TRUs elements tend to have larger thermal cross sections and, therefore, the thermal flux can be severely depreciated; adjusting the moderator-to-fuel ratio can re-establish a portion of the thermal spectrum).

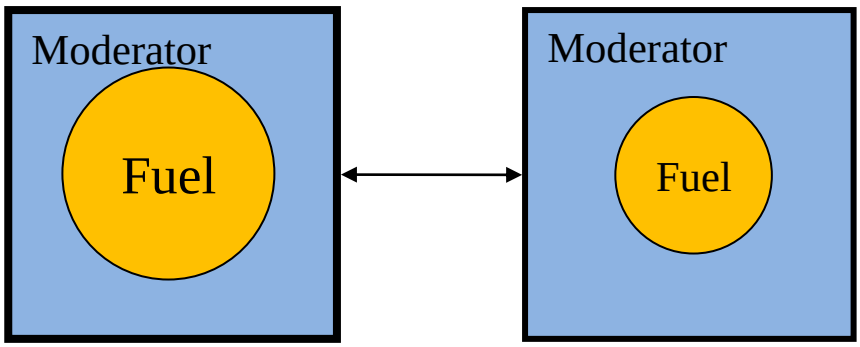


Figure 3.5 Modified Pin Radii

The modified radius study is done for IMF-UOX and IMF-MOX case only, not for MOX cases. The analysis is done for the first cycle, and the optimal radius is assumed to be applicable throughout the multi-recycling process.

The optimal radius used for IMF-UOX is 1.1 times the original radius while the optimal radius used for IMF-MOX remains the original radius as 1.26cm.

Details about the optimal radius search are presented in Appendix B.

By applying the radius modification along with other changes that have been described in previous section, a comprehensive list of the IMF-UOX and IMF-MOX models studied in this thesis are given in Table 3.4:

Table 3.4 Case Descriptions for IMF-UOX and IMF-MOX Case

Case Name	Subcase Name	TRU From	IMF radius (orignl)	IMF pins	UOX or MOX pins	UO_2 enrich (w%)	TRU % in MOX	Assem Power (MWt)	Days Burned
IMF-UOX	IMFU1	Legacy	1.1x	180	84	5.00	13.3	16.4	1500
	IMFU2	IMFU1/Legacy	1.1x	180	84	5.00	20.7	16.4	1500
	IMFU3	IMFU2/Legacy	1.1x	180	84	5.00	26.7	16.4	1500
	IMFU4	IMFU3/Legacy	1.1x	180	84	5.00	31.5	16.4	1500
	IMFU5	IMFU4/Legacy	1.1x	180	84	5.00	35.3	16.4	1500
	IMFU6	IMFU5/Legacy	1.1x	180	84	5.00	38.3	16.4	1500
	IMFU7	IMFU6/Legacy	1.1x	180	84	5.00	40.7	16.4	1500
IMF-MOX*	IMFM1	Legacy	1.0x	180	84	3.40	15.0	16.4	1500
	IMFM2	IMFM1/Legacy	1.0x	180	84	3.40	28.1	16.4	1500
	IMFM3	IMFM2/Legacy	1.0x	180	84	3.40	37.5	16.4	1500

*The IMF-MOX multi-recycling stops at third cycle due to rapid rising TRU percentage required to compensate for reactivity loss.

3.3 Multi-recycling Strategies

Both the MOX and IMF designs will employ multi-recycling strategy in order to enhance the TRU burnup benefit.

3.3.1 MOX Homogeneous Recycling

Throughout the recycling process, the Pu content is fixed at 8w% HM. The first generation MOX will use the Pu vector discharged from legacy UOX fuel. Successive recyclings will use the Pu discharged from previous cycle and make up for the rest of Pu by utilizing Pu from legacy UOX fuel. Meanwhile, the U-235 enrichment in the Uranium supplement is adjusted for each cycle to ensure that the fuel assembly can last through the imposed discharge burnup (60GWd/tHM). The recovery efficiency of Pu is set to be 99.9%. The remaining isotopes, 0.1% Pu and all the fission products and MAs, will go directly to the repository.

For Am-coated MOX, the Am used to fabricate the coating layer in the current cycle comes from what is discharged from previous cycle. The first cycle, however, does not have a predecessor and the Am used for the first generation of coated MOX is obtained from the legacy UOX fuel.

A multi-recycling scheme is given in Figure 3.6, black lines and boxes indicate normal MOX-EU recycling, the added-on red part indicates Am recycling scheme for coated MOX, the blue dot line defines once-through cycle.

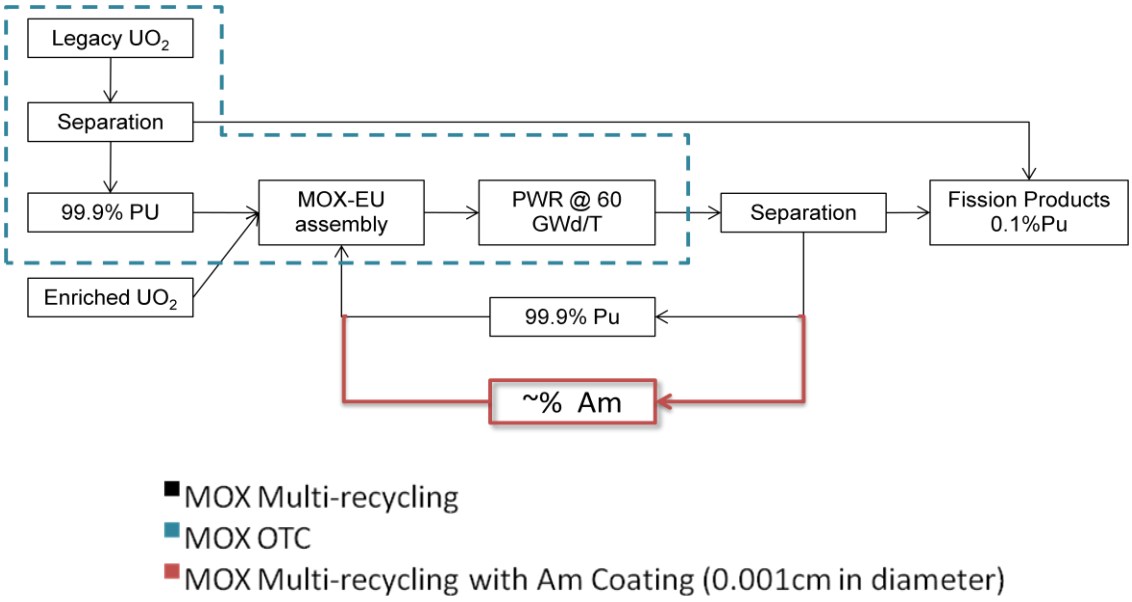


Figure 3.6 MOX-EU Homogeneous Assembly Multi-recycling Strategy[13]

3.3.2 IMF Heterogeneous Recycling

Similar to the MOX strategy, the first generation of IMF pins will be fabricated using the TRUs discharged from legacy UO_2 assemblies. For successive recyclings, the inner pins (UOX or MOX) will be replaced with fresh ones. The TRUs discharged from the previous cycle will be used to fabricate the IMF pins used for next cycle. As explained before, fresh TRUs (TRUs from legacy UOX) need to be blended into next generation IMF pins in order to compensate for the reactivity loss due to the TRU degradation (decrease in fissile isotopes).

The recycling schemes for IMF-UOX and IMF-MOX are given below in Figure 3.7 and Figure 3.8, respectively.

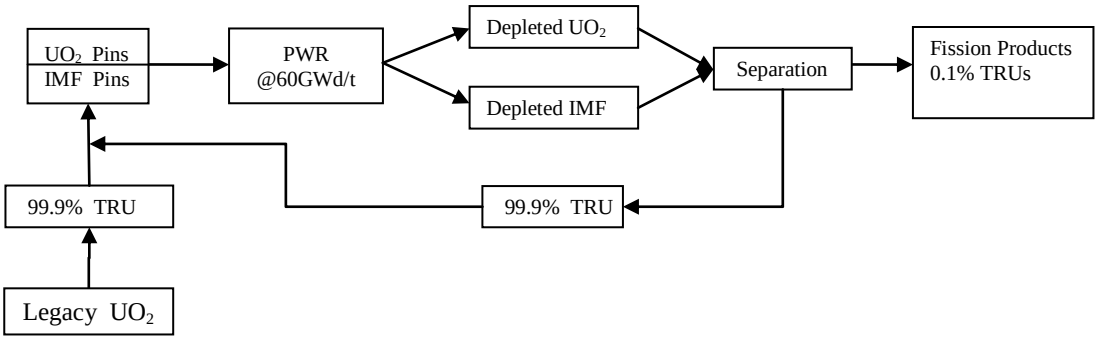


Figure 3.7 IMF-UOX DUPLEX Assembly Multi-recycling Strategy

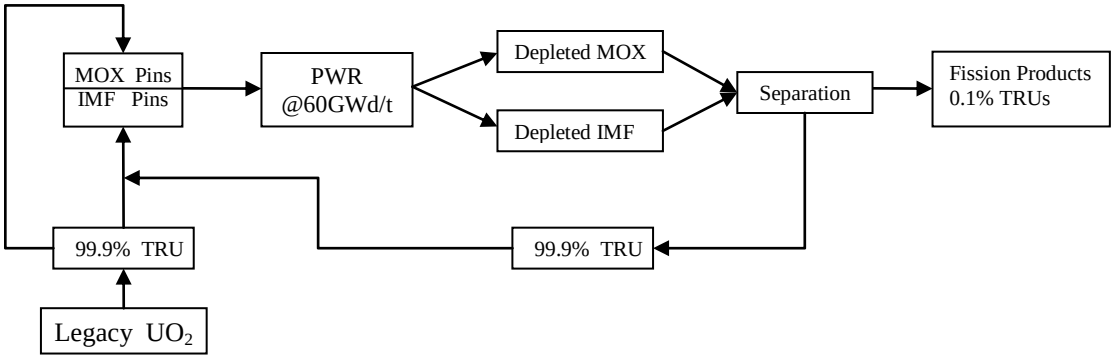


Figure 3.8 IMF-MOX DUPLEX Assembly Multi-recycling Strategy

For any of the recycling processes mentioned above, the newly fabricated fuel is aged for 2 years before it is put into the reactor for irradiation. And after burning, a 5-year cooling is imposed for the spent fuel to be cooled down.

4. TECHNICAL APPROACH

This research is entirely based on computer simulations, to be exact, on neutron transport calculation to simulate fuel burnup depletion and isotopic decay calculation to evaluate radiotoxicity and heat evolution after discharge. Each design is accepted and compared to others only if it meets all the criteria set forth. These criteria are described below and the codes for transport and decay calculation are introduced briefly.

4.1. Methodology

4.1.1 Fuel Assembly Energy Equivalence

To ensure that the envisioned fuel assembly designs meet the campaign length requirement of 60GWd/tHM and thus generate the same amount of energy as nowadays UOX fuel, the concept of Energy Equivalence is developed. This concept is based on a linear reactivity model and assumes a four-batch core with a cycle length of 15GWd/tHM. Consequently, at the end of a cycle the average burnup will be 37.5GWd/tHM. Assuming that a fuel assembly with burnup of 37.5GWd/tHM is representative of the core, we need to verify that k_∞ = 1.035 at that average burnup, where we have assumed a core leakage of 3.5%. A comparison between 4.9w% enriched UOX assembly and MOX with 12w% Pu 0.25w% enriched Uranium are given in Figure 4.1:

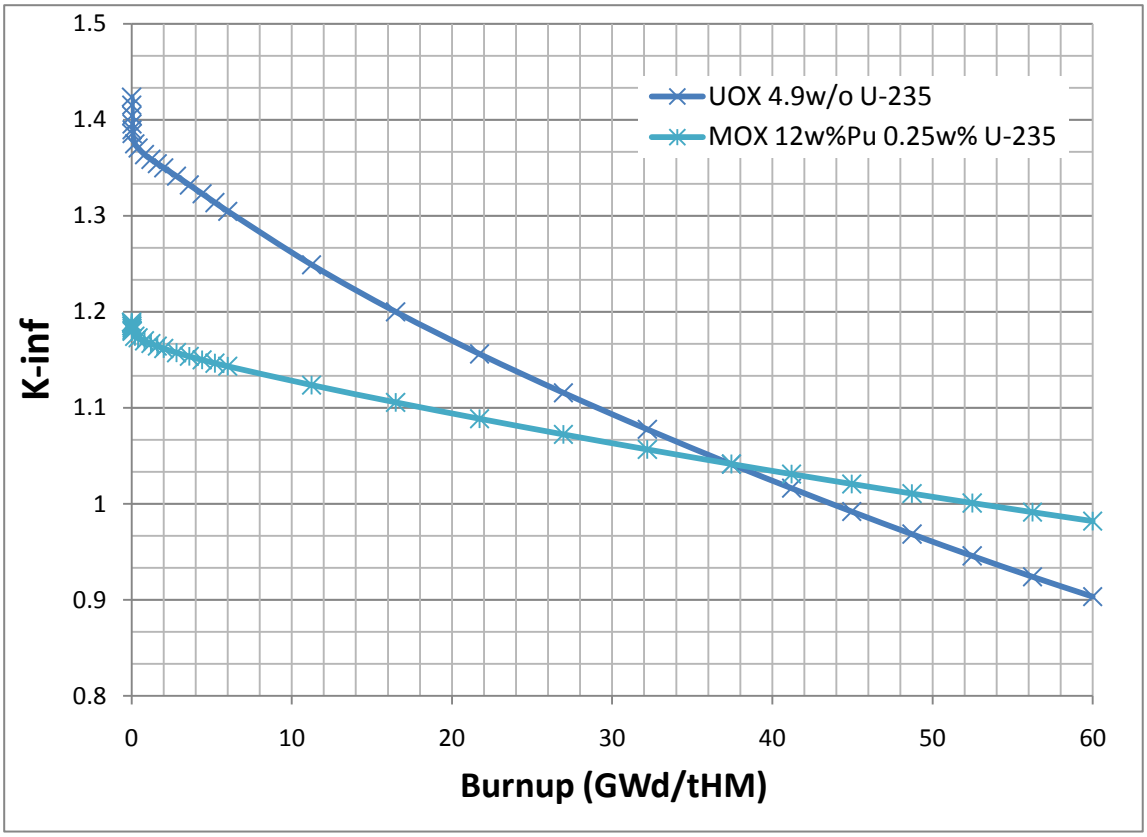


Figure 4.1 Energy Equivalence Analysis between 4.9w% UOX and 12w% Pu MOX

4.1.2 Void Coefficient Issues

The reactivity void coefficient is calculated before a fuel composition and assembly configuration is accepted, in order to respect the safety margin. This calculation is performed only for a single pin configuration in the case of a homogeneous assembly design in order to speed up the process. For heterogeneous assemblies, like DUPLEX, a 1/8 symmetry of the assembly is modeled. The criterion is

chosen as follows: the k_∞ at any voiding condition should not surpass the k_∞ obtained under nominal conditions, that is:

$$k_\infty\left(\rho^{nominal}\right) \geq k_\infty(\rho) \quad \forall \rho \leq \rho^{nominal}$$

An example can be found in Figure 3.1, where voiding calculations for MOX with different Pu loading are plotted for different voiding conditions.

4.1.3 Design Procedures

Each design type follows the same basic design process outlined in Figure 4.2. Several check points to determine if a design is acceptable fall under the design criteria. The first check is to determine if there is a net positive void coefficient. If a positive void coefficient appears, then either the fuel composition must be adjusted or the recycling should stop. The next check is to determine if the assembly meets the energy equivalence criteria. This is done by evaluating the k_∞ of the assembly at the averaged core burnup. Once an assembly passes these two checks, it is then computed with the lattice physics code again with soluble boron in the system. The final pass or fail check is for the power profile. The process is repeated until an equilibrium trend for the multi-recycling process is found. Practically we stop at 7^{th} cycle and assume that the equilibrium is reached until this point. Please refer to Section 6.1 to see how the isotopic compositions approach equilibrium through the multi-recycling process.

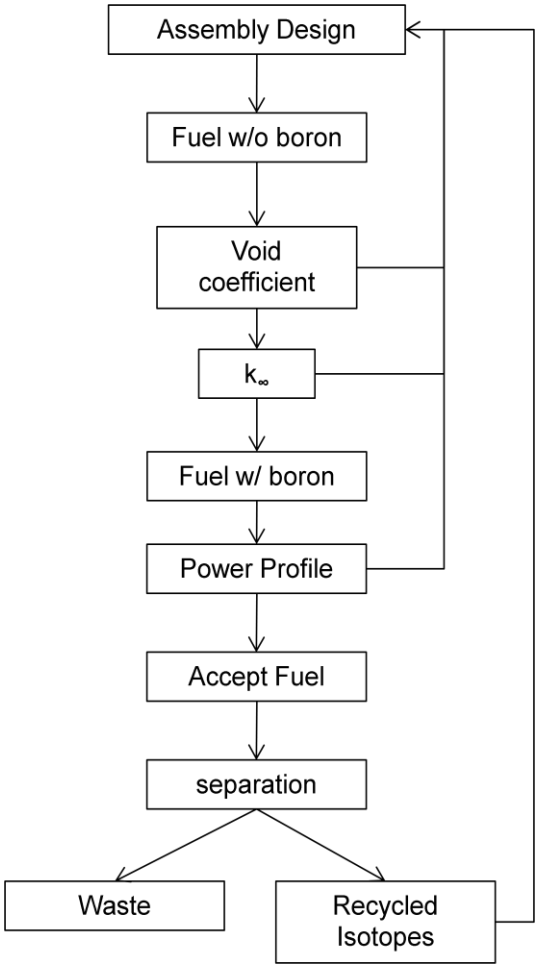


Figure 4.2 Assembly Design Process[13]

4.2 Fuel Assembly Lattice Code: DRAGON

The neutron distribution and fuel composition burnup are computed using a lattice physics code. The transport code should be able to calculate k-inf as a function of burnup, isotopic concentration as a function of burnup, power map as a function of burnup and etc. The code chosen for this research is DRAGON[16]. DRAGON was chosen because it has various neutron cross section libraries such as JEF2.2, ENDF/B-VI

available, and each library is available in an array of energy groups' settings. More importantly, the diversity and completeness of the library collection enables DRAGON to predict accurately the evolution of Transuranics, which is at the center of this research.

DRAGON is a lattice code based on modular designs. The various modules allows DRAGON to account for : interpolation of microscopic cross sections through standard libraries; resonance self-shielding calculations in multidimensional geometries; multi-group and multidimensional neutron flux calculations which can take into account neutron leakage; transport-transport or transport-diffusion equivalence calculations as well as editing of condensed and homogenized nuclear properties for reactor calculations; and finally isotopic depletion calculations. The modules used in this study include: LIB, GEO, SYBILT, USS, ASM, FLU, EDI and EVO[16].

4.3 Isotopic Depletion and Decay Code: ORIGEN

The code used for decay and radiotoxicity and heat calculation is ORIGEN. After each assembly design has been accepted and 'burned' with boron in the core, the discharged waste is accumulated and fed into ORIGEN to perform a long-term isotopic decay calculation that includes radiotoxicity and decay heat is calculated at each time step. Although DRAGON is also capable of dealing with activation and decay calculations, it does not compute the heat load or radiotoxicity of the fuel. The ORIGEN code is used for long-term (up to millions of years) decay calculations. ORIGEN is a

SCALE system module to calculate fuel depletion, actinide transmutation, fission product buildup and decay, and associated radiation source terms. It is developed and managed by Oak Ridge National Laboratory. The primary advantage of ORIGEN over other burnup codes is its capability to treat the full isotopic transition matrix rather than a limited number of transmutation chains, and this is crucial for us who want to track higher actinides which are usually neglected when doing conventional design. This capability in ORIGEN arises from a clever application of the matrix exponential method[17]. Another advantage of ORIGEN is that it can automatically calculate the hazards such as radiotoxicity and decay heat load, which we are concerned with.

4.4 From Isotopic Concentration to Hazards

After each assembly design is accepted and 'burned' with boron using DRAGON, the discharged isotopic concentrations (in atom density: atoms/(barn cm)) are stored in the DRAGON output file. A series of Perl scripts have been developed to extract these isotopic concentrations, as well as other information such as k_∞ and power peaking factors, and then feed those concentrations into an ORIGEN input deck template to initiate decay calculation and hazard evaluation. As required by ORIGEN input format, those atom densities are converted to moles/(barn cm) within the Perl script. The output from ORIGEN is therefore normalized to unit volume, that is, 1 barn cm ($=10^{-24}cm^3$). In order to get total hazard associated with the waste, one need to multiply the normalized value by the volume of fuel assembly or reactor fuel region. Hazards of

concern here include ingestion radiotoxicity, inhalation radiotoxicity, and decay heat, each of which is calculated at every decay time step by ORIGEN. The ingestion (inhalation) radiotoxicity is defined as the volume of water (air) required to dilute the toxic material to its maximum permissible concentration. The dilution volume is a measure of the radioactive toxicity of the material for cases of direct ingestion (inhalation)[18]. As can be noted in the definition, there are two ways to compute the radiotoxicity, that is, ingestion toxicity in water volume and inhalation toxicity in air volum. The analyses carried out in this research implements both.

These two measures are related to one other, however, not in a linear fashion. Because an individual isotope can cause biological effects of different level, depending on whether it is ingested or inhaled. That is to say, the same isotope can have different radio-biological factors when evaluating material's radiotoxicity with different definitions. Figure 4.3 and Figure 4.4 show an example of radiotoxicity evaluation for discharged modern UOX fuel. Differences and common features between this two definition can be seen clearly.

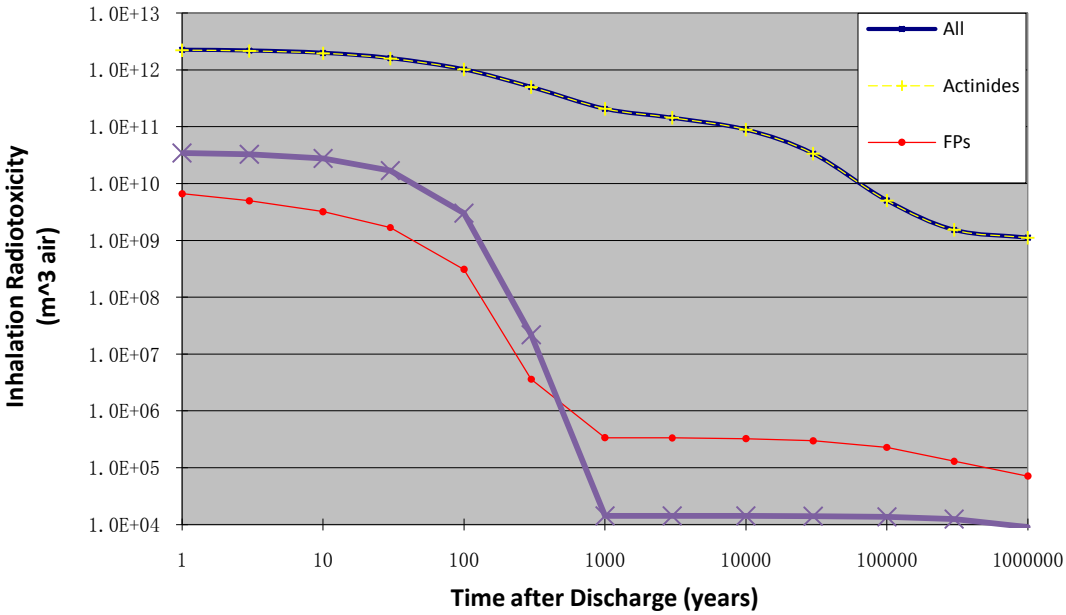


Figure 4.3 Inhalation Radiotoxicity as a Function of Time

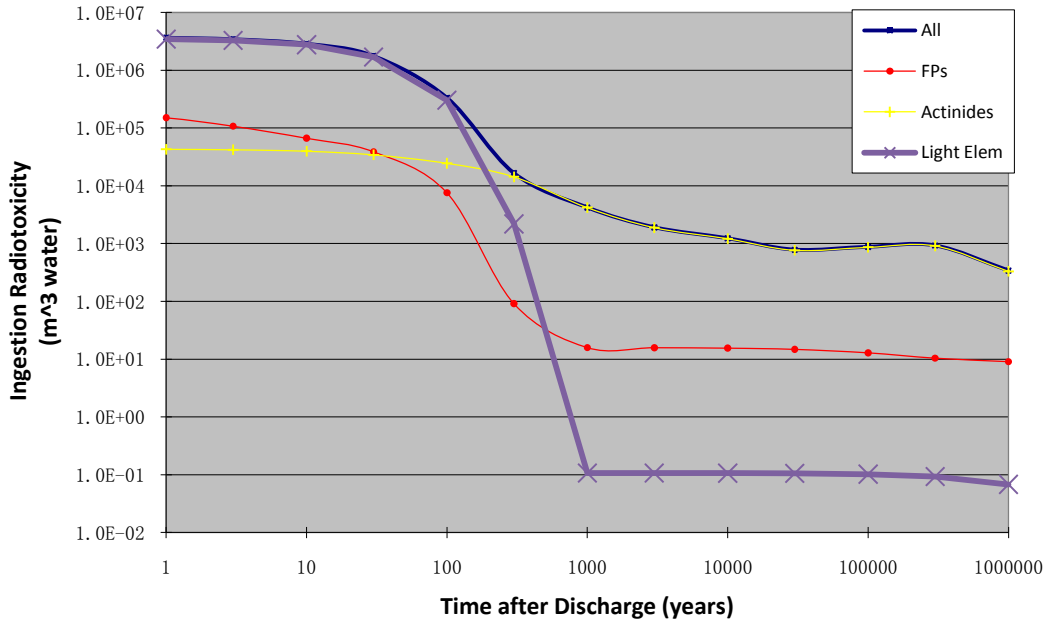


Figure 4.4 Ingestion Radiotoxicity as a Function of Time

As can be seen from the figures, in the first few decades, fission products and light elements' inhalation toxicity is higher than that of actinides, while the formers' ingestion toxicity is lower than the latters'. This significant difference can cause inconsistency between the analysis comparing inhalation toxicity and that comparing ingestion toxicity of each fuel design. Due to this reason, the reader should be aware that the results from the two analyses may have different read.

5. BENCHMARK

In this section, we perform a few benchmarks calculations to test the DRAGON software against published results. The DRAGON code is benchmarked against Youniou and Vasile's paper[5] for UOX/MOX cases and against Goldmann's thesis[6] for IMF cases. Also the APOLLO code is used in evaluating DRAGON's ability to predict IMF fuel's composition during irradiation.

5.1. UOX/MOX Benchmark

The Pu and Am burnup after once through cycle for different assembly designs were evaluated using DRAGON and the results are compared to the data found in Youinou and Vasile's article[5]. Designs compared include: UOX assembly with 4.9w% enrichment in U-235, MOX assembly with 4w% Pu and 3.7w% U-235, MOX assembly with 8w% Pu and 2.3w% U-235, and MOX assembly with 12w% Pu and 0.3% U-235. All assemblies above employ 17x17 conventional PWR assembly lattice, and the discharge burnup is set to be 60GWd/tHM with a core power of 3800MW for 193 assemblies.

Table 5.1 Mass Balance Comparison between 4 Different Assembly Designs[5]

		UO_2 (4.9w% U235)	MOX (4w% Pu)	MOX (8w% Pu)	MOX (12w% Pu)
		Δkg/TWh-e	Δkg/TWh-e	Δkg/TWh-e	Δkg/TWh-e
Pu	Youniou	26	-20	-48	-70
	DRAGON	27	-19	-48	-71
	Difference (%)	3.8%	-5.0%	0.0%	1.4%
Am	Youniou	1.6	6	10	14
	DRAGON	1.6	6.4	11	16
	Difference (%)	0.0%	6.7%	10.0%	14.3%

As can be seen from Table 5.1 above, the difference between DRAGON and Youinou's results on Pu burnup is within 5%. The difference on Am mass balance is larger, but since we are not recycling Am in our MOX assemblies and we are only interested in MOX with 8w% or less Pu, the difference is within acceptable range.

5.2. IMF Benchmark

The benchmark geometry considered here is a CONFU assembly, the case referred to as imf60a in Goldmann's thesis. The TRUs weight percentage in 60 peripheral IMF pins is 7.6w% and U-235 enrichment in 204 central UOX pins is 4.3w%. The assembly power is 16.4MW/Assembly and the fuel assembly is irradiated for 1500

days. Both the k-inf as a function of burnup (see Figure 5.1) and assembly discharge mass (see Figure 5.2) were compared between DRAGON's result and Goldmann's thesis.

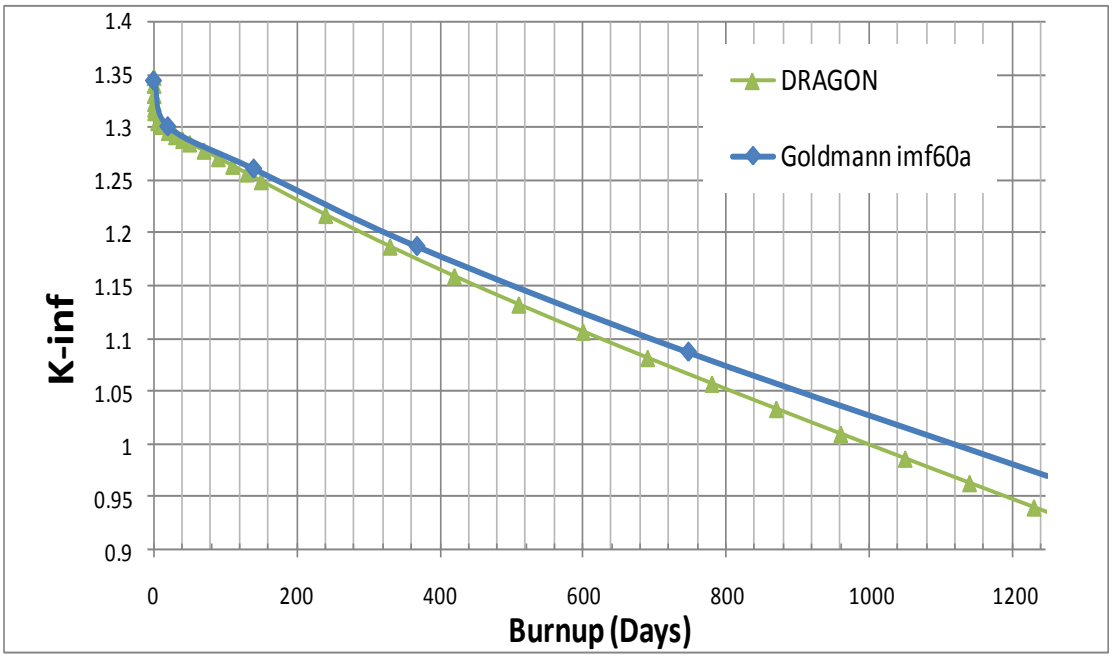


Figure 5.1 k-inf as a Function of Burnup for imf60a

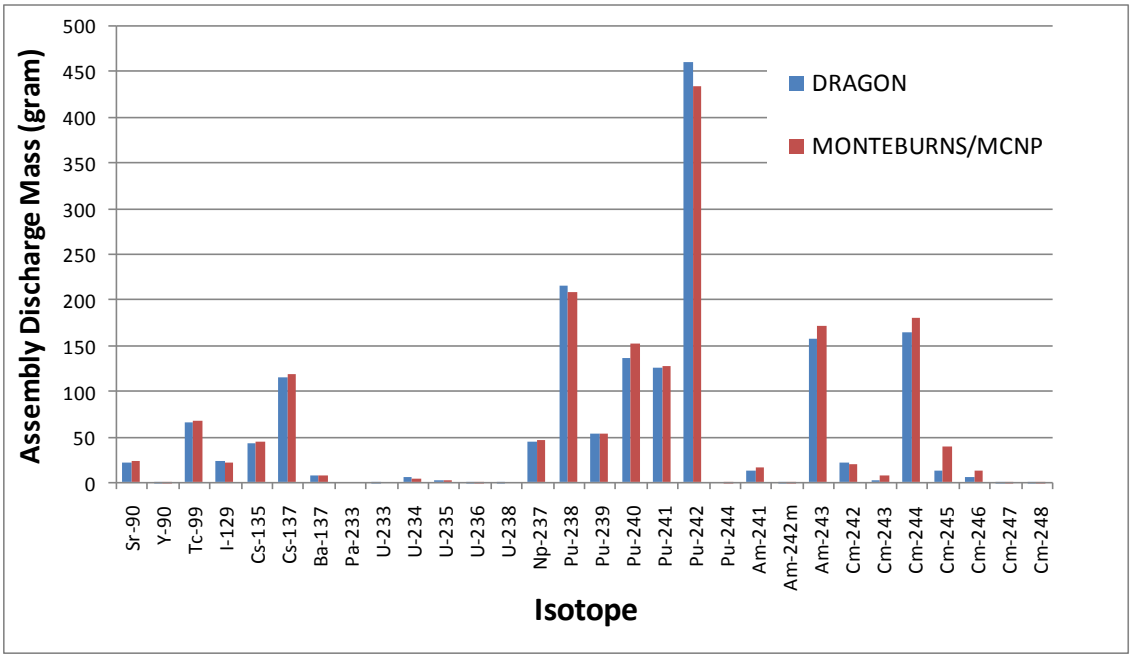


Figure 5.2 Assembly Discharge Mass for imf60a

As can be seen from Figure 5.2, the heavy metal discharge computed by DRAGON matches very well with that found in Goldmann's thesis. From Figure 5.1, we see that at beginning of cycle the k-inf matches with Goldmann's result as well, however, DRAGON's result begins to deviate from Goldmann's result when burn-up goes on. At average core burnup (around 1000 days), difference between these two becomes about 3000 pcm.

Considering that the DRAGON code used here is significantly different from the MCNP code that Goldmann used (DRAGON is a deterministic code while MCNP is a stochastice code) and the model specification found in Goldmann's thesis is not fully defined, we have also benchmarked DRAGON with another deterministic code, APOLLO, which is widely used in the French nuclear industry. This time, a single IMF

pin with reflective boundary conditon on all four sides is modeled. As can be seen from Figure 5.3 and Figure 5.4 below, the DRAGON and APOLLO results are in very good agreement on both the k-inf values and the discharge concentrations.

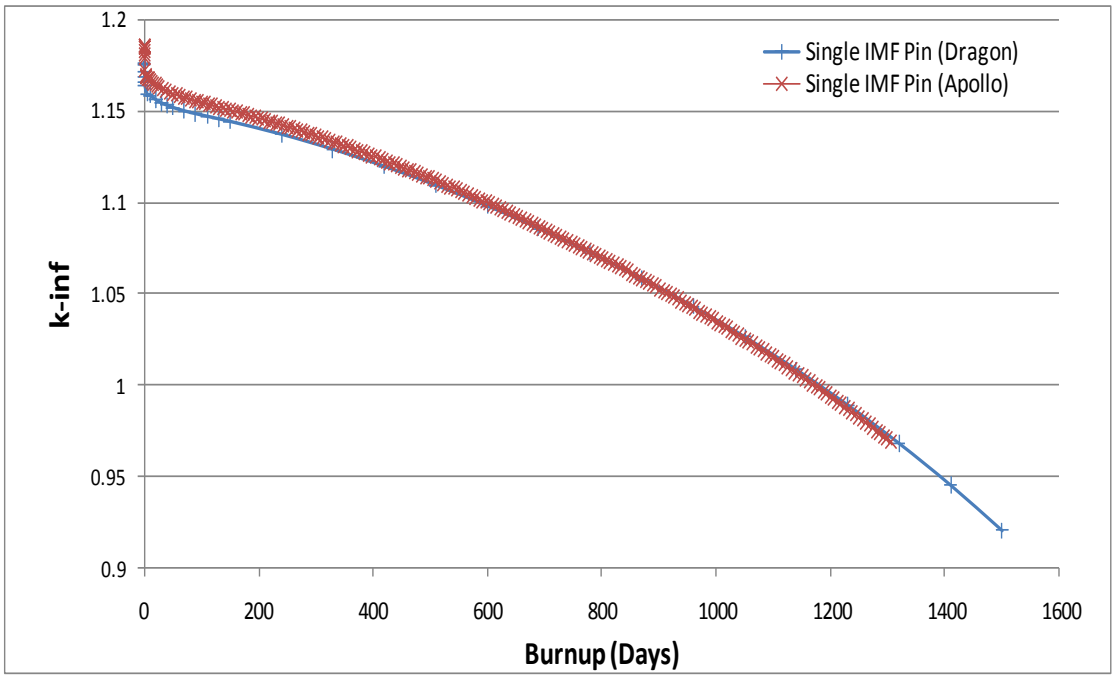


Figure 5.3 k-inf as a Function of Burnup for Single Reflected IMF Pin

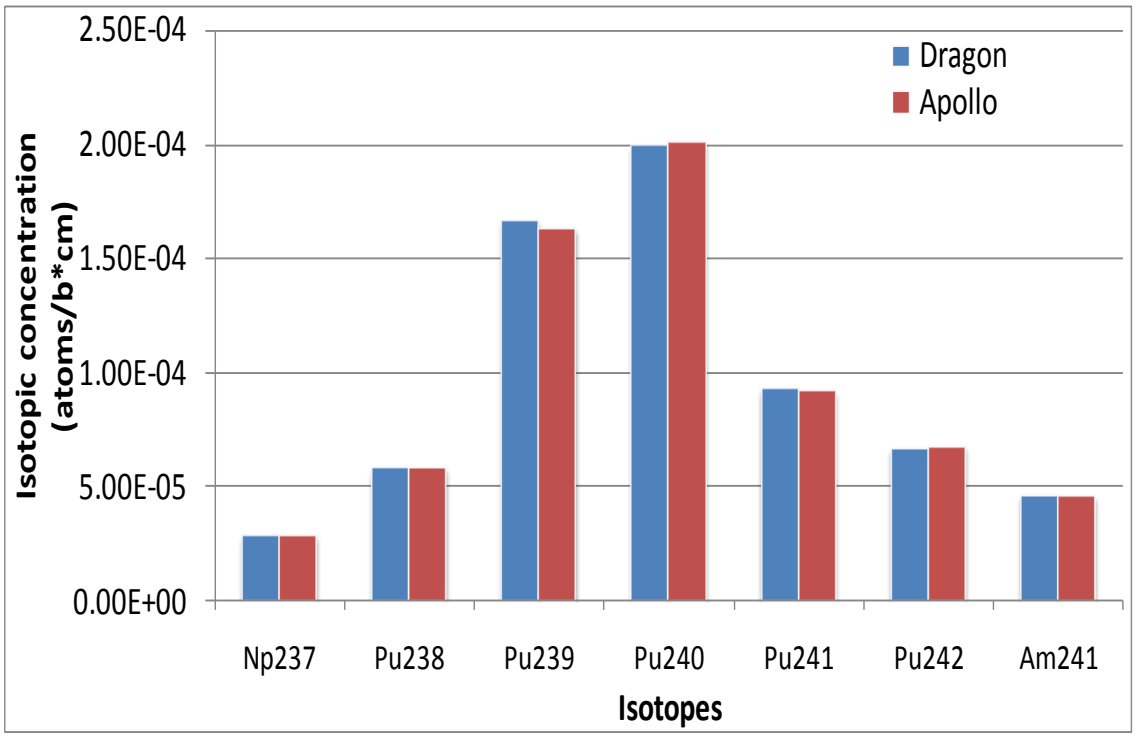


Figure 5.4 Isotopics Discharge Concentrations for Single Reflected IMF Pin

Despite some observable discrenpancy on k-inf for the imf60a benchmark case, the overall performance of DRAGON is quite satisfying. We conclude that DRAGON is capable of predicting the MOX and IMF fuel's behavior well enough for the purpose of this research.

6. RESULTS

All the 5 cases: MOX assembly with once-through cycle (OTC) and multi-recycling (M-R), Americium-coated MOX assembly with M-R, IMF-UOX assembly with M-R, and IMF-MOX assembly with M-R, including the variant Am-coating thickness study that have been described in Section 3, were evaluated using the tools and methods presented in Section 4. The results are rendered in terms of TRU mass balance, inhalation/ingestion radiotoxicity, and decay heat generation. Energy equivalence verification, voiding calculation, and Pu fissile content at beginning of each cycle are also presented in this section pertaining to each assembly design considered in this research.

6.1. Plutonium Isotopic Composition at Beginning of Each Cycle

The Pu isotopic compositions (or Pu vector) at beginning of cycle (BOC) are tabulated (in Table 6.1~Table 6.4) and plotted (in Figure 6.1, Figure 6.2, Figure 6.4, and Figure 6.5) as the percentage of total Pu loading for each assembly and recycling design. The Pu values shown for IMF cases are averaged over whole assembly (IMF and oxide pins). U-235 enrichments at different recycling stage and Transuranics weight percentage among IMF pins are also plotted for MOX recycling cases (see Figure 6.3) and IMF recycling cases (see Figure 6.6), respectively. The data can be found in Tables 3.2 and 3.3, respectively.

Table 6.1 Pu Vector at BOC for MOX M-R

Pu Isotope (%)	MOX-1 (MOX OTC)	MOX-2	MOX-3	MOX-4	MOX-5	MOX-6	MOX-7
238Pu	2.4	3.3	4.1	4.7	5.0	5.1	5.2
239Pu	58.2	45.5	42.0	40.7	40.0	39.6	39.4
240Pu	26.3	30.2	29.7	28.7	28.0	27.4	27.0
241Pu	6.1	11.5	12.0	11.7	11.5	11.3	11.1
242Pu	6.9	9.6	12.2	14.1	15.5	16.6	17.3
Fissile %	64%	57%	54%	52%	52%	51%	50%

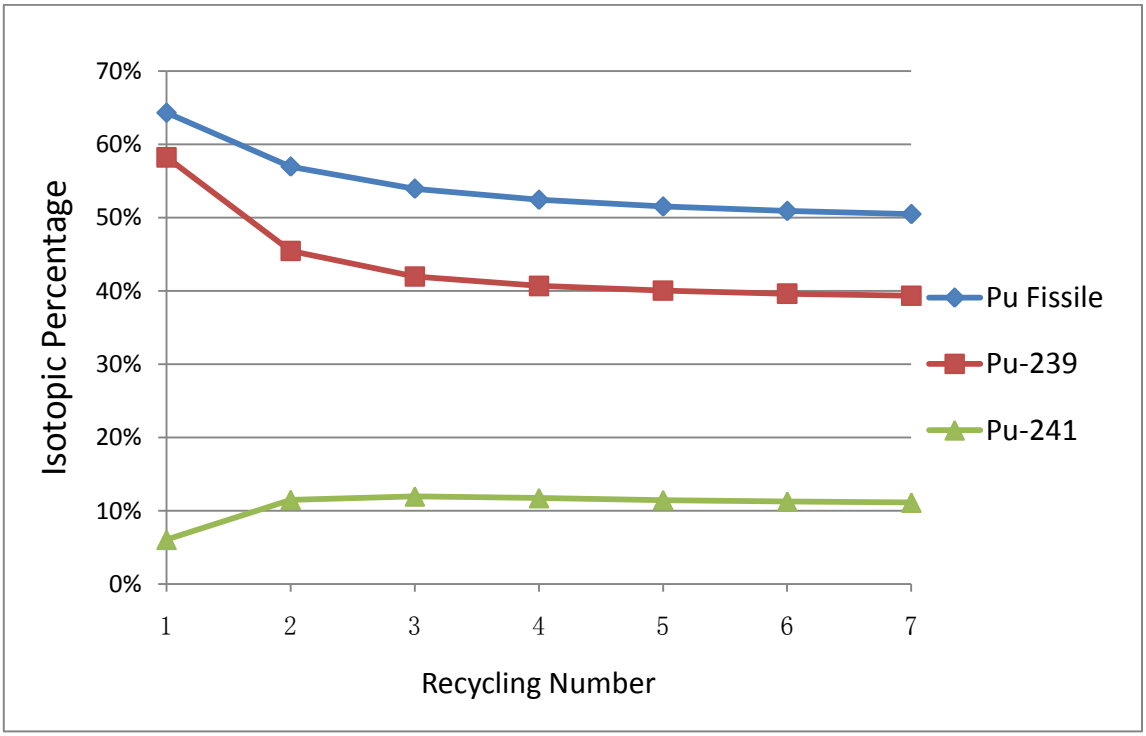


Figure 6.1 Pu Vector as a Function of Number of Recyclings for MOX M-R

Table 6.2 Pu Vector at BOC for Am-coated MOX M-R

Pu isotope (%)	cMOX-1	cMOX-2	cMOX-3	cMOX-4	cMOX-5	cMOX-6	cMOX-7
238Pu	2.4	3.5	4.4	5.0	5.3	5.5	5.5
239Pu	58.1	45.5	42.0	40.7	40.1	39.7	39.4
240Pu	26.4	30.1	29.6	28.6	27.9	27.3	27.0
241Pu	6.1	11.4	11.9	11.7	11.4	11.2	11.1
242Pu	7.0	9.5	12.1	13.9	15.3	16.3	17.0
Fissile %	64%	57%	54%	52%	52%	51%	51%

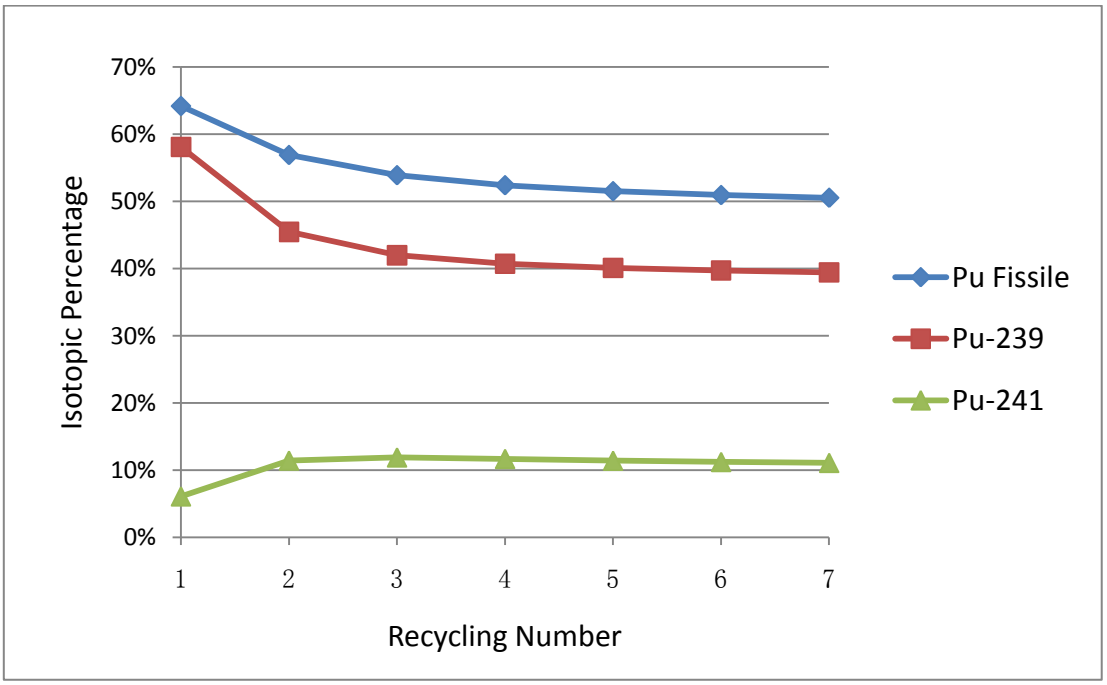


Figure 6.2 Pu Vector as a Function of Number of Recyclings for Am-coated MOX M-R

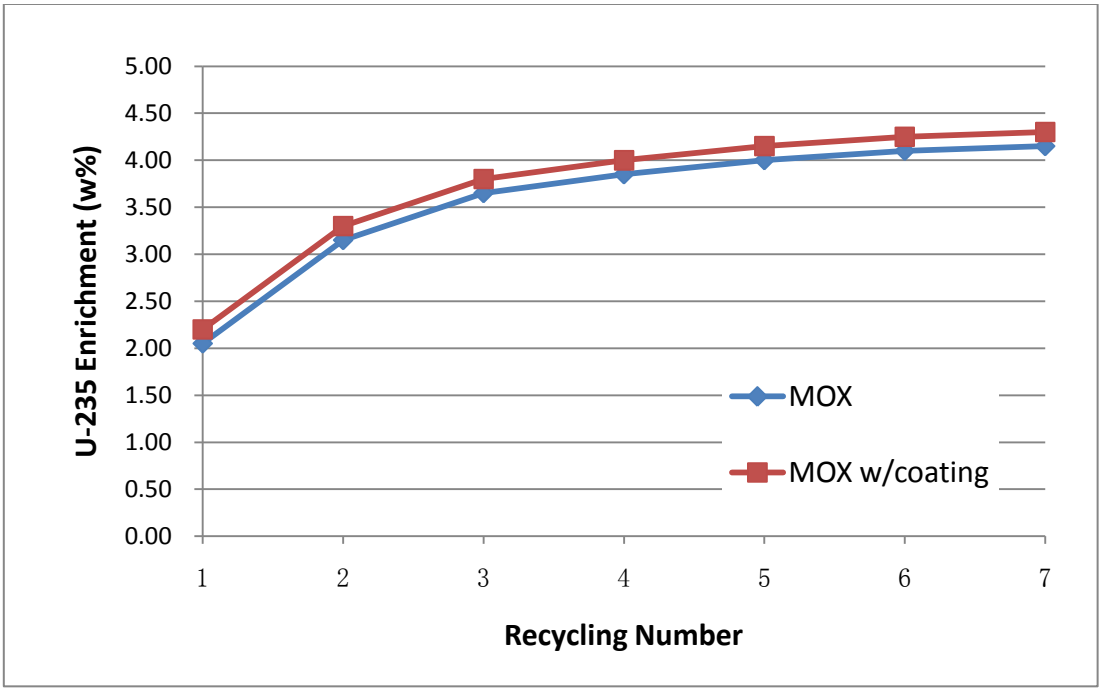


Figure 6.3 U-235 Enrichment as a Function of Number of Recyclings for MOX Cases

Table 6.3 Pu Vector at BOC for IMF-UOX M-R

Pu isotope (%)	IMF-U1	IMF-U2	IMF-U3	IMF-U4	IMF-U5	IMF-U6	IMF-U7
238Pu	2.4	7.5	10.0	11.7	12.9	13.8	14.5
239Pu	58.2	44.4	38.9	35.7	33.6	31.9	30.7
240Pu	26.3	26.8	27.7	28.3	28.7	29.0	29.2
241Pu	6.1	9.8	10.3	10.1	9.7	9.4	9.1
242Pu	6.9	11.5	13.2	14.3	15.1	15.9	16.5
Fissile %	64%	54%	49%	46%	43%	41%	40%

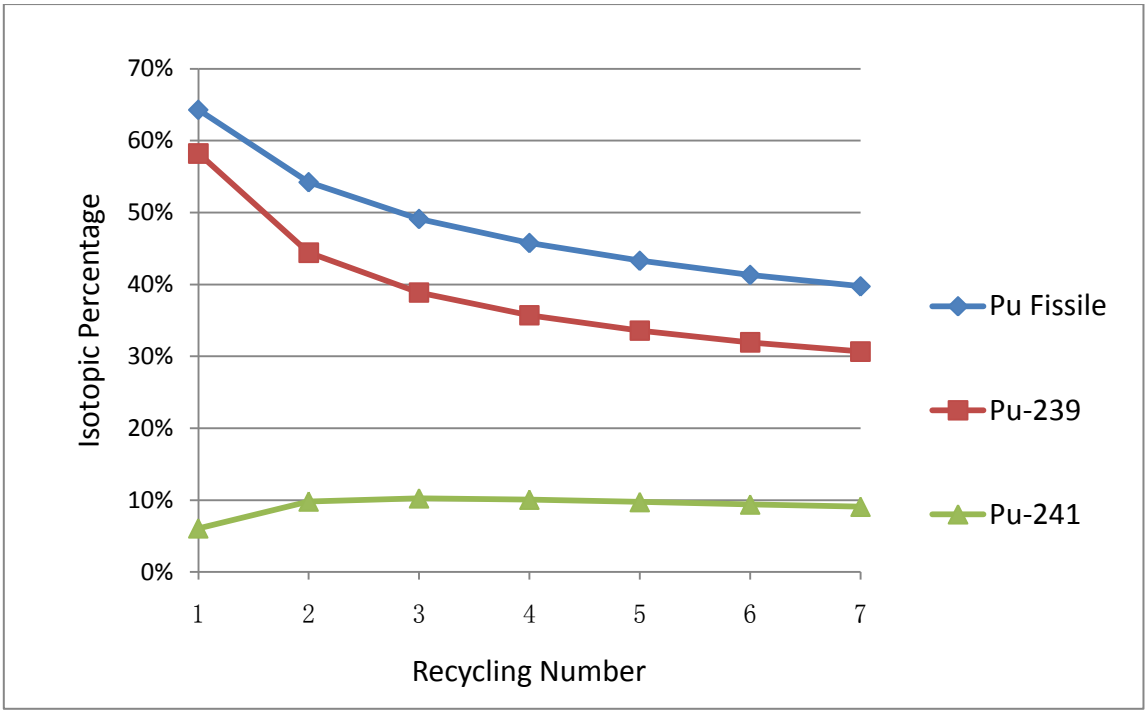


Figure 6.4 Pu Vector as a Function of Number of Recyclings for IMF-UOX M-R

Table 6.4 Pu Vector at BOC for IMF-MOX M-R

Pu isotope (%)	IMF-M1	IMF-M2	IMF-M3
238Pu	2.4	5.1	6.8
239Pu	58.2	46.6	41.5
240Pu	26.3	27.9	28.8
241Pu	6.1	9.6	10.2
242Pu	6.9	10.8	12.7
Fissile %	64%	56%	52%

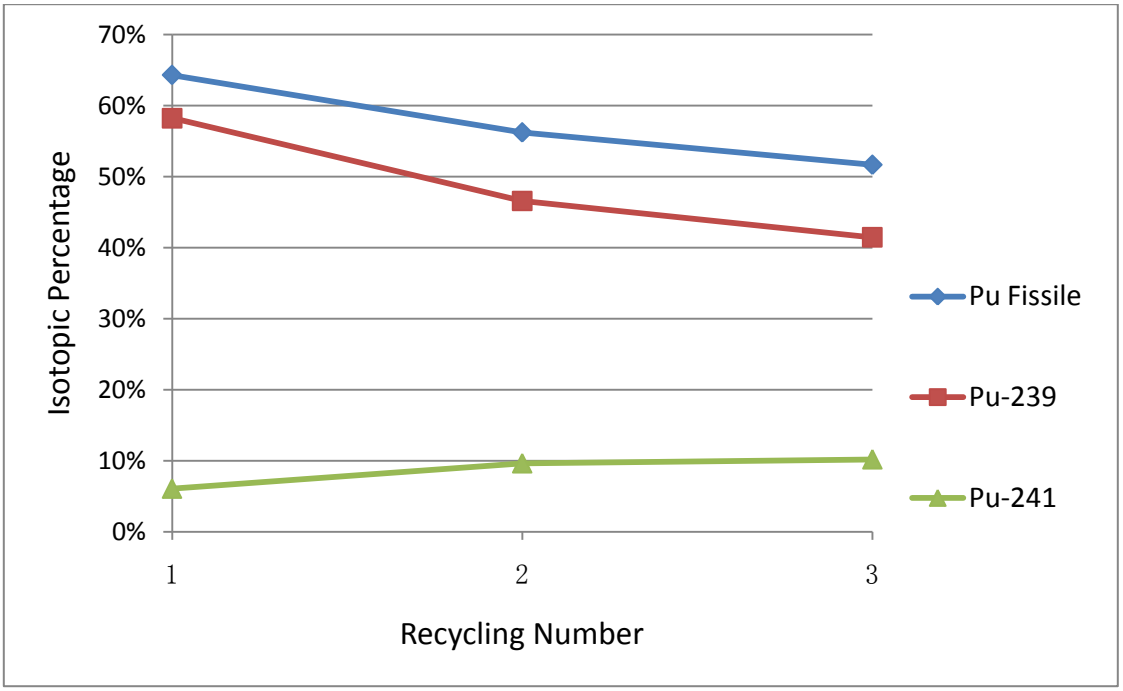


Figure 6.5 Pu Vector as a Function of Number of Recyclings for IMF-MOX M-R

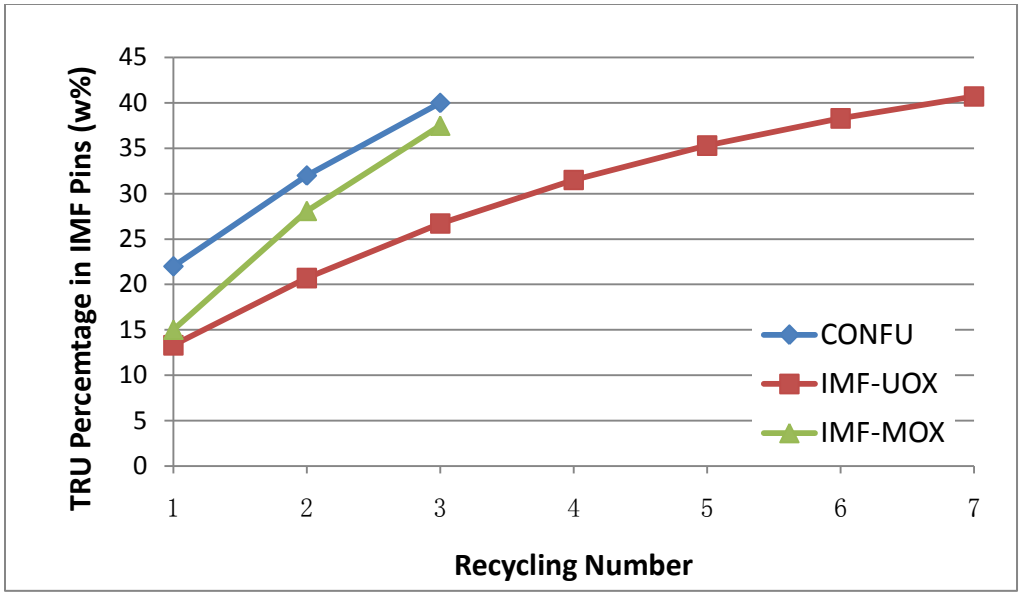


Figure 6.6 TRU Percentage as a Function of Number of Recyclings for IMF Cases

As can be seen from the tables and figures above, for MOX cases, both Pu vector and U-235 enrichment become stable after 7 cycles, which means that an equilibrium has been reached. For IMF cases, although there is a trend an towards equilibrium, the Pu content and the TRU weight percentage do not stabilize yet after 7th and 3rd cycle, respectively. For the IMF-UOX and IMF-MOX cases, the recycling process had to be stopped at these corresponding points because the TRU loading in IMF pins would exceed the 40w% limit(at 7th cycle the TRU pecentage for IMF-UOX is actually 40.7%, we neglect the excess 0.7% considering that the modeling error associated with the simulation may well mask this difference), which is a criteria that we set forth for manufacturing viability. It is also shown in Figure 6.6 that the CONFU assembly would also violate this criteria after 3rd cycle. However, CONFU assembly burns much fewer

TRUs than IMF-MOX assembly and this is why it has not been investigated further in this research.

The reason for the more rapid increase in the TRU percentage of the IMF pins of the IMF-MOX assembly over those of the IMF-UOX assembly is that the neutron spectrum experienced by the IMF pins in the IMF-MOX assembly is harder than that of the IMF pins of the IMF-UOX assembly. This is because the MOX inner pins produce a harder spectrum than the UOX inner pins, thus the average moderation in the IMF-MOX assembly is lower than that in the IMF-UOX assembly. To illustrate this argument, the spectra for Pin #2, Pin #8, and Pin#45 (see the pin indexing in Figure 6.7) are given in Figure 6.8, Figure 6.9, Figure 6.10,and Figure 6.11 for the MOX M-R, cMOX M-R, IMF-UOX, and IMF-MOX cases, respectively.

	1	2	3	4	5	6	7	8	9
9									45(IMF)
8								43	44(IMF)
7		Index Map					40	41	42(IMF)
6						WH	37	38	39(IMF)
5					31	32	33	34	35(IMF)
4				WH	26	27	WH	29	30(IMF)
3			18	19	20	21	22	23	24(IMF)
2		10	11	12	13	14	15	16	17(IMF)
1	WH	2	3	WH	5	6	WH	8	9(IMF)

Figure 6.7 Pin Indexing for 1/8th Symmetry of a Fuel Assembly

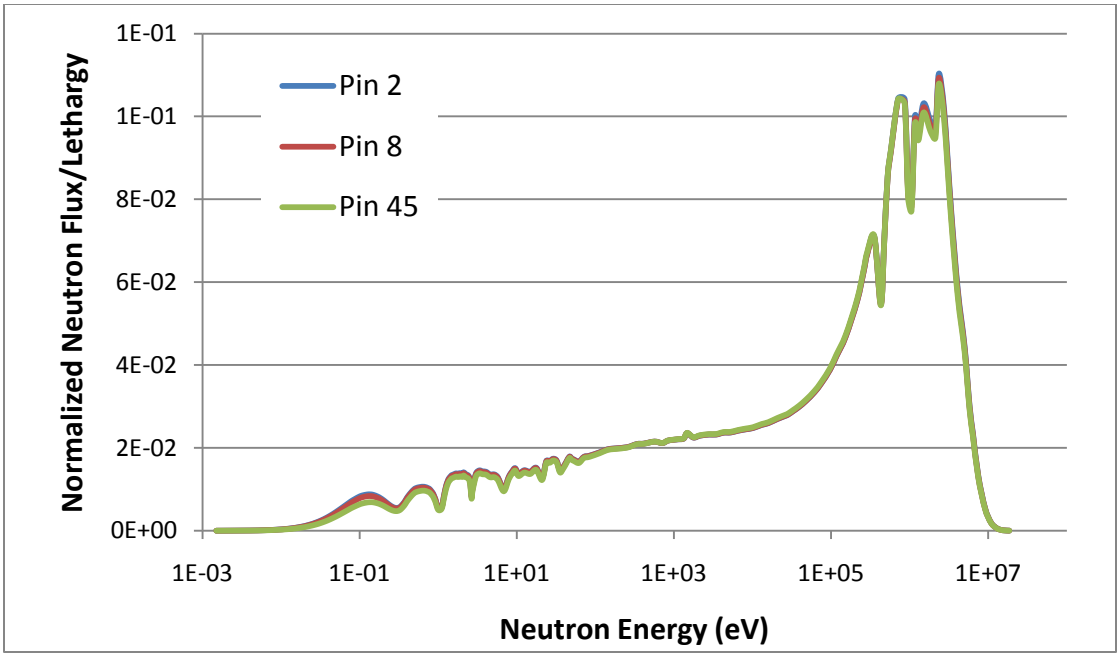


Figure 6.8 Spectra for Pin #2,#8,and #45 in MOX-1 Fuel Assembly

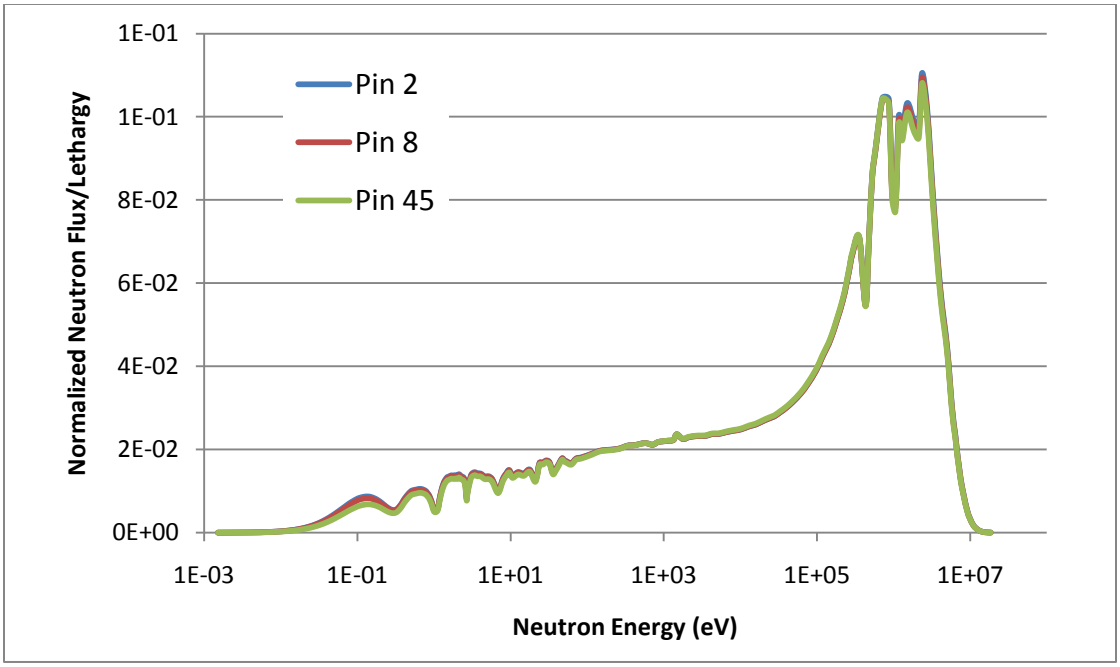


Figure 6.9 Spectra for Pin #2,#8,and #45 in cMOX-1 Fuel Assembly

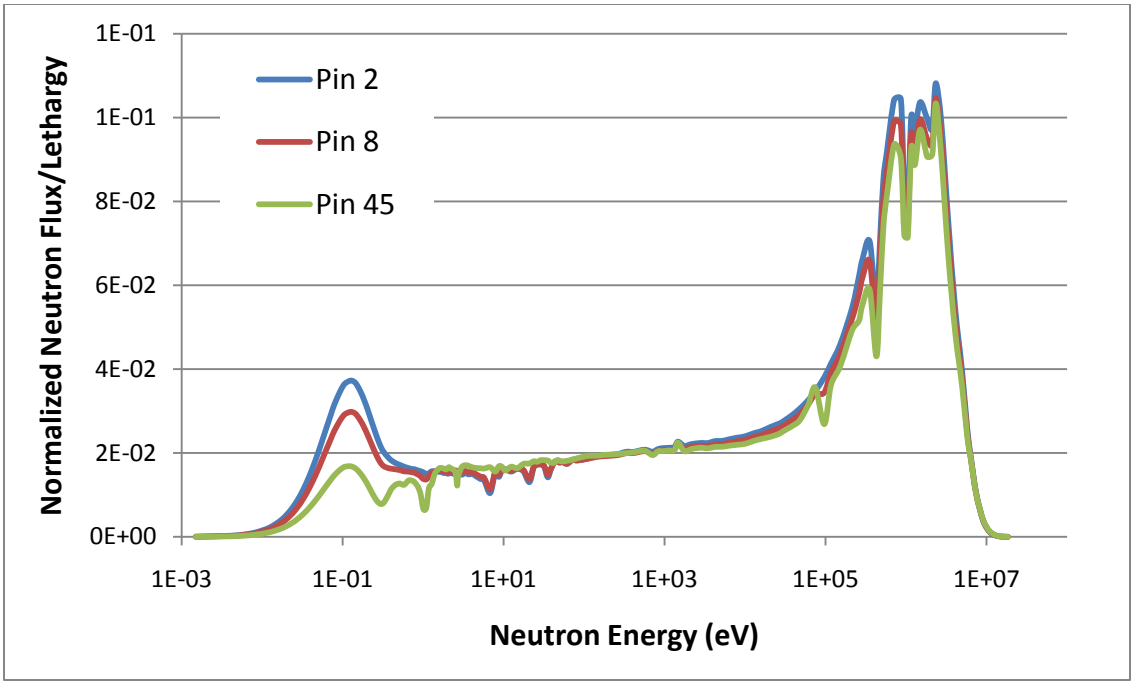


Figure 6.10 Pu Spectra for Pin #2,#8,and #45 in IMF-UOX-1 Fuel Assembly

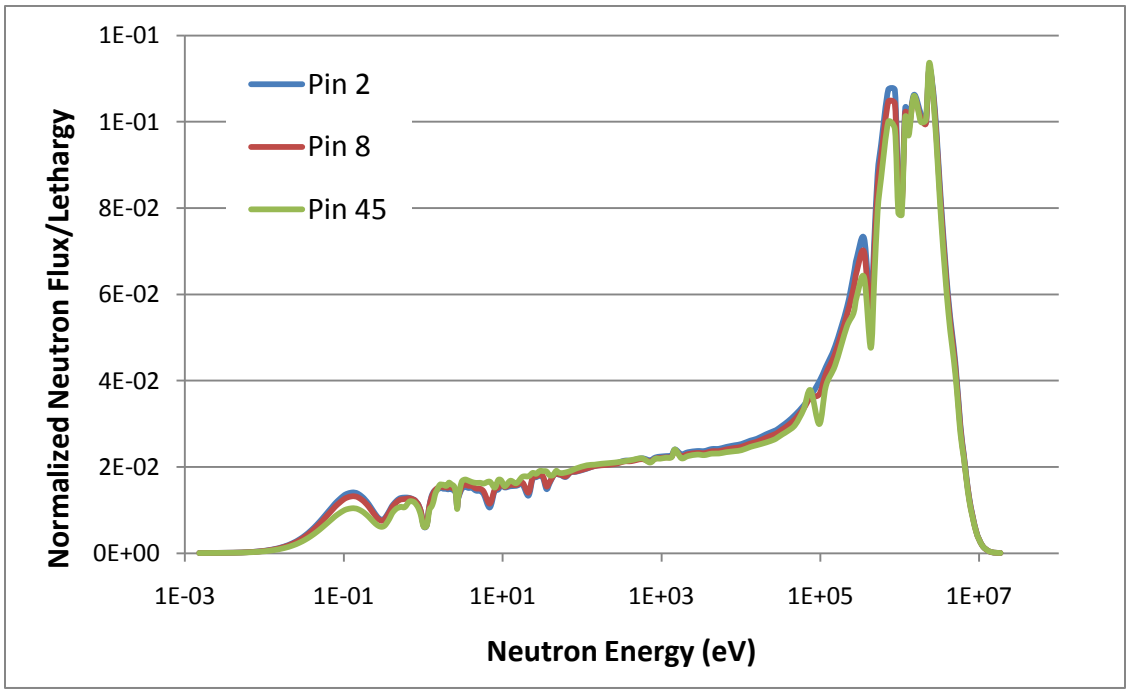


Figure 6.11 Pu Spectra for Pin #2,#8,and #45 in IMF-MOX-1 Fuel Assembly

6.2 k-inf as a Function of Burnup

An energy equivalence check against modern UOX assembly is given below in Figure 6.12 ~ Figure 6.15. The k-inf's of MOX cases are checked with a UOX assembly with 4.9w% enrichment and burned up to 60GWd/tHM. While burnup imposed on IMF cases are only 51GWd/tHM (assembly energy production equivalent to UOX) rather than 60GWd/tHM, that is we check against UOX assembly with 4.3w% enrichment with a burnup of 51GWd/tHM (as suggested by Goldmann's thesis). The analysis for MOX OTC is included in that for MOX M-R as MOX-1, since they are identical cases.

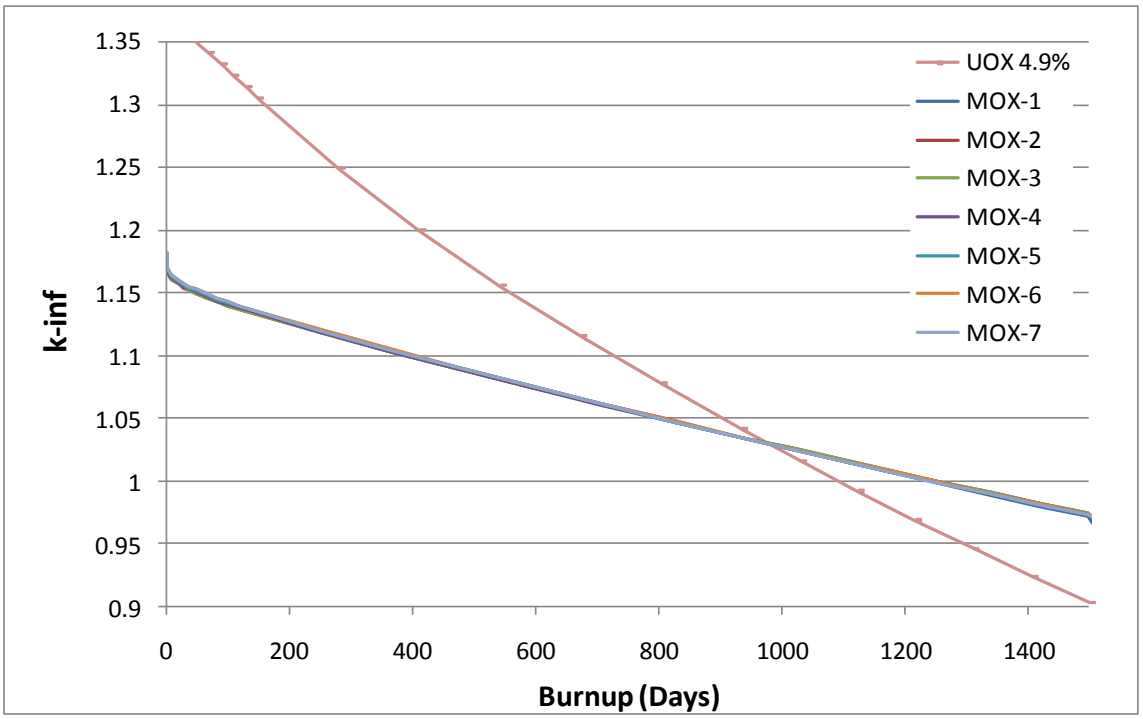


Figure 6.12 k-inf as Function of Burnup for MOX M-R

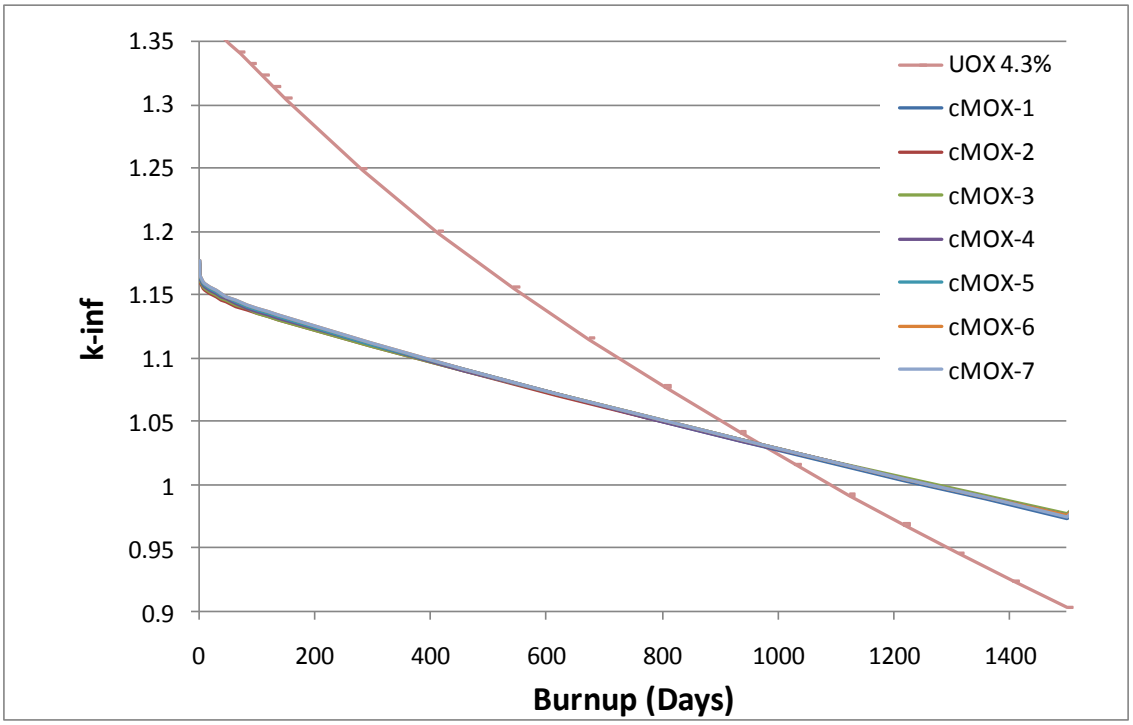


Figure 6.13 k-inf as Function of Burnup for Am-coated MOX M-R

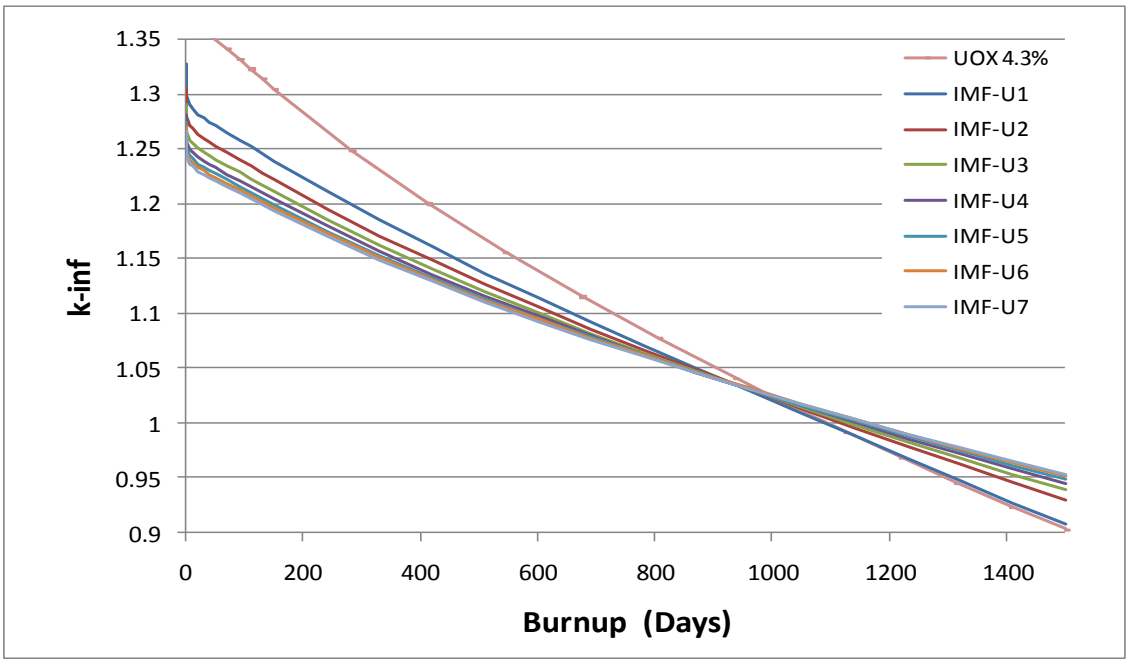


Figure 6.14 k-inf as Function of Burnup for IMF-UOX M-R

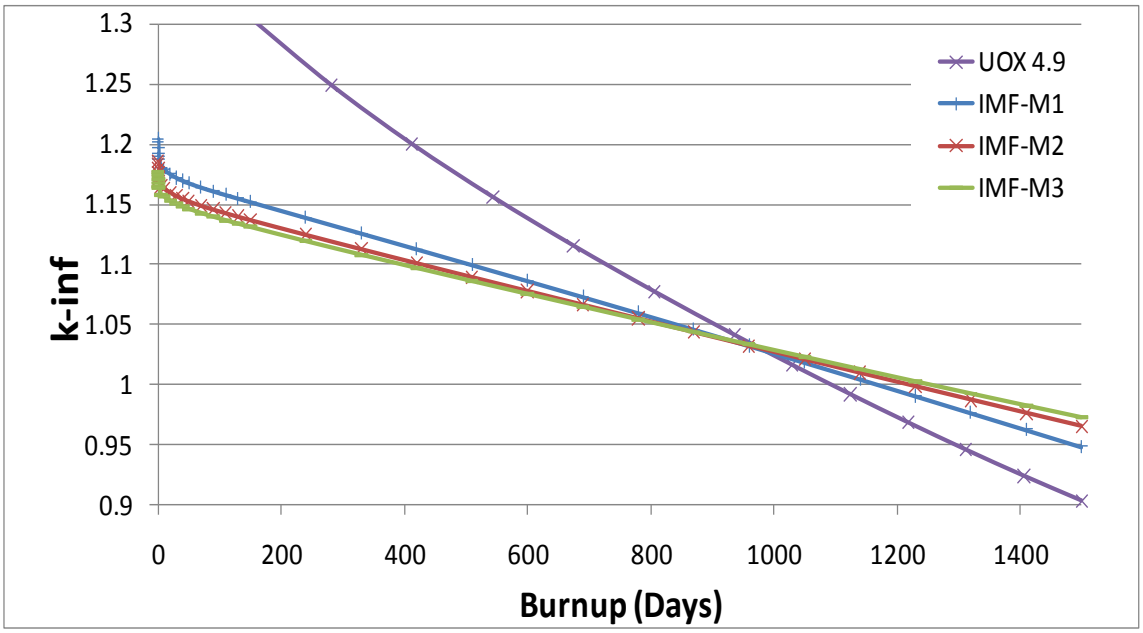


Figure 6.15 k-inf as Function of Burnup for IMF-MOX M-R

As can be seen from the figures above, all imposed energy equivalence criteria perfectly are met. That is to say the k-inf's at 937.5 day (or 5/8 of imposed burnup) is above 1.035.

6.3 Voiding Calculation

A voiding condition is simulated in the DRAGON code by reducing the moderator density. An equivalent change in moderator volume and fuel volume ratio (Vm/Vf) is calculated correspondingly and used to plot k-inf value. An example for computing nominal condtion for MOX assembly is as follows:

$$\frac{V_m}{V_f} = \frac{P^2 - N_{pin} A_{pin} - N_{GT} A_{GT}}{N_{pin} A_{pellet}} = 1.95$$

with $A_{pin} = \pi R_{pin}^2$

$A_{pellet} = \pi R_{pelle\ t}^2$

$A_{GT} = \pi (R_{GTO}^2 - R_{GTI}^2)$

where R_{pin} is the pin outer radius, which is 0.4750 cm

R_{pellet} is fuel pellet radius, which is 0.4096 cm

R_{GTO} is fuel pellet radius, which is 0.6121 cm

R_{GTI} is fuel pellet radius, which is 0.5715 cm

P is the lattice pitch, which is 1.26 cm.

Nominal conditions are denoted by vertical dashed lines in each plot. The reader should be aware that though the nominal Vm/Vf for MOX cases can be calculated as 1.95, it is not the case for the IMF cases because we are employing modified radius for the IMF pins while radius of the inner pins is unchanged. Therefore, the nominal Vm/Vf for IMF cases is case-dependent, or to be exact, IMF pin radius dependent.

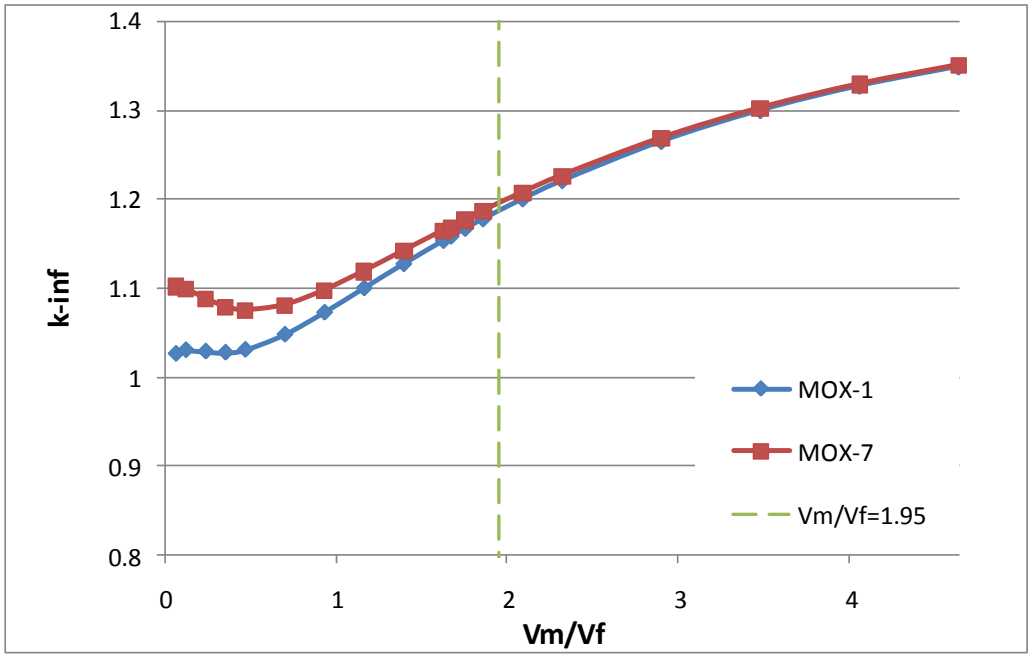


Figure 6.16 Voiding Calculation for MOX M-R

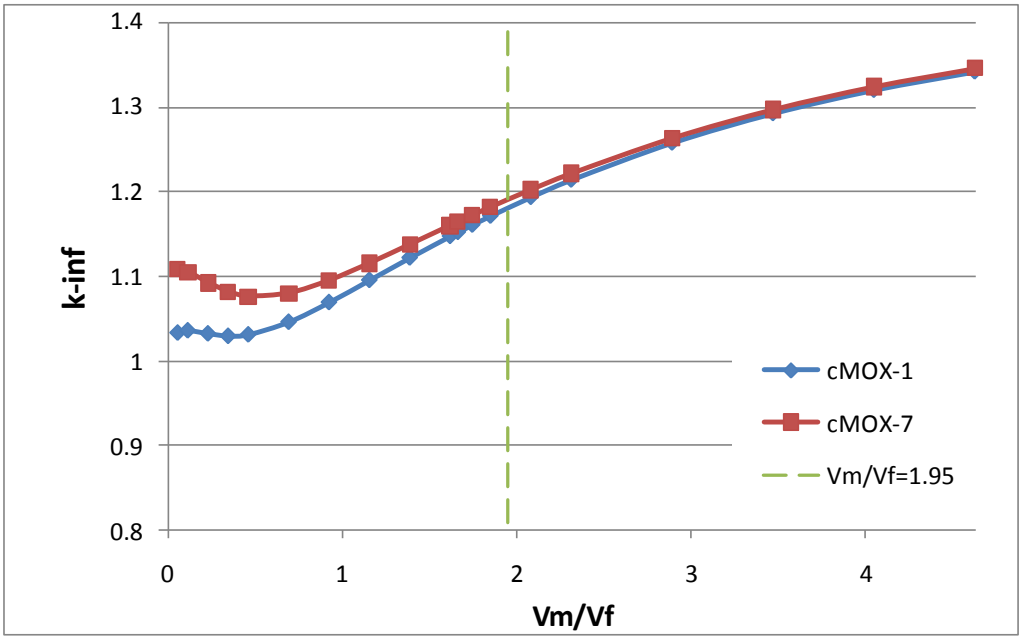


Figure 6.17 Voiding Calculation for Am-coated MOX M-R

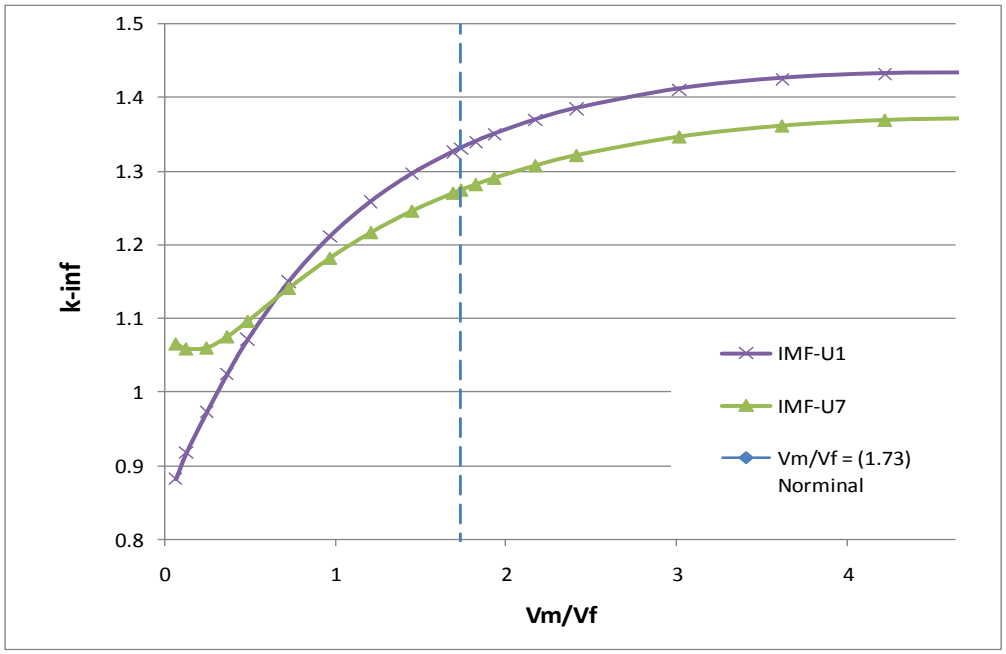


Figure 6.18 Voiding Calculation for IMF-UOX M-R

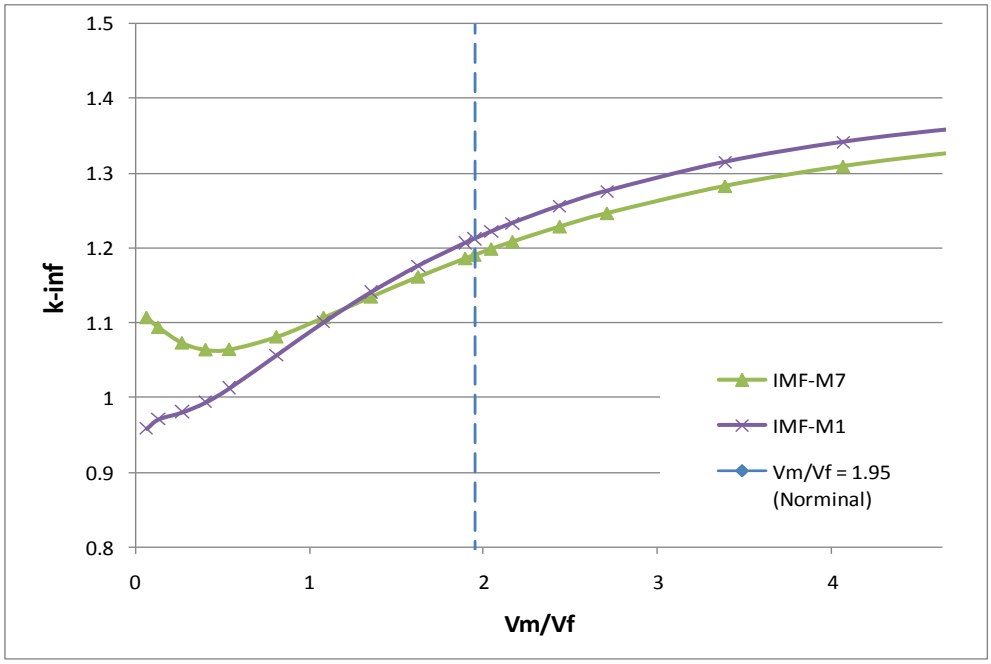


Figure 6.19 Voiding Calculation for IMF-MOX M-R

Results are evaluated for the first cycle and the last cycle in each multi-recycling process. All the k-inf's are computed at BOC. As can be seen from Figure 6.16~Figure 6.19, neither MOX designs or IMF designs violates the imposed voiding k-inf criteria, that is, the k-inf with complete voiding is lower than the k-inf at nominal operating condition. It can also be seen that the voiding behavior of IMF designs are better than that of MOX designs, which is an expected advantage for IMF design. That is, the safety margin at complete voiding condition is larger for IMF cases (20000 pcm for IMF-UOX and 8000 pcm for IMF-MOX) than for MOX cases (7000 pcm for MOX and 5000 pcm for Am-coated MOX). This is because in a IMF assembly, the bulk amount of TRUs to be burned is squeezed to the outer IMF pin zone, while in the inner zone, we have either a UOX or a MOX with smaller Pu content than the homogeneous MOX assembly designs. Therefore, the neutron spectrum in the inner zone is softer than that in MOX assemblie (see Figure 6.8 ~ Figure 6.11). It is also true that since the control rods also go through the inner zone, the control rod worth is also increased for IMF designs over MOX designs. For the same reason, the voiding and control behavior is better for IMF-UOX over IMF-MOX.

6.4 Mass Balance for Transuranics

Three kinds of TRU mass balance comparison are presented in this section: TRU net production, TRU comprehensive production, and detailed mass balance for each cycle. Each provides a unique perspective to evaluate how efficient the assembly designs are at transmuting TRU.

6.4.1 Transuranics Net Production and Transmutation Efficiency

TRU net production is defined as the TRU discharged from an assembly after once-through or multi-recycling minus the TRU required to make the very same assembly. In other words, that is the difference between discharge (before 2 years storage for the first cycle) and charge (after 5 years of cooling for the last cycle). For the MOX and IMF designs, this value should be negative, meaning that a net reduction is achieved. The significance of this value is that it can show how many TRU elements are burned using our assembly design, as opposed to conventional UOX assemblies that are net producers of TRU when they are irradiated in a reactor. The transmutation efficiency here is defined as absolute value of net production divided by charge amount.
All the values here in the tables are normalized to 1TWh electricity prodution. That is, the charge required to generate 1TWh electricity and the waste discharged after generating so much energy. OTC or M-R strategy are accounted for with this

normalization. The heat to electricity efficiency is assumed to be 33%. An example calculation can be found in Appendix C.

Table 6.5 Pu Net Production and Transmutation Efficiency

Pu	Charge (kg)	Discharge (kg)	Legacy assemblies required	Net production (kg)	Efficiency
UOX Legacy	0.00	29.50	-	29.50	-
UOX 4.9	0.00	27.07	-	27.07	-
MOX OTC	167.01	118.04	7.55	-48.97	29.32%
MOX MR	61.34	18.13	19.34	-43.21	70.45%
cMOX MR	60.72	18.17	19.28	-42.55	70.07%
IMF-UOX	40.26	24.16	11.17	-16.10	39.99%
IMF-MOX	83.49	51.26	9.93	-32.24	38.61%

Table 6.6 Am Net Production and Transmutation Efficiency

Am	Charge (kg)	Discharge (kg)	Legacy assemblies required	Net production (kg)	Efficiency
UOX Legacy	0.00	3.47	-	3.47	-
UOX 4.9	0.00	1.65	-	1.65	-
MOX OTC	0.00	10.19	-	10.19	-
MOX MR	0.00	11.96	-	11.96	-
cMOX MR	0.16	11.11	0.44	10.95	<0
IMF-UOX	4.74	3.05	11.17	-1.69	35.73%
IMF-MOX	4.21	6.58	4.26	2.37	<0

Table 6.7 Np Net Production and Transmutation Efficiency

Np	Charge (kg)	Discharge (kg)	Legacy assemblies required	Net production (kg)	Efficiency
UOX Legacy	0.00	1.91	-	1.91	-
UOX 4.9	0.00	2.07	-	2.07	-
MOX OTC	0.00	0.96	-	0.96	-
MOX MR	0.00	1.33	-	1.33	-
cMOX MR	0.00	1.35	-	1.35	-
IMF-UOX	2.61	0.92	11.17	-1.69	64.88%
IMF-MOX	2.32	2.01	4.26	-0.31	13.56%

Table 6.8 Cm Net Production and Transmutation Efficiency

Cm	Charge (kg)	Discharge (kg)	Legacy assemblies required	Net production (kg)	Efficiency
UOX Legacy	0.00	0.10	-	0.10	-
UOX 4.9	0.00	0.28	-	0.28	-
MOX OTC	0.00	2.53	-	2.53	-
MOX MR	0.00	3.21	-	3.21	-
cMOX MR	0.00	3.36	-	3.36	-
IMF-UOX	0.00	3.52	-	3.52	-
IMF-MOX	0.00	4.20	-	4.20	-

Table 6.9 Total TRU Net Production and Transmutation Efficiency

Total	Charge (kg)	Discharge (kg)	Net production (kg)	Efficiency
UOX Legacy	0.00	34.99	34.99	--
UOX 4.9	0.00	31.07	31.07	--
MOX1	167.01	131.72	-35.29	21.13%
MOX MR	61.34	34.63	-26.71	43.55%
cMOX MR	60.89	34.00	-26.89	44.16%
IMF-UOX	44.87	30.00	-14.87	33.14%
IMF-MOX	90.03	64.04	-25.99	28.86%

The colum ‘Legacy assemblies required’ in each table (Table 6.5~Table 6.9) denots the number of legacy UOX assemblies required to fabricate these advanced fuels that are needed to complete a multi-recycling process.

Overall, MOX OTC consumes the most TRUs (35.29 kg/TWh-e) while cMOX M-R case destructs the biggest fraction (44.16%) of TRU that is loaded into it. TRU transmutation efficiencies of IMF M-R cases are lower than that of MOX M-R cases, but higher than that of MOX OTC (21.13%). These results show that the multi-recycling strategy achieves good transmutation efficiency compared with MOX once-through cycle.

The difference between MOX M-R and cMOX M-R designs are small. The most noticeable difference is that cMOX M-R consumes 1 kg more Am than MOX M-R, thanks to its Am coating. Both TRU net production and transmutation efficiency of cMOX M-R are only marginally better than that of MOX M-R. This suggests that 0.001 cm coating of Am does not affect the assembly’s transmutation ability significantly. For this reason, a stand-alone study on transmutation efficiency of the Am coating by increasing coating thickness is also carried out during this research. The results are presented at the end of Section 6.

Both IMF-UOX and IMF-MOX designs are not as good as the MOX M-R designs in terms of Pu net production and Pu transmutation efficiency. However, since Np and Am are also recycled in this kind of assembly, their advantage at consuming these two Transuranics is obvious. Generally speaking, the TRU transmutation efficiency of the IMF designs is still lower than the MOX M-R cases. The IMF-UOX’s

efficiency is lower than the MOX M-R cases because the Uranium loading in the inner zone is relatively large compared to the TRU loading in IMF pins, and thus breeds TRU faster. The IMF-MOX's efficiency is lower than that of IMF-UOX because Np and Am are not recycled when fabricating those inner MOX pins and also because number of recycling cycles achieved is only 3, which is much less than the standard 7 cycles used for IMF-UOX. In no case is Cm recycled, this is because Cm is hard to fission and mostly leads to even higher actinides, such as Cf which is difficult to handle.

6.4.2 TRU Comprehensive Production

The TRU Comprehensive Production is defined as the amount of TRU discharged from advanced fuel assembly at the last cycle plus the TRU remained in the waste stream of legacy UOX assemblies that are used to make these advanced fuel assemblies, as well as the 0.1% of TRU discharged from each preceding cycle that is not recycled due to the 99.9% recovery efficiency. The Production here is also normalized to 1 TWh electricity produced. When carrying out the normalization, energy released from both advanced fuels and legacy fuels are accounted for. The significance of this figure of merit is that it compares the entire fuel cycle, be it either legacy UOX assemblies or advanced assemblies that uses legacy spent fuel as feed. This value quantifies how much TRU is finally collected as waste and sent to the repository per amount of energy produced. The analyses results are shown in Table 6.10.

Table 6.10 TRU Comprehensive Production (kg/TWh-e)

Discharge (kg)	Pu	Am	Np	Cm	Total
UOX Legacy	29.50	3.47	1.91	0.10	34.99
UOX 4.9	27.07	1.65	2.07	0.28	31.07
MOX OTC	17.79	4.48	1.77	0.47	24.51
MOX MR	5.94	6.24	1.72	1.12	15.02
cMOX MR	5.96	5.92	1.73	1.17	14.78
IMF-UOX	10.39	1.31	0.40	1.49	13.58
IMF-MOX	13.60	3.19	1.33	1.14	19.26

We can note that the TRU comprehensive productions for UOX Legacy and UOX 4.9 will be the same as their net productions, since no reprocessing or recycling are implemented for these two options.

This type of information gives a definition of energy/waste efficiency. In this case, the most waste efficient assembly design would be IMF-UOX which produces 13.58 kg TRU / TWh-e. It has to be noticed that this argument makes no sense when considering the advanced assembly alone. A certain number of legacy UOX assemblies, as specified in the ‘legacy assembly required’ column, needs to be paired with advanced assemblies to achieve the predicted energy/waste efficiency. It also does not tell you how much TRU is actually burned during that 1 TWh-e production. Nowadays, for example, we have a fixed amount of spent legacy UOX fuel, since we are no longer using that fuel in modern reactors. Although the IMF-UOX option produces the least amount of waste per 1 TWh-e, it takes more TWh-e’s than other recycling options to

consume the fixed amount of waste from spent legacy fuel and eventually leaving more final waste.

6.4.3 Detailed Mass Balance for Each Cycle:

The mass balance listed here is the mass difference between charge (before 2 years of storage) and discharge (after 5 years of cooling) for each cycle. The values shown here is for mass balance in a single fuel assembly. All the 5 advanced assembly designs are evaluated here. Once again, the MOX OTC is included in MOXM-R as its MOX-1 cycle. The percentage following the mass balance is the total mass reduction over total mass charged into the assembly at BOC. The values in red parenthesis signify negative value, that is, net reduction.

As can be seen in Table 6.11 ~ Table 6.14, from the mass balances, the MOX M-R, cMOX M-R, and IMF-UOX cases have almost reached equilibrium after 7 cycles since the burnup percentage is relatively stable. For the IMF-MOX case the equilibrium is obviously not achieved yet since the burnup percentage still varies as the cycle number progresses. We had to stop recycling for IMF-MOX due to maximum TRU percentage criterion set forth. However, it can be seen that IMF-MOX cases are most efficient as cycle-wise transmutation. But its overall efficiency is not as outstanding because it was stopped after the 3rd cycle as opposed to other options that went as far as the 7th cycle.

Table 6.11 Detailed Mass Balance for MOX M-R

	MOX-1		MOX-2		MOX-3		MOX-4		MOX-5		MOX-6		MOX-7	
	△	%	△	%	△	%	△	%	△	%	△	%	△	%
237	0.22		0.28		0.30		0.31		0.32		0.33		0.33	
Np	0.22		0.28		0.30		0.31		0.32		0.33		0.33	
238	0.04		0.09		(0.03)		(0.12)		(0.17)		(0.20)		(0.21)	
239	(11.17)		(7.17)		(6.09)		(5.74)		(5.56)		(5.45)		(5.39)	
240	(1.45)		(2.85)		(2.92)		(2.79)		(2.67)		(2.58)		(2.51)	
241	1.37		(0.44)		(0.68)		(0.68)		(0.65)		(0.62)		(0.60)	
242	0.23		0.28		0.05		(0.13)		(0.27)		(0.36)		(0.43)	
Pu	(10.98)	-29%	(10.10)	-27%	(9.67)	-26%	(9.46)	-25%	(9.31)	-25%	(9.21)	-25%	(9.15)	-24%
241	1.44		1.61		1.60		1.56		1.53		1.51		1.50	
242m	0.01		0.01		0.01		0.01		0.01		0.01		0.01	
243	0.85		1.01		1.12		1.19		1.24		1.27		1.30	
Am	2.29		2.64		2.74		2.77		2.79		2.80		2.81	
242	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
243	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
244	0.48		0.55		0.60		0.64		0.66		0.68		0.69	
245	0.08		0.09		0.10		0.11		0.11		0.11		0.12	
246	0.01		0.01		0.01		0.01		0.01		0.01		0.01	
247	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
248	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Cm	0.58		0.66		0.72		0.76		0.79		0.80		0.82	

Table 6.12 Detailed Mass Balance for Am-coated MOX M-R

	cMOX-1		cMOX-2		cMOX-3		cMOX-4		cMOX-5		cMOX-6		cMOX-7	
	△	%	△	%	△	%	△	%	△	%	△	%	△	%
237	0.22		0.28		0.31		0.32		0.33		0.33		0.33	
Np	0.22		0.28		0.31		0.32		0.33		0.33		0.33	
238	0.14		0.12		(0.01)		(0.10)		(0.16)		(0.19)		(0.20)	
239	(10.95)		(7.01)		(5.94)		(5.59)		(5.42)		(5.32)		(5.26)	
240	(1.40)		(2.76)		(2.82)		(2.70)		(2.58)		(2.49)		(2.43)	
241	1.38		(0.41)		(0.64)		(0.64)		(0.61)		(0.58)		(0.57)	
242	0.23		0.28		0.06		(0.11)		(0.25)		(0.34)		(0.40)	
Pu	(10.60)	-28%	(9.77)	-26%	(9.35)	-25%	(9.15)	-25%	(9.01)	-24%	(8.91)	-24%	(8.86)	-24%
241	1.24		1.47		1.46		1.43		1.41		1.39		1.38	
242m	0.01		0.01		0.01		0.01		0.01		0.01		0.01	
243	0.82		0.94		1.04		1.10		1.14		1.17		1.19	
Am	2.07		2.42		2.51		2.55		2.56		2.57		2.58	
242	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
243	0.00		0.01		0.01		0.01		0.01		0.00		0.00	
244	0.49		0.58		0.63		0.67		0.69		0.71		0.72	
245	0.09		0.10		0.11		0.12		0.12		0.12		0.12	
246	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
247	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
248	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Cm	0.58		0.69		0.74		0.79		0.81		0.83		0.85	

Table 6.13 Detailed Mass Balance for IMF-UOX M-R

	IMF-U1		IMF-U2		IMF-U3		IMF-U4		IMF-U5		IMF-U6		IMF-U7	
	△	%	△	%	△	%	△	%	△	%	△	%	△	%
237	(0.12)		(0.29)		(0.36)		(0.39)		(0.39)		(0.39)		(0.39)	
Np	(0.12)	-19%	(0.29)	-28%	(0.36)	-28%	(0.39)	-27%	(0.39)	-26%	(0.39)	-24%	(0.39)	-24%
238	0.78		0.76		0.74		0.67		0.58		0.48		0.39	
239	(3.22)		(3.51)		(3.57)		(3.56)		(3.51)		(3.45)		(3.38)	
240	(0.37)		(0.47)		(0.59)		(0.69)		(0.78)		(0.86)		(0.92)	
241	0.51		0.15		(0.03)		(0.15)		(0.22)		(0.25)		(0.28)	
242	0.64		0.45		0.37		0.32		0.28		0.24		0.21	
Pu	(1.65)	-17%	(2.62)	-16%	(3.08)	-14%	(3.41)	-13%	(3.65)	-12%	(3.83)	-11%	(3.98)	-11%
241	(0.57)		(0.39)		(0.39)		(0.39)		(0.41)		(0.42)		(0.44)	
242m	0.00		0.01		0.01		0.01		0.01		0.01		0.01	
243	0.25		0.16		0.10		0.06		0.04		0.02		0.00	
Am	(0.32)	-27%	(0.23)	-13%	(0.28)	-11%	(0.33)	-10%	(0.36)	-10%	(0.40)	-9%	(0.43)	-9%
242	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
243	0.01		0.01		0.01		0.01		0.01		0.01		0.01	
244	0.29		0.47		0.57		0.63		0.67		0.70		0.72	
245	0.04		0.09		0.11		0.12		0.12		0.13		0.13	
246	0.01		0.01		0.01		0.01		0.01		0.01		0.01	
247	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
248	0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Cm	0.35		0.58		0.69		0.76		0.81		0.85		0.88	

Table 6.14 Detailed Mass Balance for IMF-MOX M-R

	IMF-M1		IMF-M2		IMF-M3	
	△	%	△	%	△	%
237	(0.19)		(0.22)		(0.23)	
Np	(0.19)	-31%	(0.22)	-27%	(0.23)	-24%
238	0.67		0.68		0.67	
239	(8.82)		(8.85)		(8.79)	
240	(1.80)		(2.12)		(2.26)	
241	0.63		(0.08)		(0.44)	
242	0.63		0.42		0.34	
Pu	(8.69)	-39%	(9.96)	-31%	(10.48)	-26%
241	(0.17)		0.15		0.20	
242m	0.00		0.01		0.02	
243	0.55		0.37		0.27	
Am	0.38	34%	0.53	24%	0.49	15%
242	0.00		0.00		0.00	
243	0.01		0.01		0.01	
244	0.48		0.44		0.86	
245	0.07		0.08		0.16	
246	0.01		0.01		0.01	
247	0.00		0.00		0.00	
248	0.00		0.00		0.00	
Cm	0.57		0.54		1.04	

6.5 Radiotoxicity Analyses

Radiotoxicity results presented here are calculated with the ORIGEN code by feeding the waste isotopic concentrations into the code. Both inhalation radiotoxicity and ingestion radiotoxicity are evaluated for all of the 5 advanced fuel designs.

6.5.1 Inhalation Radiotoxicity Production

Three analysis, net inhalation radiotoxicity production, inhalation radiotoxicity net production benefit by isotope, and comprehensive inhalation radiotoxicity production, are presented in this section. All the results are normalized to 1 TWh of electricity produced.

6.5.1.1 Net Inhalation Radiotoxicity Production

Similar to the net production concept first introduced in mass balance section, the net production here is defined as toxicity of the waste discharged from advanced fuel after recycling process minus toxicity of the TRU that are used to form the advanced fuel.

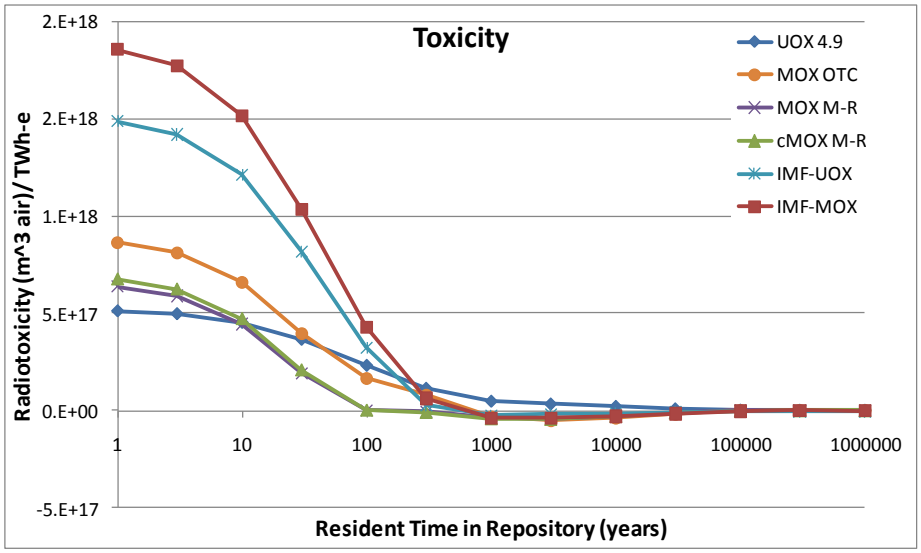


Figure 6.20 Net Inhalation Radiotoxicity Production

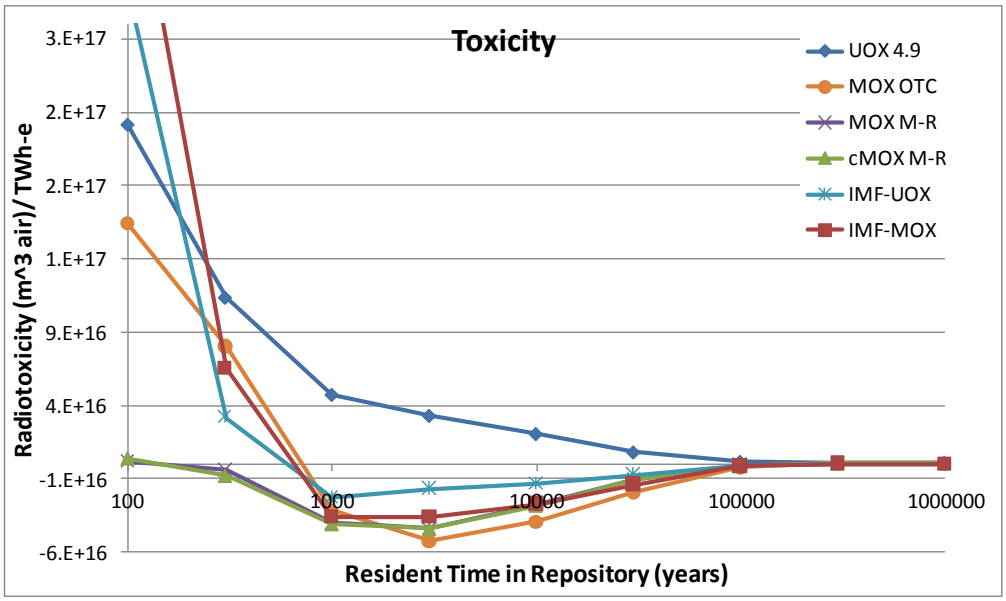


Figure 6.21 Net Inhalation Radiotoxicity Production (Zoom)

It can be seen from Figure 6.20 that all advanced fuel designs are more toxic than conventional UOX fuel in the first a few decades. That is because of the contribution from Cm-244 (for MOX cases) or Cm-244 and Pu-238 (for IMF cases). The accumulation of Cm-244 for those advanced fuels are understandable, since they are loaded with heavier isotopes, such as Np, Pu, and Am and thus radiative captures in these isotopes lead to a faster production of Cm. For Pu in IMF designs, although total amount is reduced, a closer scrutiny of the isotopic mass balance shows that Pu-238 actually gets accumulated through the recycling process and it is highly toxic. The main reason for that is the recycling of Np-237 gives rise to the production of new Pu-238. The production chain is as follows:

$$\mathrm{Np237} \xrightarrow{(\mathrm{n},\gamma)} \mathrm{Np238} \xrightarrow{\beta-} \mathrm{Pu238}$$

However Pu-238 decays with a half life of 87.7 years to U-234 and decays away after 1000 years.

10 years after discharge, the MOX M-R cases already show their advantages over UOX fuel. After 300 year, toxicity of IMF cases finally drop below that of the UOX case. A zoomed-in view in Figure 6.21 shows that before and somewhere after 1000^{th} year MOX M-R or cMOX M-R option yields the maximum benefit. Once again the difference between MOX M-R and cMOX M-R is unperceivable.

6.5.1.2 Inhalation Radiotoxicity Net Reduction Benefits by Isotopes

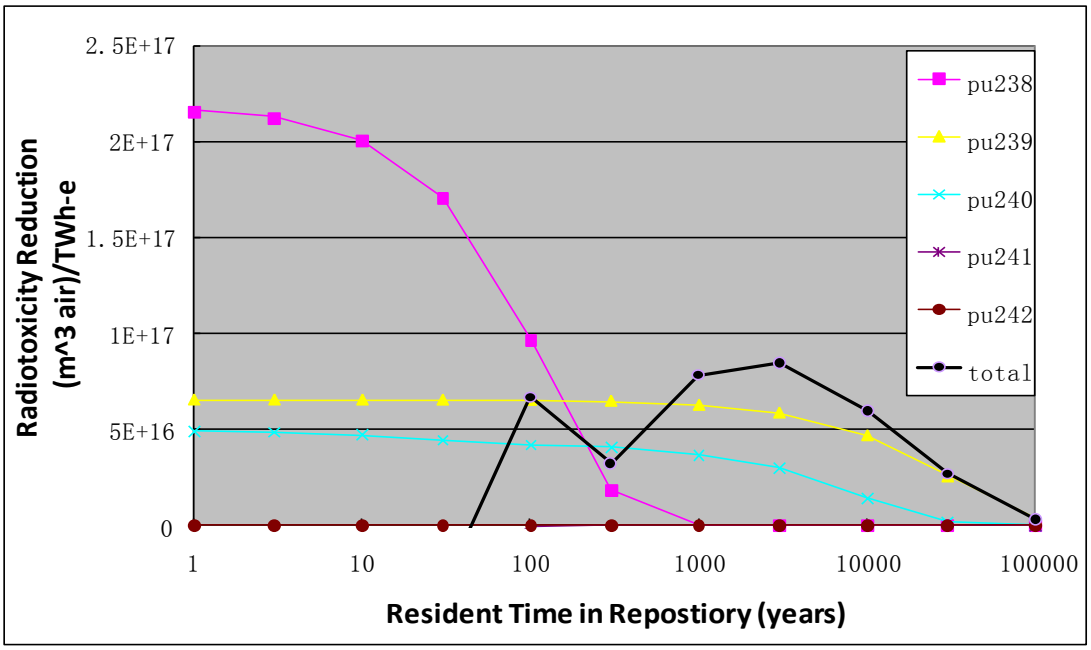


Figure 6.22 Inhalation Net Reduction Benefits Decomposition for MOX OTC

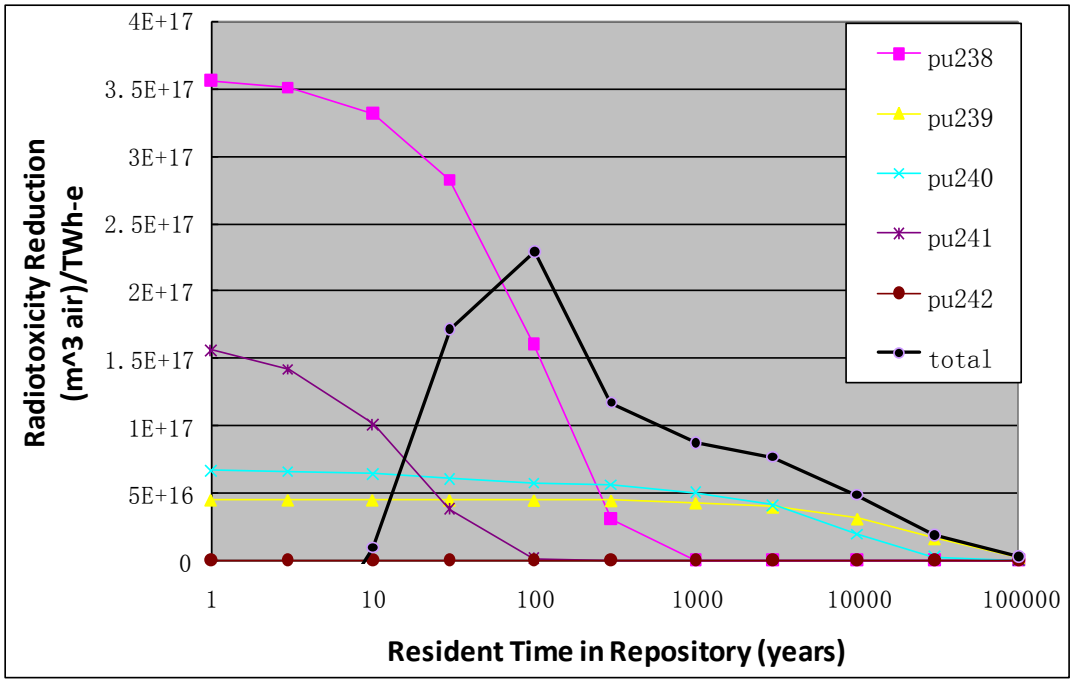


Figure 6.23 Inhalation Net Reduction Benefits Decomposition for MOX M-R

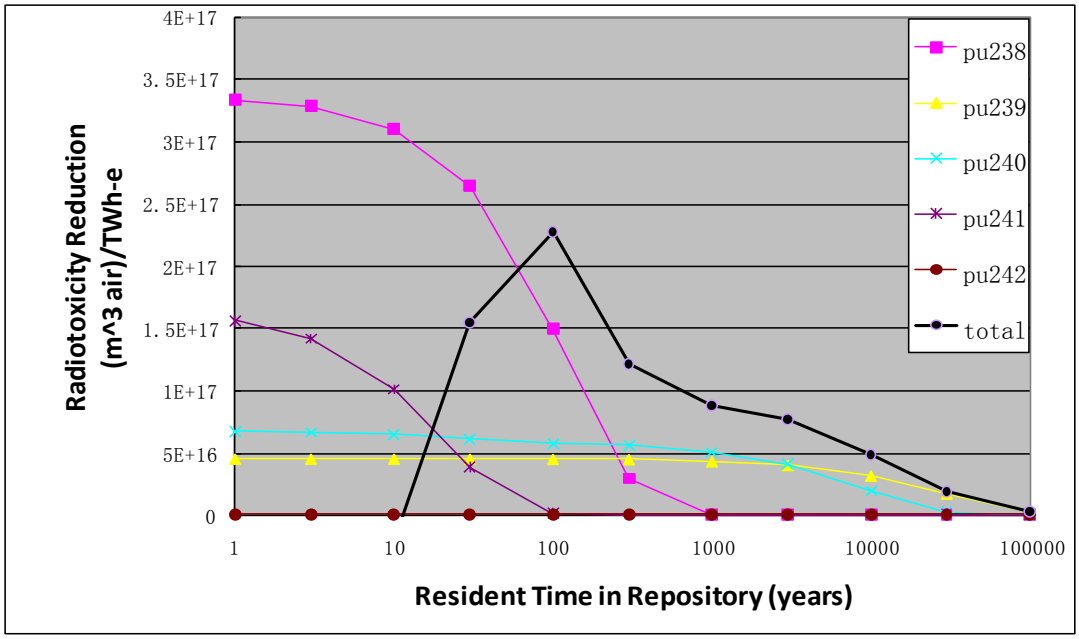


Figure 6.24 Inhalation Net Reduction Benefits Decomposition for cMOX M-R

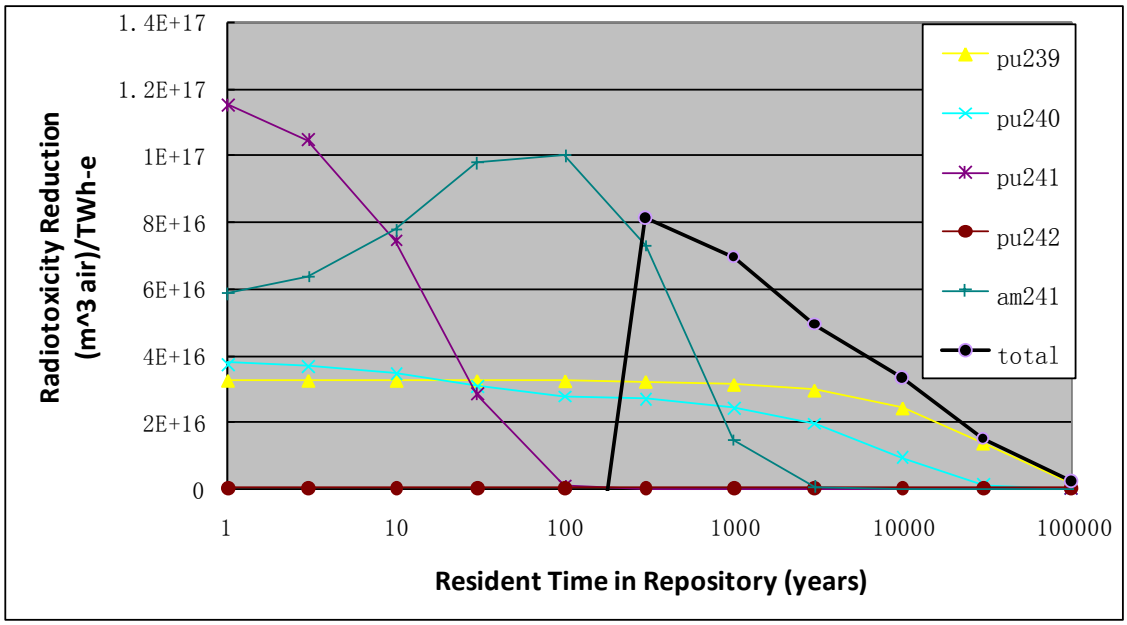


Figure 6.25 Inhalation Net Reduction Benefits Decomposition for IMF-UOX

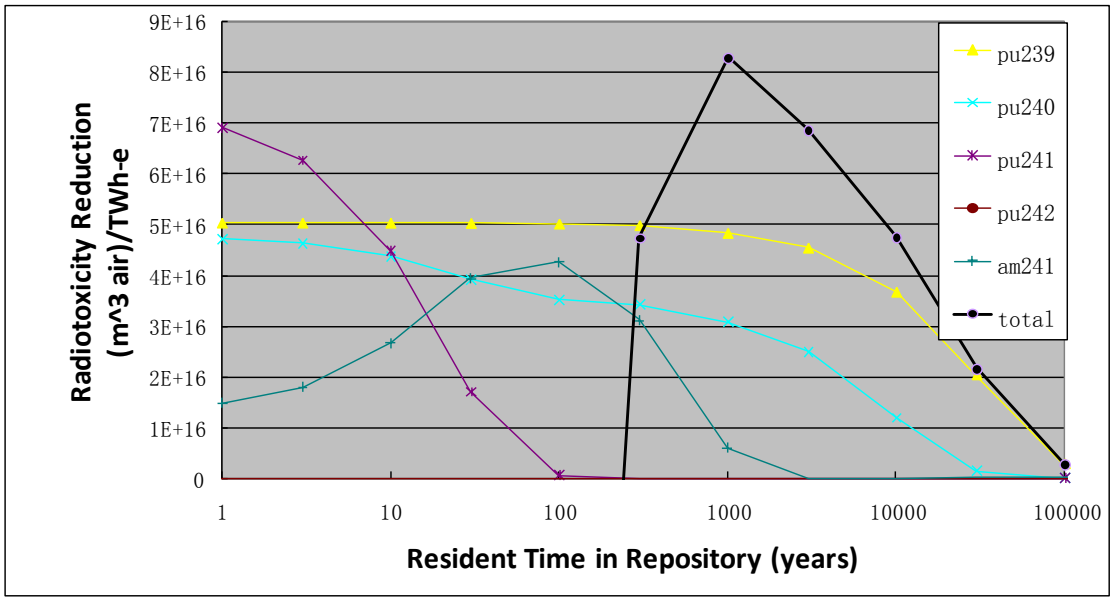


Figure 6.26 Inhalation Net Reduction Benefits Decomposition for IMF-MOX

The inhalation radiotoxicity net reduction benefits are defined as net production of conventional UOX fuel net minus the production of advanced fuels. A positive value shows how much benefit can be obtained by adopting these evolutionary fuel assembly concepts as opposed to using conventional UOX fuel assemblies. Negative values are not shown in the plots. The results are decomposed by isotopes to show the contribution from some of the most important transuranium isotopes.

As can be observed in Figure 6.22 through Figure 6.26, for the MOX cases, Pu-238 plays an important role in radiotoxicity benefit from the beginning to hundreds of years. The long term toxicity benefit is dominated by either Pu-329 or Pu-240, the contribution of these two isotopes are of the same order. However, for the IMF cases, the Pu-238 net reduction is negative and there is no benefit. For the IMF-UOX, Pu-241 is the most important contributor in the early years and then Am-241 takes over. For the IMF-MOX designs, similar patterns are found but since Am-241 is not fully recycled, its contribution is much less than for the IMF-UOX case. In the long run, Pu-239 and Pu-240 are still the most important contributors for both IMF-UOX and IMF-MOX.

6.5.1.3 Comprehensive Inhalation Radiotoxicity Production

Similar to the comprehensive production concept first introduced in the mass balance section, the comprehensive inhalation radiotoxicity production here is defined as toxicity of the waste discharged from advanced fuels after multi-recycling process plus the toxicity that remains in the waste stream of spent legacy UOX that are reprocessed to manufacture these advanced fuels. It provides a measure for energy/toxicity efficiency.

Figure 6.27 Comprehensive Inhalation Radiotoxicity Production

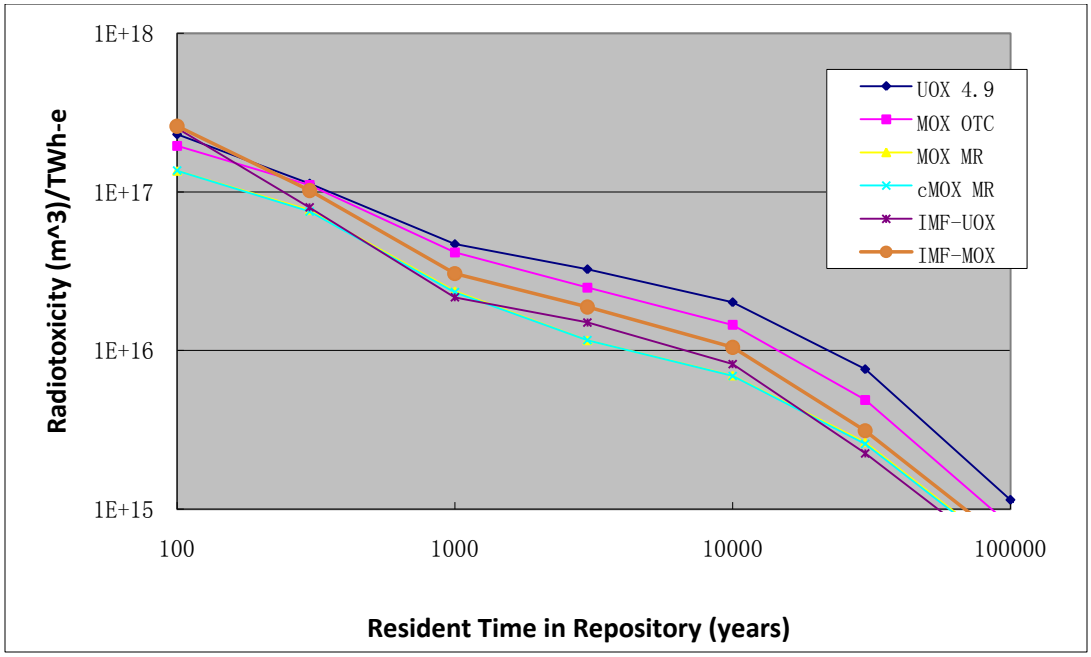


Figure 6.28 Comprehensive Inhalation Radiotoxicity Production (Zoom)

These results seen in Figure 6.27 and Figure 6.28 suggest that the MOX M-R and cMOX M-R strategies are the optimal choice almost for all times, except that at around 1000th year they are marginally outplayed by the IMF-UOX. The IMF-UOX design, however, is more toxic than the conventional UOX during the first hundred years.

6.5.2 Ingestion Radiotoxicity Production

Three analyses are performed in this section: net ingestion radiotoxicity production, ingestion radiotoxicity net production benefit by isotope, and comprehensive ingestion radiotoxicity production. All the results are normalized to 1 TWh of electricity produced.

6.5.2.1 Net Ingestion Radiotoxicity Production

The definition of net ingestion radiotoxicity production here is similar to that of net inhalation toxicity production except that the toxicity here is replaced by ingestion radiotoxicity and is measured in cubic meter of air instead of water.

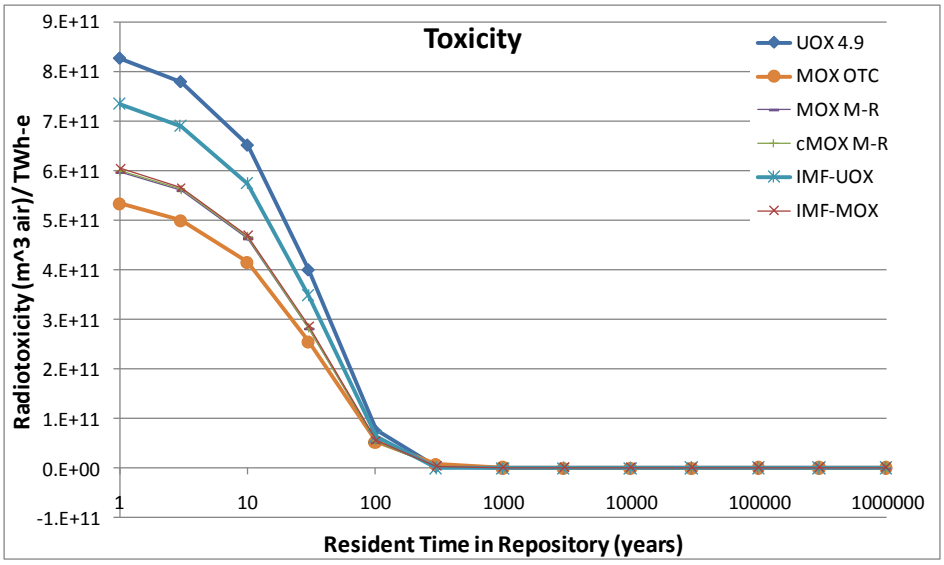


Figure 6.29 Net Ingestion Radiotoxicity Production

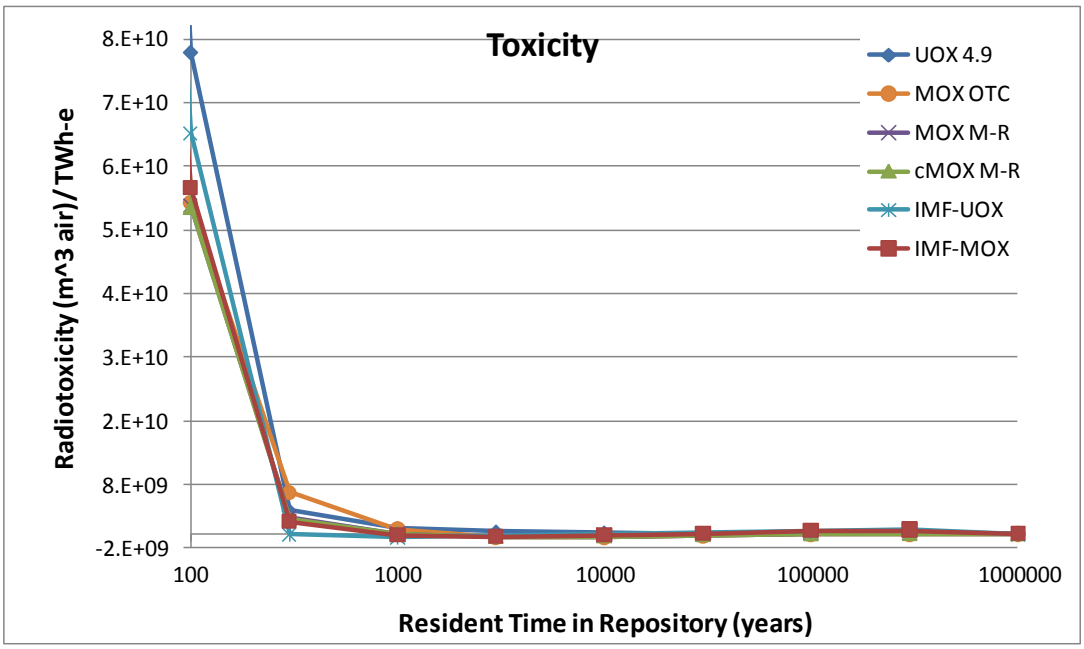


Figure 6.30 Net Ingestion Radiotoxicity Production (Zoom)

Unlike the inhalation toxicity, the ingestion toxicity analyses presented here (Figure 6.39 and Figure 6.30) for all of the advanced fuel designs show a lower toxicity than conventional UOX fuel assemblies from the time of discharge. This is because Sr-90 and Cs-137 (fission products) have more weight in terms of ingestion radiotoxicity while the weight of Pu-238 that dominates the inhalation toxicity at beginning stage decreases dramatically. Sr-90 and Cs-137 are products of UOX fuel burnup and its amount in spent MOX or spent IMF assemblies is significantly reduced. However both have very short half life (28.15 years for Sr-90 and 30 years for Cs-137). A close look at the zoom-in plot in Figure 6.30 shows that between hundreds and thousands of years after discharge, the IMF-UOX design reduces the most amount of toxicity.

6.5.2.2 Ingestion radiotoxicity net reduction benefit by isotope

The net reduction concept here is very similar to that used in inhalation toxicity analyses except that the inhalation toxicity has been replaced by the ingestion toxicity. During the first 100 years in repository, ingestion toxicity is dominated by Sr-90 and Cs-137, which are not long-lived Transuranics and the first century is also not a major concern for the repository. Therefore, in the analyses below we neglect the early time periods and focus on the time periods between 100 and 100,000 years. Only Transuranics elements that are the most relevant are plotted for each fuel assembly design.

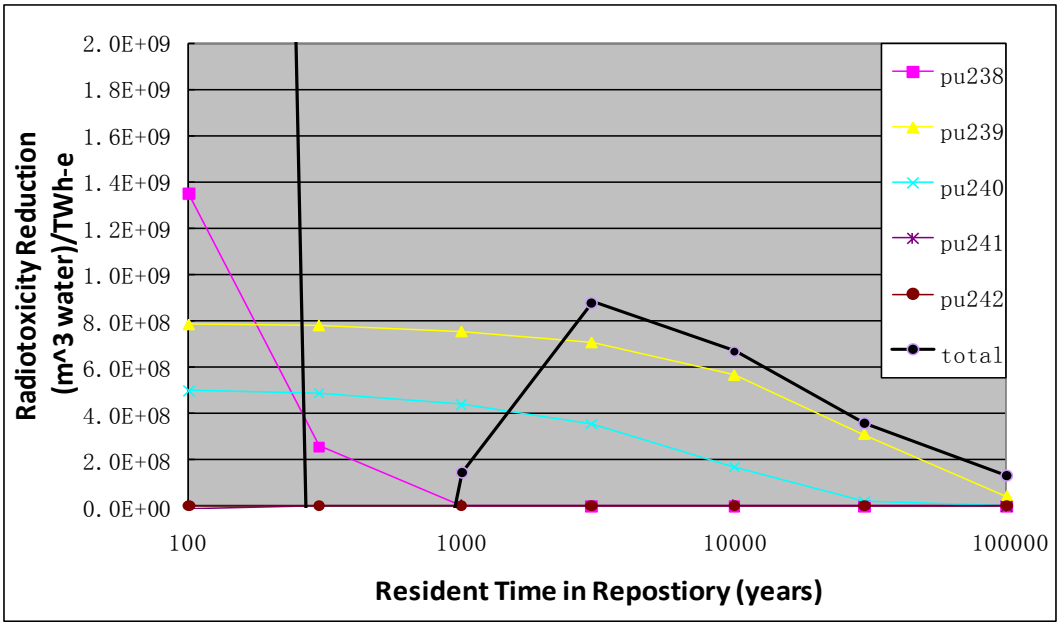


Figure 6.31 Ingestion Net Reduction Benefit Decomposition for MOX OTC

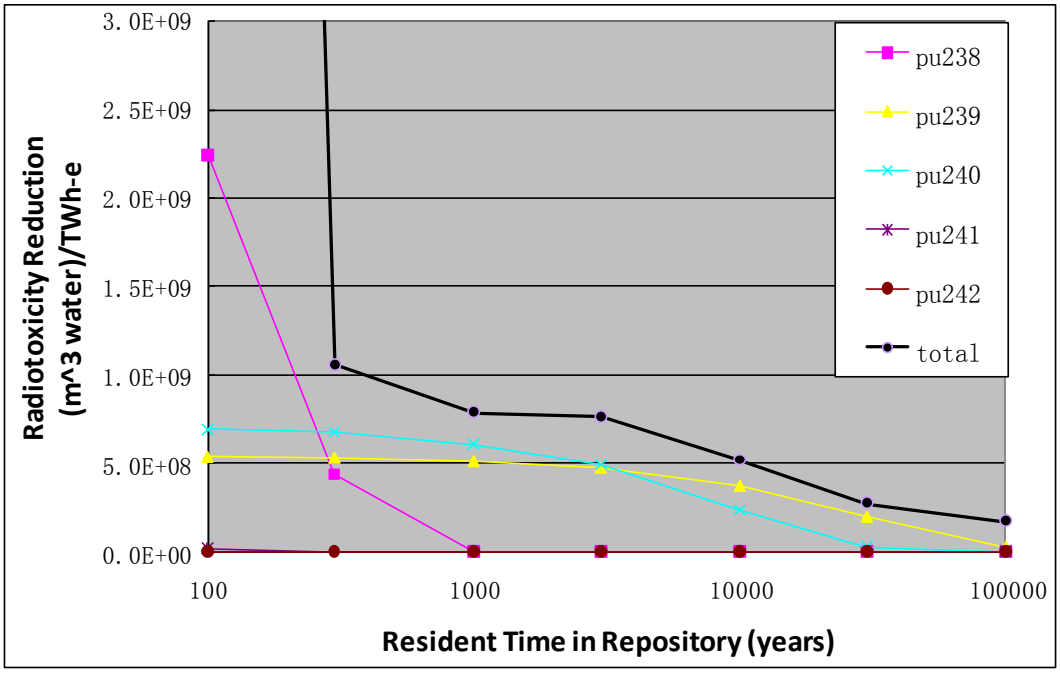


Figure 6.32 Ingestion Net Reduction Benefit Decomposition for MOX M-R

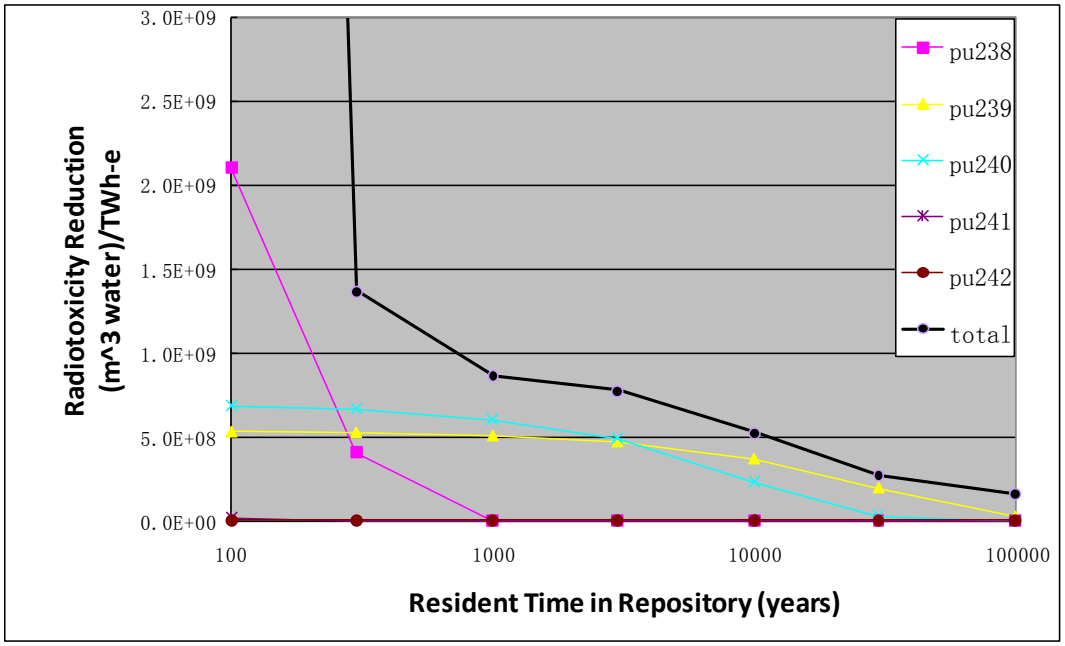


Figure 6.33 Ingestion Net Reduction Benefit Decomposition for cMOX M-R

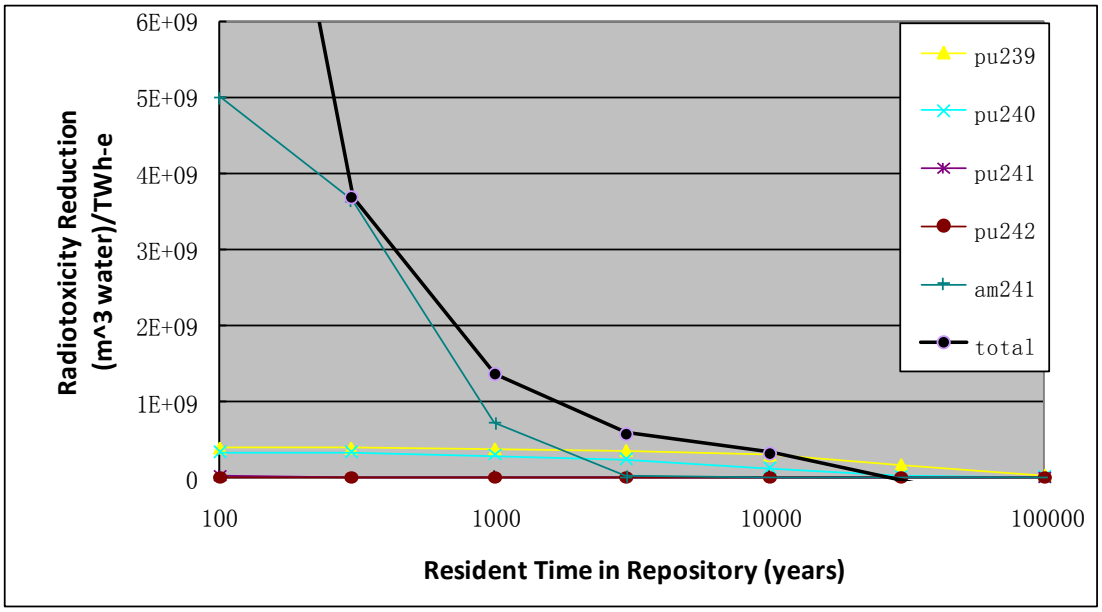


Figure 6.34 Ingestion Net Reduction Benefit Decomposition for IMF-UOX

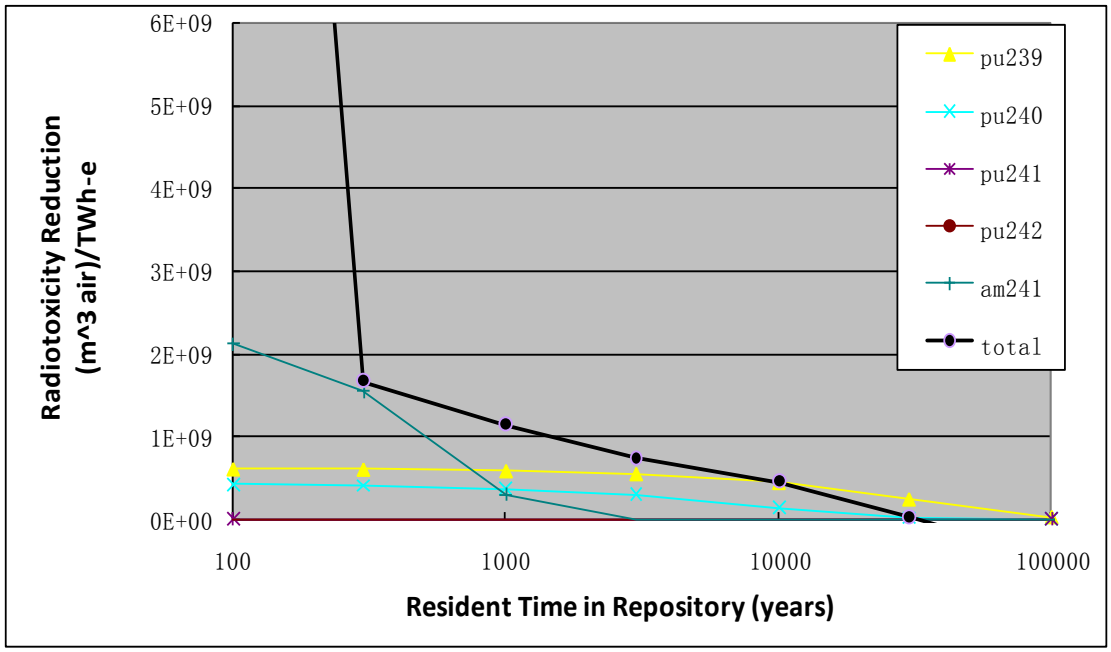


Figure 6.35 Ingestion Net Reduction Benefit Decomposition for IMF-MOX

As can be seen from Figure 6.31 through Figure 6.35, for the MOX cases the largest toxicity contributor is still Pu-238 for the first few hundreds of years followed by Pu-239 and Pu-240 for the remainder of the time. For IMF cases, however, Pu-241 is no longer playing an important role in toxicity net reduction benefit. For both IMF-UOX and IMF-MOX design, Am-241 dominates from the beginning until around 1000 years, then, as in the MOX cases, Pu-239 and Pu-240 stand out for the remainder of the duration.

6.5.2.3 Comprehensive Ingestion Radiotoxicity Production

The comprehensive toxicity concept used here is also similar to that used in inhalation radiotoxicity analysis. The differences still reside in the type of toxicity calculated and the measure employed.

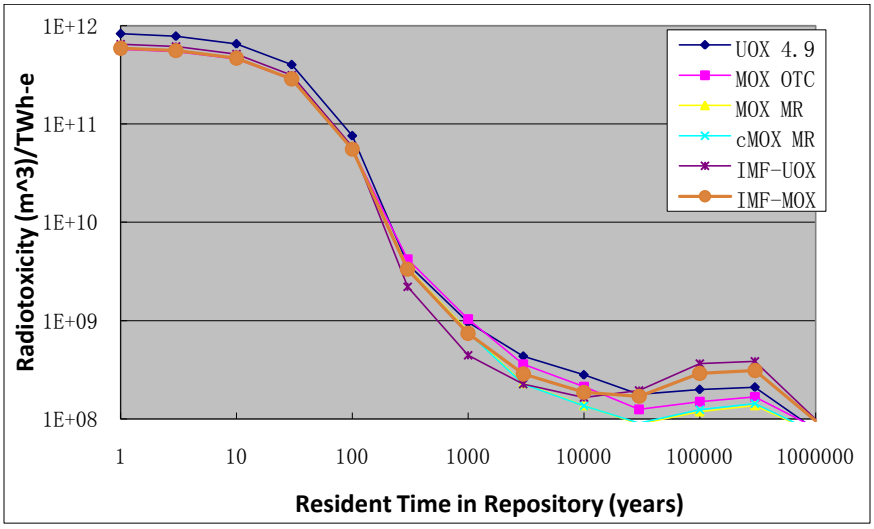


Figure 6.36 Comprehensive Ingestion Radiotoxicity Production

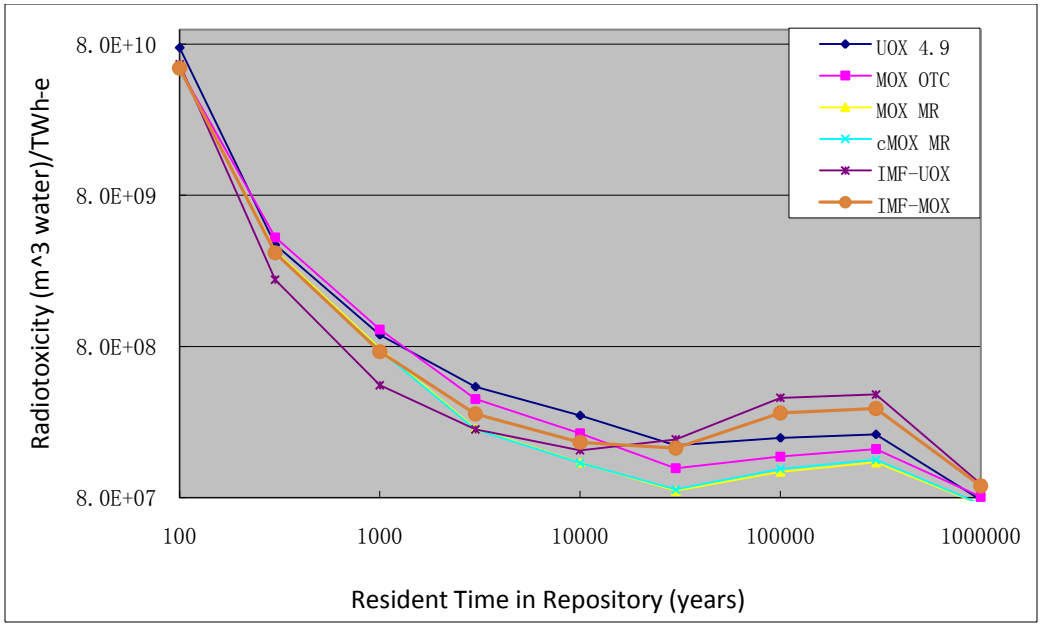


Figure 6.37 Comprehensive Ingestion Radiotoxicity Production (Zoom)

The plots in Figure 6.36 and Figure 6.37 suggest that during the first few thousands of years after discharge, the IMF-UOX design is the best choice while for periods beyond 3000 years MOX M-R or cMOX M-R would be the optimal option. It should be pointed out that after 30,000 years, toxicities for all cases begin to experience a temporary increase and then vanish as time goes on. The principal cause for the toxicity increase is Ra226 and Pb210. These two isotopes get accumulated in long term and their radio-biological factors are significantly increased in ingestion toxicity analyses than in inhalation toxicity analyses. During this increase period, toxicities of both IMF cases can be higher than that of conventional UOX fuels.

6.6 Decay Heat Analyses

All the analyses performed in this section are analogous to those of the inhalation and ingestion radiotoxicity analyses. The only difference is that the impact of the waste is evaluated in decay heat and the measure is Watts. As before, all the results are normalized to 1 TWh of electricity produced.

6.6.1 Net Decay Heat Production

The net decay heat production is defined in a similar manner. At the beginning, the decay heat of all advanced fuel designs is higher than that of conventional UOX fuel. The main contributor is still Cm-244 for MOX cases and Pu-238 for IMF cases.

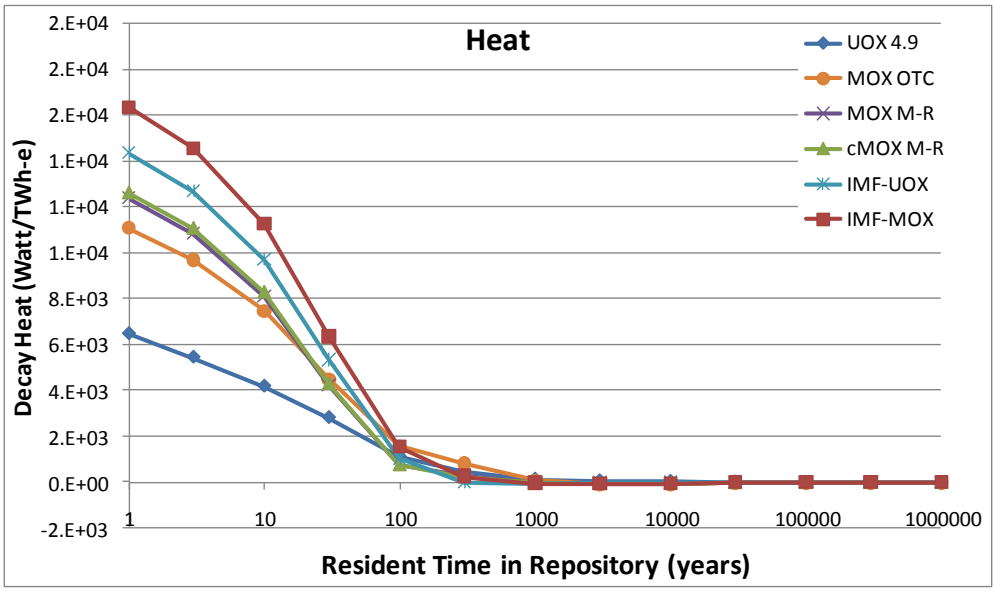


Figure 6.38 Net Decay Heat Production

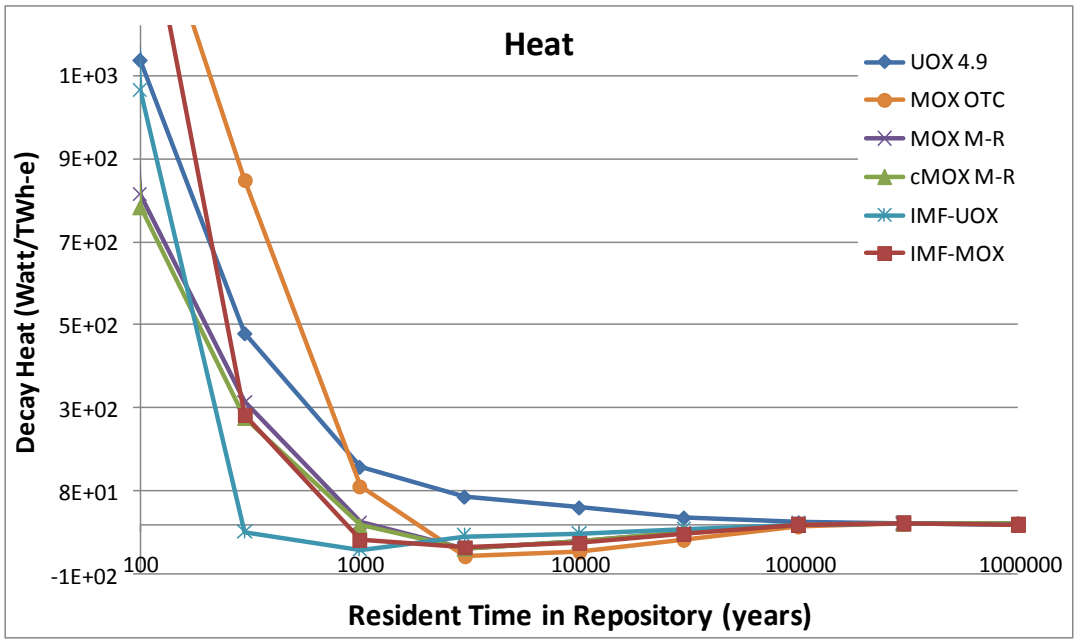


Figure 6.39 Net Decay Heat Production (Zoom)

Figure 6.38 and Figure 6.39 contrasts from the inhalation toxicity analyses. Both MOX M-R and cMOX M-R designs have decay heat levels that do not fall below UOX level until around 100 years. The MOX OTC option is not able to break even with the standard UOX fuel assembly until around 1000 years. The set-in time for IMF-UOX cases, however, is brought forward to about 100 years and its decay heat net reduction between few hundreds of years to few thousands of years is notably greater than other recycling options.

As stated in the reference[3] 1, the decay heat at 1500 years after the repository closes is the most helpful metric to compare options based on heat analyses. Therefore, the decay heat analyses favor the IMF-UOX design.

6.6.2 Decay Heat Net Reduction Benefit by Isotope

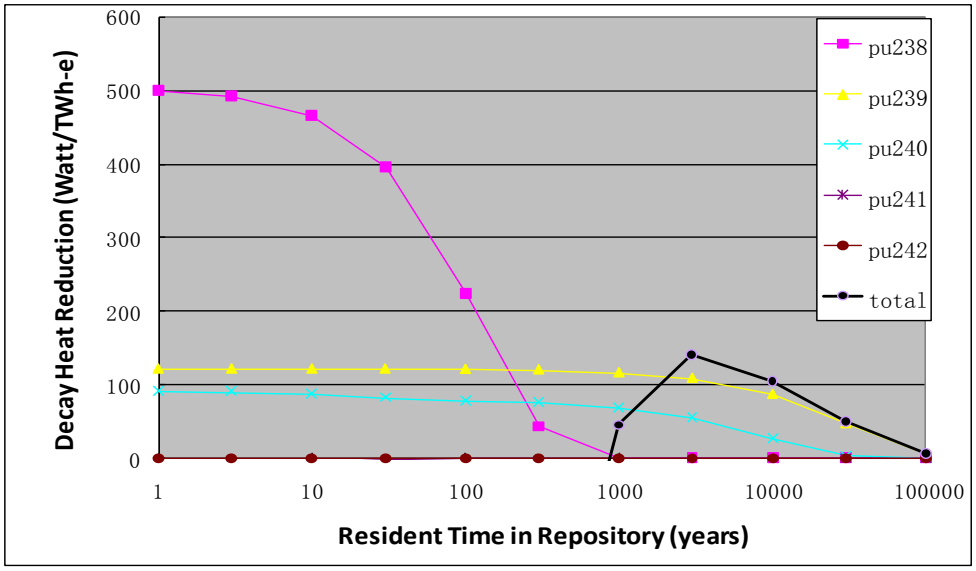


Figure 6.40 Decay Heat Net Reduction Benefit Decomposition for MOX OTC

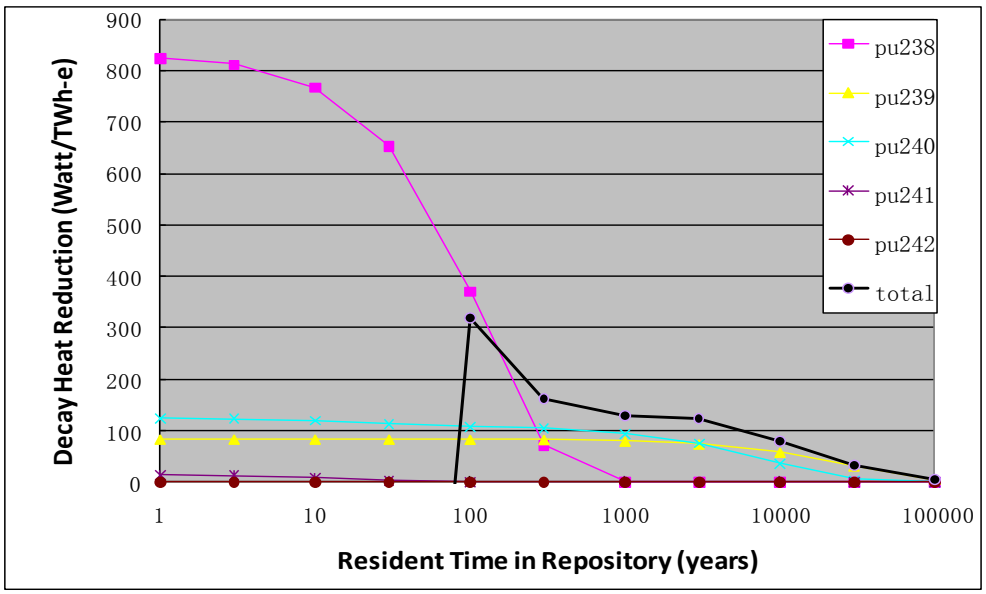


Figure 6.41 Decay Heat Net Reduction Benefit Decomposition for MOX M-R

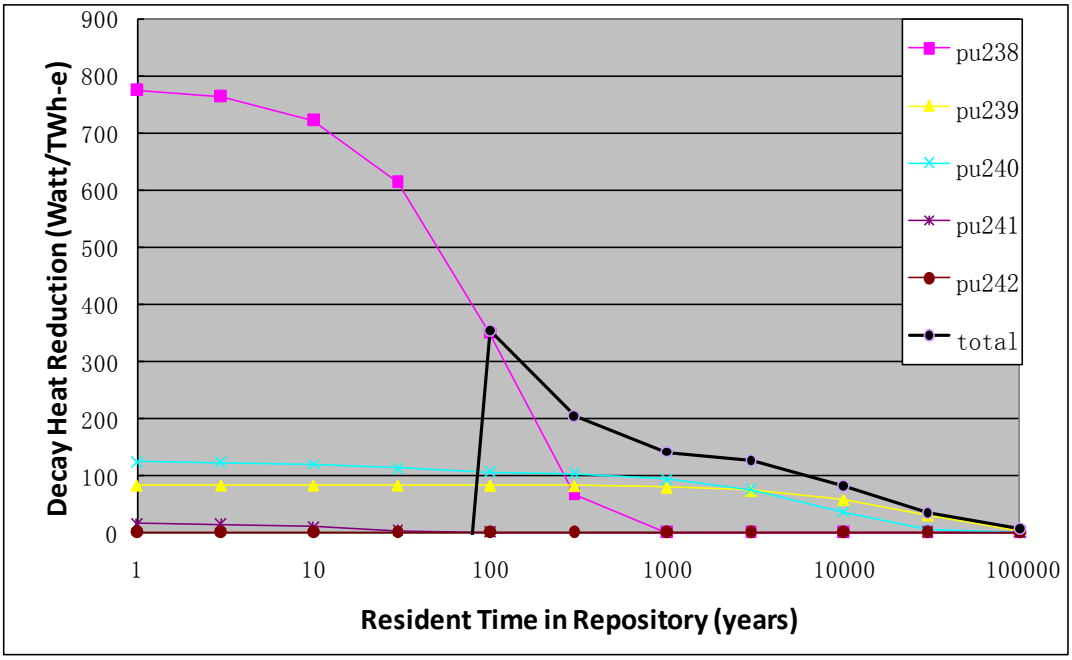


Figure 6.42 Decay Heat Net Reduction Benefit Decomposition for cMOX M-R

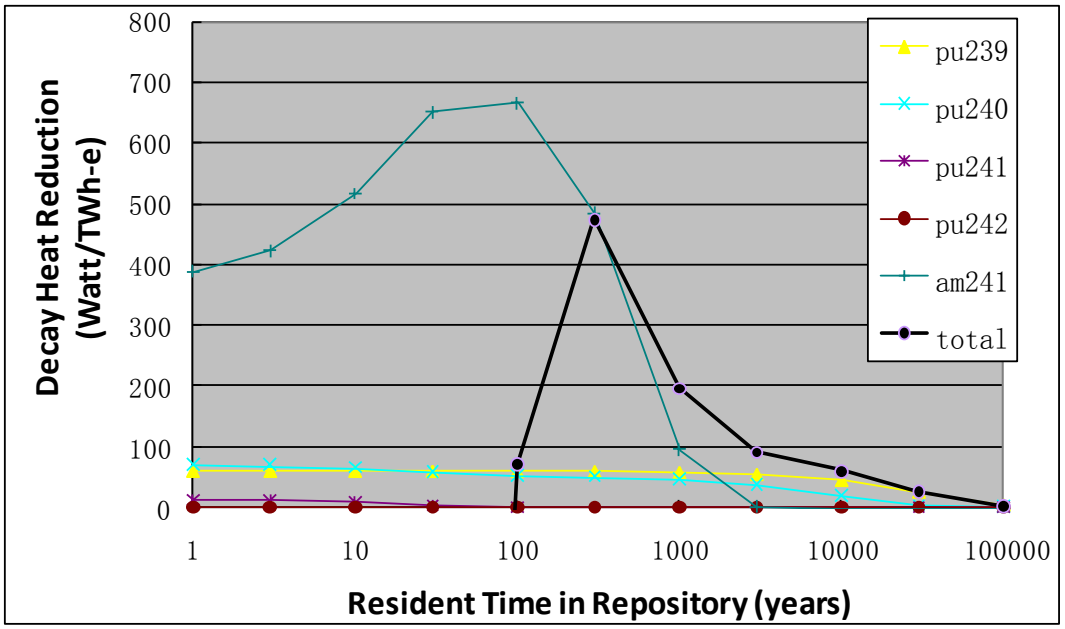


Figure 6.43 Decay Heat Net Reduction Benefit Decomposition for IMF-UOX M-R

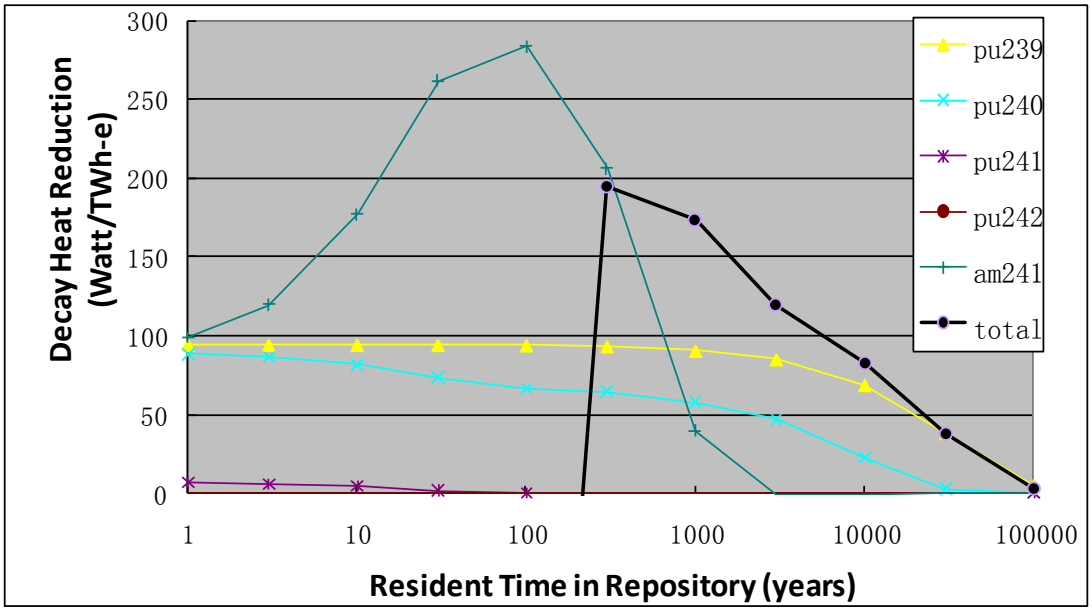


Figure 6.44 Decay Heat Net Reduction Benefit Decomposition for IMF-MOX M-R

It can be seen from Figure 6.40 through Figure 6.44 that, as in toxicity analyses, for MOX cases, the main contributor is Pu-238 before 300 years and after that moment the main contributors are Pu-239 and Pu-240. For the IMF design, Am-241 dominates from the beginning until 1000th year. In the long run, the dominating isotopes for the IMF designs are also Pu-239 followed by Pu-240.

6.6.3 Comprehensive Decay Heat Production

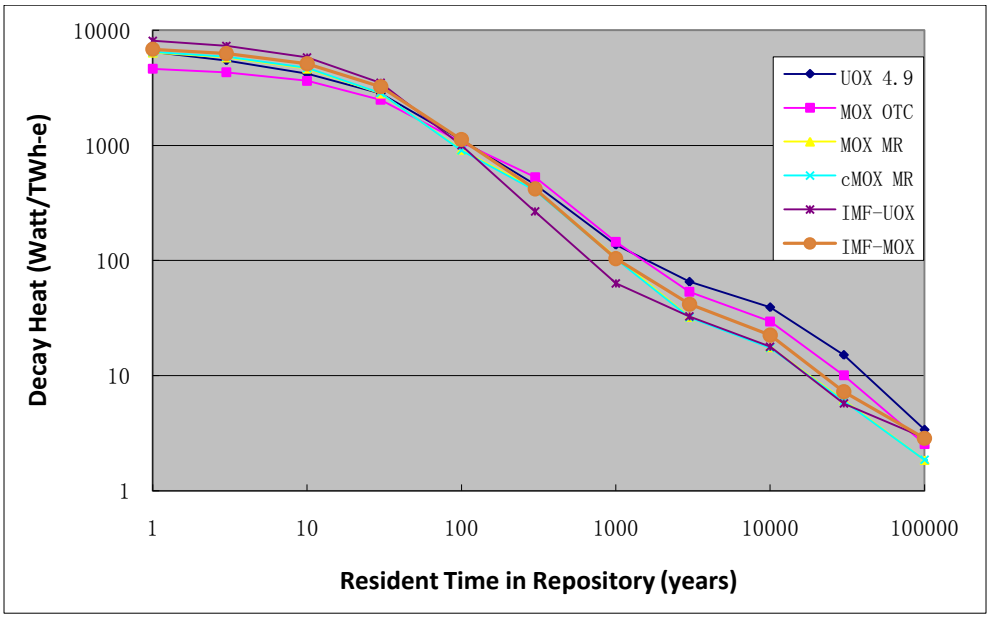


Figure 6.45 Comprehensive Decay Heat Production

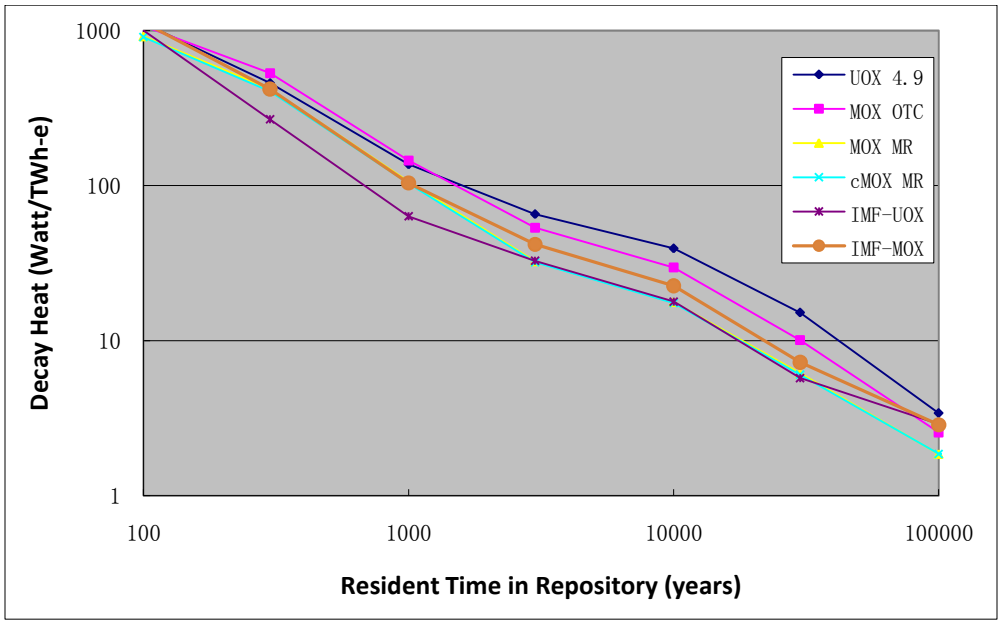


Figure 6.46 Comprehensive Decay Heat Production (Zoom)

As can be seen in Figure 6.45 and Figure 6.46, at the key time period for decay heat restrictions, that is, between 100 years and beyond 1000 years, the IMF-MOX design is better than others. In the first a few years after discharge, however, IMF-UOX is more toxic than conventional UOX assembly while IMF-MOX and the two MOX M-Rs are at the same level as UOX assembly.

6.7 Coating Thickness Variation

As an extended study for the Am-coated MOX M-R assembly design, different coating thickness, ranging from 0 cm to 0.01 cm (measured in diameter), are performed to assess the ability of Am consumption. The study is carried out for both modern UOX and MOX assemblies with once-through cycle strategy. All the assemblies are burned to 60GWd/tHM and values tabulated below are evaluated at 1000 years after discharge.

6.7.1 UOX with Am Coating

Am, Cm, toxicity and heat net production and corresponding benefit are tabulated below along with corresponding coating thickness. The net production is defined as assembly total discharge minus assembly total charge. The “benefit” listed in the Table 6.7.1 is difference between the coated value and the uncoated value.

Table 6.15 Mass Balance, Toxicity and Heat Results for UOX with Coating

Thickness Diameter (cm)	Net Production (/TWh-e)					Am Benefit	Toxicity Benefit	Heat Benefit
	Am (kg)	Cm (kg)	Am + Cm (kg)	Toxicity (m^3 air)	Heat (Watts)			
0	1.56	0.25	1.82	3.45E+16	99.86			
0.001	1.03	0.32	1.35	3.40E+16	95.22	0.53	4.96E+14	4.65
0.002	0.50	0.38	0.89	3.35E+16	90.61	1.06	1.01E+15	9.26
0.004	-0.56	0.51	-0.05	3.25E+16	81.42	2.12	2.00E+15	18.45
0.006	-1.62	0.64	-0.99	3.15E+16	72.29	3.19	2.98E+15	27.57
0.008	-2.69	0.76	-1.92	3.05E+16	63.25	4.25	3.97E+15	36.61
0.01	-3.75	0.89	-2.86	2.95E+16	54.29	5.32	4.94E+15	45.58

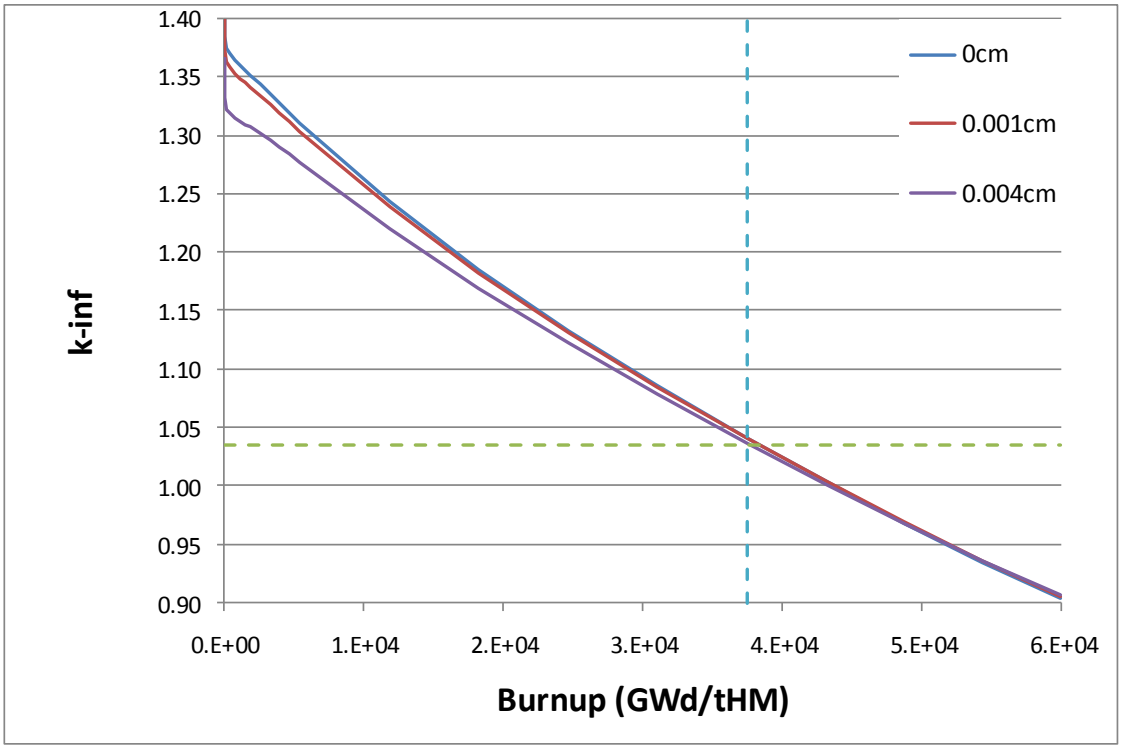


Figure 6.47 k-inf as a Function of Burnup for Various Coating Thickness on UOX

Table 6.15 shows that all three kinds of benefits (Am benefit, toxicity benefit, and heat benefit) increase almost linearly with an increasing coating volume, which is in turn due to the increasing coating thickness. However, according to Figure 6.47, 4.9w% (enrichment upper limit) enriched UOX assembly coated with an Am coating thicker than 0.004 cm will not last through the imposed 60GWd/tHM burnup. But as can be seen from Table 6.7.1, even at 0.004 cm, the Am coating already begins to negate the Am production, that is, a net reduction is achieved.

6.7.2 MOX with Am Coating

For the analyses of the MOX assembly with Am coating, the MOX fuel is set to contain 8w% Pu and the U-235 enrichment varies depending on the coating thickness, ranging from 2.2w% to 4.9w%, so as to compensate the reactivity loss due to the use of coating. Besides, for thick coating cases, the equivalent amount of Am is also ‘fabricated’ as an inner zone (labeled as ‘in’) to see whether placing Am in a faster neutron environment helps to destroy it.

Table 6.16 Mass Balance, Toxicity and Heat Results for MOX with Coating

Thickness Diameter (cm)	Net Production / TWh-e					Am Benefit	Toxicity Benefit	Heat Benefit
	Am (kg)	Cm (kg)	Am + Cm (kg)	Toxicity (m^3 air)	Heat (Watts)			
0	10.13	2.52	12.65	2.32E+17	690.19			
0.002	9.18	3.49	12.67	2.31E+17	677.75	0.95	1.34E+15	12.44
0.008	6.37	2.79	9.15	2.27E+17	642.43	3.76	5.27E+15	47.76
0.008 (in)	6.94	2.65	9.60	2.29E+17	653.51	3.19	2.56E+15	36.68
0.036	-5.74	3.50	-2.23	2.02E+17	458.42	15.87	3.03E+16	231.78
0.036(in)	-3.00	3.27	0.28	2.05E+17	492.12	13.13	2.67E+16	198.07

Case description:

0.008 cm: MOX with 8w% fresh Pu and 2.2w% enriched U.

MOX with 8w% 7th cycled Pu and 4.9w% enriched U is also possible, but not tabulated here.

0.036 cm: MOX with 8w% fresh Pu and 4.9% enriched U.

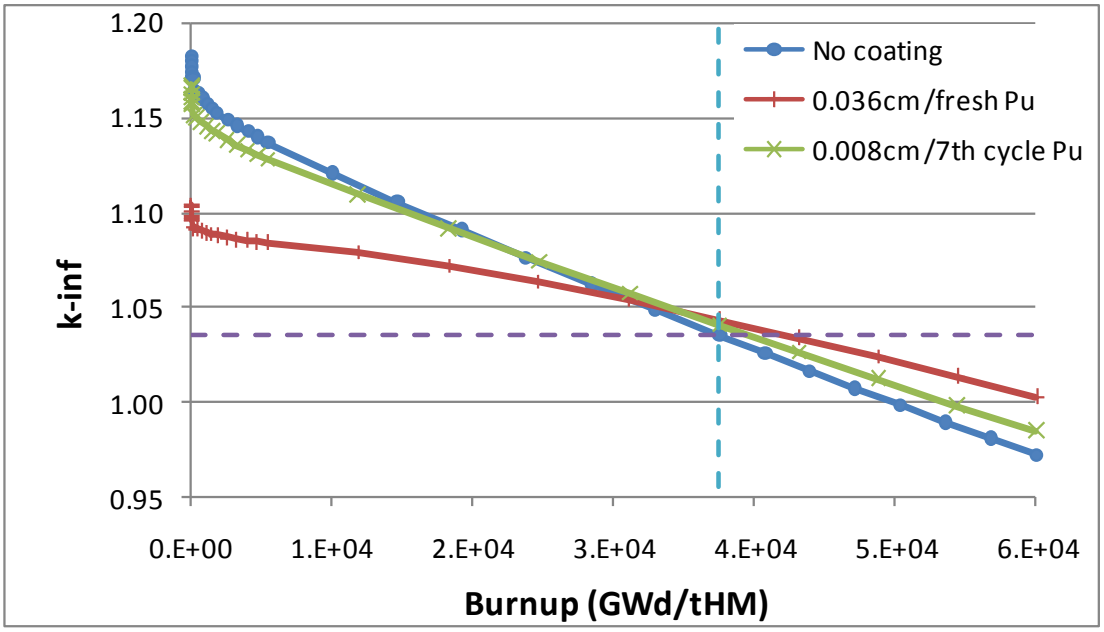


Figure 6.48 k-inf as a Function of Burnup for Various Coating Thickness on MOX

As can be seen from Table 6.16, for the same coating thickness, the Am benefit is slightly lower for the MOX assembly than that for the UOX assembly. The reason is that in UOX assembly the neutron spectrum is softer and the main component of Am, Am-241, is a thermal neutron absorber. However, the softer spectrum also tends to transmute Am into higher actinides such as Cm rather than fission it. For this reason, the toxicity benefit and heat benefit is actually higher for the MOX assembly.

Furthermore, the fissile content in Pu in MOX fuel provides another degree of freedom to compensate for the reactivity loss. As can be seen from Figure 6.48, with fresh Pu (64% fissile) from spent legacy UOX, the MOX assembly can sustain a 0.036 cm thick Am coating while still being able to achieve the imposed campaign length. If loaded with 7^{th} generation Pu (50% fissile), that is the Pu used for the 7^{th} cycle in the MOX M-R design, only a 0.008 cm thick Am coating will be allowed while respecting the 5w% Uranium enrichment limit. This also provides a clue for choosing coating thickness for the MOX M-R design. That is, if we want to recycle MOX assemblies up to 7^{th} cycle, the thickest coating that can be applied is 0.008 cm.

Placing the same Am into an inner zone within the fuel pin does not yield better transmutation benefit. Outer-surface coating will be the preferred choice if coating method is to be employed.

Generally speaking, MOX coating will be more versatile than UOX coating, and can load more, and thus consume more Am than its UOX counterpart.

7. CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

In this study, five advanced TRU burner fuel assembly designs were investigated: MOX once-through cycle, MOX multi-recycling, Am-coated MOX multi-recycling, IMF with UOX inner zone multi-recycling, and IMF with MOX inner zone multi-recycling. Among them, the Am-coated MOX M-R and IMF-MOX M-R designs are new to this research. The IMF-UOX M-R design based on DUPLEX fuel assembly layout is also new. Mass balance, radiotoxicity, and decay heat analyses are carried out for and compared between all these five designs and a separate coating thickness study is also performed.

From a TRU mass balance point of view, one can pursue maximum reduction for a given energy produced (transmutation speed), or maximum fraction destruction of what is loaded into the fuel (transmutation efficiency), or minimum final waste per TWh electricity produced (energy/waste efficiency). This study shows that: the MOX OTC design, which burns 35.29 kg TRU per 1 TWh electricity generation, has the largest transmutation speed; the Am-coated MOX M-R design, which consumes 44.16% of initial TRU loading, has the best transmutation efficiency; the IMF-UOX design, which produces 13.58 kg TRU per 1TWh-e, has the greatest energy/waste efficiency. Generally speaking, multi-recycling strategies dramatically increase the transmutation efficiency but reduce the consumption speed.

The radiotoxicity net production analyses reflect findings in mass balance study, but because of a different figure of merit, the ranking are slightly changed. For the time

period of most concern, that is, between few hundreds of year to few thousands of years, the inhalation toxicity analyses agree with mass balance study and the MOX M-R design and cMOX M-R design reduce toxicity by highest amount among advanced fuel designs, while the ingestion toxicity analysis shows that the IMF-UOX design is the best choice. The reason why the ingestion toxicity analyses depart from the mass balance study is that Am-241 is highly ingestion toxic and it is fully recycled only in the IMF-UOX design, but this fact is masked by Pu net production in the mass balance study. Since in a repository, the most probable contamination is via radioactive waste's contact with underground water, the ingestion toxicity analysis is considered to have more practical importance. Since Am-241 is also the most significant decay heat source, the decay heat analyses also suggests the IMF-UOX design as the best option.

All the comprehensive production analyses on toxicity and decay heat confirm the findings in mass balance study, that is, the IMF-UOX is the most energy/hazard efficient option among those being compared.

Generally speaking, the IMF-UOX design is the best in terms of hazard reduction speed and energy/hazard efficiency, but Am-coated MOX M-R is able to consume the most fraction of the TRU waste that we have at hand.

The advantages of the two new fuel assembly concepts: Am-coated MOX M-R and IMF-MOX M-R are not fully revealed. There are various reasons for that and each of them suggests a direction for further research.

For the Am-coated MOX design, the benefit of burning Am in the coating layer is not obvious when the thickness is only 0.002 cm thick. However, the coating thickness

study suggests that for a multi-recycling process the thickness can be increased to 0.008 cm and thus an Am reduction benefit about 4 times larger can be obtained. However, this study is carried out only for single cycle. A multi-recycling simulation needs to be done to confirm the viability and benefit.

For the IMF-MOX M-R design, the recycling has to be stopped at 3rd cycle. Therefore, the transmutation efficiency is greatly reduced. The reason for that is the neutron spectrum in IMF pins is relatively hard thus reducing the reactivity worth of newly blend-in fresh TRU. After the 3rd cycle, newly blend-in TRU and recycled TRU from previous cycle add up to more than 40w% of IMF pin, which is the upper limit imposed on IMF pin's TRU loading. One way to circumvent this is to use cross-shape cross-sectional geometry for IMF pins instead of conventional cylinder geometry to increase the moderator to fuel ratio for IMF pins. This cross-shape fuel concept was first brought forward by French national laboratory but has not ye been implemented. Another way to compensate for the reactivity loss is to increase the U-235 enrichment in MOX inner pins rather than blending-in fresh TRU. But we can not totally rely on this method since U-235 enrichment is not legally allowed to exceed 5w%.

Also, as we can note from hazard analyses performed in this research, Am-241 plays an important role in both ingestion radiotoxicity and decay heat, but it is not recycled in any MOX pins. If we can recycle Am in MOX pins, maybe together with Np and Cm, a much greater benefit should be expected.

Finally, it has to be pointed out that since the advanced fuel assembly designs tend to produce a harder spectrum, the neutron leakage rate from the core is expected to

be higher than that found in conventional designs because fast neutrons tend to have larger mean free path. Therefore the reactor pressure vessel will see a higher neutron influence, which is harmful to its material integrity. One way to prevent the pressure vessel from increased radiation damage is to place a heavy steel reflector between the fuel and the core barrel[19]. Another important fact is that not all the recycling (partitioning) process assumed in this research is currently available. For example this UREX processes are only tested in laboratory scale[4], and no test on IMF recycling has been performed to our knowledge. These issues are critical for the viability of the advanced fuel multi-recycling scheme, but they are beyond the scope of this research.

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APPENDIX A

ISOTOPIC CONCENTRATION FOR IMPORTANT ISOTOPES AT DIFFERENT BURNUP STAGES.

AVERAGED OVER FUEL REGION, IN UNIT OF ATOMS/(BARN CM).

MOX – 1

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.34E-05	2.96E-05
Y90	0.00E+00	8.50E-09	7.43E-09
Tc99	0.00E+00	7.55E-05	7.57E-05
I129	0.00E+00	1.73E-05	1.74E-05
Cs135	0.00E+00	6.46E-05	6.47E-05
Cs137	0.00E+00	8.60E-05	7.66E-05
Ba137	0.00E+00	4.66E-06	1.40E-05
Pa233	7.31E-25	3.49E-13	3.73E-13
U233	1.72E-27	9.91E-11	1.16E-10
U234	3.54E-10	1.50E-06	3.37E-06
U235	4.45E-04	2.03E-04	2.03E-04
U236	5.15E-11	5.00E-05	5.02E-05
U238	2.10E-02	2.02E-02	2.02E-02
Np237	6.79E-15	1.03E-05	1.08E-05
Pu238	4.48E-05	4.48E-05	4.71E-05
Pu239	1.08E-03	5.25E-04	5.27E-04
Pu240	4.88E-04	4.12E-04	4.16E-04
Pu241	1.13E-04	2.29E-04	1.80E-04
Pu242	1.28E-04	1.40E-04	1.40E-04
Am241	5.41E-09	2.19E-05	7.05E-05
Am242m	0.00E+00	5.09E-07	4.97E-07
Am243	0.00E+00	4.12E-05	4.12E-05
Cm242	0.00E+00	4.16E-06	3.07E-09
Cm243	0.00E+00	1.87E-07	1.67E-07
Cm244	0.00E+00	2.84E-05	2.35E-05
Cm245	0.00E+00	4.01E-06	4.00E-06
Cm246	0.00E+00	3.36E-07	3.36E-07
Cm247	0.00E+00	7.31E-09	7.31E-09
Cm248	0.00E+00	4.86E-10	4.87E-10

MOX – 2

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.65E-05	3.24E-05
Y90	0.00E+00	9.29E-09	8.13E-09
Tc99	0.00E+00	7.58E-05	7.60E-05
I129	0.00E+00	1.68E-05	1.69E-05
Cs135	0.00E+00	6.56E-05	6.56E-05
Cs137	0.00E+00	8.58E-05	7.64E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.38E-24	4.52E-13	4.79E-13
U233	3.25E-27	1.44E-10	1.66E-10
U234	4.75E-10	2.09E-06	4.67E-06
U235	6.84E-04	3.22E-04	3.22E-04
U236	5.90E-11	7.53E-05	7.55E-05
U238	2.08E-02	1.99E-02	1.99E-02
Np237	1.28E-14	1.33E-05	1.39E-05
Pu238	6.02E-05	6.20E-05	6.46E-05
Pu239	8.41E-04	4.85E-04	4.87E-04
Pu240	5.59E-04	4.13E-04	4.19E-04
Pu241	2.13E-04	2.43E-04	1.91E-04
Pu242	1.77E-04	1.91E-04	1.91E-04
Am241	1.02E-08	2.76E-05	7.92E-05
Am242m	0.00E+00	6.70E-07	6.54E-07
Am243	0.00E+00	4.94E-05	4.94E-05
Cm242	0.00E+00	5.21E-06	3.93E-09
Cm243	0.00E+00	2.59E-07	2.31E-07
Cm244	0.00E+00	3.24E-05	2.67E-05
Cm245	0.00E+00	4.52E-06	4.52E-06
Cm246	0.00E+00	3.60E-07	3.60E-07
Cm247	0.00E+00	7.64E-09	7.64E-09
Cm248	0.00E+00	4.87E-10	4.88E-10

MOX – 3

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.81E-05	3.38E-05
Y90	0.00E+00	9.68E-09	8.47E-09
Tc99	0.00E+00	7.61E-05	7.63E-05
I129	0.00E+00	1.66E-05	1.67E-05
Cs135	0.00E+00	6.58E-05	6.59E-05
Cs137	0.00E+00	8.58E-05	7.65E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.44E-24	4.95E-13	5.23E-13
U233	3.38E-27	1.68E-10	1.92E-10
U234	6.06E-10	2.59E-06	5.60E-06
U235	7.93E-04	3.76E-04	3.76E-04
U236	5.80E-11	8.65E-05	8.67E-05
U238	2.07E-02	1.98E-02	1.98E-02
Np237	1.34E-14	1.45E-05	1.51E-05
Pu238	7.67E-05	7.30E-05	7.52E-05
Pu239	7.77E-04	4.74E-04	4.76E-04
Pu240	5.50E-04	4.00E-04	4.06E-04
Pu241	2.22E-04	2.40E-04	1.88E-04
Pu242	2.26E-04	2.28E-04	2.28E-04
Am241	1.07E-08	2.78E-05	7.86E-05
Am242m	0.00E+00	6.80E-07	6.64E-07
Am243	0.00E+00	5.47E-05	5.47E-05
Cm242	0.00E+00	5.21E-06	3.96E-09
Cm243	0.00E+00	2.62E-07	2.33E-07
Cm244	0.00E+00	3.54E-05	2.92E-05
Cm245	0.00E+00	4.91E-06	4.91E-06
Cm246	0.00E+00	3.87E-07	3.87E-07
Cm247	0.00E+00	8.16E-09	8.16E-09
Cm248	0.00E+00	5.17E-10	5.17E-10

MOX – 4

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.87E-05	3.44E-05
Y90	0.00E+00	9.85E-09	8.62E-09
Tc99	0.00E+00	7.61E-05	7.63E-05
I129	0.00E+00	1.65E-05	1.66E-05
Cs135	0.00E+00	6.57E-05	6.58E-05
Cs137	0.00E+00	8.58E-05	7.65E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.41E-24	5.13E-13	5.41E-13
U233	3.31E-27	1.79E-10	2.04E-10
U234	6.85E-10	2.88E-06	6.11E-06
U235	8.36E-04	3.97E-04	3.97E-04
U236	5.61E-11	9.11E-05	9.13E-05
U238	2.06E-02	1.98E-02	1.98E-02
Np237	1.31E-14	1.51E-05	1.57E-05
Pu238	8.67E-05	7.88E-05	8.08E-05
Pu239	7.53E-04	4.68E-04	4.69E-04
Pu240	5.32E-04	3.88E-04	3.95E-04
Pu241	2.17E-04	2.34E-04	1.84E-04
Pu242	2.61E-04	2.55E-04	2.55E-04
Am241	1.05E-08	2.72E-05	7.68E-05
Am242m	0.00E+00	6.64E-07	6.48E-07
Am243	0.00E+00	5.81E-05	5.81E-05
Cm242	0.00E+00	5.09E-06	3.87E-09
Cm243	0.00E+00	2.57E-07	2.29E-07
Cm244	0.00E+00	3.75E-05	3.09E-05
Cm245	0.00E+00	5.19E-06	5.19E-06
Cm246	0.00E+00	4.10E-07	4.10E-07
Cm247	0.00E+00	8.65E-09	8.65E-09
Cm248	0.00E+00	5.51E-10	5.51E-10

MOX – 5

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.92E-05	3.48E-05
Y90	0.00E+00	9.98E-09	8.74E-09
Tc99	0.00E+00	7.62E-05	7.64E-05
I129	0.00E+00	1.64E-05	1.65E-05
Cs135	0.00E+00	6.57E-05	6.57E-05
Cs137	0.00E+00	8.58E-05	7.65E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.38E-24	5.26E-13	5.54E-13
U233	3.24E-27	1.86E-10	2.11E-10
U234	7.27E-10	3.04E-06	6.38E-06
U235	8.69E-04	4.13E-04	4.13E-04
U236	5.46E-11	9.45E-05	9.47E-05
U238	2.06E-02	1.98E-02	1.98E-02
Np237	1.28E-14	1.54E-05	1.60E-05
Pu238	9.20E-05	8.18E-05	8.35E-05
Pu239	7.41E-04	4.65E-04	4.66E-04
Pu240	5.17E-04	3.80E-04	3.86E-04
Pu241	2.12E-04	2.30E-04	1.81E-04
Pu242	2.87E-04	2.75E-04	2.75E-04
Am241	1.02E-08	2.66E-05	7.54E-05
Am242m	0.00E+00	6.50E-07	6.34E-07
Am243	0.00E+00	6.04E-05	6.04E-05
Cm242	0.00E+00	4.99E-06	3.79E-09
Cm243	0.00E+00	2.51E-07	2.24E-07
Cm244	0.00E+00	3.88E-05	3.21E-05
Cm245	0.00E+00	5.37E-06	5.36E-06
Cm246	0.00E+00	4.24E-07	4.24E-07
Cm247	0.00E+00	8.94E-09	8.94E-09
Cm248	0.00E+00	5.71E-10	5.71E-10

MOX – 6

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.96E-05	3.51E-05
Y90	0.00E+00	1.01E-08	8.81E-09
Tc99	0.00E+00	7.63E-05	7.65E-05
I129	0.00E+00	1.64E-05	1.65E-05
Cs135	0.00E+00	6.57E-05	6.57E-05
Cs137	0.00E+00	8.59E-05	7.65E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.36E-24	5.35E-13	5.62E-13
U233	3.18E-27	1.90E-10	2.16E-10
U234	7.47E-10	3.11E-06	6.50E-06
U235	8.90E-04	4.24E-04	4.24E-04
U236	5.35E-11	9.68E-05	9.70E-05
U238	2.06E-02	1.98E-02	1.98E-02
Np237	1.26E-14	1.57E-05	1.63E-05
Pu238	9.46E-05	8.31E-05	8.47E-05
Pu239	7.33E-04	4.62E-04	4.64E-04
Pu240	5.07E-04	3.74E-04	3.80E-04
Pu241	2.09E-04	2.27E-04	1.78E-04
Pu242	3.06E-04	2.89E-04	2.89E-04
Am241	1.00E-08	2.62E-05	7.43E-05
Am242m	0.00E+00	6.39E-07	6.24E-07
Am243	0.00E+00	6.20E-05	6.20E-05
Cm242	0.00E+00	4.91E-06	3.73E-09
Cm243	0.00E+00	2.47E-07	2.20E-07
Cm244	0.00E+00	3.97E-05	3.28E-05
Cm245	0.00E+00	5.48E-06	5.48E-06
Cm246	0.00E+00	4.34E-07	4.34E-07
Cm247	0.00E+00	9.14E-09	9.14E-09
Cm248	0.00E+00	5.85E-10	5.85E-10

MOX – 7

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.98E-05	3.53E-05
Y90	0.00E+00	1.01E-08	8.85E-09
Tc99	0.00E+00	7.63E-05	7.65E-05
I129	0.00E+00	1.64E-05	1.64E-05
Cs135	0.00E+00	6.56E-05	6.56E-05
Cs137	0.00E+00	8.59E-05	7.65E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	1.34E-24	5.39E-13	5.67E-13
U233	3.14E-27	1.92E-10	2.18E-10
U234	7.55E-10	3.14E-06	6.54E-06
U235	9.01E-04	4.28E-04	4.28E-04
U236	5.27E-11	9.80E-05	9.82E-05
U238	2.06E-02	1.97E-02	1.97E-02
Np237	1.24E-14	1.58E-05	1.64E-05
Pu238	9.56E-05	8.35E-05	8.51E-05
Pu239	7.28E-04	4.60E-04	4.62E-04
Pu240	5.00E-04	3.69E-04	3.76E-04
Pu241	2.06E-04	2.25E-04	1.77E-04
Pu242	3.20E-04	2.99E-04	2.99E-04
Am241	9.90E-09	2.59E-05	7.36E-05
Am242m	0.00E+00	6.31E-07	6.16E-07
Am243	0.00E+00	6.32E-05	6.32E-05
Cm242	0.00E+00	4.86E-06	3.68E-09
Cm243	0.00E+00	2.45E-07	2.18E-07
Cm244	0.00E+00	4.05E-05	3.34E-05
Cm245	0.00E+00	5.58E-06	5.57E-06
Cm246	0.00E+00	4.43E-07	4.42E-07
Cm247	0.00E+00	9.33E-09	9.33E-09
Cm248	0.00E+00	5.98E-10	5.98E-10

cMOX – 1

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.36E-05	2.99E-05
Y90	0.00E+00	8.56E-09	7.49E-09
Tc99	0.00E+00	7.53E-05	7.55E-05
I129	0.00E+00	1.71E-05	1.72E-05
Cs135	0.00E+00	6.47E-05	6.47E-05
Cs137	0.00E+00	8.56E-05	7.63E-05
Ba137	0.00E+00	4.64E-06	1.40E-05
Pa233	2.79E-21	3.62E-13	3.85E-13
U233	8.73E-24	1.05E-10	1.22E-10
U234	3.52E-10	1.58E-06	3.64E-06
U235	4.75E-04	2.19E-04	2.19E-04
U236	5.12E-11	5.31E-05	5.33E-05
U238	2.09E-02	2.00E-02	2.00E-02
Np237	1.73E-11	1.06E-05	1.12E-05
Pu238	4.46E-05	4.92E-05	5.18E-05
Pu239	1.07E-03	5.30E-04	5.31E-04
Pu240	4.85E-04	4.11E-04	4.16E-04
Pu241	1.12E-04	2.28E-04	1.79E-04
Pu242	1.28E-04	1.39E-04	1.39E-04
Am241	1.08E-05	2.32E-05	7.16E-05
Am242m	7.45E-09	5.49E-07	5.36E-07
Am243	1.67E-06	4.15E-05	4.15E-05
Cm242	3.01E-14	4.52E-06	3.33E-09
Cm243	0.00E+00	2.26E-07	2.02E-07
Cm244	0.00E+00	2.90E-05	2.39E-05
Cm245	0.00E+00	4.13E-06	4.13E-06
Cm246	0.00E+00	3.54E-07	3.54E-07
Cm247	0.00E+00	7.84E-09	7.84E-09
Cm248	0.00E+00	5.40E-10	5.41E-10

cMOX – 2

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.67E-05	3.26E-05
Y90	0.00E+00	9.34E-09	8.18E-09
Tc99	0.00E+00	7.56E-05	7.58E-05
I129	0.00E+00	1.67E-05	1.67E-05
Cs135	0.00E+00	6.56E-05	6.56E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	2.03E-21	4.61E-13	4.88E-13
U233	6.34E-24	1.51E-10	1.73E-10
U234	5.08E-10	2.28E-06	5.08E-06
U235	7.13E-04	3.38E-04	3.38E-04
U236	5.84E-11	7.80E-05	7.82E-05
U238	2.06E-02	1.98E-02	1.98E-02
Np237	1.26E-11	1.35E-05	1.42E-05
Pu238	6.43E-05	6.77E-05	7.04E-05
Pu239	8.37E-04	4.89E-04	4.90E-04
Pu240	5.54E-04	4.12E-04	4.18E-04
Pu241	2.11E-04	2.42E-04	1.91E-04
Pu242	1.75E-04	1.89E-04	1.89E-04
Am241	7.86E-06	2.86E-05	7.99E-05
Am242m	5.87E-08	7.02E-07	6.85E-07
Am243	4.55E-06	5.01E-05	5.01E-05
Cm242	2.37E-13	5.45E-06	4.11E-09
Cm243	0.00E+00	2.85E-07	2.54E-07
Cm244	0.00E+00	3.41E-05	2.81E-05
Cm245	0.00E+00	4.89E-06	4.89E-06
Cm246	0.00E+00	4.16E-07	4.16E-07
Cm247	0.00E+00	9.25E-09	9.25E-09
Cm248	0.00E+00	6.40E-10	6.41E-10

cMOX – 3

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.82E-05	3.40E-05
Y90	0.00E+00	9.72E-09	8.52E-09
Tc99	0.00E+00	7.58E-05	7.60E-05
I129	0.00E+00	1.65E-05	1.65E-05
Cs135	0.00E+00	6.58E-05	6.59E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	1.97E-21	5.03E-13	5.31E-13
U233	6.15E-24	1.76E-10	2.00E-10
U234	6.47E-10	2.81E-06	6.07E-06
U235	8.21E-04	3.93E-04	3.93E-04
U236	5.75E-11	8.91E-05	8.93E-05
U238	2.05E-02	1.97E-02	1.97E-02
Np237	1.22E-11	1.48E-05	1.54E-05
Pu238	8.19E-05	7.93E-05	8.16E-05
Pu239	7.73E-04	4.77E-04	4.79E-04
Pu240	5.45E-04	3.99E-04	4.06E-04
Pu241	2.19E-04	2.39E-04	1.88E-04
Pu242	2.22E-04	2.25E-04	2.25E-04
Am241	7.63E-06	2.88E-05	7.94E-05
Am242m	6.53E-08	7.13E-07	6.95E-07
Am243	4.77E-06	5.53E-05	5.53E-05
Cm242	2.64E-13	5.44E-06	4.14E-09
Cm243	0.00E+00	2.87E-07	2.56E-07
Cm244	0.00E+00	3.70E-05	3.05E-05
Cm245	0.00E+00	5.28E-06	5.28E-06
Cm246	0.00E+00	4.42E-07	4.42E-07
Cm247	0.00E+00	9.74E-09	9.74E-09
Cm248	0.00E+00	6.66E-10	6.67E-10

cMOX – 4

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.89E-05	3.45E-05
Y90	0.00E+00	9.89E-09	8.66E-09
Tc99	0.00E+00	7.59E-05	7.61E-05
I129	0.00E+00	1.64E-05	1.64E-05
Cs135	0.00E+00	6.58E-05	6.58E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	1.89E-21	5.21E-13	5.49E-13
U233	5.90E-24	1.87E-10	2.12E-10
U234	7.30E-10	3.12E-06	6.61E-06
U235	8.64E-04	4.14E-04	4.14E-04
U236	5.56E-11	9.37E-05	9.39E-05
U238	2.05E-02	1.97E-02	1.97E-02
Np237	1.17E-11	1.53E-05	1.59E-05
Pu238	9.25E-05	8.55E-05	8.73E-05
Pu239	7.49E-04	4.71E-04	4.73E-04
Pu240	5.27E-04	3.87E-04	3.94E-04
Pu241	2.15E-04	2.33E-04	1.83E-04
Pu242	2.56E-04	2.51E-04	2.51E-04
Am241	7.31E-06	2.82E-05	7.76E-05
Am242m	6.40E-08	6.95E-07	6.78E-07
Am243	5.08E-06	5.87E-05	5.87E-05
Cm242	2.59E-13	5.32E-06	4.04E-09
Cm243	0.00E+00	2.81E-07	2.50E-07
Cm244	0.00E+00	3.91E-05	3.23E-05
Cm245	0.00E+00	5.57E-06	5.57E-06
Cm246	0.00E+00	4.67E-07	4.67E-07
Cm247	0.00E+00	1.03E-08	1.03E-08
Cm248	0.00E+00	7.07E-10	7.07E-10

cMOX – 5

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.94E-05	3.50E-05
Y90	0.00E+00	1.00E-08	8.77E-09
Tc99	0.00E+00	7.60E-05	7.62E-05
I129	0.00E+00	1.63E-05	1.64E-05
Cs135	0.00E+00	6.57E-05	6.58E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	1.82E-21	5.33E-13	5.61E-13
U233	5.70E-24	1.94E-10	2.20E-10
U234	7.74E-10	3.27E-06	6.88E-06
U235	8.96E-04	4.30E-04	4.30E-04
U236	5.41E-11	9.70E-05	9.72E-05
U238	2.04E-02	1.96E-02	1.96E-02
Np237	1.13E-11	1.56E-05	1.63E-05
Pu238	9.79E-05	8.84E-05	9.01E-05
Pu239	7.38E-04	4.68E-04	4.70E-04
Pu240	5.13E-04	3.79E-04	3.86E-04
Pu241	2.10E-04	2.29E-04	1.80E-04
Pu242	2.81E-04	2.69E-04	2.69E-04
Am241	7.06E-06	2.76E-05	7.62E-05
Am242m	6.17E-08	6.81E-07	6.64E-07
Am243	5.33E-06	6.09E-05	6.09E-05
Cm242	2.49E-13	5.20E-06	3.96E-09
Cm243	0.00E+00	2.75E-07	2.45E-07
Cm244	0.00E+00	4.05E-05	3.35E-05
Cm245	0.00E+00	5.75E-06	5.75E-06
Cm246	0.00E+00	4.83E-07	4.83E-07
Cm247	0.00E+00	1.06E-08	1.06E-08
Cm248	0.00E+00	7.31E-10	7.32E-10

cMOX – 6

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.97E-05	3.53E-05
Y90	0.00E+00	1.01E-08	8.85E-09
Tc99	0.00E+00	7.60E-05	7.62E-05
I129	0.00E+00	1.63E-05	1.63E-05
Cs135	0.00E+00	6.57E-05	6.58E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	1.78E-21	5.42E-13	5.69E-13
U233	5.56E-24	1.98E-10	2.24E-10
U234	7.94E-10	3.35E-06	7.00E-06
U235	9.18E-04	4.41E-04	4.41E-04
U236	5.31E-11	9.92E-05	9.94E-05
U238	2.04E-02	1.96E-02	1.96E-02
Np237	1.10E-11	1.59E-05	1.65E-05
Pu238	1.01E-04	8.97E-05	9.13E-05
Pu239	7.31E-04	4.66E-04	4.68E-04
Pu240	5.03E-04	3.73E-04	3.80E-04
Pu241	2.07E-04	2.26E-04	1.78E-04
Pu242	2.99E-04	2.83E-04	2.83E-04
Am241	6.89E-06	2.72E-05	7.52E-05
Am242m	6.00E-08	6.70E-07	6.54E-07
Am243	5.50E-06	6.25E-05	6.25E-05
Cm242	2.43E-13	5.12E-06	3.90E-09
Cm243	0.00E+00	2.71E-07	2.41E-07
Cm244	0.00E+00	4.15E-05	3.42E-05
Cm245	0.00E+00	5.87E-06	5.87E-06
Cm246	0.00E+00	4.94E-07	4.93E-07
Cm247	0.00E+00	1.09E-08	1.09E-08
Cm248	0.00E+00	7.48E-10	7.48E-10

cMOX – 7

	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.99E-05	3.54E-05
Y90	0.00E+00	1.01E-08	8.89E-09
Tc99	0.00E+00	7.60E-05	7.62E-05
I129	0.00E+00	1.62E-05	1.63E-05
Cs135	0.00E+00	6.57E-05	6.57E-05
Cs137	0.00E+00	8.54E-05	7.61E-05
Ba137	0.00E+00	4.62E-06	1.39E-05
Pa233	1.75E-21	5.46E-13	5.74E-13
U233	5.47E-24	1.99E-10	2.26E-10
U234	8.02E-10	3.38E-06	7.04E-06
U235	9.29E-04	4.46E-04	4.46E-04
U236	5.24E-11	1.00E-04	1.01E-04
U238	2.04E-02	1.96E-02	1.96E-02
Np237	1.08E-11	1.60E-05	1.66E-05
Pu238	1.02E-04	9.02E-05	9.16E-05
Pu239	7.26E-04	4.64E-04	4.66E-04
Pu240	4.96E-04	3.69E-04	3.76E-04
Pu241	2.04E-04	2.24E-04	1.76E-04
Pu242	3.12E-04	2.93E-04	2.93E-04
Am241	6.78E-06	2.69E-05	7.44E-05
Am242m	5.89E-08	6.62E-07	6.46E-07
Am243	5.62E-06	6.36E-05	6.36E-05
Cm242	2.38E-13	5.07E-06	3.85E-09
Cm243	0.00E+00	2.68E-07	2.39E-07
Cm244	0.00E+00	4.22E-05	3.48E-05
Cm245	0.00E+00	5.97E-06	5.97E-06
Cm246	0.00E+00	5.03E-07	5.02E-07
Cm247	0.00E+00	1.11E-08	1.11E-08
Cm248	0.00E+00	7.63E-10	7.64E-10

IMF-UOX – 1

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	5.43E-05	4.82E-05	0.00E+00	1.39E-05	1.23E-05
Y90	0.00E+00	1.41E-08	1.21E-08	0.00E+00	3.62E-09	3.09E-09
Tc99	0.00E+00	7.25E-05	7.28E-05	0.00E+00	4.05E-05	4.06E-05
I129	0.00E+00	1.31E-05	1.31E-05	0.00E+00	1.08E-05	1.09E-05
Cs135	0.00E+00	3.14E-05	3.15E-05	0.00E+00	2.71E-05	2.71E-05
Cs137	0.00E+00	8.29E-05	7.39E-05	0.00E+00	4.99E-05	4.44E-05
Ba137	0.00E+00	3.98E-06	1.30E-05	0.00E+00	2.52E-06	7.96E-06
Pa233	0.00E+00	7.67E-13	7.86E-13	2.70E-14	9.66E-13	9.63E-13
U233	0.00E+00	7.10E-11	1.08E-10	1.27E-16	7.93E-11	1.24E-10
U234	1.22E-06	6.69E-07	1.12E-06	2.45E-10	2.06E-06	6.53E-06
U235	1.15E-03	2.19E-04	2.19E-04	2.14E-11	6.52E-07	6.58E-07
U236	0.00E+00	1.48E-04	1.48E-04	3.56E-11	2.30E-07	3.13E-07
U238	2.21E-02	2.11E-02	2.11E-02	1.65E-13	1.24E-09	2.46E-09
Np237	0.00E+00	2.23E-05	2.28E-05	8.39E-05	2.77E-05	2.79E-05
Pu238	0.00E+00	1.09E-05	1.12E-05	3.10E-05	1.06E-04	1.12E-04
Pu239	0.00E+00	1.58E-04	1.61E-04	7.45E-04	4.63E-05	4.64E-05
Pu240	0.00E+00	7.27E-05	7.31E-05	3.37E-04	1.53E-04	1.60E-04
Pu241	0.00E+00	4.72E-05	3.71E-05	7.77E-05	9.86E-05	7.75E-05
Pu242	0.00E+00	2.17E-05	2.17E-05	8.88E-05	1.32E-04	1.32E-04
Am241	0.00E+00	1.70E-06	1.17E-05	1.30E-04	1.56E-05	3.64E-05
Am242m	0.00E+00	2.72E-08	2.65E-08	8.94E-08	2.98E-07	2.90E-07
Am243	0.00E+00	5.46E-06	5.46E-06	2.00E-05	4.17E-05	4.17E-05
Cm242	0.00E+00	6.97E-07	3.67E-10	6.06E-14	1.03E-05	5.15E-09
Cm243	0.00E+00	2.19E-08	1.95E-08	0.00E+00	7.13E-07	6.36E-07
Cm244	0.00E+00	2.60E-06	2.15E-06	0.00E+00	3.95E-05	3.27E-05
Cm245	0.00E+00	1.97E-07	1.97E-07	0.00E+00	4.82E-06	4.82E-06
Cm246	0.00E+00	2.44E-08	2.44E-08	0.00E+00	1.08E-06	1.08E-06
Cm247	0.00E+00	3.62E-10	3.62E-10	0.00E+00	2.67E-08	2.67E-08
Cm248	0.00E+00	2.86E-11	2.86E-11	0.00E+00	2.78E-09	2.79E-09

IMF-UOX – 2

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	5.21E-05	4.62E-05	0.00E+00	1.59E-05	1.41E-05
Y90	0.00E+00	1.35E-08	1.16E-08	0.00E+00	4.06E-09	3.53E-09
Tc99	0.00E+00	6.94E-05	6.96E-05	0.00E+00	4.75E-05	4.77E-05
I129	0.00E+00	1.24E-05	1.25E-05	0.00E+00	1.25E-05	1.26E-05
Cs135	0.00E+00	3.19E-05	3.19E-05	0.00E+00	3.94E-05	3.95E-05
Cs137	0.00E+00	7.89E-05	7.03E-05	0.00E+00	5.67E-05	5.05E-05
Ba137	0.00E+00	3.83E-06	1.24E-05	0.00E+00	2.78E-06	8.96E-06
Pa233	0.00E+00	7.54E-13	7.74E-13	4.38E-14	2.00E-12	2.01E-12
U233	0.00E+00	7.86E-11	1.15E-10	2.06E-16	2.09E-10	3.03E-10
U234	1.22E-06	6.88E-07	1.11E-06	1.24E-09	5.95E-06	1.54E-05
U235	1.15E-03	2.51E-04	2.51E-04	2.68E-11	2.08E-06	2.10E-06
U236	0.00E+00	1.46E-04	1.46E-04	5.93E-11	4.64E-07	6.59E-07
U238	2.21E-02	2.12E-02	2.12E-02	4.49E-13	2.64E-09	5.09E-09
Np237	0.00E+00	2.20E-05	2.24E-05	1.36E-04	5.77E-05	5.82E-05
Pu238	0.00E+00	1.03E-05	1.06E-05	1.57E-04	2.31E-04	2.37E-04
Pu239	0.00E+00	1.73E-04	1.75E-04	9.33E-04	1.71E-04	1.71E-04
Pu240	0.00E+00	7.10E-05	7.13E-05	5.62E-04	3.64E-04	3.75E-04
Pu241	0.00E+00	4.87E-05	3.83E-05	2.06E-04	1.99E-04	1.57E-04
Pu242	0.00E+00	1.94E-05	1.94E-05	2.42E-04	2.65E-04	2.65E-04
Am241	0.00E+00	1.87E-06	1.22E-05	1.62E-04	4.83E-05	9.04E-05
Am242m	0.00E+00	3.12E-08	3.05E-08	4.10E-07	1.15E-06	1.12E-06
Am243	0.00E+00	4.83E-06	4.83E-06	6.76E-05	7.87E-05	7.87E-05
Cm242	0.00E+00	6.60E-07	3.62E-10	2.78E-13	1.55E-05	9.54E-09
Cm243	0.00E+00	2.03E-08	1.81E-08	0.00E+00	1.01E-06	9.03E-07
Cm244	0.00E+00	2.20E-06	1.81E-06	0.00E+00	6.82E-05	5.63E-05
Cm245	0.00E+00	1.73E-07	1.73E-07	0.00E+00	1.05E-05	1.05E-05
Cm246	0.00E+00	1.82E-08	1.82E-08	0.00E+00	1.33E-06	1.33E-06
Cm247	0.00E+00	2.67E-10	2.67E-10	0.00E+00	3.28E-08	3.28E-08
Cm248	0.00E+00	1.97E-11	1.97E-11	0.00E+00	2.45E-09	2.45E-09

IMF-UOX – 3

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	5.10E-05	4.53E-05	0.00E+00	1.68E-05	1.49E-05
Y90	0.00E+00	1.32E-08	1.13E-08	0.00E+00	4.28E-09	3.74E-09
Tc99	0.00E+00	6.79E-05	6.81E-05	0.00E+00	5.10E-05	5.12E-05
I129	0.00E+00	1.21E-05	1.22E-05	0.00E+00	1.33E-05	1.34E-05
Cs135	0.00E+00	3.21E-05	3.21E-05	0.00E+00	4.72E-05	4.73E-05
Cs137	0.00E+00	7.70E-05	6.86E-05	0.00E+00	5.99E-05	5.33E-05
Ba137	0.00E+00	3.75E-06	1.21E-05	0.00E+00	2.90E-06	9.43E-06
Pa233	0.00E+00	7.45E-13	7.65E-13	5.38E-14	2.78E-12	2.80E-12
U233	0.00E+00	8.24E-11	1.18E-10	2.52E-16	3.32E-10	4.62E-10
U234	1.22E-06	6.97E-07	1.11E-06	2.22E-09	1.01E-05	2.44E-05
U235	1.15E-03	2.67E-04	2.67E-04	3.14E-11	3.39E-06	3.44E-06
U236	0.00E+00	1.44E-04	1.44E-04	8.22E-11	6.57E-07	9.58E-07
U238	2.21E-02	2.12E-02	2.12E-02	6.91E-13	3.88E-09	7.47E-09
Np237	0.00E+00	2.17E-05	2.21E-05	1.67E-04	8.03E-05	8.12E-05
Pu238	0.00E+00	9.98E-06	1.03E-05	2.81E-04	3.52E-04	3.58E-04
Pu239	0.00E+00	1.79E-04	1.81E-04	1.09E-03	3.14E-04	3.14E-04
Pu240	0.00E+00	7.02E-05	7.05E-05	7.79E-04	5.64E-04	5.78E-04
Pu241	0.00E+00	4.90E-05	3.86E-05	2.89E-04	2.75E-04	2.16E-04
Pu242	0.00E+00	1.83E-05	1.83E-05	3.73E-04	3.88E-04	3.88E-04
Am241	0.00E+00	1.94E-06	1.24E-05	2.19E-04	8.99E-05	1.48E-04
Am242m	0.00E+00	3.28E-08	3.20E-08	1.25E-06	2.39E-06	2.33E-06
Am243	0.00E+00	4.52E-06	4.53E-06	1.04E-04	1.08E-04	1.08E-04
Cm242	0.00E+00	6.38E-07	3.56E-10	8.44E-13	2.00E-05	1.46E-08
Cm243	0.00E+00	1.94E-08	1.73E-08	0.00E+00	1.28E-06	1.14E-06
Cm244	0.00E+00	2.00E-06	1.65E-06	0.00E+00	8.30E-05	6.85E-05
Cm245	0.00E+00	1.59E-07	1.59E-07	0.00E+00	1.33E-05	1.33E-05
Cm246	0.00E+00	1.56E-08	1.56E-08	0.00E+00	1.24E-06	1.23E-06
Cm247	0.00E+00	2.26E-10	2.26E-10	0.00E+00	2.95E-08	2.95E-08
Cm248	0.00E+00	1.61E-11	1.61E-11	0.00E+00	1.78E-09	1.78E-09

IMF-UOX – 4

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	5.03E-05	4.47E-05	0.00E+00	1.74E-05	1.54E-05
Y90	0.00E+00	1.30E-08	1.12E-08	0.00E+00	4.42E-09	3.87E-09
Tc99	0.00E+00	6.70E-05	6.72E-05	0.00E+00	5.32E-05	5.34E-05
I129	0.00E+00	1.19E-05	1.20E-05	0.00E+00	1.38E-05	1.39E-05
Cs135	0.00E+00	3.22E-05	3.22E-05	0.00E+00	5.23E-05	5.23E-05
Cs137	0.00E+00	7.58E-05	6.75E-05	0.00E+00	6.18E-05	5.51E-05
Ba137	0.00E+00	3.70E-06	1.20E-05	0.00E+00	2.98E-06	9.72E-06
Pa233	0.00E+00	7.38E-13	7.58E-13	6.03E-14	3.35E-12	3.39E-12
U233	0.00E+00	8.47E-11	1.20E-10	2.83E-16	4.43E-10	6.01E-10
U234	1.22E-06	7.04E-07	1.10E-06	3.17E-09	1.42E-05	3.30E-05
U235	1.15E-03	2.77E-04	2.77E-04	3.52E-11	4.56E-06	4.62E-06
U236	0.00E+00	1.44E-04	1.44E-04	1.02E-10	8.21E-07	1.22E-06
U238	2.21E-02	2.12E-02	2.12E-02	9.10E-13	5.02E-09	9.66E-09
Np237	0.00E+00	2.15E-05	2.19E-05	1.87E-04	9.68E-05	9.82E-05
Pu238	0.00E+00	9.73E-06	1.00E-05	4.01E-04	4.65E-04	4.70E-04
Pu239	0.00E+00	1.83E-04	1.85E-04	1.23E-03	4.42E-04	4.42E-04
Pu240	0.00E+00	6.97E-05	7.00E-05	9.71E-04	7.42E-04	7.58E-04
Pu241	0.00E+00	4.90E-05	3.85E-05	3.46E-04	3.29E-04	2.59E-04
Pu242	0.00E+00	1.77E-05	1.77E-05	4.91E-04	5.00E-04	5.01E-04
Am241	0.00E+00	1.97E-06	1.24E-05	2.73E-04	1.31E-04	2.00E-04
Am242m	0.00E+00	3.36E-08	3.28E-08	2.46E-06	3.72E-06	3.63E-06
Am243	0.00E+00	4.33E-06	4.33E-06	1.32E-04	1.32E-04	1.32E-04
Cm242	0.00E+00	6.24E-07	3.52E-10	1.67E-12	2.33E-05	1.94E-08
Cm243	0.00E+00	1.88E-08	1.68E-08	0.00E+00	1.47E-06	1.31E-06
Cm244	0.00E+00	1.88E-06	1.55E-06	0.00E+00	9.21E-05	7.60E-05
Cm245	0.00E+00	1.49E-07	1.49E-07	0.00E+00	1.46E-05	1.46E-05
Cm246	0.00E+00	1.41E-08	1.41E-08	0.00E+00	1.14E-06	1.14E-06
Cm247	0.00E+00	2.02E-10	2.02E-10	0.00E+00	2.62E-08	2.62E-08
Cm248	0.00E+00	1.40E-11	1.40E-11	0.00E+00	1.36E-09	1.36E-09

IMF-UOX – 5

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	4.98E-05	4.43E-05	0.00E+00	1.78E-05	1.58E-05
Y90	0.00E+00	1.29E-08	1.11E-08	0.00E+00	4.52E-09	3.96E-09
Tc99	0.00E+00	6.64E-05	6.66E-05	0.00E+00	5.48E-05	5.49E-05
I129	0.00E+00	1.18E-05	1.18E-05	0.00E+00	1.42E-05	1.43E-05
Cs135	0.00E+00	3.22E-05	3.22E-05	0.00E+00	5.57E-05	5.57E-05
Cs137	0.00E+00	7.49E-05	6.68E-05	0.00E+00	6.31E-05	5.62E-05
Ba137	0.00E+00	3.67E-06	1.18E-05	0.00E+00	3.04E-06	9.92E-06
Pa233	0.00E+00	7.32E-13	7.52E-13	6.45E-14	3.76E-12	3.81E-12
U233	0.00E+00	8.63E-11	1.21E-10	3.02E-16	5.41E-10	7.18E-10
U234	1.22E-06	7.08E-07	1.10E-06	4.03E-09	1.81E-05	4.08E-05
U235	1.15E-03	2.83E-04	2.83E-04	3.82E-11	5.54E-06	5.62E-06
U236	0.00E+00	1.43E-04	1.43E-04	1.20E-10	9.58E-07	1.43E-06
U238	2.21E-02	2.12E-02	2.12E-02	1.11E-12	6.06E-09	1.17E-08
Np237	0.00E+00	2.14E-05	2.18E-05	2.00E-04	1.09E-04	1.10E-04
Pu238	0.00E+00	9.55E-06	9.83E-06	5.11E-04	5.64E-04	5.67E-04
Pu239	0.00E+00	1.85E-04	1.87E-04	1.33E-03	5.46E-04	5.46E-04
Pu240	0.00E+00	6.94E-05	6.97E-05	1.14E-03	8.95E-04	9.12E-04
Pu241	0.00E+00	4.89E-05	3.85E-05	3.85E-04	3.68E-04	2.90E-04
Pu242	0.00E+00	1.72E-05	1.72E-05	5.99E-04	6.04E-04	6.04E-04
Am241	0.00E+00	1.99E-06	1.24E-05	3.20E-04	1.69E-04	2.46E-04
Am242m	0.00E+00	3.40E-08	3.32E-08	3.75E-06	4.95E-06	4.83E-06
Am243	0.00E+00	4.20E-06	4.20E-06	1.54E-04	1.51E-04	1.51E-04
Cm242	0.00E+00	6.13E-07	3.49E-10	2.54E-12	2.57E-05	2.36E-08
Cm243	0.00E+00	1.84E-08	1.64E-08	0.00E+00	1.61E-06	1.43E-06
Cm244	0.00E+00	1.80E-06	1.48E-06	0.00E+00	9.85E-05	8.13E-05
Cm245	0.00E+00	1.43E-07	1.43E-07	0.00E+00	1.54E-05	1.54E-05
Cm246	0.00E+00	1.31E-08	1.31E-08	0.00E+00	1.06E-06	1.06E-06
Cm247	0.00E+00	1.86E-10	1.86E-10	0.00E+00	2.38E-08	2.38E-08
Cm248	0.00E+00	1.27E-11	1.27E-11	0.00E+00	1.11E-09	1.11E-09

IMF-UOX – 6

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	4.95E-05	4.40E-05	0.00E+00	1.81E-05	1.61E-05
Y90	0.00E+00	1.28E-08	1.10E-08	0.00E+00	4.59E-09	4.03E-09
Tc99	0.00E+00	6.60E-05	6.62E-05	0.00E+00	5.58E-05	5.60E-05
I129	0.00E+00	1.17E-05	1.17E-05	0.00E+00	1.44E-05	1.45E-05
Cs135	0.00E+00	3.22E-05	3.22E-05	0.00E+00	5.80E-05	5.81E-05
Cs137	0.00E+00	7.44E-05	6.63E-05	0.00E+00	6.40E-05	5.70E-05
Ba137	0.00E+00	3.64E-06	1.18E-05	0.00E+00	3.08E-06	1.01E-05
Pa233	0.00E+00	7.28E-13	7.48E-13	6.71E-14	4.04E-12	4.10E-12
U233	0.00E+00	8.73E-11	1.22E-10	3.15E-16	6.23E-10	8.14E-10
U234	1.22E-06	7.12E-07	1.10E-06	4.79E-09	2.15E-05	4.76E-05
U235	1.15E-03	2.88E-04	2.88E-04	4.03E-11	6.36E-06	6.45E-06
U236	0.00E+00	1.43E-04	1.43E-04	1.34E-10	1.07E-06	1.62E-06
U238	2.21E-02	2.12E-02	2.12E-02	1.29E-12	7.02E-09	1.35E-08
Np237	0.00E+00	2.13E-05	2.17E-05	2.08E-04	1.17E-04	1.19E-04
Pu238	0.00E+00	9.42E-06	9.70E-06	6.07E-04	6.50E-04	6.52E-04
Pu239	0.00E+00	1.86E-04	1.88E-04	1.40E-03	6.27E-04	6.27E-04
Pu240	0.00E+00	6.92E-05	6.95E-05	1.27E-03	1.02E-03	1.04E-03
Pu241	0.00E+00	4.89E-05	3.84E-05	4.13E-04	3.97E-04	3.12E-04
Pu242	0.00E+00	1.69E-05	1.69E-05	6.97E-04	6.98E-04	6.98E-04
Am241	0.00E+00	2.00E-06	1.24E-05	3.59E-04	2.00E-04	2.83E-04
Am242m	0.00E+00	3.43E-08	3.35E-08	4.95E-06	6.01E-06	5.87E-06
Am243	0.00E+00	4.10E-06	4.11E-06	1.73E-04	1.68E-04	1.68E-04
Cm242	0.00E+00	6.06E-07	3.46E-10	3.36E-12	2.74E-05	2.70E-08
Cm243	0.00E+00	1.81E-08	1.61E-08	0.00E+00	1.71E-06	1.52E-06
Cm244	0.00E+00	1.74E-06	1.44E-06	0.00E+00	1.03E-04	8.54E-05
Cm245	0.00E+00	1.38E-07	1.38E-07	0.00E+00	1.59E-05	1.58E-05
Cm246	0.00E+00	1.24E-08	1.24E-08	0.00E+00	1.01E-06	1.01E-06
Cm247	0.00E+00	1.76E-10	1.76E-10	0.00E+00	2.22E-08	2.22E-08
Cm248	0.00E+00	1.19E-11	1.19E-11	0.00E+00	9.63E-10	9.63E-10

IMF-UOX – 7

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	4.93E-05	4.38E-05	0.00E+00	1.83E-05	1.62E-05
Y90	0.00E+00	1.27E-08	1.10E-08	0.00E+00	4.63E-09	4.07E-09
Tc99	0.00E+00	6.57E-05	6.59E-05	0.00E+00	5.66E-05	5.68E-05
I129	0.00E+00	1.16E-05	1.17E-05	0.00E+00	1.46E-05	1.47E-05
Cs135	0.00E+00	3.22E-05	3.22E-05	0.00E+00	5.97E-05	5.97E-05
Cs137	0.00E+00	7.40E-05	6.59E-05	0.00E+00	6.46E-05	5.76E-05
Ba137	0.00E+00	3.63E-06	1.17E-05	0.00E+00	3.10E-06	1.01E-05
Pa233	0.00E+00	7.25E-13	7.45E-13	6.87E-14	4.24E-12	4.31E-12
U233	0.00E+00	8.81E-11	1.23E-10	3.23E-16	6.92E-10	8.92E-10
U234	1.22E-06	7.14E-07	1.10E-06	5.45E-09	2.44E-05	5.34E-05
U235	1.15E-03	2.91E-04	2.91E-04	4.19E-11	7.03E-06	7.13E-06
U236	0.00E+00	1.42E-04	1.42E-04	1.47E-10	1.16E-06	1.77E-06
U238	2.21E-02	2.12E-02	2.12E-02	1.46E-12	7.90E-09	1.52E-08
Np237	0.00E+00	2.12E-05	2.16E-05	2.13E-04	1.23E-04	1.25E-04
Pu238	0.00E+00	9.32E-06	9.60E-06	6.89E-04	7.23E-04	7.23E-04
Pu239	0.00E+00	1.87E-04	1.89E-04	1.46E-03	6.89E-04	6.89E-04
Pu240	0.00E+00	6.90E-05	6.93E-05	1.39E-03	1.13E-03	1.15E-03
Pu241	0.00E+00	4.88E-05	3.83E-05	4.32E-04	4.19E-04	3.29E-04
Pu242	0.00E+00	1.67E-05	1.67E-05	7.87E-04	7.84E-04	7.84E-04
Am241	0.00E+00	2.01E-06	1.24E-05	3.92E-04	2.27E-04	3.14E-04
Am242m	0.00E+00	3.45E-08	3.36E-08	5.99E-06	6.91E-06	6.74E-06
Am243	0.00E+00	4.04E-06	4.04E-06	1.88E-04	1.82E-04	1.82E-04
Cm242	0.00E+00	6.00E-07	3.44E-10	4.06E-12	2.87E-05	2.99E-08
Cm243	0.00E+00	1.79E-08	1.59E-08	0.00E+00	1.78E-06	1.58E-06
Cm244	0.00E+00	1.70E-06	1.40E-06	0.00E+00	1.07E-04	8.86E-05
Cm245	0.00E+00	1.34E-07	1.34E-07	0.00E+00	1.62E-05	1.62E-05
Cm246	0.00E+00	1.20E-08	1.19E-08	0.00E+00	9.78E-07	9.77E-07
Cm247	0.00E+00	1.68E-10	1.68E-10	0.00E+00	2.10E-08	2.10E-08
Cm248	0.00E+00	1.13E-11	1.13E-11	0.00E+00	8.64E-10	8.64E-10

IMF-MOX – 1

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	4.11E-05	3.65E-05	0.00E+00	1.54E-05	1.36E-05
Y90	0.00E+00	1.06E-08	9.15E-09	0.00E+00	3.98E-09	3.42E-09
Tc99	0.00E+00	7.44E-05	7.46E-05	0.00E+00	4.50E-05	4.51E-05
I129	0.00E+00	1.57E-05	1.57E-05	0.00E+00	1.20E-05	1.21E-05
Cs135	0.00E+00	4.73E-05	4.74E-05	0.00E+00	3.13E-05	3.14E-05
Cs137	0.00E+00	8.48E-05	7.56E-05	0.00E+00	5.50E-05	4.90E-05
Ba137	0.00E+00	4.07E-06	1.33E-05	0.00E+00	2.81E-06	8.81E-06
Pa233	3.65E-25	5.03E-13	5.26E-13	3.07E-14	1.14E-12	1.14E-12
U233	8.55E-28	9.34E-11	1.18E-10	1.44E-16	9.85E-11	1.52E-10
U234	1.77E-10	7.32E-07	1.78E-06	2.78E-10	2.41E-06	7.62E-06
U235	7.80E-04	2.74E-04	2.74E-04	2.43E-11	7.50E-07	7.59E-07
U236	2.57E-11	9.29E-05	9.30E-05	4.05E-11	2.57E-07	3.56E-07
U238	2.16E-02	2.07E-02	2.07E-02	1.87E-13	1.37E-09	2.73E-09
Np237	3.38E-15	1.48E-05	1.52E-05	9.54E-05	3.28E-05	3.31E-05
Pu238	2.24E-05	2.46E-05	2.64E-05	3.52E-05	1.24E-04	1.31E-04
Pu239	5.38E-04	2.63E-04	2.65E-04	8.47E-04	6.16E-05	6.17E-05
Pu240	2.43E-04	2.00E-04	2.03E-04	3.83E-04	1.83E-04	1.91E-04
Pu241	5.61E-05	1.25E-04	9.81E-05	8.84E-05	1.21E-04	9.48E-05
Pu242	6.42E-05	8.79E-05	8.79E-05	1.01E-04	1.47E-04	1.47E-04
Am241	2.70E-09	8.65E-06	3.52E-05	1.48E-04	2.03E-05	4.58E-05
Am242m	0.00E+00	1.65E-07	1.61E-07	1.02E-07	4.02E-07	3.92E-07
Am243	0.00E+00	2.78E-05	2.78E-05	2.27E-05	4.66E-05	4.66E-05
Cm242	0.00E+00	2.74E-06	1.59E-09	6.89E-14	1.15E-05	5.95E-09
Cm243	0.00E+00	1.17E-07	1.04E-07	0.00E+00	8.00E-07	7.13E-07
Cm244	0.00E+00	2.08E-05	1.72E-05	0.00E+00	4.34E-05	3.58E-05
Cm245	0.00E+00	2.48E-06	2.48E-06	0.00E+00	5.50E-06	5.50E-06
Cm246	0.00E+00	3.25E-07	3.25E-07	0.00E+00	1.12E-06	1.12E-06
Cm247	0.00E+00	6.73E-09	6.73E-09	0.00E+00	2.74E-08	2.74E-08
Cm248	0.00E+00	5.68E-10	5.69E-10	0.00E+00	2.75E-09	2.76E-09

IMF-MOX – 2

	UOX Pins			IMF Pins		
	BOC	EOC	After 5-yr Cooling	BOC	EOC	After 5-yr Cooling
Sr90	0.00E+00	3.85E-05	3.41E-05	0.00E+00	1.86E-05	1.65E-05
Y90	0.00E+00	9.84E-09	8.56E-09	0.00E+00	4.73E-09	4.13E-09
Tc99	0.00E+00	6.98E-05	7.00E-05	0.00E+00	5.66E-05	5.68E-05
I129	0.00E+00	1.46E-05	1.47E-05	0.00E+00	1.48E-05	1.49E-05
Cs135	0.00E+00	4.76E-05	4.77E-05	0.00E+00	5.28E-05	5.29E-05
Cs137	0.00E+00	7.91E-05	7.05E-05	0.00E+00	6.68E-05	5.95E-05
Ba137	0.00E+00	3.85E-06	1.25E-05	0.00E+00	3.28E-06	1.06E-05
Pa233	3.65E-25	4.88E-13	5.10E-13	4.12E-14	2.08E-12	2.11E-12
U233	8.55E-28	1.01E-10	1.25E-10	1.93E-16	2.60E-10	3.58E-10
U234	1.77E-10	7.52E-07	1.81E-06	1.66E-09	7.98E-06	2.02E-05
U235	7.80E-04	3.04E-04	3.04E-04	3.39E-11	2.68E-06	2.73E-06
U236	2.57E-11	8.98E-05	8.99E-05	9.24E-11	6.37E-07	9.61E-07
U238	2.16E-02	2.07E-02	2.07E-02	7.44E-13	4.18E-09	8.13E-09
Np237	3.38E-15	1.44E-05	1.48E-05	1.28E-04	6.02E-05	6.12E-05
Pu238	2.24E-05	2.49E-05	2.65E-05	2.10E-04	2.98E-04	3.07E-04
Pu239	5.38E-04	2.99E-04	3.00E-04	1.18E-03	3.13E-04	3.13E-04
Pu240	2.43E-04	2.04E-04	2.08E-04	8.76E-04	6.07E-04	6.24E-04
Pu241	5.61E-05	1.32E-04	1.04E-04	3.62E-04	3.15E-04	2.47E-04
Pu242	6.42E-05	8.28E-05	8.28E-05	4.01E-04	4.26E-04	4.26E-04
Am241	2.70E-09	9.78E-06	3.79E-05	2.17E-04	9.22E-05	1.58E-04
Am242m	0.00E+00	2.00E-07	1.95E-07	8.03E-07	2.45E-06	2.39E-06
Am243	0.00E+00	2.66E-05	2.66E-05	1.21E-04	1.20E-04	1.20E-04
Cm242	0.00E+00	2.61E-06	1.62E-09	5.45E-13	2.10E-05	1.52E-08
Cm243	0.00E+00	1.11E-07	9.87E-08	0.00E+00	1.33E-06	1.18E-06
Cm244	0.00E+00	1.91E-05	1.58E-05	0.00E+00	9.67E-05	7.99E-05
Cm245	0.00E+00	2.39E-06	2.39E-06	0.00E+00	1.56E-05	1.56E-05
Cm246	0.00E+00	2.61E-07	2.61E-07	0.00E+00	1.52E-06	1.52E-06
Cm247	0.00E+00	5.34E-09	5.34E-09	0.00E+00	3.65E-08	3.65E-08
Cm248	0.00E+00	4.15E-10	4.15E-10	0.00E+00	2.31E-09	2.31E-09

IMF-MOX – 3

	UOX Pins			IMF Pins		
	BOC	EOC	5yr Cooling	BOC	EOC	5yr Cooling
Sr90	0.00E+00	3.74E-05	3.32E-05	0.00E+00	1.99E-05	1.77E-05
Y90	0.00E+00	9.55E-09	8.32E-09	0.00E+00	5.06E-09	4.44E-09
Tc99	0.00E+00	6.79E-05	6.81E-05	0.00E+00	6.18E-05	6.19E-05
I129	0.00E+00	1.42E-05	1.43E-05	0.00E+00	1.60E-05	1.61E-05
Cs135	0.00E+00	4.75E-05	4.75E-05	0.00E+00	6.38E-05	6.38E-05
Cs137	0.00E+00	7.67E-05	6.83E-05	0.00E+00	7.16E-05	6.38E-05
Ba137	0.00E+00	3.74E-06	1.21E-05	0.00E+00	3.49E-06	1.13E-05
Pa233	3.65E-25	4.78E-13	5.01E-13	4.83E-14	2.78E-12	2.84E-12
U233	8.55E-28	1.04E-10	1.28E-10	2.27E-16	4.22E-10	5.54E-10
U234	1.77E-10	7.61E-07	1.81E-06	3.03E-09	1.41E-05	3.33E-05
U235	7.80E-04	3.16E-04	3.16E-04	4.20E-11	4.40E-06	4.48E-06
U236	2.57E-11	8.84E-05	8.85E-05	1.37E-10	9.48E-07	1.48E-06
U238	2.16E-02	2.07E-02	2.07E-02	1.23E-12	6.73E-09	1.30E-08
Np237	3.38E-15	1.41E-05	1.45E-05	1.50E-04	8.05E-05	8.23E-05
Pu238	2.24E-05	2.48E-05	2.64E-05	3.84E-04	4.71E-04	4.80E-04
Pu239	5.38E-04	3.12E-04	3.14E-04	1.46E-03	5.76E-04	5.76E-04
Pu240	2.43E-04	2.07E-04	2.10E-04	1.30E-03	9.97E-04	1.02E-03
Pu241	5.61E-05	1.34E-04	1.06E-04	5.23E-04	4.44E-04	3.49E-04
Pu242	6.42E-05	8.09E-05	8.09E-05	6.63E-04	6.79E-04	6.79E-04
Am241	2.70E-09	1.02E-05	3.87E-05	3.28E-04	1.83E-04	2.76E-04
Am242m	0.00E+00	2.12E-07	2.07E-07	2.87E-06	5.44E-06	5.31E-06
Am243	0.00E+00	2.61E-05	2.61E-05	1.91E-04	1.76E-04	1.76E-04
Cm242	0.00E+00	2.55E-06	1.63E-09	1.94E-12	2.80E-05	2.58E-08
Cm243	0.00E+00	1.08E-07	9.60E-08	0.00E+00	1.73E-06	1.54E-06
Cm244	0.00E+00	1.83E-05	1.51E-05	0.00E+00	1.20E-04	9.91E-05
Cm245	0.00E+00	2.31E-06	2.30E-06	0.00E+00	1.90E-05	1.90E-05
Cm246	0.00E+00	2.35E-07	2.35E-07	0.00E+00	1.35E-06	1.35E-06
Cm247	0.00E+00	4.75E-09	4.75E-09	0.00E+00	3.05E-08	3.05E-08
Cm248	0.00E+00	3.54E-10	3.54E-10	0.00E+00	1.49E-09	1.49E-09

APPENDIX B

B.1 Optimal Radius Searching for IMF-UOX Case:

	IMF Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.8	2.34E-05	2.55E-04	7.5E-06	3.97E-06	-1.11E-03
1	2.36E-05	2.84E-04	7.0E-06	3.47E-06	-9.41E-04
1.1	2.39E-05	3.00E-04	7.0E-06	3.39E-06	-8.33E-04
1.2	2.44E-05	3.15E-04	7.1E-06	3.41E-06	-7.20E-04
1.3	2.49E-05	3.29E-04	7.3E-06	3.50E-06	-6.14E-04

	UOX Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.8	2.34E-05	2.55E-04	7.49E-06	3.97E-06	2.90E-04
1	2.36E-05	2.84E-04	7.01E-06	3.47E-06	3.18E-04
1.1	2.39E-05	3.00E-04	6.99E-06	3.39E-06	3.34E-04
1.2	2.44E-05	3.15E-04	7.08E-06	3.41E-06	3.50E-04
1.3	2.49E-05	3.29E-04	7.25E-06	3.50E-06	3.65E-04

	Assembly Averaged Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.8	2.03E-06	-3.49E-05	-1.82E-05	1.89E-05	-3.21E-05
1	-3.10E-06	-7.24E-05	-2.82E-05	2.11E-05	-8.25E-05
1.1	-4.91E-06	-7.29E-05	-3.13E-05	2.21E-05	-8.70E-05
1.2	-6.31E-06	-6.39E-05	-3.27E-05	2.24E-05	-8.05E-05
1.3	-7.32E-06	-4.91E-05	-3.26E-05	2.21E-05	-6.69E-05

	Relative Magnitude	
x Radius	Concentration	Mass
0.8	37%	31%
1	95%	89%
1.1	100%	100%
1.2	93%	99%
1.3	77%	88%

Toxicity	Resident Time in Repository								
xRadius	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	3.00E+05	1.00E+06
0.8	6.88E+10	-4.07E+10	-3.40E+10	-2.37E+10	-1.83E+10	-9.82E+09	-1.15E+09	8.96E+07	-3.00E+07
1	1.12E+12	1.37E+11	-6.78E+10	-5.29E+10	-3.95E+10	-1.97E+10	-1.52E+09	8.69E+08	5.42E+07
1.1	1.53E+12	2.49E+11	-6.16E+10	-5.46E+10	-4.31E+10	-2.30E+10	-1.91E+09	1.03E+09	1.47E+08
1.2	1.86E+12	3.54E+11	-4.65E+10	-4.93E+10	-4.23E+10	-2.45E+10	-2.13E+09	1.16E+09	2.48E+08
1.3	2.06E+12	4.29E+11	-2.87E+10	-3.93E+10	-3.76E+10	-2.40E+10	-2.14E+09	1.21E+09	3.08E+08

Heat	Resident Time in Repository								
xRadius	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	3.00E+05	1.00E+06
0.8	1.36E-03	-2.61E-04	-1.02E-04	-4.19E-05	-3.15E-05	-1.68E-05	-4.97E-07	1.69E-06	6.46E-07
1	3.68E-03	1.57E-04	-1.49E-04	-7.64E-05	-5.90E-05	-2.94E-05	6.26E-06	1.00E-05	1.48E-06
1.1	4.78E-03	5.75E-04	-1.02E-04	-7.74E-05	-6.48E-05	-3.39E-05	8.26E-06	1.30E-05	2.24E-06
1.2	5.71E-03	9.95E-04	-3.33E-05	-6.57E-05	-6.26E-05	-3.55E-05	9.88E-06	1.53E-05	2.97E-06
1.3	6.27E-03	1.29E-03	2.64E-05	-4.63E-05	-5.39E-05	-3.40E-05	1.10E-05	1.66E-05	3.41E-06

B.2 Optimal Radius Searching for IMF-MOX Case:

	IMF Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.6	-8.10E-05	-1.18E-03	-1.16E-04	8.30E-05	-1.29E-03
0.7	-7.68E-05	-1.11E-03	-1.18E-04	7.56E-05	-1.23E-03
0.8	-7.21E-05	-1.03E-03	-1.18E-04	6.99E-05	-1.15E-03
0.9	-6.72E-05	-9.24E-04	-1.16E-04	6.55E-05	-1.04E-03
1	-6.25E-05	-8.08E-04	-1.11E-04	6.14E-05	-9.19E-04
1.1	-5.83E-05	-6.89E-04	-1.02E-04	5.68E-05	-7.92E-04
1.2	-5.43E-05	-5.77E-04	-9.24E-05	5.16E-05	-6.72E-04
1.3	-5.04E-05	-4.78E-04	-8.22E-05	4.57E-05	-5.65E-04

	UOX Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.6	1.65E-05	-3.54E-04	2.99E-05	2.66E-05	-2.81E-04
0.7	1.64E-05	-3.22E-04	3.01E-05	2.61E-05	-2.49E-04
0.8	1.63E-05	-2.88E-04	3.04E-05	2.59E-05	-2.15E-04
0.9	1.63E-05	-2.55E-04	3.08E-05	2.58E-05	-1.82E-04
1	1.65E-05	-2.27E-04	3.12E-05	2.59E-05	-1.53E-04
1.1	1.67E-05	-2.03E-04	3.16E-05	2.61E-05	-1.29E-04
1.2	1.71E-05	-1.84E-04	3.19E-05	2.66E-05	-1.09E-04
1.3	1.75E-05	-1.68E-04	3.22E-05	2.71E-05	-9.16E-05

	Assembly Averaged Concentration Net Production				
x Radius	Np	Pu	Am	Cm	Total
0.6	2.47E-06	-4.72E-04	9.00E-06	3.47E-05	-4.26E-04
0.7	-9.88E-07	-4.69E-04	2.64E-06	3.54E-05	-4.32E-04
0.8	-4.04E-06	-4.58E-04	-3.77E-06	3.60E-05	-4.30E-04
0.9	-6.59E-06	-4.39E-04	-9.52E-06	3.67E-05	-4.18E-04
1	-8.68E-06	-4.11E-04	-1.39E-05	3.72E-05	-3.97E-04
1.1	-1.04E-05	-3.78E-04	-1.67E-05	3.72E-05	-3.68E-04
1.2	-1.16E-05	-3.42E-04	-1.80E-05	3.66E-05	-3.35E-04
1.3	-1.25E-05	-3.05E-04	-1.82E-05	3.53E-05	-3.00E-04

	Relative Magnitude	
x Radius	Concentration	Mass
0.6	99%	86%
0.7	100%	91%
0.8	99%	96%
0.9	97%	99%
1	92%	100%
1.1	85%	99%
1.2	77%	96%
1.3	69%	92%

Toxicity	Resident Time in Repository								
xRadius	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	3.00E+05	1.00E+06
0.6	-2.48E+13	-5.09E+13	-5.28E+13	-4.75E+13	-3.32E+13	-1.51E+13	-1.69E+12	1.58E+11	4.29E+10
0.7	2.08E+13	-4.53E+13	-5.70E+13	-5.11E+13	-3.55E+13	-1.60E+13	-1.78E+12	1.72E+11	3.75E+10
0.8	1.03E+14	-2.97E+13	-6.03E+13	-5.44E+13	-3.78E+13	-1.70E+13	-1.87E+12	2.04E+11	4.21E+10
0.9	2.22E+14	-2.32E+12	-6.14E+13	-5.68E+13	-3.97E+13	-1.80E+13	-1.97E+12	2.56E+11	6.12E+10
1	3.58E+14	3.38E+13	-5.99E+13	-5.77E+13	-4.10E+13	-1.90E+13	-2.08E+12	3.18E+11	9.39E+10
1.1	4.87E+14	7.13E+13	-5.65E+13	-5.73E+13	-4.15E+13	-1.97E+13	-2.15E+12	3.76E+11	1.30E+11
1.2	5.95E+14	1.04E+14	-5.22E+13	-5.57E+13	-4.10E+13	-2.00E+13	-2.18E+12	4.18E+11	1.56E+11
1.3	6.75E+14	1.29E+14	-4.76E+13	-5.28E+13	-3.97E+13	-1.98E+13	-2.16E+12	4.41E+11	1.66E+11

Heat	Resident Time in Repository								
xRadius	1.00E+02	3.00E+02	1.00E+03	3.00E+03	1.00E+04	3.00E+04	1.00E+05	3.00E+05	1.00E+06
0.6	3.62E-01	-6.61E-02	-8.31E-02	-7.73E-02	-5.60E-02	-2.70E-02	-2.87E-03	5.36E-04	1.30E-04
0.7	4.72E-01	-5.15E-02	-9.05E-02	-8.35E-02	-6.00E-02	-2.85E-02	-2.69E-03	8.85E-04	1.51E-04
0.8	6.84E-01	-2.22E-03	-9.36E-02	-8.90E-02	-6.38E-02	-2.99E-02	-2.27E-03	1.51E-03	2.48E-04
0.9	1.01E+00	9.47E-02	-8.81E-02	-9.25E-02	-6.69E-02	-3.14E-02	-1.63E-03	2.40E-03	4.37E-04
1	1.40E+00	2.33E-01	-7.28E-02	-9.31E-02	-6.88E-02	-3.27E-02	-9.14E-04	3.41E-03	7.05E-04
1.1	1.79E+00	3.80E-01	-5.24E-02	-9.11E-02	-6.91E-02	-3.34E-02	-2.10E-04	4.35E-03	9.78E-04
1.2	2.10E+00	5.03E-01	-3.36E-02	-8.70E-02	-6.77E-02	-3.34E-02	4.30E-04	5.12E-03	1.19E-03
1.3	2.33E+00	5.83E-01	-1.96E-02	-8.11E-02	-6.49E-02	-3.27E-02	9.83E-04	5.67E-03	1.32E-03

APPENDIX C

C.1 Example of Energy Normalization for Pu Net Production

C1.1 Pu Net Production for Modern UOX OTC Case

$$W_{Pu} = \frac{m_{UOX}^{Pu}}{E_{UOX}} \cdot E_{thermal} = \frac{m_{UOX}^{Pu}}{E_{UOX}} \cdot \frac{1TWhe}{\eta} = 27.07$$

where W_{Pu} is Pu net production per 1 TWh-e;

$m_{UOX}^{Pu} = 6.013$ kg is the mass of Pu discharged from a single UOX assembly;

$E_{UOX} = 0.6731$ TWh is the thermal energy produced by a single UOX assembly;

$E_{thermal}$ is the total thermal energy to which we scale the Pu net production;

$\eta = 33\%$ is the thermal-to-electricity efficiency.

C1.2 Pu Net Production for MOX OTC Case

$$W_{Pu} = \frac{m_{MOX\,1}^{Pu} - 99.9\% \cdot 7.55 \cdot m_{UOX\_lega}^{Pu}}{E_{MOX\,1}} \cdot \frac{1TWhe}{\eta} = -48.97$$

where $m_{MOX\,1}^{Pu} = 26.43$ kg is the mass of Pu discharged from a single MOX OTC assembly;

$m^{Pu}_{UOX\_lega} = 4.952$ kg is the mass of Pu discharged from a single Legacy UOX assembly;

$E_{MOX\,1} = 0.6754$ TWh is the thermal energy produced by a single MOX OTC assembly.

C1.3 Pu Net Production for MOX M-R Case

$$W_{Pu} = \frac{m^{Pu}_{MOXMR} - 99.9\% \cdot 19.34 \cdot m^{Pu}_{UOX\_lega}}{E_{MOXMR}} \cdot \frac{1TWhe}{\eta} = -43.21$$

where $m^{Pu}_{MOXMR} = 28.26$ kg is the mass of Pu waste from 7 multi-recycled MOX assemblies, it equals to the Pu discharged from 7th generation MOX assembly plus 0.1% of the Pu discharged from all previous MOX assemblies;

$E_{MOXMR} = 4.728$ TWh is the thermal energy produced by 7 multi-recycled MOX assemblies, it equals to 7 times $E_{MOX\,1}$.

C.2 Example of Energy Normalization for Pu Comprehensive Production

C.2.1 Pu Comprehensive Production for Modern UOX OTC case

$$W_{Pu} = \frac{m^{Pu}_{UOX}}{E_{UOX}} \cdot E_{thermal} = \frac{m^{Pu}_{UOX}}{E_{UOX}} \cdot \frac{1TWhe}{\eta} = 27.07$$

C.2.2 Pu Comprehensive Production for MOX OTC Case

$$W_{Pu} = \frac{m_{MOX\,1}^{Pu} + 0.1\% \cdot 7.55 \cdot m_{UOX\_lega}^{Pu}}{E_{MOX\,1} + 7.55 \cdot E_{UOX\_lega}} \cdot \frac{1TWhe}{\eta} = 17.79$$

where $E_{UOX\_lega} = 0.5076$ TWh is the thermal energy produced by a single Legacy UOX assembly.

C.2.3 Pu Comprehensive Production for MOX M-R Case

$$W_{Pu} = \frac{m_{MOXMR}^{Pu} + 0.1\% \cdot 19.34 \cdot m_{UOX\_lega}^{Pu}}{E_{MOXMR} + 19.34 \cdot E_{UOX\_lega}} \cdot \frac{1TWhe}{\eta} = 5.94$$

APPENDIX D

EXAMPLE OF PERL SCRIPTS FOR AM-COATED MOX CASE

D.1 [masterc_002Z.pl]:

Master script to invoke a series of sub-scripts to assemble the DRAGON input file, invoke DRAGON run, and post process the DRAGON output file, such as extract k-inf data, isotopic concentration data, and power maps.

```
#!/usr/bin/perl

# B Bradley, Z Yunhuang, Texas A&M University

# use warnings;

$file = $ARGV[0];
print "in = $file \n";
open (APPEND , ">>Log\.txt");
print APPEND "\n File: $file" ;

#Create x2m file and move file to archive
########
# Important use of this file!!!!!!!!!!!!!
# Be sure to change $phrase = "perl ******* $file\n" ;
# where ****** is the type of input deck you wish to create
########

$phrase ="perl assemblyc_002Z.pl $file\n" ;
$phrasee = "mv $file archived" ;
print "phrase is $phrase \n" ;
system($phrase) ;
system($phrasee) ;
sleep 1;

#Running file in Dragon
$file2 = "$file"."\.x2m" ;
print "file2 is $file2\n" ;
$phrase2 = "nohup rdragon ./data/$file2" ;
system($phrase2) ;
wait ;
```

```
#Process data
$file3 = "$file"."\.result";

$phrase3 = "perl ./Linux/isotopics_Z6.pl ./Linux/$file3" ;
$phrase4 = "perl ./Linux/kinf_cool.pl ./Linux/$file3" ;
$phrase5 = "perl ./Linux/power_map.pl ./Linux/$file3" ;

system($phrase3);
sleep 2;
system($phrase4);
sleep 1;
system($phrase5);
sleep 1;

$file4 = "$file"."\.conc\.txt";

$phrase6 = "perl ./Linux/tru.pl ./Linux/$file4";
$phrase7 = "perl ./Linux/wastec.pl ./Linux/$file4";
$phrase8 = "perl ./Linux/sepc.pl ./Linux/$file4";

system($phrase6);
sleep 1;
system($phrase7);
sleep 1;
system($phrase8);
sleep 1;

#store files in seperate folder
$file5 = "$file"."\.adam\.txt";
$file6 = "$file"."\.tru\.txt";
$file7 = "$file"."\.waste\.txt";
$file8 = "$file"."\.sep\.txt";
$file9 = "$file"."\.kinf\.txt";

$phrase9 = "mkdir ./Linux/$file\_folder";
$phrase10 =
"mv ./Linux/$file3 ./Linux/$file4 ./Linux/$file5 ./Linux/$file6 ./Linux/$file7 ./Linux/$fil
e8 ./Linux/$file9 ./Linux/$file\_folder";
system($phrase9);
sleep 1;
system($phrase10);
sleep 1;
exit 0;
```

D.2 [assemblyc_002Z.pl]:

Script to assemble DRAGON input deck according to fuel specification file given separately.

```
#!/usr/bin/perl

# B Bradley, Y Zhang, Texas A&M University\
#Generating input deck for Assembly coated with 0.002mm(diameter) AmO2-ZrO2
#Power Density, Discharge Burnup, Burnup Time Step FIXED

# use warnings;
$file   = $ARGV[0];


open ( INPUT , "<$file");
while (<INPUT>) {
   $line = $_ ;
   chomp $line;
   $line=~ s/\r//;

   if($line=~ /Title/){
         $line=~ s/Title/ / ;
      $line=~ s/\t//g ;
         $line=~ s/\s+//g ;
         $Title = $line ;
   }
   if($line =~ /Fuel/){
      $line =~ s/Fuel Density/ / ;
      $line=~ s/\t//g ;
      $line=~ s/\s+//g ;
      $Density = $line ;
   }
   if($line=~ /Pu\%/){
         $line=~ s/Pu\%/ / ;
      $line=~ s/\t//g ;
         $PU = $line ;
   }
   if($line=~ /U\%/){
         $line=~ s/U\%/ / ;
      $line=~ s/\t//g ;
         $U = $line ;
   }
   if($line=~ /U235/){
```

```
        $line=~ s/U235/ / ;
    $line=~ s/\t//g ;
        $U235 = $line ;
}
if($line=~ /U238/){
        $line=~ s/U238/ / ;
    $line=~ s/\t//g ;
        $U238 = $line ;
}
if($line=~ /Pu238/){
        $line=~ s/Pu238/ / ;
    $line=~ s/\t//g ;
        $Pu238 = $line ;
}
if($line=~ /Pu239/){
        $line=~ s/Pu239/ / ;
    $line=~ s/\t//g ;
        $Pu239 = $line ;
}
if($line=~ /Pu240/){
        $line=~ s/Pu240/ / ;
    $line=~ s/\t//g ;
        $Pu240 = $line ;
}
if($line=~ /Pu241/){
        $line=~ s/Pu241/ / ;
    $line=~ s/\t//g ;
        $Pu241 = $line ;
}
if($line=~ /Pu242/){
        $line=~ s/Pu242/ / ;
    $line=~ s/\t//g ;
        $Pu242 = $line ;
}
if($line=~ /Am241\s/){
        $line=~ s/Am241/ / ;
    $line=~ s/\t//g ;
        $Am241 = $line ;
}
if($line=~ /O16\s/){
        $line=~ s/O16/ / ;
    $line=~ s/\t//g ;
        $O16 = $line ;
}
```

```
   if($line=~ /Am241c/){
      $line=~ s/Am241c/ / ;
      $line=~ s/\t//g ;
      $Am241c = $line ;
   }
   if($line=~ /Am242c/){
      $line=~ s/Am242c/ / ;
      $line=~ s/\t//g ;
      $Am242c = $line ;
   }
   if($line=~ /Am242mc/){
      $line=~ s/Am242mc/ / ;
      $line=~ s/\t//g ;
      $Am242mc = $line ;
   }
   if($line=~ /Am243c/){
      $line=~ s/Am243c/ / ;
      $line=~ s/\t//g ;
      $Am243c = $line ;
   }
   if($line=~ /O16c/){
      $line=~ s/O16c/ / ;
      $line=~ s/\t//g ;
      $O16c = $line ;
   }
   if($line=~ /Zr0c/){
      $line=~ s/Zr0c/ / ;
      $line=~ s/\t//g ;
      $Zr0c = $line ;
   }
   next:
}

$sumPU=$Pu238+$Pu239+$Pu240+$Pu241+$Pu242;
$vPu238=$Pu238/$sumPU;
$vPu239=$Pu239/$sumPU;
$vPu240=$Pu240/$sumPU;
$vPu241=$Pu241/$sumPU;
$vPu242=$Pu242/$sumPU;

open ( OUT   , ">$Title\.x2m" );
print OUT "* ----
* ----
* 17 x 17 Fuel Assembly
```

```
* Pitch = 1.26
* Fuel Pin Radius = 0.4096
* Coating Thickness = 0.001
* Clad Outter Radius = 0.4750
* Fuel Type = MOX $PU% PU $U% U-235 with AmO2-ZrO2 Coating
* Dragon DLIB Library
* BURN POWER (KW/KG) = 36.05
* Total Burnup (MWD/KG) = 60.0
* Porosity = (1 - 95%)
* ----
* Pu Vector:
* Pu238% = $vPu238
* Pu239% = $vPu239
* Pu240% = $vPu240
* Pu241% = $vPu241
* Pu242% = $vPu242
* ----
* Define STRUCTURES and MODULES used
* ----
LINKED_LIST
LIBRARY LIBRARY2 ASSMB VOLMATF PIJ FLUX BURNUP COOL1 COOL2
 DATABASE ISOT PMAP ;

SEQ_ASCII
database ;

MODULE
GEO: SYBILT: USS: ASM: FLU: EVO: EDI: COMPO: DELETE: END: LIB: UTL: ;
*
* ----
* Define variables and initialize
* Burnup paremeters
* a) Decay
* = Cooled for 2 years post fabrication
* b) Irradiation
* = 36.05 kw/kg for 0.0 to 1500.0 days
* c) Decay
* = Cooled for 5 years
* ----
REAL
Power Delt Timec Timei Timef Multi :=
36.05 0.2 1.0 0.0 0.0 3.3 ;
* ----
* Depletion data from file DLIB_J2
```

```
* Microscopic cross sections from file DLIB_J2
* ----

*----
* CONCENTRATIONS ARE TAKEN FROM APOLLO-2, USING IMPS FOR THE RELEVANT MEDIA
*
* only the following modifications were performed:
* 1) Apollo-2 gives the concentration of H2O. We used that number for O16 and double that number for H1_H20
* 2) idem for UO2
* 3) ZRNAT does not exist in the Dragon lib, it has been replaced by Zr91
* ----

LIBRARY := LIB: :: EDIT 1
  NMIX 8 CTRA NONE
  SUBG     (*HELIOS TYPE PROBABILITY TABLES*)
  DEPL LIB: DRAGON FIL: DLIB_J2
  MIXS LIB: DRAGON FIL: DLIB_J2
  MIX 1 581.0
            H1_H2O   4.8135E-02
            O16      2.4068E-02
  MIX 2 581.0
            Fe54 8.7320E-06
            Fe56 1.3808E-04
            Fe57 3.3121E-06
            Fe58 4.2154E-07
            Cr50 3.3496E-06
            Cr52 6.4519E-05
            Cr53 7.3151E-06
            Cr54 1.8172E-06
            O16  3.1289E-04
            Zr0  4.3062E-02
  MIX 3 613.95
            Fe54 7.8188E-06
            Fe56 1.2364E-04
            Fe57 2.9658E-06
            Fe58 3.7746E-07
            Cr50 2.9993E-06
            Cr52 5.7772E-05
            Cr53 6.5501E-06
            Cr54 1.6272E-06
            O16  2.8017E-04
            Zr0  3.8559E-02 3 IRSET 0.0 81
```

```
  MIX 4 900.0
              O16      $O16c
              U235     0.0000E+00
              U238     0.0000E+00
              Pu238    0.0000E+00
              Pu239    0.0000E+00
              Pu240    0.0000E+00
              Pu241    0.0000E+00
              Pu242    0.0000E+00
              Am241    $Am241c   2 IRSET 0.0 81
              Am242    $Am242c   2 IRSET 0.0 81
              Am242m   $Am242mc  2 IRSET 0.0 81
              Am243    $Am243c   2 IRSET 0.0 81
              Zr0      $Zr0c     2 IRSET 0.0 81

  MIX 5 900.0
              O16      $O16
              U235     $U235   1 IRSET 0.0 81
              U238     $U238   1 IRSET 0.0 81
              Pu238    $Pu238   1 IRSET 0.0 81
              Pu239    $Pu239   1 IRSET 0.0 81
              Pu240    $Pu240   1 IRSET 0.0 81
              Pu241    $Pu241   1 IRSET 0.0 81
              Pu242    $Pu242   1 IRSET 0.0 81
              Am241    0.0000E+00
              Am242    0.0000E+00
              Am242m   0.0000E+00
              Am243    0.0000E+00
              Zr0      0.0000E+00
  MIX 6 COMB 5 1.0
  MIX 7 COMB 5 1.0
  MIX 8 COMB 5 1.0
;

*----
*----
* Geometry ASSMB : a 17 X 17 normal PWR assembly
* contains C1 : cell without fuel, WH
* C2 : normal fuel cell
* C3 : peripheral cell
* C4 : corner cell
* C5 : IT cell
*----
ASSMB := GEO: :: CAR2D 9 9 EDIT 5
```

```
 X- DIAG X+ REFL Y- SYME Y+ DIAG
 CELL  C1 C2 C2 C1 C2 C2 C1 C2 C3
              C2 C2 C2 C2 C2 C2 C2 C3
                  C2 C2 C2 C2 C2 C2 C3
            C1 C2 C2 C1 C2 C3
                C2 C2 C2 C2 C3
                    C1 C2 C2 C3
                        C2 C2 C3
                            C2 C3
                                C4
 ::: C1 := GEO: CARCEL 2
           MESHX 0.0 1.26 MESHY 0.0 1.26
           RADIUS 0.0 0.5715 0.6121 MIX 1 2 1 ;
 ::: C2 := GEO: CARCEL 6
           MESHX 0.0 1.26 MESHY 0.0 1.26
             RADIUS 0.0
                  0.2917947
                  0.3690943
                  0.4022112
                  0.4096
                  0.4106
                  0.4750
                  MIX 8 7 6 5 4 3 1 ;
::: C3 := GEO: C2 MESHX 0.0 1.30 ;
 ::: C4 := GEO: C3 MESHY 0.0 1.30 ;
;



*----
* Transport calculation SYBILT
*----
VOLMATF := SYBILT: ASSMB ::
 EDIT 0
 MAXR 5000 MAXZ 150000 QUA2 20 8 ;

*----
* COOL1 loop: cool for 2 years (Post fabrication)
*----
EVALUATE Timef := 0.001 ;
WHILE Timei Timef < DO
IF Timei 0.0 = THEN
  COOL1 LIBRARY := EVO: LIBRARY VOLMATF ::
    EDIT 3 EXTR DEPL <<Timei>> <<Timef>> YEAR COOL ;
```

```
ELSE
  COOL1 LIBRARY := EVO: COOL1 LIBRARY VOLMATF ::
    EDIT 3 EXTR DEPL <<Timei>> <<Timef>> YEAR COOL ;
ENDIF ;
EVALUATE Timei := Timef ;
IF Timef 1.0 < THEN
  EVALUATE Timef := Timei Multi * ;
ELSE
  EVALUATE Timef := 2.0 ;
ENDIF ;
ENDWHILE ;


*----
* Self-Shielding calculation SHI
* Flux calculation for keff
*----

LIBRARY2 := USS: LIBRARY VOLMATF :: EDIT 0 PASS 3
  CALC   REGI W1 U234  ALL
         REGI W1 U235  ALL
         REGI W1 U236  ALL
         REGI W1 Pu238 ALL
         REGI W1 Pu239 ALL
         REGI W1 Pu240 ALL
         REGI W1 Pu241 ALL
         REGI W1 Pu242 ALL
         REGI W1 Am241 ALL
         REGI W1 Am242 ALL
         REGI W1 Am242m ALL
         REGI W1 Am243 ALL
         REGI W1 Zr0   ALL

*        REGI W1 U238 ALL
         REGI W1 U238 5
         REGI W2 U238 6
         REGI W3 U238 7
         REGI W4 U238 8
    ENDC ;



PIJ := ASM: LIBRARY2 VOLMATF ::
  EDIT 0 ARM ;
```

```
FLUX := FLU: PIJ LIBRARY2 VOLMATF ::
  TYPE B ;

PMAP := EDI: FLUX LIBRARY2 VOLMATF ::
  EDIT 5
  MERG
  REGI 1 1 1
      2 2 2 2 2 2 2
      3 3 3 3 3 3 3
      4 4 4
      5 5 5 5 5 5 5
      6 6 6 6 6 6 6
      7 7 7
      8 8 8 8 8 8 8
      9 9 9 9 9 9 9
      10 10 10 10 10 10 10
      11 11 11 11 11 11 11
      12 12 12 12 12 12 12
      13 13 13 13 13 13 13
      14 14 14 14 14 14 14
      15 15 15 15 15 15 15
      16 16 16 16 16 16 16
      17 17 17 17 17 17 17
      18 18 18 18 18 18 18
      19 19 19 19 19 19 19
      20 20 20 20 20 20 20
      21 21 21 21 21 21 21
      22 22 22 22 22 22 22
      23 23 23 23 23 23 23
      24 24 24 24 24 24 24
      25 25 25
      26 26 26 26 26 26 26
      27 27 27 27 27 27 27
      28 28 28
      29 29 29 29 29 29 29
      30 30 30 30 30 30 30
      31 31 31 31 31 31 31
      32 32 32 32 32 32 32
      33 33 33 33 33 33 33
      34 34 34 34 34 34 34
      35 35 35 35 35 35 35
      36 36 36
      37 37 37 37 37 37 37
      38 38 38 38 38 38 38
```

```
      39 39 39 39 39 39 39
      40 40 40 40 40 40 40
      41 41 41 41 41 41 41
      42 42 42 42 42 42 42
      43 43 43 43 43 43 43
      44 44 44 44 44 44 44
      45 45 45 45 45 45 45
  COND
  MICR RES
  SAVE ;


*----
* Burnup loop: for first step BURNUP is created
* while for other steps it is modified
*----
EVALUATE Timei := 0.0 ;
WHILE Timei Timec < DO
EVALUATE Timef := Timei Delt + ;
IF Timei 0.0 = THEN
  BURNUP LIBRARY2 := EVO: LIBRARY2 FLUX VOLMATF ::
    EDIT 3 DEPL <<Timei>> <<Timef>> DAY POWR <<Power>> ;
ELSE
  BURNUP LIBRARY2 := EVO: BURNUP LIBRARY2 FLUX VOLMATF ::
    EDIT 3 EXTR DEPL <<Timei>> <<Timef>> DAY POWR <<Power>> ;
ENDIF ;
LIBRARY2 := USS: LIBRARY LIBRARY2 VOLMATF :: EDIT 0 PASS 3
  CALC   REGI W1 U234  ALL
         REGI W1 U235  ALL
         REGI W1 U236  ALL
         REGI W1 Pu238 ALL
         REGI W1 Pu239 ALL
         REGI W1 Pu240 ALL
         REGI W1 Pu241 ALL
         REGI W1 Pu242 ALL
         REGI W1 Am241 ALL
         REGI W1 Am242 ALL
         REGI W1 Am242m ALL
         REGI W1 Am243 ALL
         REGI W1 Zr0   ALL

*        REGI W1 U238 ALL
         REGI W1 U238 5
         REGI W2 U238 6
```

```
        REGI W3 U238 7
        REGI W4 U238 8
    ENDC ;

PIJ := DELETE: PIJ ;
PIJ := ASM: LIBRARY2 VOLMATF ::
  EDIT 0 ARM ;
FLUX := FLU: FLUX PIJ LIBRARY2 VOLMATF ::
  TYPE B ;

PMAP := EDI: PMAP FLUX LIBRARY2 VOLMATF ::
  EDIT 5
  MERG
  REGI 1 1 1
      2 2 2 2 2 2
      3 3 3 3 3 3
      4 4 4
      5 5 5 5 5 5
      6 6 6 6 6 6
      7 7 7
      8 8 8 8 8 8
      9 9 9 9 9 9
      10 10 10 10 10 10 10
      11 11 11 11 11 11 11
      12 12 12 12 12 12 12
      13 13 13 13 13 13 13
      14 14 14 14 14 14 14
      15 15 15 15 15 15 15
      16 16 16 16 16 16 16
      17 17 17 17 17 17 17
      18 18 18 18 18 18 18
      19 19 19 19 19 19 19
      20 20 20 20 20 20 20
      21 21 21 21 21 21 21
      22 22 22 22 22 22 22
      23 23 23 23 23 23 23
      24 24 24 24 24 24 24
      25 25 25
      26 26 26 26 26 26 26
      27 27 27 27 27 27 27
      28 28 28
      29 29 29 29 29 29 29
      30 30 30 30 30 30 30
      31 31 31 31 31 31 31
```

```
      32 32 32 32 32 32 32
      33 33 33 33 33 33 33
      34 34 34 34 34 34 34
      35 35 35 35 35 35 35
      36 36 36
      37 37 37 37 37 37 37
      38 38 38 38 38 38 38
      39 39 39 39 39 39 39
      40 40 40 40 40 40 40
      41 41 41 41 41 41 41
      42 42 42 42 42 42 42
      43 43 43 43 43 43 43
      44 44 44 44 44 44 44
      45 45 45 45 45 45 45
  COND
  MICR RES
  SAVE ;

BURNUP LIBRARY2 := EVO: BURNUP LIBRARY2 FLUX VOLMATF ::
   EDIT 3 SAVE <<Timef>> DAY POWR <<Power>> ;

*----
* change delta t for burnup and final time if required
*----
IF Timef Timec = THEN
  IF Timec 1040.0 = THEN
   EVALUATE Delt Timec := 156.0 1664.0 ;
  ENDIF ;
  IF Timec 150.0 = THEN
   EVALUATE Delt Timec := 178.0 1040.0 ;
  ENDIF ;
  IF Timec 50.0 = THEN
   EVALUATE Delt Timec := 20.0 150.0 ;
  ENDIF ;
  IF Timec 10.0 = THEN
   EVALUATE Delt Timec := 10.0 50.0 ;
  ENDIF ;
  IF Timec 5.0 = THEN
   EVALUATE Delt Timec := 5.0 10.0 ;
  ENDIF ;
  IF Timec 1.0 = THEN
   EVALUATE Delt Timec := 4.0 5.0 ;
  ENDIF ;
ENDIF ;
```

```
 EVALUATE Timei := Timef ;
ENDWHILE ;

*----
* COOL2 loop: cool for 5 years
*----
EVALUATE Timei := 0.0 ;
EVALUATE Timef Multi := 0.001 3.3 ;
WHILE Timei Timef < DO
IF Timei 0.0 = THEN
  COOL2 LIBRARY2 := EVO: LIBRARY2 VOLMATF ::
    EDIT 3 EXTR DEPL <<Timei>> <<Timef>> YEAR COOL ;
ELSE
  COOL2 LIBRARY2 := EVO: COOL2 LIBRARY2 VOLMATF ::
    EDIT 3 EXTR DEPL <<Timei>> <<Timef>> YEAR COOL ;
ENDIF ;
EVALUATE Timei := Timef ;
IF Timef 3.0 < THEN
  EVALUATE Timef := Timei Multi * ;
ELSE
  EVALUATE Timef := 5.0 ;
ENDIF ;
ENDWHILE ;

QUIT \"LIST\" .";
close OUT ;
close INPUT ;

print "title **********: $Title \n" ;

$Title = "$Title"."\.x2m" ;

print "title $Title \n" ;
$phrase = "mv $Title ./data/$Title \n" ;
print " Performing: $phrase " ;

# system('cp $Title \.\/data\/$Title') ;
system($phrase) ;

exit 0;
```

D3. [isotopics_Z6.pl]:

Script that extracts fuel and Am coating isotopic concentration data at each burnup step and homogenize them over the fuel region.

```
#!/usr/bin/perl

# B Bradley, Y Zhang, Texas A&M University

#use warnings

####################
#Obtains the complete isotopics from the output.  Combines the radial separations in the pin to form one averaged isotopic output.
####################
$file     = $ARGV[0];
print "The input is  : $file\n";
$file =~s/result/conc/;
$file_out = $file.'.txt' ;
$file =~ s/conc/result/;
print "The output is : $file_out\n";


open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );


# array definition

@myarray3= () ;
@myarray2= () ;
@myarray= () ;
$debug=0;

#read the output file portion with the 2D power
$i=0;
$bu=0;
$start=0;
$end=0;

$read_bu=0;
@bu_array = ();
$bu_array[1] = "-9999" ;
```

```
while (<INPUT>) {
   $line = $_ ;
   chomp $line;
      # look for bu steps
   if($line=~ /\    FUEL BURNUP/) {
         $dim = $#bu_array;
         $dim = $dim+1 ;
         $line=~ s/\    FUEL BURNUP          \=   / / ;
         $line=~ s/ MW\*D\/TONNE/ / ;
         $line=~ s/\s+// ;
         $bu_array[$dim] = $line;
         next;
   }

      # look for line with: ISOTOPIC DENSITIES AFTER BURNUP FOR MIXTURE
   if($line=~ / ISOTOPIC DENSITIES AFTER BURNUP FOR MIXTURE \=   4 /) {
         @myarray2= () ;
         @myarray3= () ;
      $region = 0;
         $bu=$bu+1;
         $start=1;
   }

      # look for line with: ISOTOPIC DENSITIES AFTER BURNUP FOR MIXTURE
   if(($line=~ / ISOTOPIC DENSITIES AFTER BURNUP FOR MIXTURE/)&&($start
== 1)) {
         $start = 2;
         $region=$region+1;
#       print "region number $region\n";
         next;
   }

      # Average the concentrations over the pin
     if(($start>0)&&($line=~ / OPTIONS/)) {
           $start=0;
           @isototal = () ;
        @isot = ();
           for ($i = 1 ; $i <= $region ; $i++ ) {
              @isotopics   = split (/\s+/, $myarray2[$i]);
              $dim2=$#isotopics;
              for ($j=1; $j<= $dim2; $j++ ) {
                    $isot[$j] = $isot[$j]+$isotopics[$j]*$area[$region+1-$i];
              }
           }
```

```
            for($i = 1 ; $i <= $dim2; $i++ ) {
               $isototal[1] = $isototal[1]." ".$isot[$i]/$atot;
          }
            $isotot[$bu]=$isototal[1];
      }
      #close loop for finding isotopics
      if(($line=~/^$/)&&($start==2)){
            $start=1;
          next;
      }
      #build isotopic arrays (myarray3 is for building names and myarray2 is for obtaining
the values)
      if($start==2) {
            $line=~ s/\:/ /g ;
            $myarray3[$region]=$myarray3[$region].$line;
            $line=~ s/\s+[A-Z][a-z0-9][0-9\s][0-9\s][0-9\s][\sm]/ /g;
            $myarray2[$region]=$myarray2[$region].$line;
      }
   #Begin finding radii
   if($line=~/^ \:\:\: C2 \:\= GEO\: CARCEL 6/){
         $start=5;
       next;
   }
   #Close radii loop and calculate individual and total areas
   if(($line=~/           MIX/)&&($start==6)){
      $start=0;
      @rad = split(/\s+/, $radius);
      $dim3 = $#rad;
         #print "Dim3    $dim3\n";
      for ($i=2;$i<=$dim3-1;$i++){
            $area[$i-1] = 3.14159*($rad[$i]**2-$rad[$i-1]**2);
            $atot = $atot+$area[$i-1];
            print "Area  $i-1   $area[$i-1]\n";
            print "Total Area  $atot\n";
      }
         next;
   }
   #Find the radii separations in the pin
   if(($line=~/  RADIUS/)&&($start==5)){
         $line=~ s/  RADIUS/ /;
      $line=~ s/\s\s\s+\d\d\d\d/ /;
      $radius = $line;
      $start = 6;
         next;
```

```
        }
   if($start==6){
      $line=~ s/\s+/ /;
      $line=~ s/\s\s\s+\d\d\d\d/ /;
      $radius = $radius.$line;
     # print"$radius\n";
   }

}

$myarray = $myarray3[2];
@hh = split (/\s+[0-9]\.[0-9]+E[\-\+][0-9]+/, $myarray);
$dim =$#hh;
   for ($i = 0 ; $i <= $dim ; $i++ ) {
#       print "$hh[$i]\n";
   }
   if($debug>0){
         print "dim $dim \n";
         print " only the nuclide numbers\n";
         for ($i = 1 ; $i <= $dim ; $i++ ) {
            print "$hh[$i]\n";
         }
   }


   for ($i = 1 ; $i <= $bu ; $i++ ) {
      @qq   = split (/\s+/, $isotot[$i]);
      $dim2 =$#qq;
      for ($j=0; $j<= $dim2; $j++ ) {
         $hh[$j] = $hh[$j]." ".$qq[$j+1];
      }
   }

   if($debug>0){
      print "screen printout of the result\n";
      for ($i = 1 ; $i <= $dim ; $i++ ) {
            print "$hh[$i]\n";
      }
   }

   $dim_bu = $#bu_array;
   for ($i = 1 ; $i <= $dim_bu ; $i++ ) {
      print OUT "$bu_array[$i]"."  ";
   }
```

```
print OUT "\n";

for ($i = 0 ; $i <= $dim2 ; $i++ ) {
    print OUT "$hh[$i]\n";
}

exit 0;
```

D4. [kinf_cool.pl]:

Script that extracts k-inf at each burnup step.

```
#!/usr/bin/perl

# B Bradley, Y Zhang, Texas A&M University

#use warnings

###############
#Obtain the kinf as a function of burnup
###############

$file     = $ARGV[0];
print "The input is  : $file\n";
$file =~ s/result/kinf/;
$file_out = $file.'.txt' ;
$file =~ s/kinf/result/;

print "The output is : $file_out\n";


open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );


# array definition

$debug=0;

#read the output file portion with the 2D power
$i=0;
$bu=0;
$start=0;
$end=0;

$read_bu=0;
@bu_array = ();
$bu_array[0]= "0.000000E+00 ";
@kinf_array = ();

while (<INPUT>) {
      $line = $_ ;
```

```
        chomp $line;
        # debug print
        if($debug>10){
                print "line  read"."\n".$line."\n" ;
        }

        # look for bu steps
        if($line=~ /\    FUEL BURNUP/) {
              print "$line\n" ;
                  $line=~ s/\    FUEL BURNUP          \=   / / ;
                  $line=~ s/ MW\*D\/TONNE/ / ;
              $line=~ s/\s+// ;
                  $bu_array[$dim+1] = $line;
                  $dim = $dim+1 ;
                  next;
        }

     #build kinf array
     if($line=~ /\+\+ TRACKING CALLED\=/){
             print "$line\n" ;
              $line=~ s/ \+\+ TRACKING CALLED\=[\s\d][\s\d]+ TIMES FINAL/ / ;
                  $line=~ s/KINF\=/ / ;
                  $line=~ s/FINAL[\s\w\W]+/ /;
             $dim = $#kinf_array+1;
              $kinf_array[$dim] = $line;
            #  print "$dim\n";
             next;
        }

}
print OUT "Burnup MWd/t      Kinf\n" ;
$dim_bu = $#bu_array;
for ($i = 0 ; $i <= $dim_bu ; $i++ ) {
        print OUT "$bu_array[$i]"."  "."$kinf_array[$i]\n";
     #  print "$i\n";
}
print OUT "\n";


exit 0;
```

D5. [power_map.pl]:

Script that extract flux and H-factor ($H = \sum_i E_i \cdot \Sigma_i$) at each burnup step and build power map based on these two sets of data.

```
#!/usr/bin/perl

# B Bradley, Y Zhang, Texas A&M University

#use warnings

##########################
#This script creates an output for the power map
##########################
$file     = $ARGV[0];
$file =~s/result/adam/;
$file_out = $file.'.txt' ;
$file =~s/adam/result/;

print "The input is  : $file\n";
print "The output is : $file_out\n";


open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );


# array definition

@vol= () ;
@nu1= () ;
@nu2= () ;
@nutot= () ;
@nusum= () ;
@nusum1= () ;
@nusum2= () ;
$debug=0;

#read the output file portion with the 2D power
$i=0;
$nuclide_nbr=0;
$bu=0;
$start=0;
$switch=0;
```

```
$end=0;

$read_bu=0;
@bu_array = ();
$bu_array[1] = "0" ;
$energ[0]= "0";
$voltot= "0";
$pintot= "0";

while (<INPUT>) {
	$line = $_ ;
	chomp $line;
	# debug print
	if($debug>10){
		print "line  read"."\n".$line."\n" ;
	}
	#Obtain assembly parameters
	if($line =~ /\* Pitch \=/){
	   $line=~ s/\* Pitch \=/ /;
	   $line=~ s/\s\s\s\s+\S+/ /;
	   $pitch = $line ;
	}
	if($line =~ /\* Fuel Pin Radius \=/){
	   $line=~ s/\* Fuel Pin Radius \=/ /;
	   $line=~ s/\s\s\s\s+\S+/ /;
	   $fuel_radius = $line ;
	}
	if($line =~ /\* Clad Outter Radius \=/){
	   $line=~ s/\* Clad Outter Radius \=/ /;
	   $line=~ s/\s\s\s\s+\S+/ /;
	   $clad_radius = $line ;
	}
	if($line =~ /\* Fuel Type \=/){
	   $line=~ s/\* Fuel Type \=/ /;
	   $line=~ s/\s\s\s\s+\S+/ /;
	   $fuel = $line ;
	}
	if($line =~ /\* a\) Power \=/){
	   $line=~ s/\* a\) Power \=/ /;
	   $line=~ s/\s\s\s\s+\S+/ /;
	   $power = $line ;
	}
	# look for bu steps
	if($line=~ /\    FUEL BURNUP/) {
```

```
        $dim = $#bu_array;
        $dim = $dim+1 ;
        $line=~ s/\    FUEL BURNUP          \=   / / ;
        $line=~ s/ MW\*D\/TONNE/ / ;
        $line=~ s/\s+// ;
        $bu_array[$dim] = $line;
         next;
}

# look for line to begin identifying region volumes
if($line=~ / EDI: SAVE MICROLIB INFO ON DIRECTORY/) {
        $bu=$bu+1;
        $start=1;
        next;
}

# building array with volumes
if(($start==1)&&($line=~ / E N E R G Y   L I M I T S/)) {
        $start=0;
}
if(($start==1)&&($line=~ /     REGION      VOLUME/)) {
    next;
}
if($start==1) {
        $line=~ s/\s+\d[\s\d]\s+/ /g ;
        $vol[$bu]=$vol[$bu].$line;
}

#Enter Iterations for Finding Reaction rates
if($line=~ / F L U X E S   A N D   R E A C T I O N   R A T E S/){
    $rates = 1 ;
    next;
}

#look for line to begin first group fission rate
if(($rates==1)&&($line=~ / G R O U P   \:   1/)){
                $start=2;
                        next;
           }
#Skips line
if(($start==2)&&($line=~ / REGION   AVERAGE/)) {
        next;
}
```

```
        #Create array for region average flux
        if(($start==2)&&($line=~ /          FLUX/)) {
           next;
        }
                if($start==2){
                   $line=~ s/\s+\S+\s+// ;
                   $line=~ s/\s+\S+[\s\S]+/ / ;
                   $flux[$bu]=$flux[$bu].$line;
                }

        #Ends first group
        if(($start==2)&&($line=~ /^$/)) {
              $start=99;
        }

        #sum the nu
        if(($start==99)&&($line=~ / MERGED\/CONDENSED SET OF X\-S SAVED
IN LCM DIRECTORY/)) {
              $start=0;
                                  $rates=0;
                        }


        if($line=~ /CROSS SECTION OF MERGED\/CONDENSED ISOTOPE
'\*MAC\*/) {
        $switch = 1; #Entering H-FACTOR block for this burup step
        $line_copy = $line;
        $line=~s/CROSS SECTION OF MERGED\/CONDENSED ISOTOPE
'\*MAC\*RES0*//;
        $line=~s/'://g;
        $i = $line;
        next;
        }

        if(($switch==1)&&($line=~ / LCMLIB: CONTENT OF ACTIVE
DIRECTORY/)) {
        $switch = 0; #end of block, reset switch
        $HFactors[$bu] = [@temp];  #store H-FACTOR for the $bu burnup step
        $H_bu=$bu;

        next;
        }

        if(($switch==1)&&($line=~ /H-FACTOR/)) {
```

```
        $switch=2;  #begin to collect H-FACTOR information
        next;
        }

        if($switch==2) {
        $temp[$i] = $line;   #collectiong H-FACTOR
        $switch=1;
        next;
        }
}
#END OF WHILE LOOP
print OUT "

****************************
****************************
ASSEMBLY PARAMETERS
FUEL TYPE
$fuel

POWER
$power

PITCH
$pitch cm

FUEL PIN RADIUS
$fuel_radius cm

CLAD OUTTER RADIUS
$clad_radius cm
****************************
****************************\n\n";
@vols =split(/\s+/, $vol[1]);
$dim2 = $#vols;
for ($i = 1 ; $i <= $dim2 ; $i++ ) {
        print "$vols[$i]\n";
}

($junk, @volss) = @vols;
@volsorted = sort { $b <=> $a } @volss;
$j = 1;
for($i = 0; $i <= $#volsorted; $i ++) {
        if(($i == 0) || ($volsorted[$i] != $volsorted[$i-1])) {
                $volsortedd[$j] = $volsorted[$i];
```

```
                $j++;
        }
}

print "@volsortedd";
print "\n";

for($i = 1 ; $i <= $dim2 ; $i++ ) {
        for($j = 1; $j<=$#volsortedd; $j ++) {
                if($vols[$i]==$volsortedd[$j]) {
                        if( ($j==3) || ($j==4) || ($j==5) ) {
                                $vols[$i] = $vols[$i]*2;
                        }
                        elsif( $j==6 ) {
                                $vols[$i] = $vols[$i]*8;
                        }
                }
        }
}
print "Expanded Vols\n";
for ($i = 1 ; $i <= $dim2 ; $i++ ) {
   $voltot = $voltot + $vols[$i] ;
        print "$vols[$i]\n";
}



for ($j = 1 ; $j <=$bu ; $j++){
   @burn =split(/\s+/, $bu_array[$dim]);
   @energ = ();
      $energtot = "0";
   @flu = split(/\s+/, $flux[$j]);
   for ($i =1 ; $i <= $dim2 ; $i++){
      $energ[$i] = $flu[$i-1]*$vols[$i]*$HFactors[$j][$i];
        $energtot=$energtot+$energ[$i];
   }

   print OUT "\nPeaking Factors for Burnup $bu_array[$j] MWd/t\n" ;
   $eneravg = $energtot/$dim2 ;

   for ($i =1 ; $i <= $dim2; $i++){
      $enereg[$i] = $flu[$i-1]*$HFactors[$j][$i];
      $pintot=$pintot+$enereg[$i];
   }
```

```
    $pinavg=$pintot/$dim2;

    print OUT "Region      Factors\n";
    for ($i =1 ; $i <= $dim2 ; $i++){
       $peak[$i] = $energ[$i]/$eneravg;
        print OUT "$i     ";
        print OUT "$peak[$i]\n" ;
    }
}
exit 0;
```

D6. [tru.pl]:

Script that extract Transuranics elements' (Np, Pu, Am, Cm) isotopic concentration at each time step.

```
#!/usr/bin/perl

# B Bradley, Texas A&M University

#use warnings

#Reads from a list to find isotops required for separation

$file     = $ARGV[0];
print "The input is  : $file\n";
$file =~ s/conc\.txt/tru/;
$file_out = $file.'.txt' ;
$file =~ s/tru/conc\.txt/;
print "The output is : $file_out\n";

open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );


# array definition
$debug=0;
@elements =
("U235","U238","Pu238","Pu239","Pu240","Pu241","Pu242","Am241","Am242","Am2
43","Np237","Np238","Np239","Cm241","Cm242","Cm243","Cm244","Cm245");
$dim=$#elements;
LINE : while (<INPUT>) {
          $line = $_ ;
          chomp $line;
       # Find all TRU isotopes
          if($line=~ /\-9999/) {
                print OUT "$line\n" ;
                   next;
          }
       for($i=0;$i<=$dim;$i++){
       if($line =~ /$elements[$i]/) {
             print OUT "$line\n";
          }
       }
}
```

```
print OUT "\n";

exit 0;
```

D7. [wastec.pl]:

Script that collect concentrations of isotopes that are not recycled at the end of cooling stage.

```
#!/usr/bin/perl

# B Bradley, Y Zhang Texas A&M University

#use warnings
#This file reads all isotopes that are not on the list for separation from the isotopics file

$file     = $ARGV[0];
print "The input is  : $file\n";
$file =~ s/conc\.txt/waste/;
$file_out = $file.'.txt' ;
$file =~ s/waste/conc\.txt/;
print "The output is : $file_out\n";

open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );


# array definition
$debug=0;
@elements =
("Pu238","Pu239","Pu240","Pu241","Pu242","Am241","Am242","Am242m","Am243");
$dim=$#elements;
LINE : while (<INPUT>) {
          $line = $_ ;
          chomp $line;
       # Find all NON TRU isotopes
          if($line=~ /\-9999/) {
                $bu = $line;
             @burn = split(/\s+/, $bu);
             $dim1 = $#burn ;
             print OUT "Isotopics  Burnup \= $burn[$dim1-1] Cooling \= 5 years\n\n\n";
             next ;
          }
       for($i=0;$i<=$dim;$i++){
       if($line =~ /$elements[$i]/) {
          next LINE ;
          }
       }
```

```
        $w = $line ;
        @waste = split(/\s+/, $w);
        $dim = $#waste ;
        print OUT "$waste[1]     $waste[$dim]\n";
}

print OUT "\n";


exit 0;
```

D8. [sepc.pl]:

Script that extract conctrations of isotopes that are recycled at the end of cooling stage.

```
#!/usr/bin/perl

# J Ragusa, B Bradley, Y Zhang, Texas A&M University

#use warnings
#################
#This script takes into account the efficiency of the partitioning process.  The isotopes to be considered are found in the array defined by "@isotopes"
#The partitioned isotopes used for recycling is written to a file $file.sep.txt, while the remainder is appended in the waste file.
#################
$file     = $ARGV[0];
print "The input is  : $file\n";
$file =~ s/conc\.txt/sep/;
$file_out = $file.'.txt' ;
$file =~s/sep/waste/;
$file_append = $file.'.txt';
$file =~ s/waste/conc\.txt/;
print "The output is : $file_out\n";
print "The appended file is : $file_append\n";


open ( INPUT , "<$file" );
open ( OUT   , ">$file_out" );
open (APPEND , ">>$file_append");


# array definition
$debug=0;
@isotopes =
("Pu238","Pu239","Pu240","Pu241","Pu242","Am241","Am242","Am242m","Am243");
$dim=$#isotopes;
@isoburn = ();
@recycle = ();
@trash = ();
LINE : while (<INPUT>) {
   $line = $_ ;
   chomp $line;
      # Find all TRU isotopes
```

```
    for($i=0;$i<=$dim;$i++){
        if($line =~ /$isotopes[$i]\s/) {
        $isoburn[$i] = $line;
        }
    }
}

for($i=0;$i<=$dim;$i++){
    @sp = split(/\s+/, $isoburn[$i]);
    $dim2 = $#sp;
    for($j=$dim2;$j<=$dim2;$j++){
        $trash[$j] = $sp[$j]*0.001;
        print APPEND "$sp[1]    $trash[$j]\n";
    }
}
print OUT "Recycled isotopes\n";
for($i=0;$i<=$dim;$i++){
    @sp = split(/\s+/, $isoburn[$i]);
    $dim2 = $#sp;
    for($j=$dim2;$j<=$dim2;$j++){
      $recycle[$j] = $sp[$j]*0.999;
      print OUT "$sp[1]    $recycle[$j]\n";
    }
}

print OUT "\n";


exit 0;
```

D9. [pinmasterc_002Z.pl]:

Script that invoke pinc_002Z.pl to build a series of DRAGON input decks with different moderator density to simulate voiding condition and run these input decks with DRAGON. It also collects k-inf at different voiding conditions into a single file after the DRAGON runs are done.

```
#!/usr/bin/perl

# B Bradley, Y Zhang, Texas A&M University

# use warnings;

$file = $ARGV[0];
print "in = $file \n";
open (APPEND , ">>Log\.txt");
print APPEND " File: $file\n" ;

#Create x2m file and move file to archive
$phrase ="perl pinc_002Z.pl $file\n" ;
$phrasee = "mv $file archived" ;
print "phrase is $phrase \n" ;
system($phrase) ;
system($phrasee) ;
sleep 1;

for ($i = 0 ; $i<= 18 ; $i++){
print "Running Process $i\n" ;
#Running file in Dragon
$file2 = "$file"."\.$i"."\.x2m" ;
print "file2 is $file2\n" ;
$phrase2 = "nohup /bin/sh rdragon ./data/$file2" ;
system($phrase2) ;
wait ;
}

for ($i = 0 ; $i<= 18 ; $i++){
#Process data
$file3 = "$file"."\.$i"."\.result";
$phrase3 = "perl ./Linux/voidk.pl ./Linux/$file3" ;
system($phrase3);
sleep 1;
}
```

```
$phrase9 = "mkdir ./Linux/$file\_folder";
system($phrase9);
sleep 1;
$phrase8 = "mkdir ./data/$file\_folder";
system($phrase8);
sleep 1;


for ($i = 0 ; $i<= 18 ; $i++){
#store files in seperate folder
$file4 = "$file"."\.$i"."\.void\.txt";
$file5 =  "$file"."\.$i"."\.result";
$phrase10 = "mv ./Linux/$file5 ./Linux/$file4 ./Linux/$file\_folder";
system($phrase10);
$file8 = "$file"."\.$i"."\.x2m" ;
$phrase11 = "mv ./data/$file8 ./data/$file\_folder";
system($phrase11);
sleep 1;
}



exit 0;
```

D10. [pinc_002Z.pl]:

Script that build DRAGON input deck according to moderator density given separately. A Sub-script called by pinmaster_002Z.pl

```
#!/usr/bin/perl

# B Bradley, Texas A&M University

# use warnings;
$file   = $ARGV[0];

@Oxygen = ("8.3645E-4","1.6729E-03","3.3458E-03","5.0187E-03","6.6916E-
03","1.0037E-02","1.3383E-02","1.6729E-02","2.0075E-02","2.3421E-02","2.4068E-
02","2.5261E-02","2.6766E-02","3.0112E-02","3.3458E-02","4.1822E-02","5.0187E-
02","5.8551E-02","6.6916E-02");
@Hydrogen = ("1.6729E-03","3.3458E-03","6.6916E-03","1.0037E-02","1.3383E-
02","2.0075E-02","2.6766E-02","3.3458E-02","4.0149E-02","4.6841E-02","4.8135E-
02","5.0521E-02","5.3533E-02","6.0224E-02","6.6916E-02","8.3645E-02","1.0037E-
01","1.1710E-01","1.3383E-01");
$dim = $#Hydrogen;
print "$dim\n";
for ($i = 0 ; $i<=$dim ; $i++){
open ( INPUT , "<$file");
while (<INPUT>) {
   $line = $_ ;
   chomp $line;
   $line=~ s/\r//;

   if($line=~ /Title/){
         $line=~ s/Title/ / ;
      $line=~ s/\t//g ;
         $line=~ s/\s+//g ;
         $Title = "$line"."\.$i" ;
   }
   if($line =~ /Power/){
      $line =~ s/Power Density/ / ;
      $line=~ s/\t//g ;
         $line=~ s/\s+//g ;
         $Power = $line ;
   }
   if($line =~ /Fuel/){
      $line =~ s/Fuel Density/ / ;
      $line=~ s/\t//g ;
```

```
   $line=~ s/\s+//g ;
   $Density = $line ;
}
if($line =~ /Time to 37\.5 GWd\/t/){
   $line =~ s/Time to 37\.5 GWd\/t/ / ;
   $line=~ s/\t//g ;
   $line=~ s/\s+//g ;
   $Tsplit1 = $line ;
}
if($line =~ /Time to 60 GWd\/t/){
   $line =~ s/Time to 60 GWd\/t/ / ;
   $line=~ s/\t//g ;
   $line=~ s/\s+//g ;
   $Tsplit2 = $line ;
}
if($line=~ /Pu\%/){
      $line=~ s/Pu\%/ / ;
   $line=~ s/\t//g ;
      $PU = $line ;
}
if($line=~ /U\%/){
      $line=~ s/U\%/ / ;
   $line=~ s/\t//g ;
      $U = $line ;
}
if($line=~ /U235/){
      $line=~ s/U235/ / ;
   $line=~ s/\t//g ;
      $U235 = $line ;
}
if($line=~ /U238/){
      $line=~ s/U238/ / ;
   $line=~ s/\t//g ;
      $U238 = $line ;
}
if($line=~ /Pu238/){
      $line=~ s/Pu238/ / ;
   $line=~ s/\t//g ;
      $Pu238 = $line ;
}
if($line=~ /Pu239/){
      $line=~ s/Pu239/ / ;
   $line=~ s/\t//g ;
      $Pu239 = $line ;
```

```
}
if($line=~ /Pu240/){
        $line=~ s/Pu240/ / ;
    $line=~ s/\t//g ;
        $Pu240 = $line ;
}
if($line=~ /Pu241/){
        $line=~ s/Pu241/ / ;
    $line=~ s/\t//g ;
        $Pu241 = $line ;
}
if($line=~ /Pu242/){
        $line=~ s/Pu242/ / ;
    $line=~ s/\t//g ;
        $Pu242 = $line ;
}
if($line=~ /Am241\s/){
        $line=~ s/Am241/ / ;
    $line=~ s/\t//g ;
        $Am241 = $line ;
}
if($line=~ /O16\s/){
        $line=~ s/O16/ / ;
    $line=~ s/\t//g ;
        $O16 = $line ;
}
        if($line=~ /Am241c/){
    $line=~ s/Am241c/ / ;
    $line=~ s/\t//g ;
    $Am241c = $line ;
}
if($line=~ /Am242c/){
    $line=~ s/Am242c/ / ;
    $line=~ s/\t//g ;
    $Am242c = $line ;
}
if($line=~ /Am242mc/){
    $line=~ s/Am242mc/ / ;
    $line=~ s/\t//g ;
    $Am242mc = $line ;
}
if($line=~ /Am243c/){
    $line=~ s/Am243c/ / ;
    $line=~ s/\t//g ;
```

```
      $Am243c = $line ;
   }
   if($line=~ /O16c/){
      $line=~ s/O16c/ / ;
      $line=~ s/\t//g ;
      $O16c = $line ;
   }
   if($line=~ /Zr0c/){
      $line=~ s/Zr0c/ / ;
      $line=~ s/\t//g ;
      $Zr0c = $line ;
   }
   next:
}
$Tsplit3 = $Tsplit2+(365*5);  #Append 5 years cooling
$Tsplit3 = $Tsplit3."0";
$inter1 = ($Tsplit1-780)/10;
$int1 = $inter1."0";
$inter2 = ($Tsplit2-$Tsplit1)/10;
$int2 = $inter2."0";
$inter3 = ($Tsplit3-$Tsplit2)/2;
$int3 = $inter3."0";
$step1 = $Tsplit1 - 730;
$step2 = $Tsplit2 - 730;
$step3 = $Tsplit3 - 730;

open ( OUT   , ">$Title\.x2m" );
print OUT "* ----
* Voiding Caculation
* 17 x 17 Fuel Assembly
* MOX $PU% PU $U% U-235
* Dragon DLIB Library
* BURN POWER (KW/KG) = $Power
* MOX TEMPERATURE = 928
* NUMBER OF DAYS = 1950
* Fuel Density = $Density
*
* ----
* Define STRUCTURES and MODULES used
* ----
LINKED_LIST
LIBRARY LIBRARY2 ASSMB VOLMATF PIJ FLUX BURNUP EDITION
DATABASE ISOT ;
SEQ_ASCII
```

```
database ;
MODULE
GEO: SYBILT: USS: ASM: FLU: EDI: COMPO: DELETE: END: LIB: ;
* ----
* Depletion data from file DLIB_J2
* Microscopic cross sections from file DLIB_J2
* ----
LIBRARY := LIB: ::
  NMIX 7 CTRA NONE
  SUBG
  DEPL LIB: DRAGON FIL: DLIB_J2
  MIXS LIB: DRAGON FIL: DLIB_J2
  MIX 1 581.0
   H1_H2O = H1_H2O $Hydrogen[$i]  O16_H2O = O16 $Oxygen[$i]
*    B10  = B10 4.6863E-06
*    B11  = B11 1.8745E-05
  MIX 2 613.95
    Fe54 7.8188E-06
    Fe56 1.2364E-04
    Fe57 2.9658E-06
    Fe58 3.7746E-07
    Cr50 2.9993E-06
    Cr52 5.7772E-05
    Cr53 6.5501E-06
    Cr54 1.6272E-06
    O16  2.8017E-04
    Zr0  3.8559E-02 3 IRSET 0.0 81
 MIX 3 900.0
            O16     $O16c
*             U234    0.0000E+00
            U235    0.0000E+00
*             U236    2.2889E-02
            U238    0.0000E+00
            Pu238   0.0000E+00
            Pu239   0.0000E+00
            Pu240   0.0000E+00
            Pu241   0.0000E+00
            Pu242   0.0000E+00
            Am241   $Am241c   2 IRSET 0.0 81
            Am242   $Am242c   2 IRSET 0.0 81
            Am242m  $Am242mc  2 IRSET 0.0 81
            Am243   $Am243c   2 IRSET 0.0 81
            Zr0     $Zr0c     2 IRSET 0.0 81
 MIX 4 900.00
```

```
              O16      $O16
*             U234     1.2232E-06   1 IRSET 0.0 81
              U235     $U235   1 IRSET 0.0 81
*             U236     2.2889E-02   1 IRSET 0.0 81
              U238     $U238   1 IRSET 0.0 81
              Pu238    $Pu238   1 IRSET 0.0 81
              Pu239    $Pu239   1 IRSET 0.0 81
              Pu240    $Pu240   1 IRSET 0.0 81
              Pu241    $Pu241   1 IRSET 0.0 81
              Pu242    $Pu242   1 IRSET 0.0 81
              Am241    0.0000E+00
              Am242    0.0000E+00
              Am242m   0.0000E+00
              Am243    0.0000E+00
              Zr0      0.0000E+00
  MIX 5 COMB 4 1.0
  MIX 6 COMB 4 1.0
  MIX 7 COMB 4 1.0
;
*----
* Geometry ASSMB : a regular PWR assembly cell
ASSMB := GEO: :: CARCEL 6
        X- REFL X+ REFL MESHX 0.0 1.26
        Y- REFL Y+ REFL MESHY 0.0 1.26
 RADIUS 0.0 0.2917947 0.3690943 0.4022112
         0.4096 0.4106 0.475
         MIX 7 6 5 4 3 2 1
;

*----
* Self-Shielding calculation SHI
* Transport calculation SYBILT
* Flux calculation for keff
*----
VOLMATF := SYBILT: ASSMB ::
 EDIT 3
 MAXR 5000 MAXZ 150000 QUA2 20 8 ;

LIBRARY2 := USS: LIBRARY VOLMATF :: EDIT 2 PASS 3
  CALC   REGI W1 U234  ALL
       REGI W1 U235  ALL
       REGI W1 U236  ALL
       REGI W1 Pu238 ALL
       REGI W1 Pu239 ALL
```

```
        REGI W1 Pu240 ALL
        REGI W1 Pu241 ALL
        REGI W1 Pu242 ALL
        REGI W1 Am241 ALL
        REGI W1 Zr0   ALL

        REGI W1 U238 3
        REGI W2 U238 4
        REGI W3 U238 5
        REGI W4 U238 6
    ENDC
;

PIJ := ASM:  LIBRARY2 VOLMATF :: EDIT 2 ;

FLUX := FLU:  PIJ LIBRARY2 VOLMATF ::
  EDIT 2 TYPE B KEFF 1.0 ;

END: ;
QUIT \"LIST\" .";


close OUT ;
close INPUT ;


print "title **********: $Title \n" ;

$Title = "$Title"."\.x2m" ;

print "title $Title \n" ;
$phrase = "mv $Title ./data/$Title \n" ;

# system('cp $Title \.\/data\/$Title') ;
system($phrase) ;
}
exit 0;
```

D11. [orign_mole.pl]:

Script that build ORIGEN input deck with waste concentrations extracted from DRAGON output file and an ORIGEN input deck template, OrigenTemplt.inp.

```
#!/usr/bin/perl

# Y Zhang, Texas A&M University

#This script is used to feed isotopic information from Waste file into OrigenArp input
                        file
#The resulting .inp file can be run in OrigenArp for a decay calculation

#use warnings;

$file_in   = $ARGV[0];
print "The input is : $file_in\n";
$template = "OrigenTemplt.inp" ;
$ElemList = "Elements.txt";
$file_out  = $file_in;
$file_out  =~s/\..*/\.inp/;
print "The output is : $file_out\n";

@isotpID = ();
@isotpConctr = () ;
$found = 0;
$i = 0;
$start=0;

$unit = 0 ; #Set input concentration Unit to moles;
$cutoff = 0.005; #Set Irradiation output table cutoff

open ( ElemList , "<$ElemList");
while(<ElemList>) {
   $line = $_ ;
   chomp $line;
                        @temp = split(/\s+/, $line);
   $Elements[$i] = $temp[0];
                        $Z[$i] = $temp[1];
                        $i++;
}
```

```
close ElemList;
open ( INPUT , "<$file_in");      #Extract and lump isotopic information from Waste.txt
                                  file
while (<INPUT>) {
                                   $line = $_ ;
   chomp $line;

                                  if($line=~ /[a-zA-Z]+\d+/) {
                                     @vector = split(/\s+/, $line); #vector[0] for NuID, vector[1] for
                                  Concentration
                                          $vector[1] = $vector[1]/0.6022;  #convert atom/b.cm to
                                  mole/cc
                                          if($vector[1]>=1e-25) {
                                                  $A=$vector[0];
                                                  $A=~s /[a-zA-Z]+//g;    #mass number

                                                  if($A=~/(\d){3}/) {     #format texting for mass
                                  number
                                                  }
                                                  elsif($A=~/(\d){2}/) {
                                                          $A="0".$A;
                                                  }
                                                  elsif($A=~/(\d){1}/) {
                                                          $A="00".$A;
                                                  }

                                                  $ID=$vector[0];
                                                  @IDs = split(/\d+/, $ID);
                                                  for($i=0; $i<=$#Elements; $i++) {
                                                          if($IDs[0] eq $Elements[$i]) {
                                                            $IDs[0] = $Z[$i];  #atomic number
                                                          }
                                                  }
                                                  if($IDs[1] eq "m") {
                                                           $IDs[1] = 1;
                                                  }
                                                  else {
                                                           $IDs[1] = 0;
                                                  }
                                                  $vector[0] = $IDs[0].$A.$IDs[1];
                                                  print "$vector[0]   $vector[1]\n";
                                                  for($i=0; $i<=$#isotpID; $i++) {
                                                          if($vector[0] eq $isotpID[$i]) {   #check if
                                  this Isotope ID already appeared and documented
```

```
                                        $isotpConctr[$i] = $isotpConctr[$i]
                        + $vector[1] ; #collect concentration
                                        $found = 1;
                                }
                        }
                        if($found == 0) {
                                $i = $#isotpID + 1;     #if ID not found
                        documented, create it
                                $isotpID[$i] = $vector[0];
                                $isotpConctr[$i] = $vector[1];
                                if($IDs[0]<=40) {       #Z<=Zr is considered
                        Light Element
                                        $lib[$i] = 1;
                                }
                                elsif($IDs[0]<=88) {    #Z<Ac is considered
                        Fission Product
                                        $lib[$i] = 3;
                                }
                                else {                  #Z>=Ac is Acitinde
                                        $lib[$i] = 2;
                                }
                        }
                $found = 0;
                   }
                }
}
# for($i=0; $i<=$#isotpID; $i++) {   #test isotopes lumping
# print "$isotpID[$i]   $isotpConctr[$i]\n";
# }
# close INPUT ;

open ( TEMP , "<$template");
open ( OUT ,   ">$file_out");
while(<TEMP>) {
   $line = $_ ;
#    chomp $line;
   $line=~ s/InputUnit/$unit/;  #Set input  Unit
                        $line=~ s/cutoff/$cutoff/;

                        if($line=~ /73\$\$/) {       #feed isotope ID's
                           $isoID = "73\$\$";
                           for($i=0; $i<=$#isotpID; $i++) {
                             $isoID = $isoID." ".$isotpID[$i];
                                  $residual = ($i + 2)%10 ;
```

```
            if($residual == 0) {
              $isoID = $isoID."\r\n";
             }
   }
         $line = $isoID."\r\n";
}
if($line=~ /74\*\*/) {       #feed isotope Concentration's
   $isoCC = "74\*\*";
   for($i=0; $i<=$#isotpID; $i++) {
     $isoCC = $isoCC." ".$isotpConctr[$i];
            $residual = ($i + 2)%3 ;
            if($residual == 0) {
              $isoCC = $isoCC."\r\n";
             }
   }
         $line = $isoCC."\r\n";
}

if(($start==0)&&($line=~ /56\$\$/)) {    #set the total isotopes
number
  $start=1;
  $L=$line;
  $L=~ s/a13.*\n/a13/;
  $R=$line;
  $R=~ s/.*a14/a14/;
  $isotot=$#isotpID+1;
  $line=$L." ".$isotot." ".$R;
}

if($line=~ /75\$\$/) {
   $line="75\$\$";
   for($i=0; $i<=$#isotpID; $i++) {
      $line=$line." ".$lib[$i];
                  $residual = ($i + 2)%30 ;
             if($residual == 0) {
               $line = $line."\r\n";
             }
   }
         $line=$line."\r\n";
}

if($line=~ /copy ft71f001/) {
         chomp $line;
   $line=~s/[a-zA-Z]+\.f71.*\n*//;
```

```
        $line=$line.$file_out."\r\n";
                                $line=~s/\.inp/\.f71/;
                            }

                            print OUT $line;
}

close TEMP ;
close OUT ;

exit 0;
```

D12. [OrigenTemplt.pl]:

Template file for building ORIGEN input deck. Isotopic concentrations are fed from outer source. Inhalation radiotoxicity and decay heat as functions of decay time are printed in the output file.

```
'This SCALE input file was generated by
'OrigenArp Version  2.00   2-12-2002
#origens
0$$ a11 71 e t
Decay Case
3$$ 21 1 1 0 a16 InputUnit a33 0 e t
35$$ 0 t
54$$ a8 1 a11 0 e
56$$ a2 7 a6 1 a10 0 a13 21 a14 5 a15 3 a17 4 e
57** 0 a3 1e-05 e  t
Decay for 1 M years
1 MTU
60** 0.3 1 3 10 30 100 300
61** fcutoff
65$$
'Gram-Atoms   Grams   Curies   Watts-All   Watts-Gamma
 3z   1   0   0   3z   3z   3z   6z
 3z   1   0   0   3z   3z   3z   6z
 3z   1   0   0   3z   3z   3z   6z
73$$  Nuclide ID
74**  Nuclide Concentration
75$$ 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
t
56$$ 0 0 a10  1 e t
56$$ 0 0 a10  2 e t
56$$ 0 0 a10  3 e t
56$$ 0 0 a10  4 e t
56$$ 0 0 a10  5 e t
56$$ 0 0 a10  6 e t
56$$ 0 0 a10  7 e t
54$$ a8 1 a11 0 e
56$$ a2 7 a6 1 a10 7 a14 5 a15 3 a17 4 e
57** 0 a3 1e-05 e  t
Decay for 1 M years
1 MTU
60** 1000 3000 10000 30000 100000 300000 1000000
61** f0.05
```

```
65$$
'Gram-Atoms   Grams   Curies   Watts-All   Watts-Gamma
 3z   1   0   0   3z   3z   3z   6z
 3z   1   0   0   3z   3z   3z   6z
 3z   1   0   0   3z   3z   3z   6z
t
56$$ 0 0 a10  1 e t
56$$ 0 0 a10  2 e t
56$$ 0 0 a10  3 e t
56$$ 0 0 a10  4 e t
56$$ 0 0 a10  5 e t
56$$ 0 0 a10  6 e t
56$$ 0 0 a10  7 e t
56$$ f0 t
end
=opus
TYPARAMS=NUCLIDES
UNITS=AIRM
LIBTYPE=ALL
TIME=YEARS
NPOSITION=1 2 3 4 5 6 7 8 9 10 11 12 13 14 end
end
=opus
TYPARAMS=NUCLIDES
UNITS=WATTS
LIBTYPE=ALL
TIME=YEARS
NPOSITION=1 2 3 4 5 6 7 8 9 10 11 12 13 14 end
end
#shell
copy ft71f001 D:\Transmutation\Sample_Problems\MOX.f71
del ft71f001
end
```

VITA

Mr. Yunhuang Zhang received his Bachelor of Science degree in engineering physics from Tsinghua University (Beijing, China) in 2007. He entered the nuclear engineering graduate program at Texas A&M University (College Station, TX, U.S.A.) in August 2007 and received his Master of Science degree in December 2009. His research interests include advanced nuclear fuel assembly design and fuel recycling in thermal reactors.

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