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Fast Reactor Recycle Fuel Thermal Load

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Abstract

A series of calculations were performed modeling fast reactor core loadings for conversion ratios varying from 0 to 1 in 0.25 step increments to estimate the fuel thermal load from startup through five recycles. The heat loadings are expressed as a function of a future prototypical transportation cask thermal limit to provide an operational perspective. Since neither the physical characteristics nor dimensions of the fast reactor fuel are clearly defined at the present time, thermal power was selected as a measure to estimate the transportability with respect to current design technology

The most significant conclusion is after approximately five years of cooling, the fast reactor spent fuel thermal loads are approximately equivalent to the initial heat load prior to irradiation. Therefore, transport casks for shipping fresh fuel should be designed to also accommodate the same fuel following irradiation and five years of cooling. Current design technology and transport regulations can be applied to encompass fast reactor recycle fuel; however, cask capacities will likely be lower than light water reactor spent nuclear fuel due to thermal and shielding requirements. Related observations include the heat load of the fuel, both when initially charged and 5 years following discharge, depends almost entirely upon the transuranic content; and the transuranic content of the discharge fuel is tightly linked to the TRU content of the initial fuel charge; being reduced by approximately one quarter each recycle. In general, thermal loads for fast reactor (FR) fresh and spent recycle fuel are an order of magnitude higher than high burnup LWR spent fuel, after both have been allowed to decay for 5 years.

Introduction

Established by President GW Bush under the Advanced Energy Initiative, the Global Nuclear Energy Partnership (GNEP) seeks to develop worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy to meet growing electricity demand. GNEP will use a nuclear fuel cycle that enhances energy security, while promoting non-proliferation, by having nations with secure, advanced nuclear capabilities provide fuel services — fresh fuel and recovery of used fuel — to other nations who agree to employ nuclear energy

for peaceful power generation purposes only. The closed fuel cycle model envisioned by this partnership requires development and deployment of technologies which enable recycling and consumption of long-lived radioactive waste.

The proposed use of fast reactors in an advanced nuclear fuel cycle as a way to burn long-lived transuranic actinides, and thereby reduce the repository impacts of heat load and radiotoxicity from the waste generated in production of electricity, has recently seen a marked resurgence in interest as part of the Global Nuclear Energy Partnership. Fast Reactors (FRs) will require a significant shift in current handling and transportation procedures of nuclear fuel, because the transuranic (TRU) elements constituting FR fuel may be considerably "hotter", both thermally and radioactively, in comparison to spent light water reactor (LWR) fuel. FR fuel may also be recycled multiple times, leading to an evolution in the isotopic composition of the contained TRU material.

The purpose of this study was to examine the heat load of both fresh and spent FR fuel through multiple recycles. These values were used to assess the impacts upon transportation throughout the fuel cycle. Specifically, this report compared the heat load of the fuel to the heat limits of transportation canisters.

A series of calculations was performed to estimate the heat generation rate of fast reactor fuels during transportation both to the reactor as "fresh" fuel and after discharge as "spent" fuel. Core loadings for conversion ratios varying from 0 to 1 in 0.25 step increments were simulated covering initial startup, in which TRU characteristics of LWR discharge material was assumed, through five successive recycles of the TRU produced. The heat loadings were compared to a likely thermal limit of a future prototypical transportation cask to provide an operational perspective. A major conclusion, discussed in greater detail below, is after a five-year "cooling" period, the heat generation of the spent fuel is comparable to that produced by the fuel being loaded into the reactor, and a single cask design will likely accommodate shipments of fast reactor recycle fuel both prior to and following irradiation. In addition, current design technologies are applicable to fast reactor fuel, however, reductions in payload capacity are very likely. Results indicate thermal loads for fast reactor fuel are about an order of magnitude higher than LWR spent nuclear fuel (SNF), which could have a significant impact on operational efficiencies. Once fast reactor fuel physical characteristics and dimensions are more clearly defined, evaluations should be conducted to improve cask designs to accommodate higher payloads.

Methodology and Assumptions

The Department of Energy has recently considered moving towards a "clean" repository concept of operations, which entails sealing the spent nuclear fuel at the generating reactor sites in specially designed canisters suitable for direct emplacement with no further required repackaging. A new container is being developed to perform the clean repository handling and transportation tasks, which is referred to as the Transportation, Aging, and Disposal (TAD) canister [1]. The TAD was designed with multiple objectives in mind to simplify and lower the costs for handling and storing nuclear waste, and is assumed the most likely canister to be used for moving fuel assemblies around in the nuclear fuel cycle. Various overpacks are employed depending on whether the canister is used for storage, transportation, or aging.

The total thermal power limit for the TAD is 25 kW, which is consistent with other current cask designs. The TAD has not been designed to accommodate fast reactor or recycled spent nuclear fuels; however, for the purpose of this report it will be assumed that 25 kW is the thermal limit, and this number will specify how many fuel assemblies can be accommodated by one canister.

As part of the Advanced Fuel Cycle Initiative (AFCI) and Global Nuclear Energy Partnership (GNEP) programs, various studies have previously investigated fast reactor fuel compositions. Reference [2] examined fast reactor core designs based on the S-PRISM design. The fuel characteristics and loadings for conversion ratios of 0.0, 0.25, 0.50, 0.75, and 1.0 were given, in which both oxide and metal fuel have been examined. The conversion ratio is defined as the number of transuranic atoms produced per transuranic atom fissioned in a converter type of nuclear reactor. Isotopic charge data was provided; however, the discharge data were not presented. This reference formed the basis for the fuel compositions used for this study.

Reference [3] provided limited data on how the fast reactor fuel loadings change with successive recycles. Charge and discharge data were given for a conversion ratio of 0.25, along with information on how the transuranic to heavy metal loading varied along with multiple recycles. These data were used to approximate the change in enrichments with recycle number for this study.

ORIGEN 2.2 [4] was used for all of the calculations using the Fast Flux Test Facility (FFTF) cross-sections. Metal fuel was assumed, although the oxide fuel had similar results. The LWR source term used to calculate the transuranic isotope ratios was also obtained from an ORIGEN run, based upon a 60,000 MWD/MT burnup, 4.03% initial enrichment, and 5 year decay time.

The fuel composition and isotopic loadings of TRU and Uranium were given in Reference [2]. Both startup fuel compositions and equilibrium fuel assemblies were examined for the first recycle into a fast reactor, but due to the similarity of the thermal results, only the equilibrium fuel assemblies were used for the subsequent multi-recycle cases. Conversion ratios of 1.00, 0.75, 0.50, 0.25, and 0.00 were executed.

For all runs, the FR was assumed to be a 1,000 MW_{th} core, the fuel was burned to 175,000 MWD/MT (175 GWD/MT), and the fuel residence time was 4.5 years; which implies a core loading of about 8.5 MTHM assuming a 90% availability factor. For the multi-recycle runs, a 5-year decay time was assumed between each recycle. For each recycle, the $_{92}U^{235}$ content was kept constant with the amount of $_{92}U^{238}$ being varied to accommodate changes in the quantity of TRU; and the TRU/HM ratio was modified slightly to sustain the reactivity as the Pu isotopics changed. It was assumed that the TRU/HM percentage would need to change by the following increments on each subsequent recycle: no change for CR 0.0 and CR 1.0 cores, a +2% change for the CR 0.75 core, a +4% change for the CR 0.5 core, and a +5% change for the CR 0.25 core.

The ORIGEN results included the charge and discharge isotopics for the actinides and daughters along with the fission products. Activation products were not included since the structure of the fuel was not well known and the light nuclei contribution due to cladding and structural materials would differ greatly with respect to each assembly design. The discharge isotopics were examined at 1, 2, 5, 50, and 100 year decay times.

Results and Conclusions

Figure 1 shows the total heat load of the fast reactor fuel assemblies for the first recycle. The five different conversion ratios are shown along with the equilibrium core fuel (solid lines) as compared to the startup core fuel (dotted lines). Only slight differences were observed between the startup and equilibrium fuel cores (differential values at 5 years of cool time: CR 0 - 23%, CR 0.25 - 18%, CR 0.5 - 9.3%, CR 0.75 - 2.1%, CR 1.0 - 4.8%); thus only the equilibrium fuel was considered for the subsequent recycles.

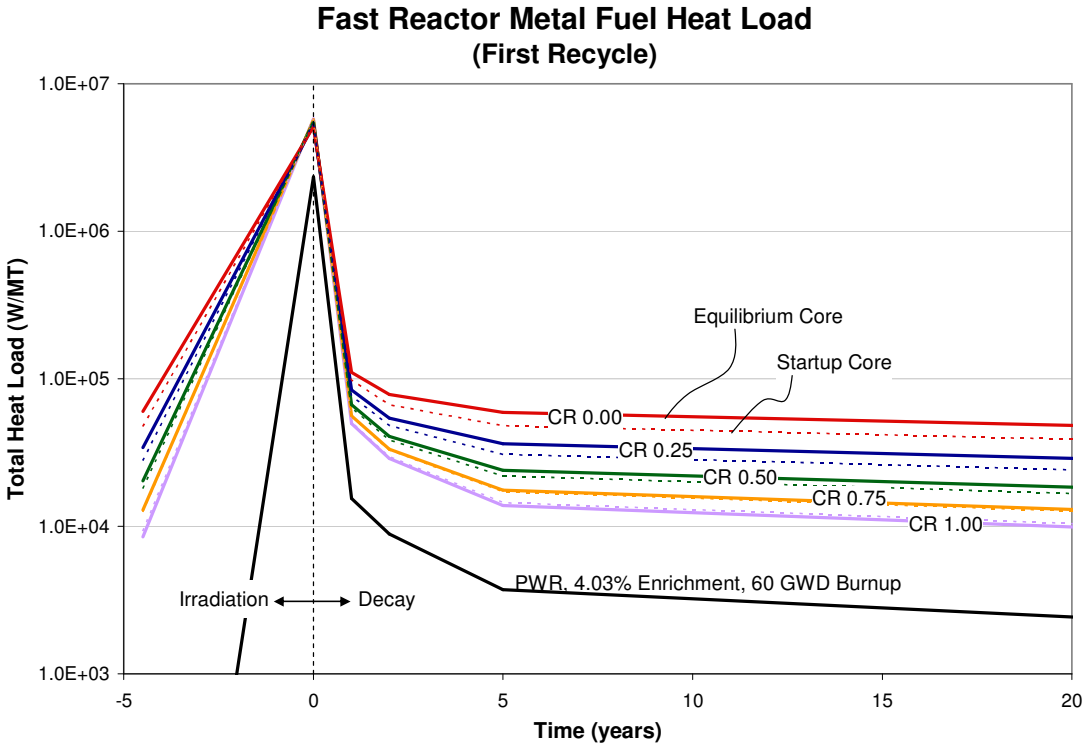

Figure 1. FR Heat Load (First Recycle)

The starting point of each line represents the total heat load of the fuel prior to insertion into the reactor. The fuel is irradiated for 4.5 years; therefore zero time on the graph represents the heat load when the fuel is discharged. It takes about 5 years for the spent FR fuel to cool down close to the same level prior to irradiation, although there are slight differences between the various conversion ratios.

Also present in Figure 1 for comparison is the thermal load for the original light water reactor (LWR) spent fuel source, term which is an order of magnitude less than the CR 0.50 case after five years of decay and the differential continues into the future. The implication with regard to cask capacity for transportation is the recycle fuel would be limited to about a tenth of the LWR spent nuclear fuel (SNF) for the CR 0.5 case, and decrease by another half if shipping thermally hotter inert matrix fuel (IMF), on a per mass basis.

Figure 2 shows the change in heat load of FR fuel following multiple recycles for a conversion ratio of 0.5. There is only a slight increase (<15% at 5 years cool time) in heat load from one recycle to the next. The graph also shows the heat load of the spent FR fuel decreases to the level of the initial load after only about 5 years, therefore, it is recommended the fuel be allowed to cool at least five years prior to shipment.

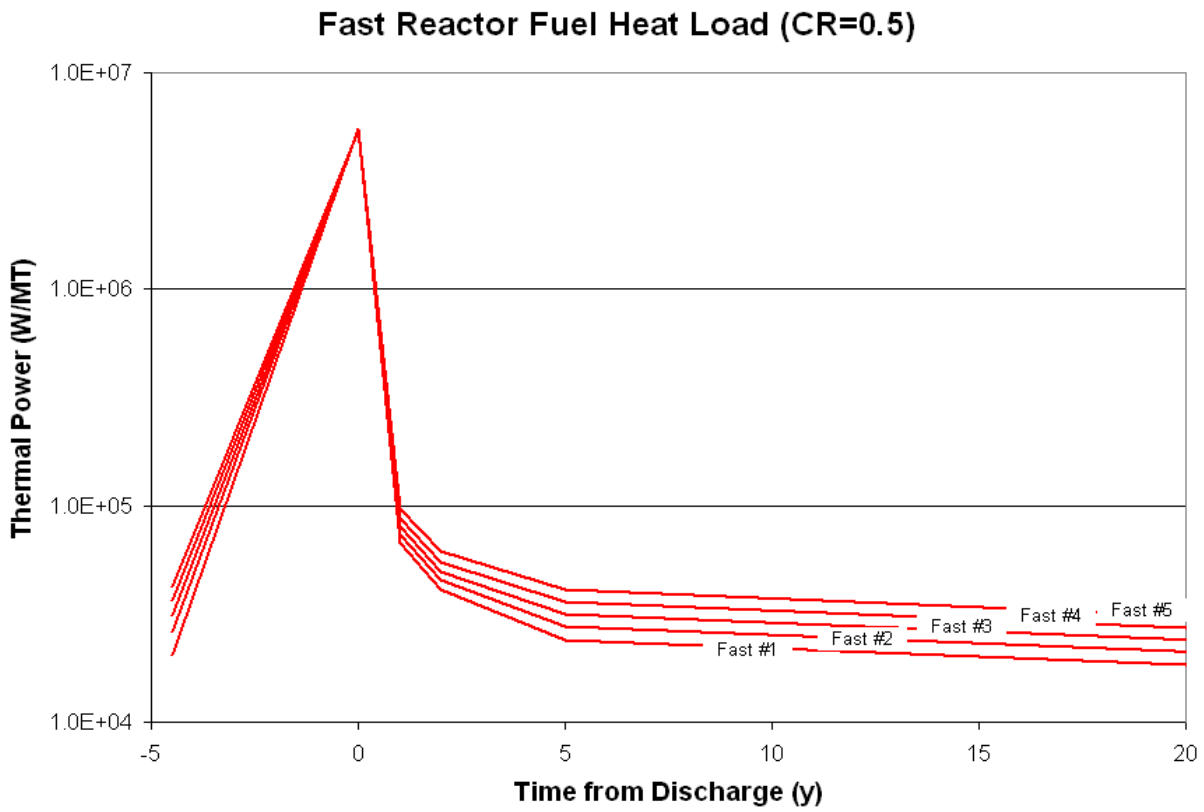

Figure 2. Multi-Recycle Heat Load Change

Table 1 summarizes the total loading in metric tons of five-year cooled fuel that can be placed into a transportation cask as a function of conversion ratio and recycle number, based upon the 25 kW heat rejection limit. Likely conversion ratios for burning actinides are between 0.5 and 0.75, with the corresponding maximum cask loading ranging from 0.6 to 1.4 MT depending on the recycle number.

	CR1.0	CR0.75	CR0.5	CR0.25	CR0.0
Recycle 1	1.8	1.4	1.0	0.7	0.4
Recycle 2	2.1	1.4	0.9	0.6	0.4
Recycle 3	2.4	1.4	0.8	0.5	0.3
Recycle 4	2.5	1.4	0.7	0.4	0.3
Recycle 5	2.6	1.3	0.6	0.4	0.3

Table 1. Maximum FR Loading in a Transportation Cask (MT) Based on a 25 kW Thermal Limit

Table 2 converts the masses from the previous table into the maximum integral number of fuel assemblies which can be accommodated based upon the following assembly masses, which are a function of conversion ratio: CR 1.0 - 116.3 kg, CR 0.75 - 93.3 kg, CR 0.5 - 65.5 kg, CR 0.25 - 41.1 kg, and CR 0.0 - 25.2 kg. Note that these numbers are solely based upon the derived assembly masses obtained from Reference 2 of an alternative compact design of the S-PRISM concept, and can be easily modified if the fuels design for the advanced burner reactor changes. The actual final design of the advanced burner reactor will very likely have much different fuel assembly characteristics and physical dimensions than the reference values utilized in the present analysis, and the derived cask quantity limits are hypothetical.

For all cores, there are a total of 144 fuel assemblies per core, so if the values in Table 2 are divided by 144, the result is the percentage of one core that can be transported with one cask.

	CR1.0	CR0.75	CR0.5	CR0.25	CR0.0
Recycle 1	16	15	16	17	17
Recycle 2	18	16	14	14	15
Recycle 3	21	15	12	12	13
Recycle 4	22	15	11	10	12
Recycle 5	23	14	9	9	11

Table 2. Maximum FR Loading (Number of Fuel Assemblies) in a Transport Cask Based on a 25 kW Thermal Limit

Figure 3 shows the evolution of isotopic concentrations as the fuel is recycled. For the "near-breeder," the plutonium concentration (and particularly the fissile isotopes) approaches a "steady-state" of almost 97% of TRU, of which approximately 2/3 is ^{239}Pu. In addition, Americium starts at nearly 5% of TRU, and is depleted over the successive recycles, as are the remainder higher elements denoted in the gray portion of the graph. The depletion of americium and the heat-producing plutonium isotopes with additional recycles is the reason the FR loading capacity as shown in Tables 1 and 2 increases for the CR 1.0 case. Conversely, in the zero conversion ratio core the plutonium content diminishes slightly (a little over 1% per recycle), but the concentration of fissile isotopes drops dramatically and the Americium and remainder higher isotopes build up as expected. This is the reason the FR loading capacity shown in Tables 1 and 2 decreases for the CR 0.0 case.

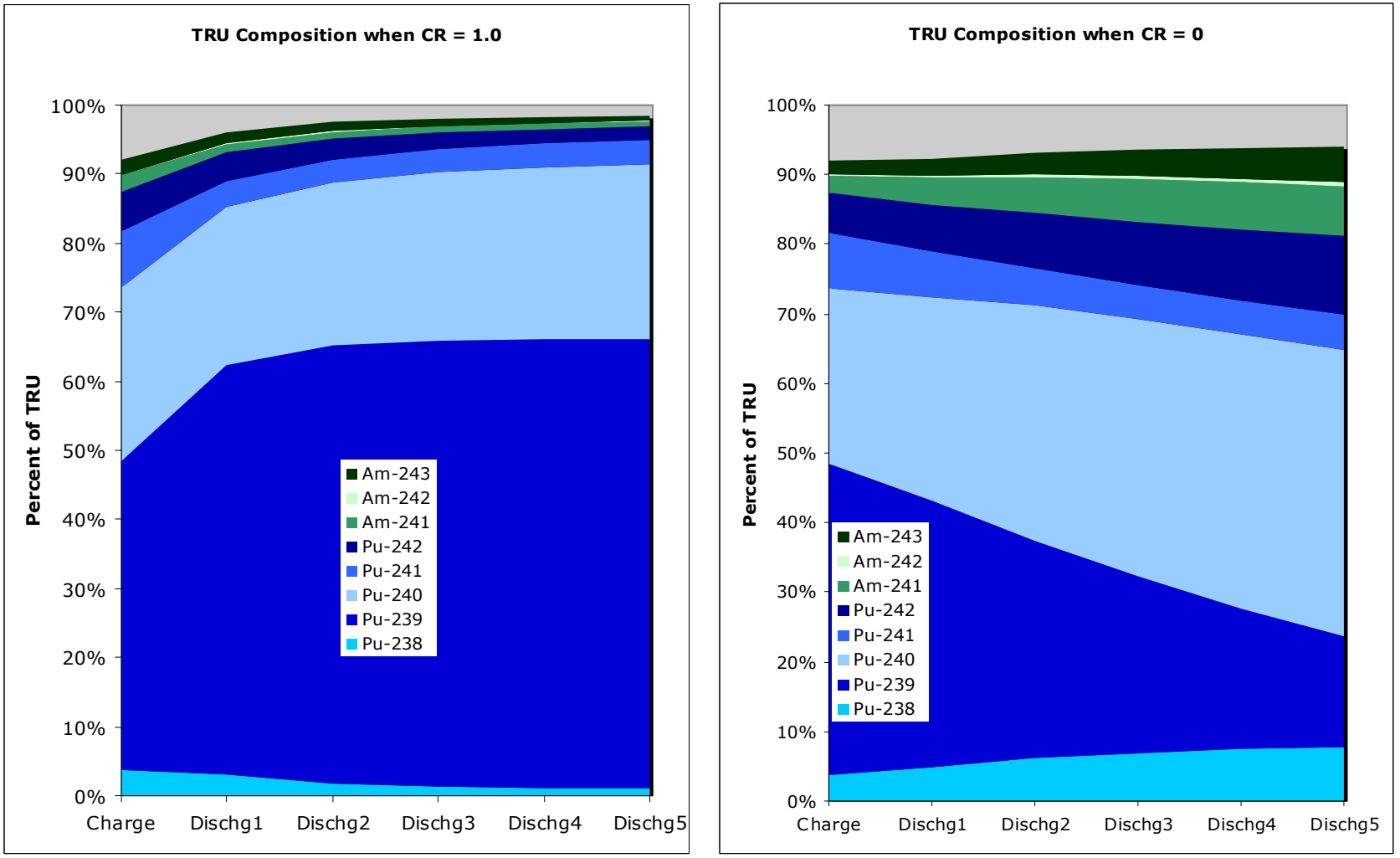

Figure 3. Isotopic Evolution of TRU as a Function of Conversion Ratio and Recycle Number

Figures 4 and 5 provide a more detailed comparison of the thermal loads for the fast reactor recycle fuel versus the reference light water reactor source term utilized throughout the study for the first and fifth recycles, respectively. Beginning with the 5 year cooling period (following the rapid post-irradiation fission product decay occurring shortly after discharge), the curves of different remaining transuranic content smoothly transition to the end of the century with nearly constant separation. The behavior of the curves are similar in both the first and last recycles, with the order of magnitude separation between the centerline CR 0.50 case and LWR reference for the first recycle increasing by approximately another quarter for last recycle. The TRU contribution to heat load in spent PWR fuel is smaller than the fission product contribution, but for discharged FR fuel, the TRU contribution is higher than the fission products.

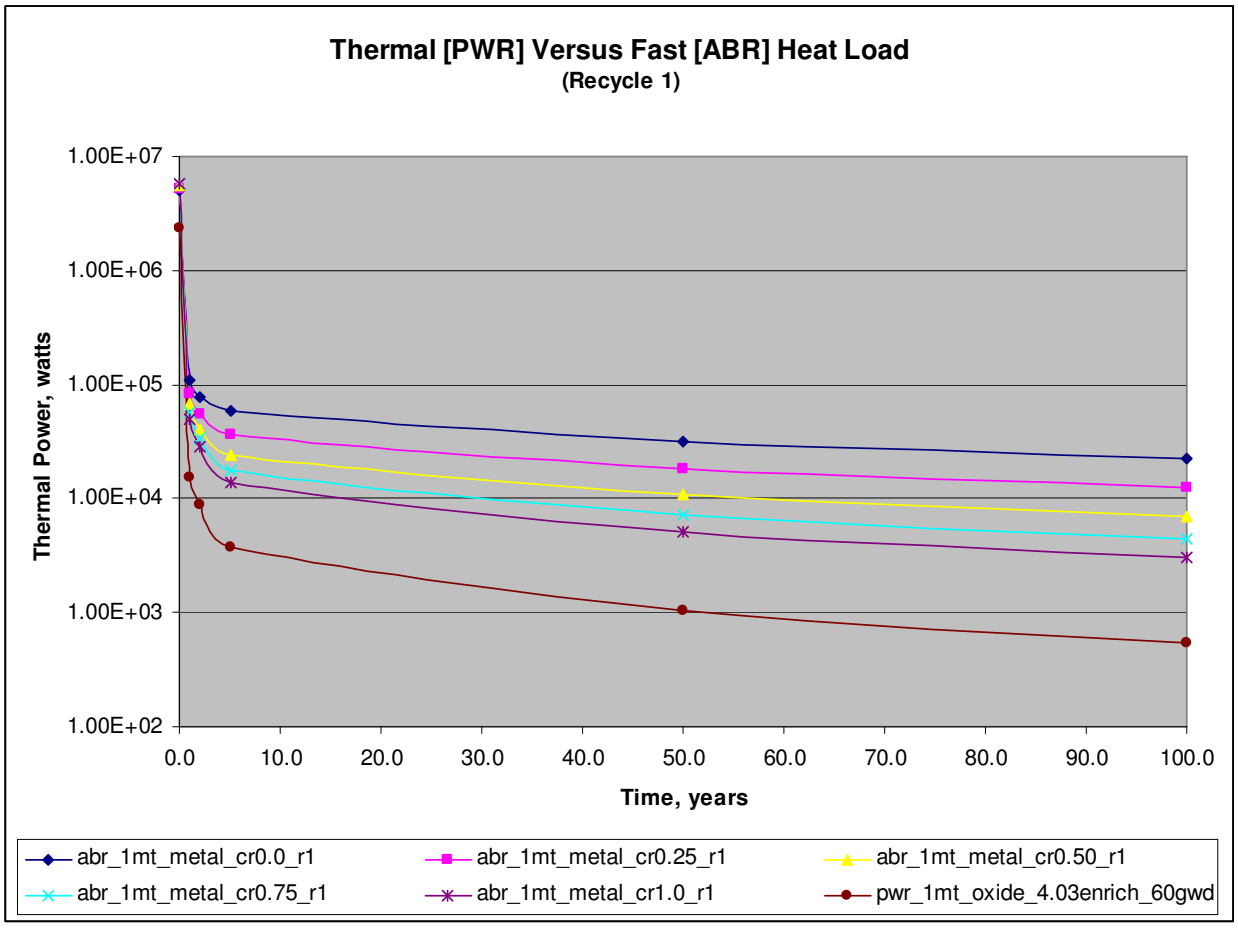

Figure 4. Thermal Versus Fast Reactor Heat Load – First Recycle

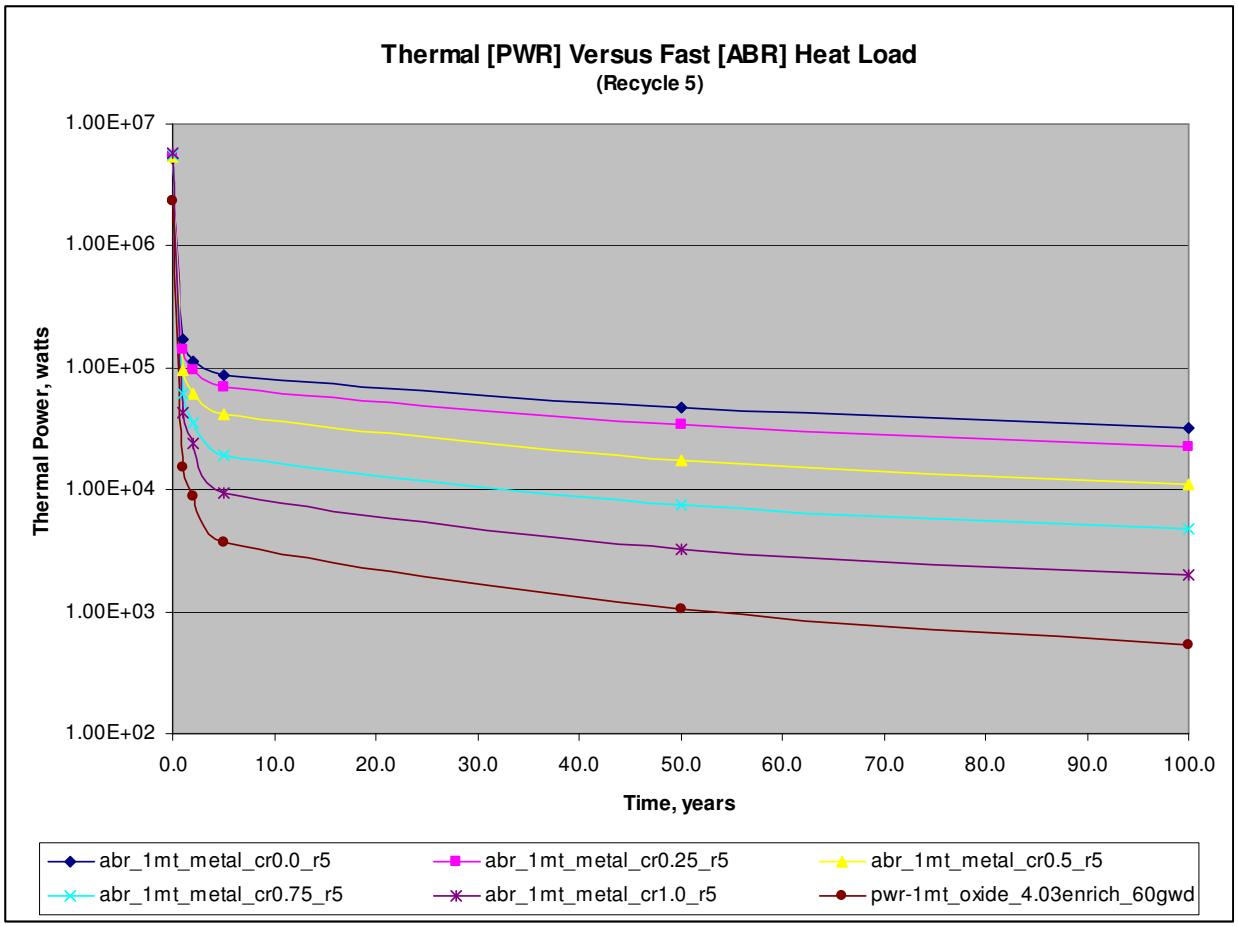

Figure 5. Thermal Versus Fast Reactor Heat Load – Fifth Recycle

Although the final physical dimensions and mass of the future fast reactor recycle fuel assemblies is uncertain, the ten-fold increase in thermal load results in a directly proportional decrease in the amount which can transported in the reference cask considered in the present study.

Lastly, the results from the present study were used to assess how well fast reactors can reduce the amount of actinides. Figure 6 illustrates the results for a 0.5 conversion ratio core. The left most bar in the figure represents a set amount of TRU originating from spent light water reactor fuel (the actual amount is not important for the analysis), and the subsequent bars show the discharge quantities following recycling after 5 passes in a fast reactor. On each recycle, the total amount of TRU drops by 23%. It is also interesting to note that the relative ratios of the different actinides stay more or less the same—there is no buildup of any particular species. However, this will not be true for the CR 1.0 or zero cases based on the Figure 3 results, however it is to be recalled no reactivity compensation were added to the modeled cores.

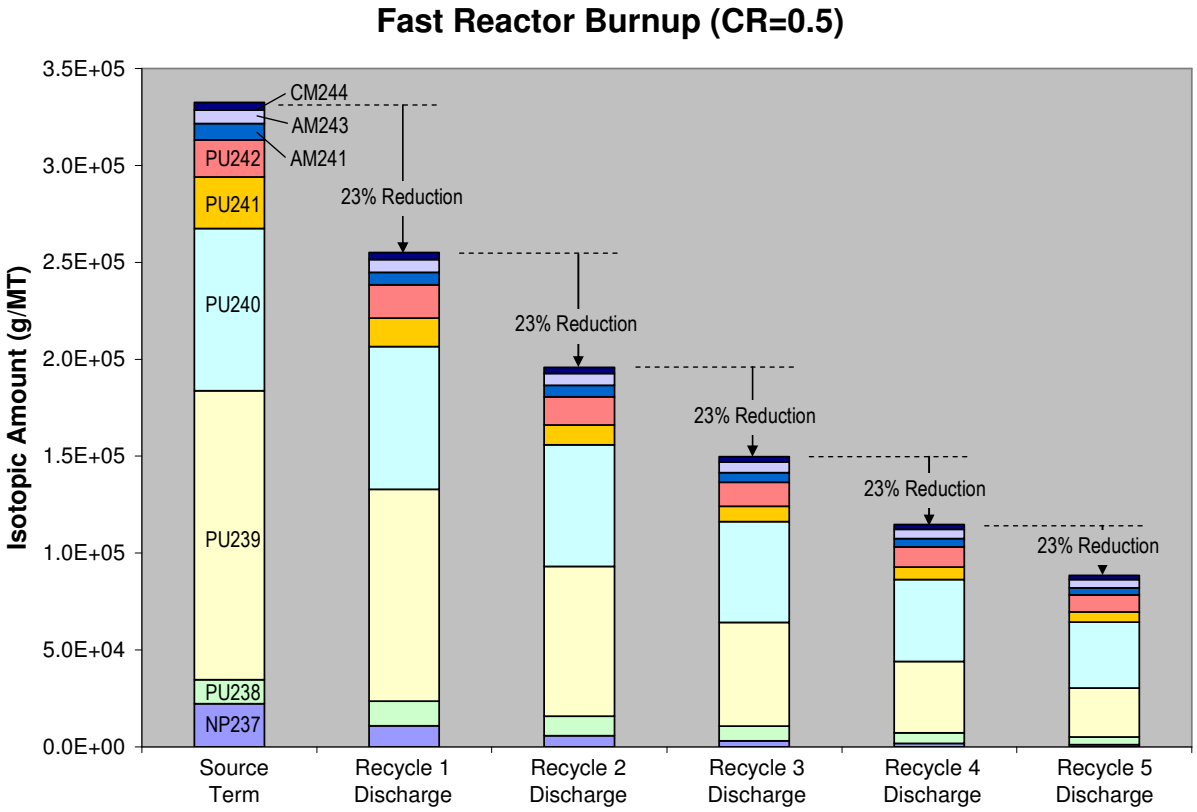

Figure 6. Burnup Percentage of Each Recycle

One interesting observation is after 5 years, the heat generation rate of the fission products is about 6-7 kW/MT fuel, for which the bulk of the heating is attributable to the TRU isotopes. As a consequence, the heat generation rate is predominantly dependent upon the amount of TRU in the fuel. A significant conclusion is after approximately five years of cooling, the fast reactor spent fuel thermal loads are approximately equivalent to the initial loading prior to irradiation; enabling transportation to be feasible should appropriate casks be developed and licensed to ship the original recycle feedstock.

As a consequence, the mass of fuel in metric tons that can be placed into a transport cask depends strongly on the conversion ratio of the core, and less strongly on the recycle number. However, the conversion ratio was not analyzed after each recycle to determine if it was remaining constant, so the results could be skewed if the parameter was varying. The TRU loading to achieve a particular conversion ratio has been studied by several organizations, and the actual fuel designs are not expected to deviate dramatically from the values employed in the present study. Thus, the results should be sufficiently "stable" to be useable in scoping studies for cask design and other aspects of fuel handling. Once baseline designs for the fuel and core are established, a more precise analysis could be performed.

References

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