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Summary Report on New Transmutation Analysis for the Evaluation of Homogeneous and Heterogeneous Options in Fast Reactors

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August 2008

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ABSTRACT

A 1000 MWth commercial-scale Sodium Fast Reactor (SFR) design was selected as the baseline in this scenario study. Traditional approaches to Light Water Reactor (LWR) Spent Nuclear Fuel (SNF) transuranic waste (TRU) burning in a fast spectrum system have typically focused on the continual homogeneous recycling (reprocessing) of the discharge fast reactor fuel. The effective reduction of transuranic inventories has been quantified through the use of the transuranics conversion ratio (TRU CR). The implicit assumption in the use of this single parameter is a homogeneous fast reactor option where equal weight is given to the destruction of transuranics, either by fission or eventual fission via transmutation. This work explores the potential application of alternative fast reactor fuel cycles in which the minor actinide (MA) component of the TRU is considered 'waste', while the plutonium component is considered as fuel. Specifically, a set of potential designs that incorporate radial heterogeneous target assemblies is proposed and results relevant to transmutation and system analysis are presented.

In this work we consider exclusively minor actinide-bearing radial targets in a continual reprocessing scenario (as opposed to deep-burn options). The potential use of targets in a deep burn mode is not necessarily ruled out as an option. However, due to work scope constraints and material limit considerations, it was preferred to leave the target assemblies reach either the assumed limit of 200 DPA at discharge or maximum allowable gas pressure caused by helium production from transmutation. The number and specific design of the target assemblies was chosen to satisfy the necessary core symmetry and physical dimensions (available space for a certain amount of mass in an assembly based on an iterated mass density).

DISCLAIMER

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GLOSSARY, ACRONYMS, AND ABBREVIATIONS

ANL	Argonne National Laboratory
DOE	Department of Energy
GNEP	Global Nuclear Energy Partnership
INL	Idaho National Laboratory
LWR	Light Water Reactor
MA	Minor Actinides
MC^2-2	Code System for Calculating Fast Neutron Spectra and Multigroup Cross-Sections
MOX	Mixed-Oxide Fuel
ORNL	Oak Ridge National Laboratory
REBUS-3	Code System for Analysis of Fast Reactor Fuel Cycles
RSICC	Radiation Safety Information Computational Center
SFR	Sodium Fast Reactor
S-PRISM	SuperPRISM Advanced Fast Reactor
SNF	Spent Nuclear Fuel
TRU	Transuranics
TRU CR	Transuranic Conversion Ratio
UOX	Uranium-Oxide Fuel
UREX	Uranium Extraction Process
VISION	Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics

1. Introduction

Traditional approaches to Light Water Reactor (LWR) Spent Nuclear Fuel (SNF) transuranic waste (TRU) burning in a fast spectrum system have typically focused on the continual homogeneous recycling (reprocessing) of the discharge fast reactor fuel. The effective reduction of transuranic inventories has been quantified through the use of the transuranics conversion ratio (TRU CR). The implicit assumption in the use of this single parameter is a homogeneous fast reactor option where equal weight is given to the destruction of transuranics, either by fission or eventual fission via transmutation. This work explores the potential application of alternative fast reactor fuel cycles in which the minor actinide (MA) component of the TRU is considered 'waste', while the plutonium component is considered as fuel. Specifically, a set of potential designs that incorporate radial heterogeneous target assemblies is proposed and results relevant to transmutation and system analysis are presented.

The proposed heterogeneous transmutation schemes present the difficulty of quantifying potential benefits (and drawbacks) with respect to transmutation performance, fuel handling, and repository benefits that would otherwise be missed if a single parameter was equally applied to all designs, such as the TRU CR. While no definitive solution is given in this work to the challenge of creating objective metrics, a variety of related metrics are offered as an attempt to understand the implications that these heterogeneous target assemblies would have on the overall fuel cycle. Relevant fuel handling metrics involve the decay heat, gamma energy, and neutron emission per mass of TRU for the driver fuel and minor actinide-bearing targets.

In this work we consider exclusively minor actinide-bearing radial targets in a continual reprocessing scenario (as opposed to deep-burn options). The potential use of targets in a deep burn mode is not necessarily ruled out as an option. The potential use of axially heterogeneous minor actinide target presents another potential area of consideration and has been recently studied as an option. Finally, the number and specific design of the target assemblies was chosen to satisfy the necessary core symmetry and physical dimensions (available space for a certain amount of mass in an assembly based on an iterated mass density).

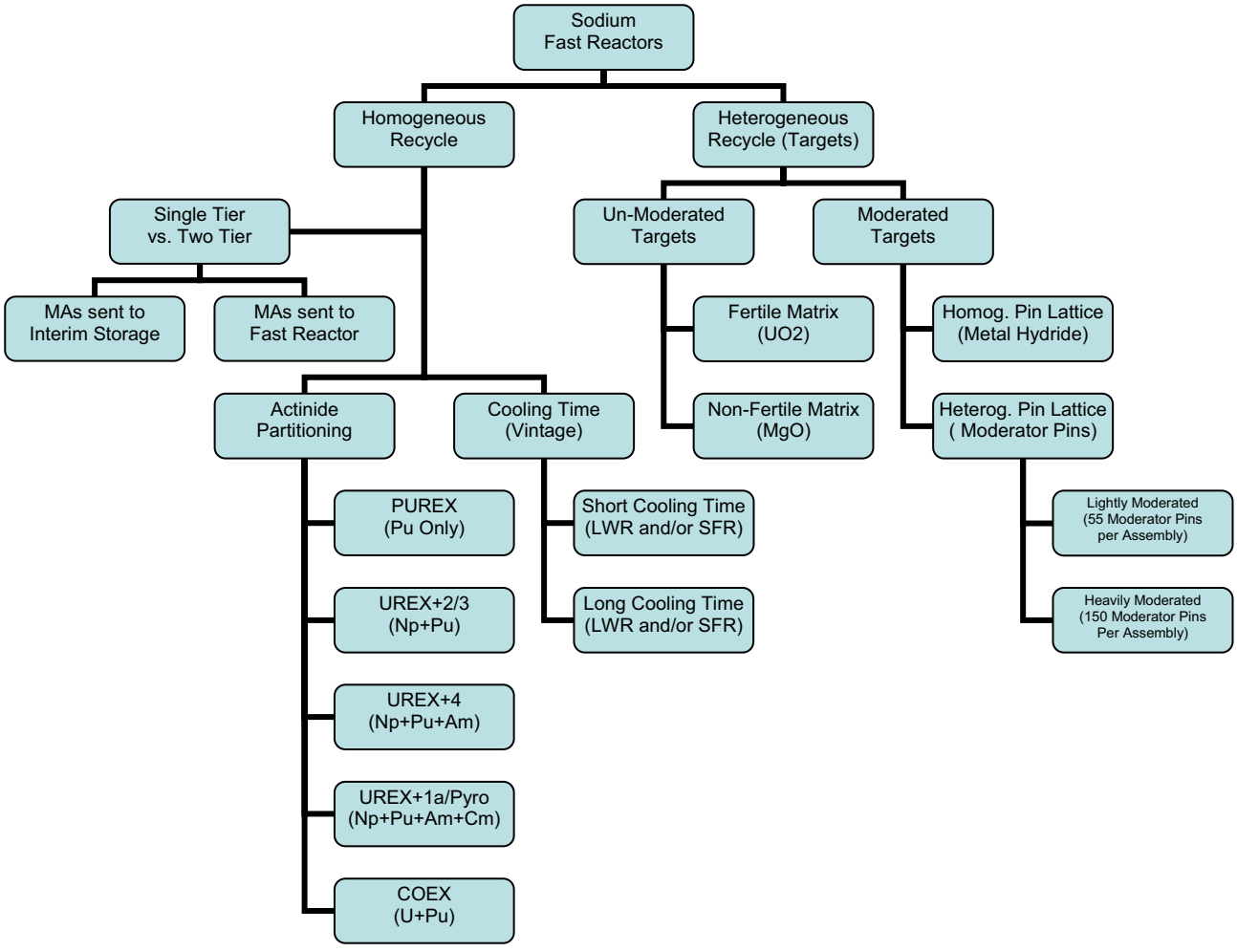
A summary of the fast reactor closed fuel cycle options studied by the fuel cycle analysis group is shown below. Beginning with the baseline case of a Sodium Fast Reactor (SFR), Table 1-1 branches into two main options; homogeneous and heterogeneous recycling. In the homogeneous option the potential of a two-tier fuel cycle, in which plutonium from the LWR SNF is irradiated in thermal MOX before being reprocessed as a fast reactor fuel, was studied. Two variations in this two-tier scenario involved the permanent storage of the minor actinides or the continual reprocessing of these elements in a fast reactor. The potential application of multiple actinide partioning schemes in homogeneous recycling was also studied. Finally, the effects of varying the LWR SNF and fast reactor discharge cooling period was studied in order to quantify their effects reactivity and fuel handling. These past studies will serve as data points for comparison in this work and the reader is directed to other reports [2] in which detailed assumption and main conclusions are presented.

The heterogeneous recycle branch, which forms the main investigative branch of this work, involves two options: un-moderated and moderated targets. The segregation of minor actinides into un-moderated target regions can be accomplished by either mixing MA with fertile uranium or fertile-free magnesium oxide. In the moderated option, further heterogeneity is explored by considering cases in which either minor actinide zirconium metal is manufactured into target pins or discrete zirconium hydride pins are present in the same target assembly as minor actinides pins (contained in a magnesium oxide matrix). These moderated designs show an increase in the transmutation rate of americium through the moderation

of the spectrum (which causes an increase in the target reaction rate) and create a net production of fissile plutonium, which is reprocessed and introduced as fuel into the driver potion of the core.

Finally, this work exclusively considers a 1000 MWth sodium-cooled oxide-fuel fast reactor with an initial TRU CR=0.75 design. This design was selected on the basis of practicality (at the time sodium cooled fast reactors with a TRU CR of 0.75 were assumed as the 'baseline'). This work does not rule out the potential for the multiplicity of permutations that can be performed when other fuel type options and TRU CR designs are considered. However, the main conclusions from this study are expected to carry over as different fuel types and TRU CR designs are studied. This work is divided as follows; Section 2 summarizes the standard LWR and SFR neutronics and depletion methodologies, along with innovative scheme to treat the heterogeneous target compositions. The assumptions for the reactor core design and fuel cycle are presented in Section 3. Finally Section 4 presents and discusses the main results from the analysis and Section 5 draws the main conclusions from this work.

Table 1-1 Summary of Sodium Fast Reaction fuel cycle options.



2. Methodology

2.1 Calculation Methods

Light Water Reactor Calculations

Estimates of the LWR SNF isotopic vector were performed with the TRITON code, which is part of the SCALE 5.1 package [3]. The TRITON code [4] acts as a link between the transport code NEWT and the depletion code ORIGEN-S [5]. The depletion code ORIGEN-S was used to predict the concentration of isotopes after cooling and storage. SCALE 5.1 was also used to calculate the decay heat, gamma heating, and neutron emission heat for the beginning-of-equilibrium cycle (BOEC) mass charge reported by REBUS-3 and was normalized on a per kg-TRU basis.

Fast Reactor Calculations

The Argonne National Laboratory fast reactor codes MC^2-2, DIF3D and REBUS were used for the reactor physics and fuel cycle calculations. The MC^2-2 code was used to generate a 33 group cross section set for each driver fuel enrichment zone, the targets, reflectors and shields [6]. Starting with an ultra-fine group ENDF-V/B cross section library, MC^2-2 creates a collapsed cross section set by performing a zero dimensional infinite dilution critical buckling search using the extended P1 method. Using this collapsed cross section set, the DIF3D diffusion code was used to solve the multi-group steady state neutron diffusion equation using a hexagonal-z nodal coordinate system [7]. In the nodal discretization, each hexagonal node in the lateral direction represents an assembly. REBUS uses DIF3D to perform a eigenvalue calculation for the uncontrolled excess reactivity at each time step in its fuel depletion algorithm. In this search, the fresh fuel transuranic enrichment is adjusted until enough beginning-of-equilibrium-cycle (BOEC) excess reactivity is present to keep the core critical until the end-of-equilibrium-cycle (EOEC). For each enrichment adjustment, the fluxes from DIF3D are used to carry out the isotopic buildup/depletion process over the time of the irradiation cycle. REBUS also performs the in-core fuel management and out-of-core cooling, reprocessing and re-fabricating for each reactor cycle. These operations are carried out until the BOEC excess reactivity is found for the prescribed cycle length.

3. Assumptions and Models

This section presents brief discussion of the LWR and SFR models and their corresponding external fuel cycle. Detailed thermal-hydraulics and material considerations, such as linear power limits and thermal conductivity models for the oxide fuel, are discussed in details in previous reports [1]. The methodology applied to the variation of the conversion ratio involved a reduction in pin diameter, which effectively reduces the fuel volume fraction. This causes the TRU enrichment to increase and consequently the conversion ratio to decrease for the same fuel cycle. Once again, detailed descriptions of this process and its effects on the thermal performance of the assembly design are available in other reports [2].

3.1 Light Water Reactor Models

For the purpose of this study it is assumed that data for pressured water reactors (PWRs) is a good representative of the commercial nuclear power fleet; in actuality only 2/3 of LWRs in the U.S. are PWRs. Representative isotopic discharge data was calculated for a PWR with 193 assemblies operating at 3000 MWth containing bundles with 264 fuel pins with an active fuel height of 3.6576 m, one instrument channel and 24 guide tubes. The specific power of the core was assumed to be 33.69 W/g for 51 GWD/MTHM burnup. Reactivity balance and mass flow data for the LWR UOX and MOX cores were obtained using the linear reactivity model (LRM) and unit assembly model assuming core leakage of 3.5%; a three-batch core was assumed.

3.2 Reference Core Design

The reference core design used in this work is derived from the oxide fueled ARR with a CR of 0.75 originally proposed by Hoffman et al in ANL-AFCI-177 [2]. This core was modified from the homogeneous geometry ARR to accommodate a heterogeneous recycling scheme utilizing MA targets located in lieu of the first row of reflector assemblies. Figure 3-1 shows the layout of the 1/3 symmetric core used in this analysis.

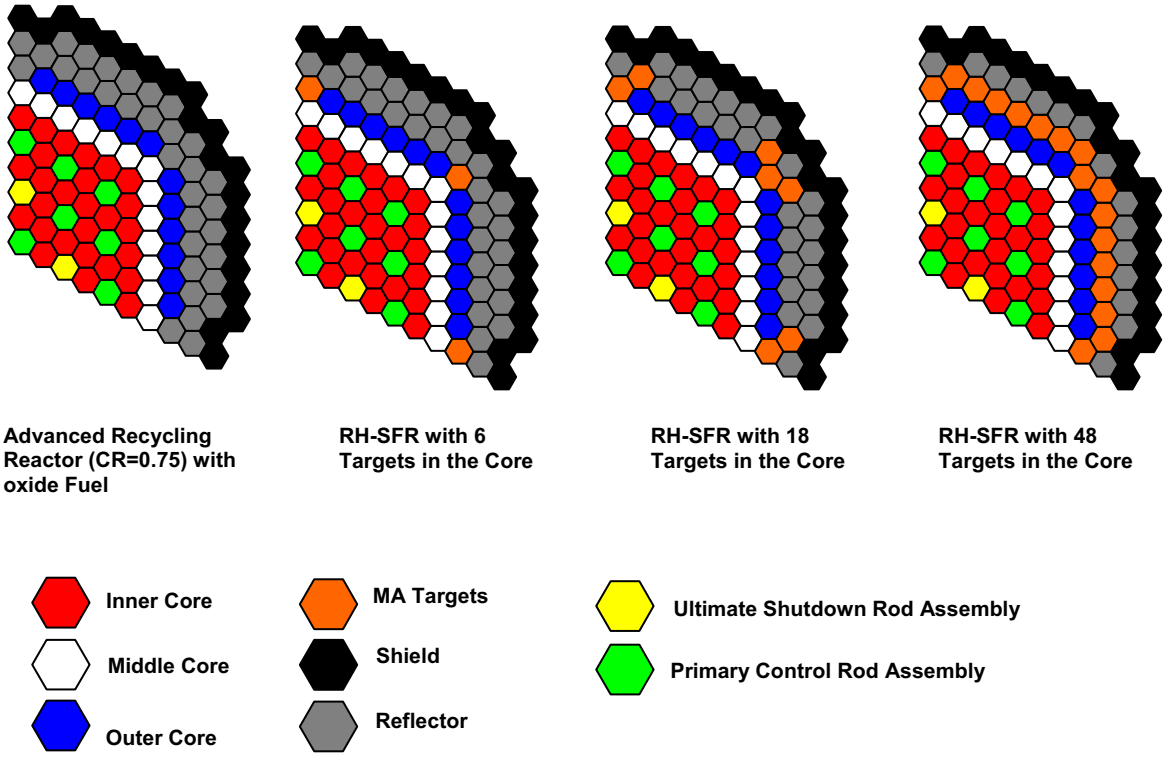


Figure 3-1: Radial heterogeneous sodium fast reactor core designs

Several heterogeneous core geometries with six, 18 and 48 targets were evaluated for the consideration of the heterogeneous targets. In all of these core geometries, the targets were placed on the outer-most row of fuel or in the reflector region. While the geometry and typical mass densities of the fuel driver region were kept constant, the volume fraction of the minor actinide-bearing target material was varied based on a fixed mass density and physical geometry of the target.

3.2.1 Recycling Scheme

The separation and recycling strategy investigated in this work assumes the ability to partition uranium, Np+Pu, and MAs (Am+Cm+Bk+Cf) into three separate waste streams. The separation strategy is outlined in Figure 2. The general philosophy of maintaining the MA inventory in transmutation targets is indicated by the hot-cell and glove-box images at the center of the figure. In each recycle, the Np+Pu produced by the targets is separated from the MAs and recycled into the next batch of driver fuel. The driver external makeup feed is comprised of LWR SNF Np+Pu and recovered uranium (uranium recovered from SNF). Also in each recycle, the Am+Cm+Bk+Cf produced by the driver fuel is separated from the Np+Pu and recycled into the next batch of targets. The transmutation target external makeup feed of MAs has the same isotopic vector as the Am+Cm+Bk+Cf corresponding to LWR SNF.

The targets are irradiated on a multi-batch basis. As opposed to some “once-through-then-out” strategies, a “batch” fraction of the targets are removed, recycled and replaced with fresh targets every cycle. This ensures that only the losses in the transuranic reprocessing are sent to a geologic disposal. Since the ratio of Np+Pu to Am+Cm+Bk+Cf in the external TRU feed rate is always respected the amount of MA

throughput in the core is approximately conserved for the two heterogeneous designs (i.e.: UO_2 vs. MgO target matrix options) of primary interest in this work.

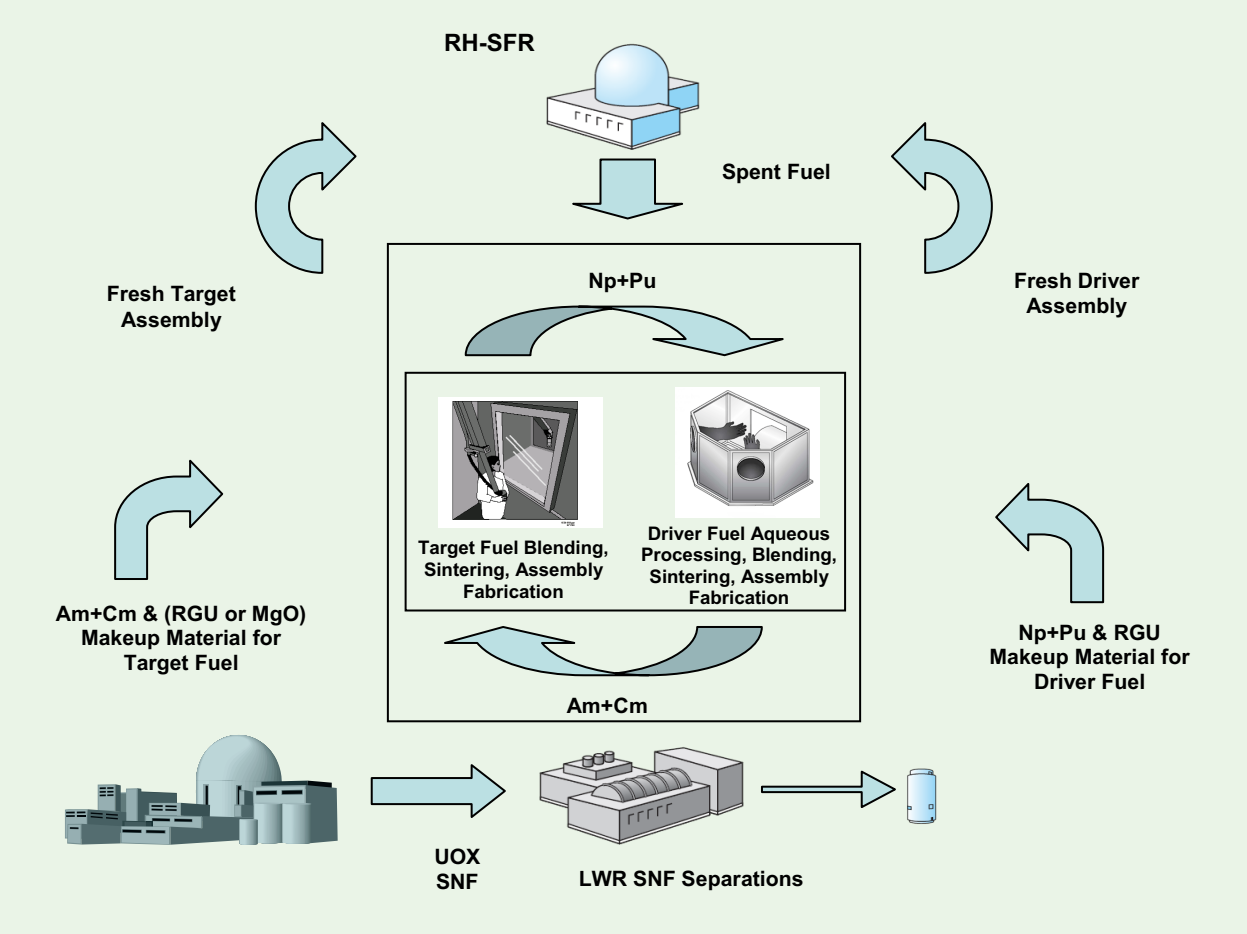


Figure 3-2: Heterogeneous recycling scheme

The following figure shows the flowchart of the heterogeneous core represented in the moderated target analysis. The LWR spent fuel is cooled for 5 years and the Np/Pu is separated from the other minor actinides. The streams are then cooled for an additional 2 years associated to the fabrication of the fuel. These two streams (EFA and EFB) are then fed into the fast reactor with the recycled minor actinides (RCYC and UREX). The driver fuel is supplemented with depleted uranium (EFC), while the targets are fabricated in a ZrH_X matrix (EFD). Two different stoichiometry of the zirconium hydride were used in this study: 1) $ZrH_{1.6}$, and 2) $ZrH_{2.7}$.

The iteration algorithm for the homogeneous moderated targets is described below:

- *Initial parameters from input file*
- *Start Loop*

- *Calculate fabrication densities*
- *Write REBUS input file*
- *Run REBUS*
- *Read output file*
- *Evaluate feed ratio (EFB/EFA)*
- *Adjust cycle length so that maximum fluence is 3.95*
- *If (feed ratio change less than 80% and more than 1%)*
    - *Interpolate to next enrichment estimate*
- *Else*
    - *Compute next enrichment from output data*
- *Verify convergence of cycle length, target enrichment and feed ratio*
- *If all converged and x.s. flag on*
    - *Update x.s. with converged output data*
- *Else if all converged and x.s. flag off*
    - *Exit loop*

The process starts by reading the initial parameters on an input file. Based on the initial target enrichment guess and the fixed fuel density of 7.15 g/cc, the fabrication densities are evaluated. This data is then written to a rebus input file and is executed. The program than reads the mass flow data and fluence data from the output file and evaluates the feed ratio and cycle length. For feed ratio change between 1% and 80%, an extrapolation/interpolation on the enrichment is performed. For very small changes (less than 1%) or very large changes (greater than 80%) in feed ratio, the new enrichment is computed from the output data to avoid unrealistic situations. When the cycle length, feed ratio and target enrichment have converged for the first time, the cross sections are updated and the process is repeated.

Additionally, the x.s. updater (mcc2updater.exe) was modified to allow different fuel temperatures to be used for the targets and driver core. An additional row is required in the "nuclides.data" file for the target temperatures.

4. Proposed Transmutation Target Designs

The heterogeneous target case 'tree', Table 1-1, was evaluated using the partitioning and transmutation strategy from Figure 3-2. The transmutation target design consists of a 271 pin lattice with identical duct, pitch and pin dimensions to that of the driver fuel assemblies. These assembly dimensions are also kept consistent with the homogeneous ARR core design investigated by Hoffman et al with oxide fuel and a conversion ratio (CR) of 0.75. These ARR dimensions are also similar (but not identical) to the S-PRISM driver assembly design.

Table 4-1: Transmutation target pin and assembly dimensions

Assembly pitch, cm	16.142
Pins per assembly	271
Spacer type	Wire wrap
Bond material in gap	He
Plenum height, cm	170.82
Core height, cm	137.16
Overall pin length, cm	422.28
Fuel smeared/ fabrication density, % TD	85/89.4
Pin outer diameter, cm	0.808
Pin pitch-to-diameter ratio	1.099

The non-moderated target assemblies only differ by the material used to fabricate the targets. Specifically, either uranium dioxide served as the fertile matrix or magnesium oxide as the inert matrix fuel. The main difference in the moderated target assembly designs investigated is the selection of a homogeneous lattice versus a heterogeneous lattice of target pins. A homogeneous target pin lattice was considered with MA-O_2/UO_2, MA-O_2/MgO or MA-Zr-H_x matrix compositions. The UO_2 and MgO matrix options draws upon a large irradiation experience database from various in-pile tests. Two heterogeneous lattices were investigated, one with 55 moderator pins, the other with 150 moderator pins (Figure 4-1). These two configurations indicate two possible scenarios of introducing increasing amounts of moderator to the target irradiation vehicle. The heterogeneous pin lattice offers the advantage of allowing the moderator to be mechanically segregated from the MA carrying pins. This could be advantageous from the standpoint of preventing hydrogen dissociation issues due to high thermal gradients in a "hot" pin.

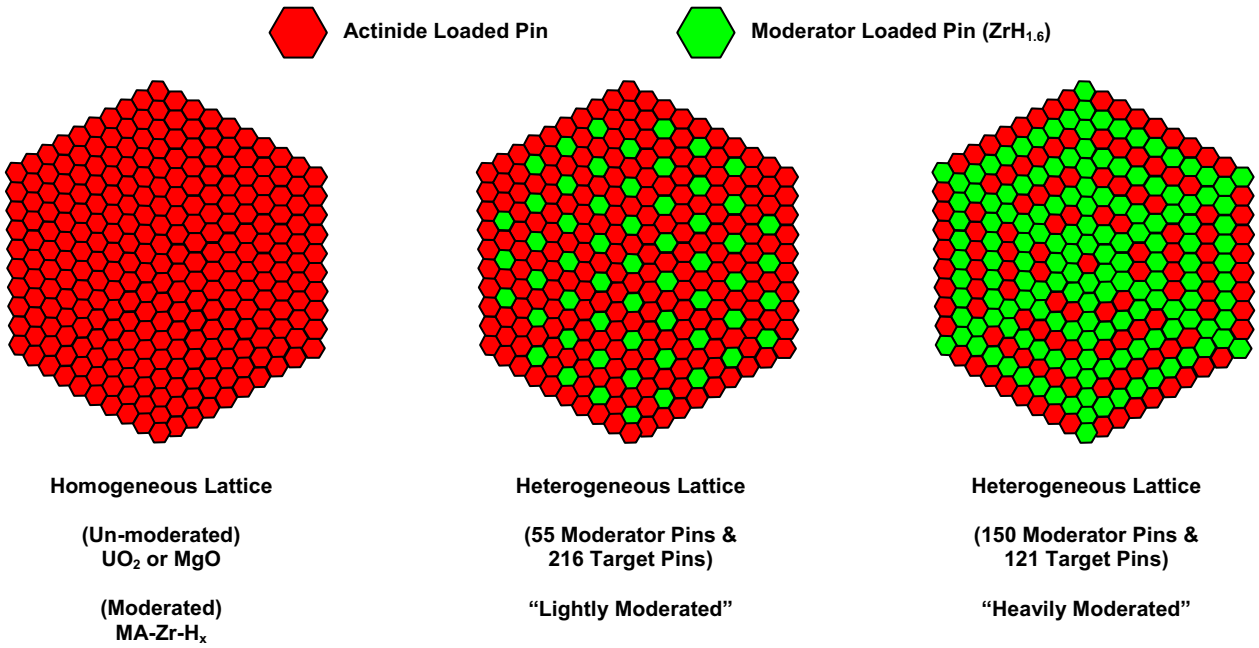


Figure 4-1: Graphical depiction of homogeneous and heterogeneous lattice geometries[a]

[a] In the MC^2-2, the heterogeneous detail of the pin-lattice geometry is lost due to its zero-dimensional homogenization scheme. To quantify the heterogeneous effect on cross section generation, an independent validation exercise was conducted to quantify the impact of heterogeneous spatial shielding effect on the cross section generation process.

5. Analysis Results

In order to provide a fair comparison between the radial heterogeneous transmutation targets, multiple objective metrics must be defined in order to assess the differences in transmutation performance. The TRU and MA consumption rate (kg/EFPY) and consumption per cycle (kg) for the complete reactor system (driver plus targets) is used as an initial system analysis estimate of the overall performance of the system. Following these metrics, a target-specific TRU and MA consumption rate and transmutation efficiency is used to further compare the performance of the targets.

5.1 Transmutation Target Physics Characterization

The addition of dedicated transmutation targets to the periphery region of a fast reactor can have significant impact on the region-averaged neutron spectrum. The number of targets can also affect this parameter, since an increase in the number of targets leads to a larger presence of certain isotopes in the target region of core. In fact, the neutron spectrum is already expected to be somewhat 'softer' in the periphery of the core due to the effect of the reflectors. Figure 5-1 shows the region-averaged neutron spectra for the proposed target designs and the reference 'homogeneous' case. The neutron spectrum for the reference case is characterized as having its highest peak in the high energy region followed by a monotonic decrease in flux as lower energy groups are examined. Similarly, the un-moderated fertile (UOX) and inert matrix target (MgO) cases exhibit a similar behavior as the reference case, while at the same time beginning to show some moderation. While the fertile target cases (UO2 18 and 48 target cases) show little relative difference in spectra, the inert matrix cases show an effective increase in moderation between the 18 and 48 MgO target case due to the overall higher presence of magnesium, a 'lighter' element that can slow down neutrons more effectively through elastic scattering interactions.

The addition of zirconium hydride (ZrH_x) either in the form of dilution rods or homogeneously mixed with the minor actinides in the form of a metal can considerably moderate the neutron spectrum. This moderation is advantageous from the point of view of americium transmutation, since the neutron capture cross section increases as the neutron spectrum becomes moderated. It is worthwhile to notice, however, that the degree of moderation is not enough to consider the region-averaged flux in the targets as 'thermal'. This 'controlled' level of moderation does not only allow the DIF3D/REBUS reactor design tool to remain valid despite being intended for purely fast spectrums, but also avoids undesirable effects such as excessive helium gas production and extremely high decay heat.

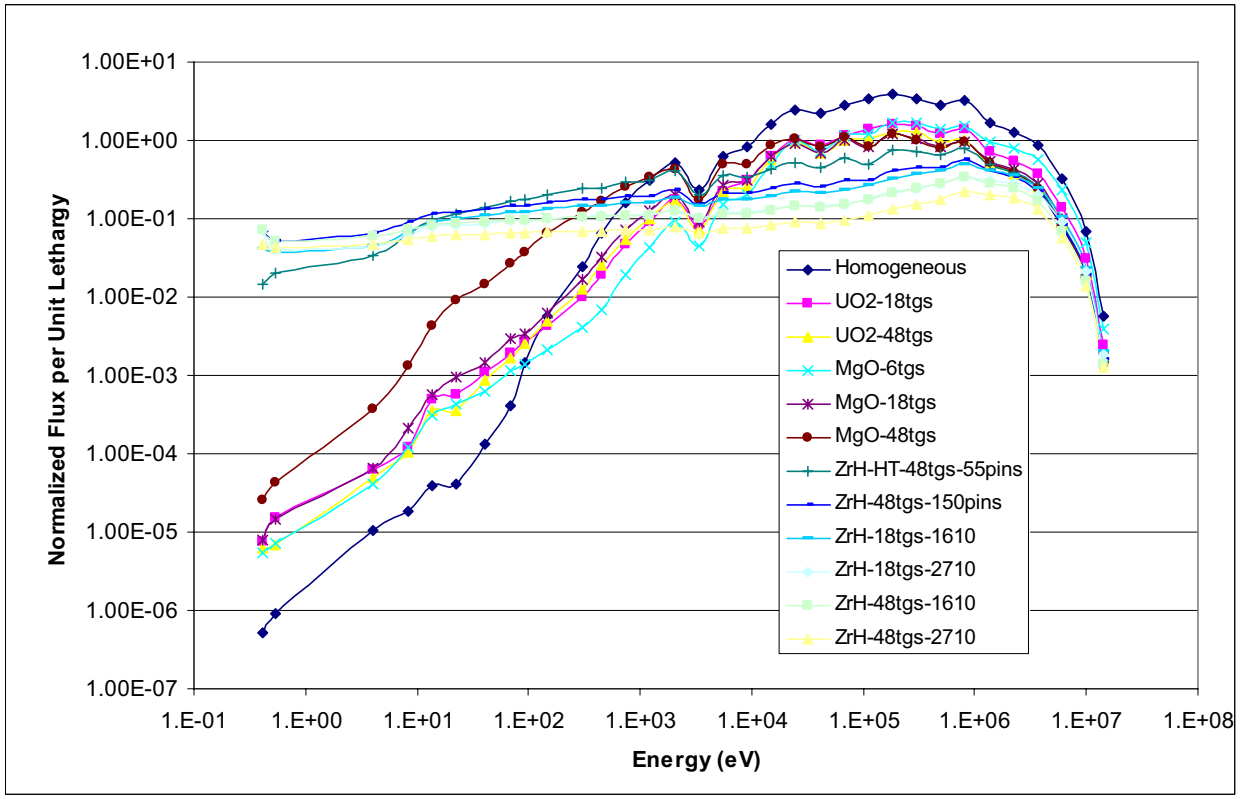


Figure 5-1: Target region-averaged neutron spectra for reference and heterogeneous target conceptual designs.

The proposed radial heterogeneous target designs were introduced to the periphery of the homogeneous reference case and the minor actinide target matrix material volume fraction adjusted accordingly so as to obtain the maximum limiting DPA (in both the core and targets) while observing the physical constraints of having a fixed pellet mass density and target assembly geometry. The exception to this rule is with the moderated target designs which were irradiated with a constant 10 cycles, which is the same as the un-moderated targets. This decision was made at the scoping calculation stage between different target designs in order to allow an equal comparison of the target design strategy based on spectral effects only. Therefore, the moderated target designs evaluated in this report have considerable margin for increasing the irradiation time which would in turn increase the burnup of the minor actinides. A detailed analysis of transmutation target designs including enhanced burnup will be offered in a complimentary report. The TRU CR was allowed to change accordingly, thus it somewhat reflect the effects that the introduction of the targets may have over the reactor system as a whole. Other overall transmutation metrics, such as TRU and MA consumption rates, were evaluated and are tabulated in Table 5-1. The first column of this table shows the cases that were analyzed, while the second column identifies the characteristic spectrum of these designs in the target region as 'fast' or 'moderated' (albeit the fact that some cases, such 48 inert MgO target case can be argued to have a softer spectrum than the other un-moderated cases). The third column shows the TRU CR for each analyzed case.

The introduction of fertile targets to the periphery of the core caused an increase in the TRU CR (particularly in 48 target case) due to the overall increase in fertile uranium, thus transforming the targets into pseudo-blankets, 'spiked' with minor actinides. This foreseen result motivated the design of fertile-

free or inert matrix targets utilizing MgO as the minor actinide-bearing material. The introduction of these targets effectively reduced the TRU CR. The desire to further enhance the transmutation of minor actinides eventually led to the introduction of moderated target assemblies. As expected, these moderated assemblies further enhanced the destruction rate of transuranics in an overall sense.

In addition to TRU CR, six other parameters are shown in Table 5-1. These parameters add further detail to the specific performance of the proposed target designs. For example, the consumption rate, defined as the averaged change in mass (over the whole core) of a certain isotope grouping over the cycle length, points to the expected net increase or decrease of a certain set of isotopes. The fourth and fifth column show the consumption rate for the TRU and MA. As expected, the TRU CR is related to the TRU consumption, thus the latter tends to increase as the TRU decreases. The inverse relation is also true; the consumption rate for the 48 target UO_2 case shows a higher TRU CR and the lowest TRU consumption. In the case of minor actinide consumption rate, the trends remain similar to the TRU consumption rate. The moderated cases tend to have both a higher TRU and MA consumption rate than the un-moderated targets. From a transmutation perspective, the non-moderated fertile free targets show benefits in TRU and MA consumption rates over the fertile and reference scenario.

The sixth and seventh column shows the necessary driver enrichment and cycle length, respectively. While the driver fuel TRU enrichment column shows very similar necessary numbers, the cycle length radically varies from case to case. This variation can be attributed to multiple competing effects such as breeding, moderation, segregation of MAs into targets, and even numerical accuracy. First, the cases in which fertile target were used as transmutation vehicles also bred plutonium, which was simulated to be separated and used as fuel in the driver region. Thus the addition of a large number of targets with a low concentration of MAs can extend the cycle length. On the other hand, the high concentration of MAs into a few targets in the periphery can decrease the cycle length due to higher number fast fissions occurring in these regions. Similar results can be found with un-moderated fertile-free targets, but with the added advantage of higher TRU and MA transmutation rates. The only exception to this general trend in cycle length is the case of the 48 fertile-free MgO targets. Further studies in this particular case will be required in order to understand the origin of this apparent discrepancy.

The effects of moderation in the cycle length also show a complex behavior. Particularly, the addition of moderation is expected to increase the transmutation of Pu-238 and lower limiting DPA by in turn lower the fast neutron fluence. In reality the heterogeneous 55 and 150 ZrH_x cases appear to generally have a longer cycle length than the homogeneous cases. However, the numerical accuracy of the iterations and the sensitivity of the cycle length to the composition of the driver/target system can cause large changes in the cycle length due to small changes in volume fractions.

Finally, the last two columns show the expected TRU and MA consumption per cycle. The same trends as discussed above are found to more or less hold. The addition of fertile target lowers the TRU consumption (due to a net production of plutonium), while the use of fertile-free MgO targets increases both TRU and MA transmutation. The moderation of the neutron spectrum in the target region appears to further increase the TRU and MA consumption, compared to the homogeneous and un-moderated target designs. The higher TRU and MA consumption rate for the homogeneous zirconium hydride/minor actinide case (column 5 and 6) is offset by the relatively short cycle length, thus giving both homogeneous and heterogeneous moderated transmutation targets an almost equal TRU and MA consumption rate per cycle.

Table 5-1 Equilibrium fuel cycle overall transmutation performance for alternative designs.

	Cases	Spectrum	TRU CR	TRU Consumption (kg/EFPY)	MA Consumption (kg/EFPY)	Fuel Enrichment	Cycle Length	TRU Consumption per Cycle (kg)	MA Consumption per Cycle (kg)
	Homogeneous	Fast	0.76	76.59	10.10	21.3%	344	72.17	9.52
Target Designs	UO2-18 tgs	Fast	0.76	76.99	10.94	21.8%	330	69.56	9.88
	UO2- 48 tgs	Fast	0.87	39.16	6.33	19.9%	353	37.84	6.11
	MgO-6 tgs	Fast	0.71	93.16	12.98	21.5%	359	91.47	12.75
	MgO-18 tgs	Fast	0.71	92.71	12.77	21.6%	356	90.31	12.44
	MgO-48 tgs	Fast	0.74	83.80	11.98	20.8%	344	78.89	11.28
	Zr-HT-48 tgs 55 pins	Moderated	0.69	100.86	14.55	21.7%	364	100.53	14.50
	Zr-HT-48 tgs 150 pins	Moderated	0.66	112.06	16.30	22.4%	348	106.65	15.51
	Zr-18 tgs 1610	Moderated	0.68	103.55	14.91	22.0%	348	98.75	14.22
	Zr-18 tgs 2710	Moderated	0.67	106.27	15.23	22.2%	344	99.98	14.33
	Zr-48 tgs 1610	Moderated	0.64	119.42	17.25	23.1%	333	108.82	15.72
	Zr-48 tgs 2710	Moderated	0.63	121.75	17.50	23.4%	322	107.48	15.45

While the overall reactor system transmutation performance parameters seem to indicate a benefit to the introduction of fertile-free and moderated targets from a TRU and MA consumption rates, fuel performance limitations must be taken into account in order to fully evaluate the potential introduction of targets into a fast reactor system. Table 5-2 presents further metrics for each of the cases discussed above in order to further understand the transmutation performance of the targets, divorced from the coupled driver/target reactor system. Beginning in the third column, the necessary volume fraction for target is shown in terms of percentages. The cases with few targets, such as the first un-moderated fertile-free MgO case, show a very high MA volume fraction. This volume fraction was computationally iterated in order to satisfy an overall fuel cycle length and maximize transmutation rate. As more targets are added into the system, a decrease in the necessary volume fraction is observed. This may be beneficial from a fuel handling perspective, since the manufacturing of a few targets with a high concentration of MAs may not be as practical as the manufacturing of many targets with lower concentrations of MAs. This will become especially evident when the decay heat, gamma energy, and neutron emission are evaluated in the next section. The middle two columns in Table 5 3 show the same TRU and MA consumption rates as Table 5 4, but specific to the target assemblies. The homogeneous case (first row) is only shown as a reference point. The target region TRU and MA consumption rates follow the same trend as the overall system. The existence of the same trend as before, increasing TRU and MA consumption with the addition of targets and moderation, shows the relative advantage a certain target design has over the other designs. Furthermore, the computation of TRU and MA transmutation efficiency shows the importance of increasing transmutation efficiencies in order to optimize TRU and MA consumption in the target regions, causing an increase in the overall reactor core TRU and MA consumption.

Table 5-2 Equilibrium fuel cycle target-specific transmutation performance for alternative designs.

	Cases	Spectrum	Target MA v/f	TRU Consumption (kg/EFPY)	MA Consumption (kg/EFPY)	TRU Transmutation Efficiency	MA Transmutation Efficiency
	Homogeneous	Fast	-	76.59	10.10	11.06%	15.55%
Target Designs	UO2-18 tgs	Fast	27.6%	-0.02	6.16	-0.09%	34.51%
	UO2- 48 tgs	Fast	8.8%	-8.32	4.83	-55.08%	32.02%
	MgO-6 tgs	Fast	85.9%	4.51	7.48	21.93%	36.36%
	MgO-18 tgs	Fast	30.6%	3.84	7.44	17.32%	33.58%
	MgO-48 tgs	Fast	7.8%	4.05	7.00	26.83%	46.36%
	Zr-HT-48 tgs 55 pins	Moderated	7.1%	6.67	8.21	60.48%	74.61%
	Zr-HT-48 tgs 150 pins	Moderated	12.8%	7.49	8.55	67.91%	77.68%
	Zr-18 tgs 1610	Moderated	21.6%	6.24	7.98	54.38%	69.59%
	Zr-18 tgs 2710	Moderated	22.4%	6.37	8.00	53.76%	67.61%
	Zr-48 tgs 1612	Moderated	8.5%	7.66	8.61	64.00%	72.10%
	Zr-48 tgs 2710	Moderated	9.2%	7.66	8.61	64.00%	72.10%

5.2 Reactor Charge and Discharge Results

The equilibrium charge mass data for all the fuel cycle scenarios were processed through internal tools and decayed using ORIGEN-S in order to calculate the decay heat, gamma heating, and neutron emission. The results are tabulated along with previous calculations of thermal LWR IMF and MOX charge neutron emission, gamma energy, and decay heat.

5.2.1 Decay Heat Results

The decay heat data for the reactor equilibrium charge for the driver and targets regions are compared in Figure 5-2. The decay heat per mass of TRU is, as expected, higher for the target assemblies compared to the driver assemblies. Figure 5-3 in turns shows the decay heat per mass of TRU for four homogeneous fast reactor cases in which single and two-tier scenarios were modeled. An inspection of the plots show that even the most limiting scenario in the homogeneous, two-tier case with a low TRU CR (with a higher TRU consumption rate), has a lower decay heat per mass of TRU than the proposed target cases. This is explained by the fact that the minor actinides within the feed for the homogeneous cores are diluted by the plutonium in the same mass stream. The minor actinides are the primary contributors of alpha, gamma and neutron mass specific emission rates within SNF. The external feed of transuranics to the targets are purely minor actinides and not diluted over plutonium, so naturally, their alpha, gamma and neutron sources are higher. The mass of TRU present in the homogeneous case, however, is much higher than in the target scenarios. It is also important to note that the decay heat for homogeneous recycling all the transuranics in the two tier case is noticeably larger than for a single-tier case. The two-tier decay heat is 1.3 times larger and 1.25 times larger for conversion ratio's 0.50 and 0.75, respectively.

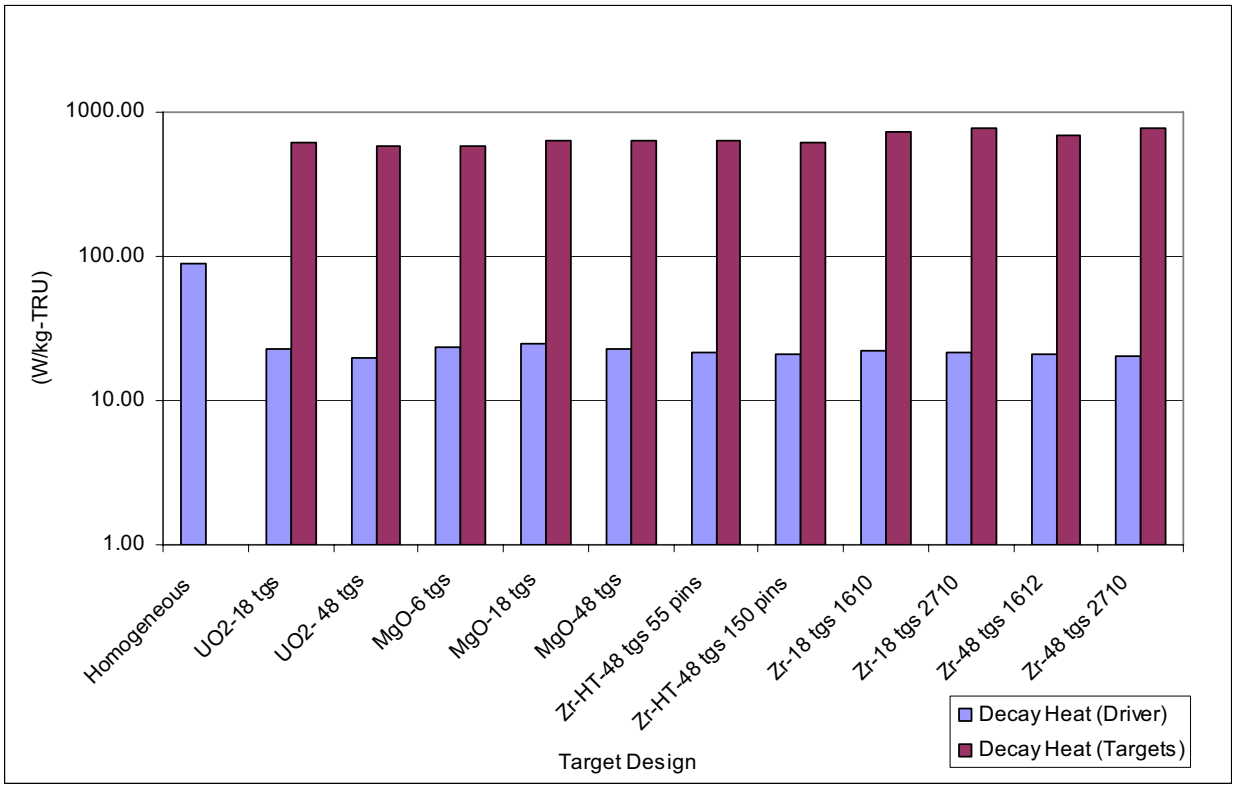


Figure 5-2 Charge decay heat per kg of TRU for driver and target designs.

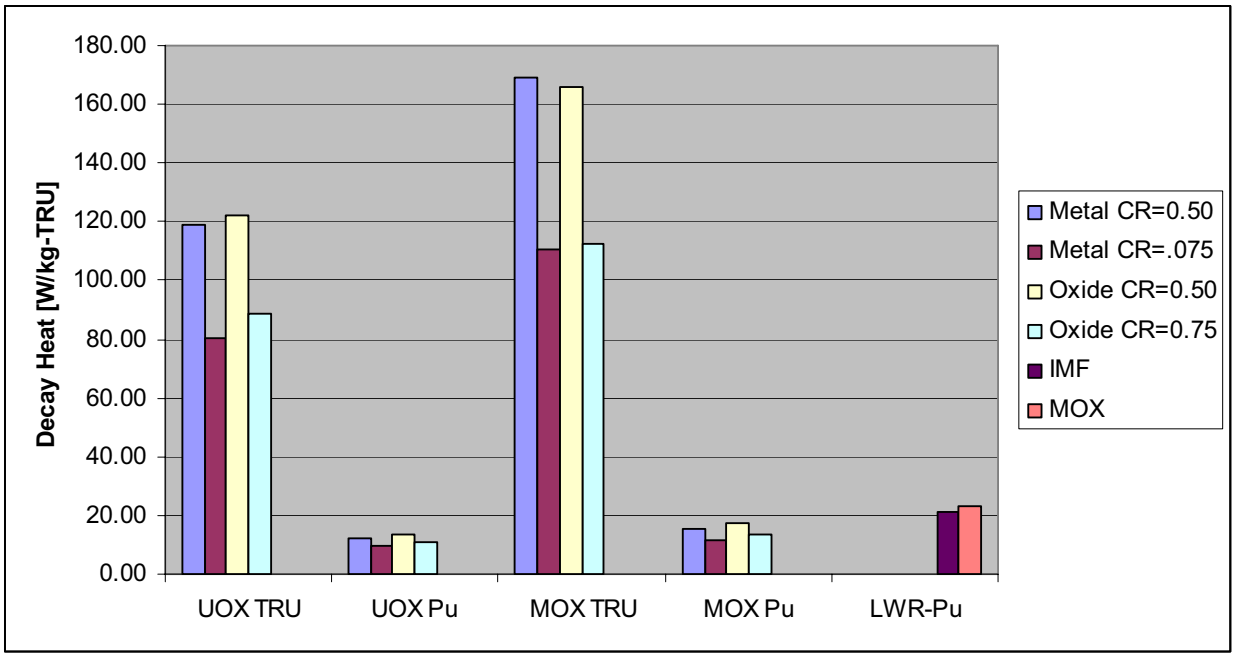


Figure 5-3 Charge decay heat per kg of TRU for SFR and thermal recycling with multiple scenarios.

5.2.2 Gamma Heating Results

The gamma heating produced by fast reactor fuel target regions is compared in Figure 5-4. The trends are similar to the decay heat data in that the additional MA targets causes the gamma heating per mass of TRU to increase. Figure 5-5 additionally shows the gamma heating released by the charge fuel decreases as the TRU CR is increased from 0.50 to 0.75. This is caused by the net lower concentration of TRU on a per kg basis. The gamma heating is also observed to be higher for the double tier MOX TRU case compared to the single tier UOX TRU. This is due to the net production of MA that the initial MOX pass produces.

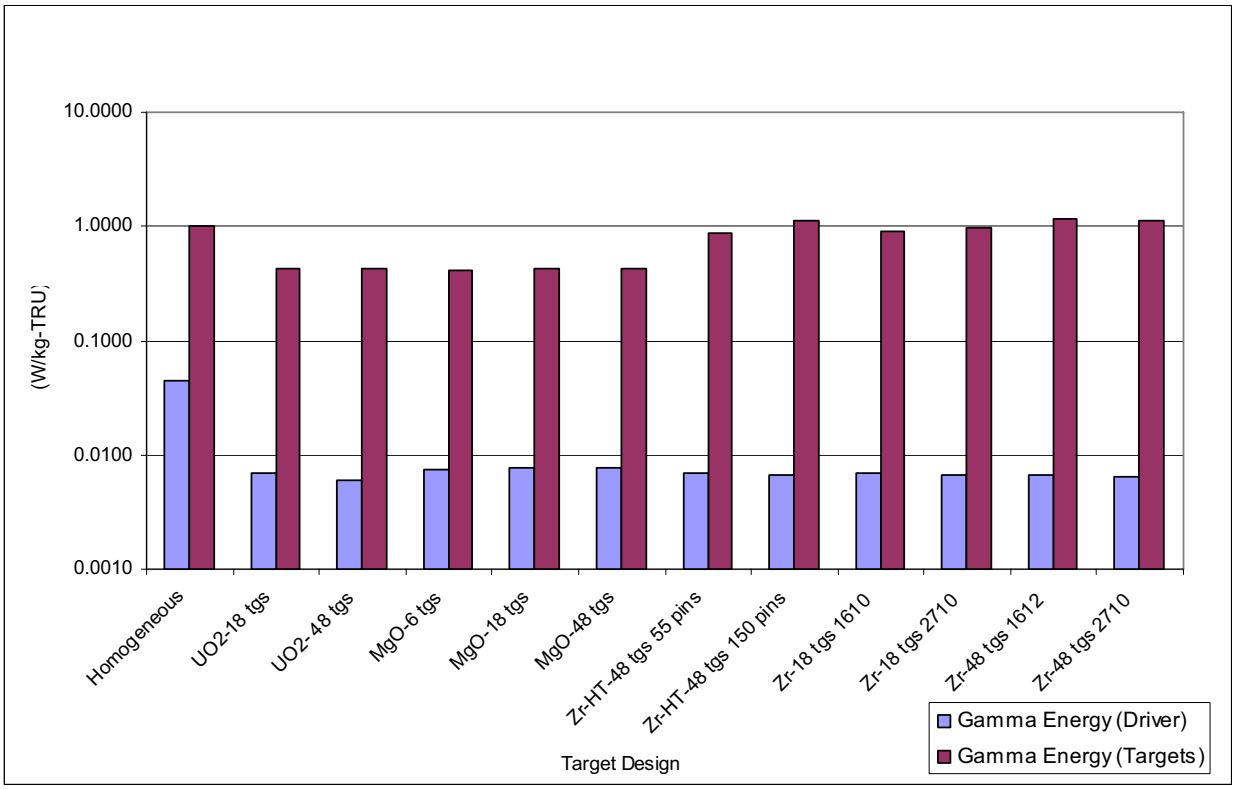


Figure 5-4 Charge gamma heating for SFR and thermal recycling with multiple scenarios.

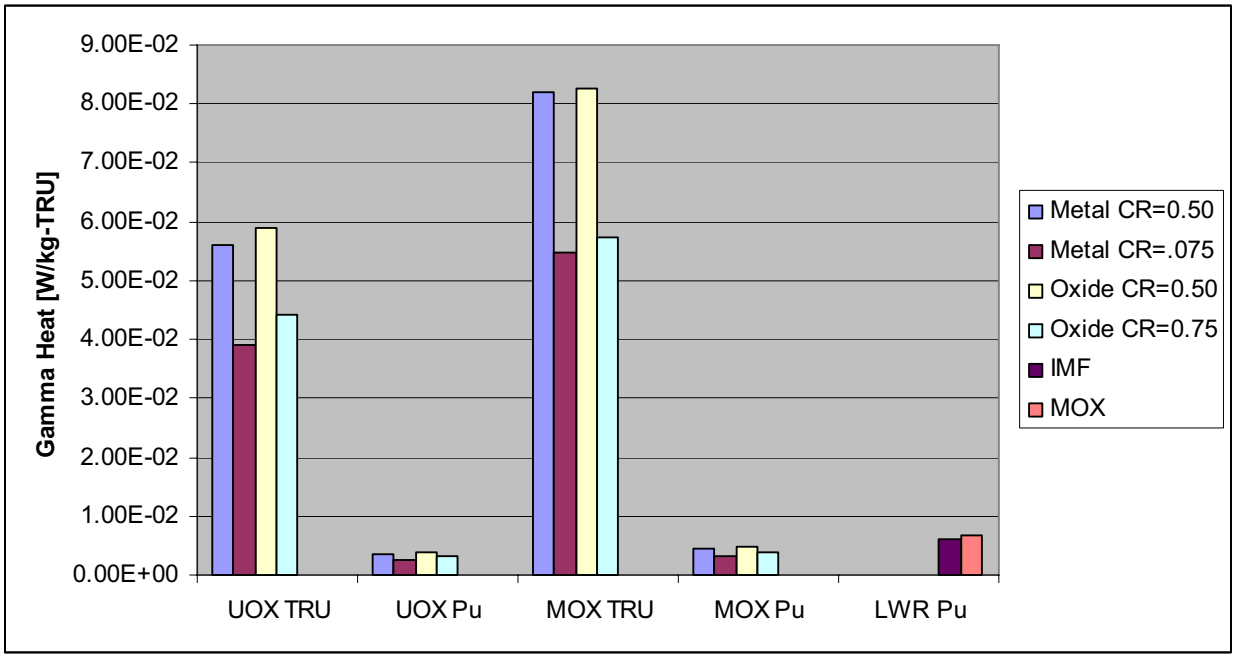


Figure 5-5 Charge gamma heating for SFR and thermal recycling with multiple scenarios.

5.2.3 Neutron Emmission Results

The neutron emission rate is shown below for all scenarios in Figure 5-6. The neutron emission for other scenarios is shown in Figure 5-7. The neutron emission is observed to greatly increase depending on the recycling strategy. For example, for single and double tier scenarios that utilize the plutonium-only fuel cycle, the neutron emission is at least two orders of magnitude less than the homogeneous all TRU scenarios. In the case of CR=0.50 and 0.75, the decrease in neutron emission is not as dramatic as in the decay heat and gamma heating parameters.

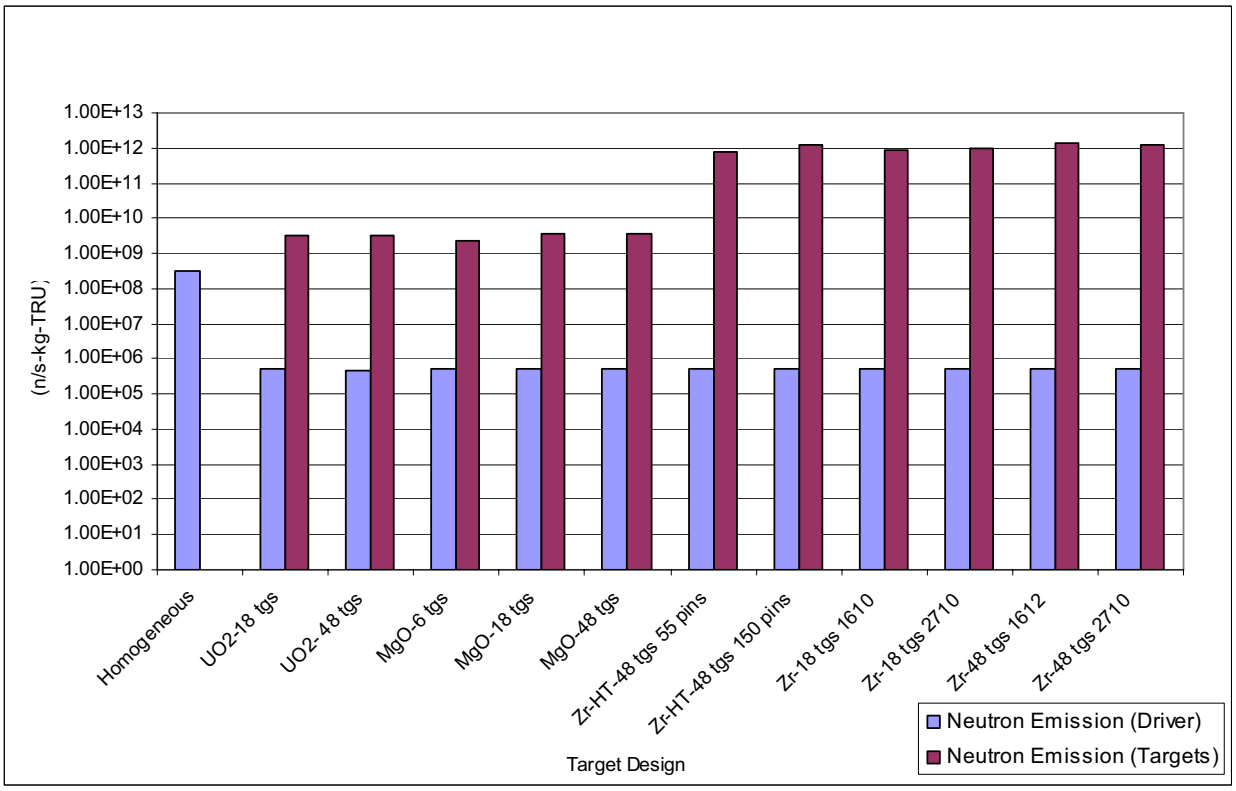


Figure 5-6 Charge neutron emissions for SFR and thermal recycling with multiple scenarios.

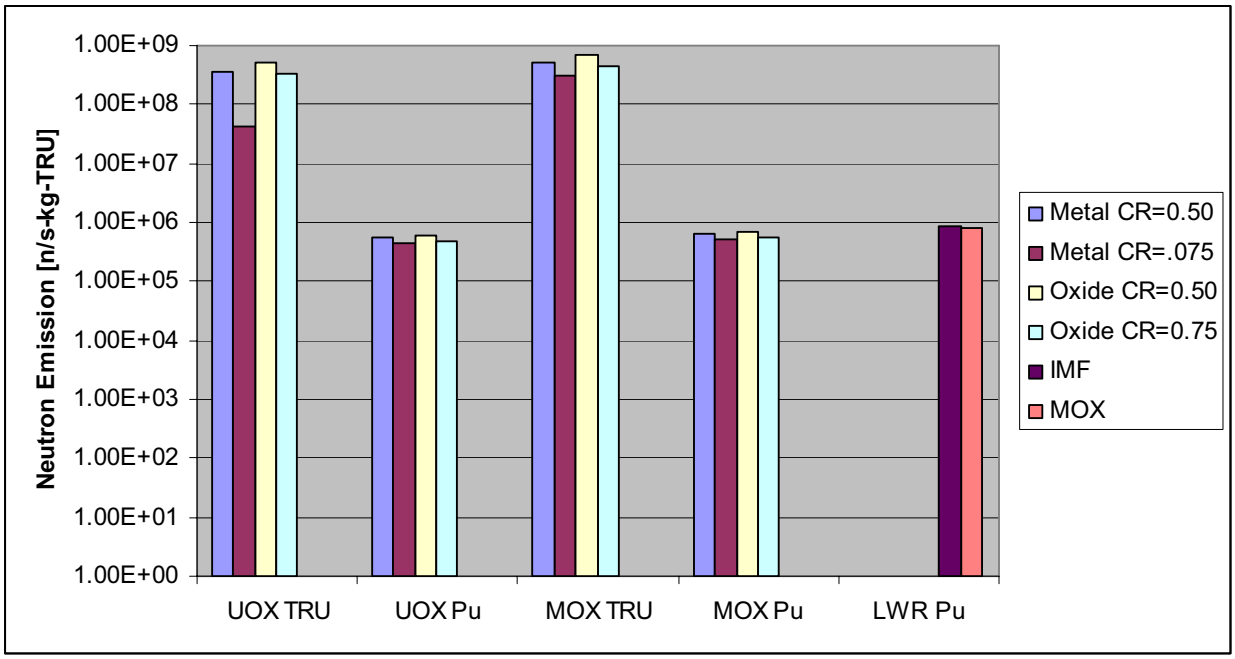


Figure 5-7 Charge neutron emissions for SFR and thermal recycling with multiple scenarios.

6. Conclusions and Future Work

Traditional approaches to Light Water Reactor (LWR) Spent Nuclear Fuel (SNF) transuranic waste (TRU) burning in a fast spectrum system have typically focused on the continual homogeneous recycling (reprocessing) of the discharge fast reactor fuel. The effective reduction of transuranic inventories has been quantified through the use of the transuranics conversion ratio (TRU CR). The implicit assumption in the use of this single parameter is a homogeneous fast reactor option where equal weight is given to the destruction of transuranics, either by fission or eventual fission via transmutation. This work explored the potential application of alternative fast reactor fuel cycles in which the minor actinide (MA) component of the TRU is considered 'waste', while the plutonium component is considered as fuel. Specifically, a set of potential designs that incorporate radial heterogeneous target assemblies is proposed and results relevant to transmutation and system analysis are presented.

The use of specialized target assemblies for burning the americium and higher mass actinide component of light water reactor spent nuclear fuel is achieved through a high transmutation rate of this higher mass actinide material, a large neutron interaction probability and high flux. A sodium fast reactor has a significantly higher flux over other reactor systems. Using hydrogenised materials, this fast flux can be "locally moderated" within a specialized transmutation assembly to give a thermal (or epithermal) neutron spectrum. This has the advantage of drastically increasing the neutron capture and fission probability (i.e., cross sections), thus transmuting much of the americium and higher mass actinide mass.

7. References

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