Transactions of the Korean Nuclear Society Spring Meeting
Chuncheon, Korea, May 25-26 2006

Self-shielding Minimization for Deep-Burn of TRU Fuel

Yonghee Kim and Jae Man Noh

Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea
yhkim@kaeri.re.kr

1. Introduction

The conventional transmutation concept is to burn TRUs (transuranic elements) in fast reactors (either critical or subcritical) based on repeated reprocessing of spent fuels. As an alternative, the deep-burn concept is under investigation, in which a ultra high burnup is pursued in order to incinerate the TRUs in a graphite-moderated, high-temperature, gas-cooled reactor without costly repeated reprocessing and re-fabrication of spent TRU fuels.[1]

In HTGRs, a ceramic-coated particle fuel (TRISO) is used. It was shown that the TRISO fuel can achieve a burnup as high as 750 GWD/t.[2] The ceramic coating layer is a very good waste container in repository for hundreds of thousands of years. Thus, a direct disposal of the deep-burned fuel would be feasible if the discharge burnup is high enough. A recent study on the deep-burn shows that the fuel burnup can be as high as ~540GWD/t with a four-batch fuel management in a prismatic HTGR core.[1] Although the achieved burnup is very high, it is considered not sufficient for a direct disposal of the spent fuel.

The objective of this study is to maximize the TRU burnup based on the physical characteristics of a TRU-loaded HTGR fuel.

2. Impact of Self-shielding on TRU Burnup

In HTGRs, TRISO particles are randomly dispersed in a graphite matrix with a relatively low volume fraction. This special fuel configuration leads to the so-called double-heterogeneity (DH) problem: a simple volume-weighted homogenization results in a large reduction of reactivity due to the substantially reduced self-shielding effects. The DH effect is very large in typical TRU fuels due to strong neutron absorbers such as Pu-240. (see Table I for the TRU composition)

A small kernel diameter (~200μm) is usually adopted to achieve a very high burnup and also reduce the self-shielding phenomenon. In a typical TRU fuel, a neutron capture of a fertile nuclide reduces the reactivity but it may increase the reactivity during fuel burnup since fertile isotopes can be transmuted to an efficient fissile isotopes.

A representative prismatic fuel cell has been analyzed by the MCCARD[3] Monte Carlo code to investigate the impact of self-shielding on the fuel burnup. The unit cell model was designed such that it should be equivalent to a whole assembly in terms of the reactivity.

Figure 1 shows the reactivity change over a depletion period. In the simulation, the temperature of fuel and graphite is 1200K and the fuel packing fraction is 12.39%. The high specific power corresponds to the typical power density of ~6.5W/cc in a 600 MWth HTGR core. The standard deviation of the k-inf value is less than 0.001 in the results.

The DH effect is huge, ~14,400pcm, leading to a subcritical condition for the fresh fuel. It is also noted that the fuel can achieve a very high burnup of ~560GWD/t in a simple single batch fuel management, assuming a 5% neutron leakage. It is important to note that the homogeneous fuel provides a much higher reactivity in the high burnup range, although it cannot achieve the initial criticality. This indicates that reducing self-shielding of the TRU fuel may provide a way to increase the discharge burnup significantly.

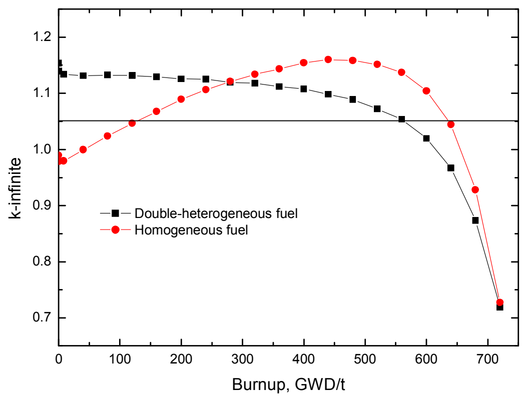

Fig. 1. Self-shielding effect of TRISO fuel.

3. Deep-Burn with Reduced Self-shielding

In the conventional TRISO fuel, the kernel diameter should be minimized for a minimal self-shielding. Obviously, the kernel diameter has a lower bound to obtain the initial criticality of the core, as shown in Fig. 1. Through a numerical study, the following TRISO specifications were selected: kernel diameter=44μm, buffer thickness=28μm, thickness of IPyC, SiC, OPyC=15μm, and packing fraction=29%. It should be noted that the TRISO fuel is only for the purpose of physics study: the technical feasibility is not a concern here.

Figure 2 shows the results of the MCCARD depletion calculation. In this case, the fuel loading is reduced relative to the reference case, thus the specific power density is higher. One can clearly see that the reactivity steadily increases up to a very high burnup and starts to decrease rapidly after the maximum. For a 5% neutron leakage, the expected discharge burnup is about 616GWD/t, which is ~10% higher than in Fig. 1. The equivalent cycle length of the core is about 700 days in the single batch depletion.

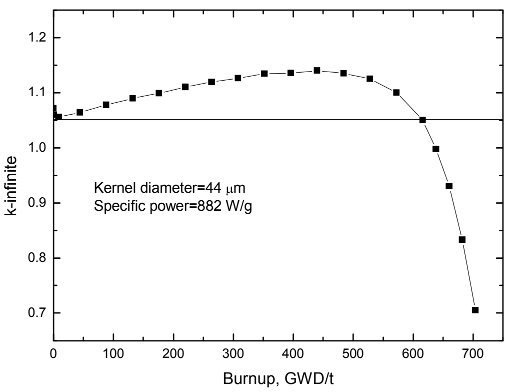

Fig. 2. Evolution of reactivity during burnup.

Table I shows the isotopic composition of the TRU fuel at the initial and at the discharge condition. After 616GWD/t burnup, about 60.7% initial heavy metal was transmuted. The transmutation rate of Pu-239 is extremely high, about 97%. From Table I, it is observed that Pu and Np isotopes are transmuted at the expense of accumulation of higher actinides such as Am and Cm. This is due to the enhanced neutron capture of fertile isotopes.

Table I. Isotopic composition (wt%) of TRU fuel.

Isotope	Initial	Final (616GWd/t)
Np-237	4.11	4.94
Pu-238	1.20	11.3
Pu-239	51.7	3.89
Pu-240	23.9	10.8
Pu-241	8.02	20.4
Pu-242	5.01	29.0
Am-241	5.01	1.7
Am-242m	0.13	0.1
Am-243	1.00	9.0
Cm-242	--	2.7
Cm-243	--	0.08
Cm-244	0.20	5.58
Cm-245	--	0.4

It is expected that fabrication of TRISO particle with a very small kernel diameter would be impractical. However, a different kernel concept could be adopted for TRISO with a small fuel particle: a graphite kernel containing granular fuel particles is a practical alternative. In such a diluted kernel concept, the fuel particle size can be easily controlled and the conventional coating technologies can be used as well.

4. Conclusions

The deep-burn approach for the transmutation of TRUs has a very high potential to resolve the spent nuclear fuel problem. The discharge burnup, without reprocessing of the spent TRU fuels, can be as high as 500~600GWD/t in a single batch fuel management, depending on the fuel design. It is expected that the discharge burnup could be substantially increased if a multi-batch fuel management scheme is adopted. The self-shielding effect of the TRUs fuel has a big impact on the discharge burnup in the deep-burn concept. A smaller kernel diameter provides a higher discharge burnup in a single-batch scheme. The TRISO fuel needs to be optimized in terms of kernel diameter, coating thickness, and packing fraction.

The above conclusion would hold if the whole core spectrum is similar to the unit cell one. In general, a softer spectrum results in a lower burnup in TRU-loaded HTGRs. In modern HTGRs, an annular core is favored to guarantee the passive safety. In this case, the core spectrum is strongly affected by the surrounding graphite reflectors and the discharge burnup may be significantly lower than the value from a unit cell analysis. Thus it would be very important to optimize the neutron spectrum in the annular core.

Acknowledgement

This study has been carried out under the Long-Term Nuclear R&D Program supported by the Ministry of Science and Technology (MOST) of Korea.

References

1. M. Richards et al., "DEEP BURN: Destruction of Nuclear Waste Using MHR Technology-Impacts on Spent Fuel Management", GLOBAL 2005, Tsukuba, Japan, Oct. 9-13, 2005.
2. C. M. Miller and W. J. Scheffel, "Post-irradiation examination and evaluation of Peach Bottom FTE-13," GA Document No. 906939, November 1985.
3. H. J. Shim et al., "Numerical Experiment on Variance Biases and Monte Carlo Neutronic Analysis with Thermal Hydraulic Feedback," Int. Conf. On Supercomputing in Nuclear Applications, SNA 2003, Sep. 22-24, 2003, Paris, France.