Proceedings of the Korean Nuclear Society Autumn Meeting
Yongpyong, Korea, October 2002

A 600 MWth Gas-Cooled Fast Reactor Fuel Cycle with a Dry Process Option for Recycling Spent Fuel

Hangbok Choi

Korea Atomic Energy Research Institute
150 Deokjin-dong, Yusong
Taejon, 305-600, Korea

ABSTRACT

The feasibility of a 600 MWth gas-cooled fast reactor (GCFR) fuel cycle has been analysed by performing recycling simulations. For the continuous recycling of self-generated spent fuel, a dry process is used to remove only the fission products from uranium-plutonium carbide fuel. The results have shown that the initial breeding gain of -0.04755 is sufficient to sustain the recycling of actinides with a reasonable amount of natural uranium and plutonium feed material.

1. INTRODUCTION

Since 1960s the GCFR has been studied in both United States[1,2] and Europe[3], and several demonstration plants have been designed and constructed. Recently, as the sodium coolant has shown many operational difficulties in a fast reactor such as the need for an intermediate coolant loop, its chemical reactivity with air and water, the lack of optical transmission and the need to manage and ultimately dispose of sodium,[4] the GCFR has received a renewed interest as a feasible option that can be used as the next generation reactor. In principle, it is possible in GCFR to fulfil several strategic requirements of the nuclear fuel cycle. For example, the high temperature gas coolant system replaces the steam cycle with a closed-loop gas turbine (Brayton) cycle. With the gas turbine, a net plant efficiency of nearly 50% can be realized, that surely improves the economics.[5] The gas coolant also enhances a low void reactivity, which allows the relaxation of safety related constraints in the core heavily loaded with higher actinides. The strong neutron spectrum caused by the gas coolant can promote higher actinide burning compared with relatively soft spectrum. The strong neutron spectrum is also beneficial to increase the breeding gain. Now it is feasible to have a near-zero breeding gain in a GCFR by using surplus commercial grade plutonium fuel. Therefore if a dry (non-aqueous) reprocess technology is introduced to recycle the fuel multiple times, the fuel can stay in the core for a long time utilizing both the initial and self-generated fissile material, without being discharged throughout plant lifetime. This is also consistent with minimizing proliferation risk by closing the fuel cycle. For the industrial application of the gas-cooled reactor, the hydrogen production as well as the electricity generation is being considered.[6]

2. REFERENCE CORE MODEL

The thermal power of the reference core is 600 MW. The core volume is 10.3 m^3, which results in a power density of 58.2 MW/m^3. The core contains 28 tons of heavy metal (HM), which gives a specific power of 21.4 kW/kgHM. In the initial core, the volume fraction of plutonium fuel (PuO_2), called “charge enrichment”, is 16.966%. The fuel used for the initial

core loading is the reprocessed plutonium (REP2016) mixed with natural uranium. The REP2016 is from the spent fuels of current French pressurized water reactors (PWRs), which are cooled down till year 2016. The chemical form of the fuel will be uranium-plutonium carbide to enhance more fissile breeding compared to the oxide fuel.[7]

2.1 Fuel Particle

In the reference core, tri-isotropic (TRISO) coated fuel particles are employed. The fuel is contained in very small spherical particles approximately 1 mm in diameter. The uranium-plutonium carbide fuel is at the center of each spherical particle and is surrounded by a number of layers. The thin carbon (pyrocarbon) layers provide the structural integrity for the fuel particle. The silicon carbide (SiC) layer is an extremely important diffusion barrier, intended to provide the containment function for the radioactive fission products.[8] The fuel particles are bonded together in fuel rods, which are contained in hexagonal blocks. In the neutronics modelling of fuel particles, the average volume ratio of fuel and matrix was determined to be 50/50. For the depletion of fuel, the maximum fuel burnup is limited to 5 wt% of initial heavy metal. The average fuel temperature was set 1227°C, which is much less than the limiting temperature (1495°C) of high temperature gas-cooled reactor (HTGR).[9]

2.2 Fuel Block

The hexagonal fuel block is the base unit that forms the reactor core. The fuel block is made of SiC which is consistent with the matrix material used for the fuel particle. For the cooling of fuel block, there are 61 vertical holes (flow tube) which are arranged in a hexagonal form with a pitch distance of 2.18 cm. The flat-to-flat diameter of the fuel block is 21.5 cm. When these blocks are deployed in the core, they are arranged with a lattice pitch of 22.2 cm to allow coolant flow between fuel blocks. For the fuel assembly lattice under the operating condition, the volume ratio of fuel, matrix, structure and coolant is 25/25/9/41.

2.3 Reactor Core

The reference core consists of 142 fuel blocks (or assemblies), surrounded by 180 reflector blocks for neutron saving and shielding purposes. The core is divided into two radial regions with different enrichments. The number of assemblies is 64 and 78 for the inner and outer regions, respectively. For reactivity and power control, six positions are reserved for control assemblies. For the emergency shutdown of the system, three positions are reserved for assemblies. The equivalent radii of the inner and outer core are 95.4 cm and 143.2 cm, respectively. The radius of the whole system including the reflector is 212.1 cm. In the axial direction, the active core height is 170 cm. In the upper and low ends of the core, axial reflectors are positions, which are 100 cm thick. The system pressure is 70 bar under normal operating condition.

3. REFERENCE CORE CALCULATION

The neutronics properties of the reference core have been calculated by ERANOS[10] code system, which has various computing modules for reactor physics and fuel cycle analyses. In the ERANOS code, the lattice parameters are generated by ECCO module, using JEF2.2 nuclear data library. In order to save computing time and working space, the diffusion option has been used for most parameteric calculations with a 33-group working library which has been generated from 1968-group master library.

3.1 Neutronic Characteristics

For the initial core loaded with uranium-plutonium fuel, the depletion calculation was performed under a 3-batch mode. The criticality was searched at the end of second cycle (burnup step) and by constraining the discharge burnup to 5 wt%. The cycle length is 782 full power days (FPDs) and the residence time (lifetime) of the fuel will be 2346 FPDs (6.4 years). The enrichments (volume fraction of plutonium over uranium-plutonium fuel) are 14.9% and 18.6% for the inner and outer cores, respectively. The reactivity swing of one cycle is estimated to be 1516 pcm based on the linear reactivity model.[11]

The neutronics parameters and peak power of the core are summarized in Table I, in which EOL indicates the end of 3rd cycle (2346 FPDs). The breeding gain of the whole core is slightly negative. It can be seen that the negative component of the breeding gain comes from the outer core, which has a higher fissile content compared to the inner core. In the initial core, the enrichment ratio of the inner and outer core is 0.80 (or 0.81 in terms of fissile content ratio). As the fissile in the outer core burns, however, the fissile content ratio increases to 0.89, and the peak power of the inner core exceeds that of the outer core at the EOL state.

Table I. Characteristic of the reference core

	Beginning-of-life (BOL)	End-of-life (EOL)
Reactivity swing per cycle (pcm)	1516	
Void reactivity (pcm)	168.8	205.0
Doppler reactivity (pcm)	2260.4	1836.7
Delayed neutron fraction (pcm)	380.7	355.1
Neutron generation time (sec)	9.04×10^{-7}	8.43×10^{-7}
Peak power density (W/cm^3)		
Inner core	78.0	86.7
Outer core	81.2	76.9
Peak linear power (W/cm)		
Inner core	102.2	113.7
Outer core	106.5	100.8
Breeding gain of the fuel cycle		
Inner core	-0.00032	
Outer core	-0.04723	
Total	-0.04755	

The variations of reactivity terms are generally consistent with the isotopic content changes. For the reactivity swing, the core reactivity decreases because of the fissile burning and fission products buildup. The void reactivity increases by 21% at EOL state because the flux level increases to compensate for the fissile loss. The Doppler reactivity decreases by 19% because of ^{238}U loss. The kinetic parameters such as the delayed neutron fraction (β_{eff}) and prompt neutron lifetime (Λ) decrease by 7% due to ^{235}U burning and ^{238}U capture. Especially the magnitude of Λ is smaller than that of thermal reactors by a factor of 100. It is true that Λ of the GCFR is similar to that of the liquid metal fast breeder reactor (LMFBR) loaded with mixed oxide fuel. However because the thermal conductivity of the gas coolant is very low (e.g., k=0.0188 W/m°K for He at 600°K) compared to that of the liquid metal (e.g., k=11.2 W/m°K for sodium at 293°K),[12] it will be necessary to confirm the integrity of the GCFR core in case of severe accidents.

3.2 Reactivity Constant

The BOL void and Doppler reactivity can be further decomposed into reaction terms using the perturbation option of ERANOS code. The void reactivity is dominated by the elastic removal reaction in the core region. In case of coolant voiding, the number of scattering reactions decreases in the coolant region, which is dominant at ~1 MeV. The Doppler reactivity is dominated by the neutron capture of fertile isotope, which is dominant at ~1 keV. Though there is a negative contribution to the Doppler reactivity by the resonance broadening of fission cross sections, it contributes to the total reactivity only by 13%. The delayed neutron fraction can be decomposed into isotope-wise contribution. It was found that ^{238}U contributes most (44%) to the delayed neutron fraction.

3.3 Breeding Gain

Using the exponential matrix method, the fuel cycle breeding gain was decomposed into isotope- and reaction-wise terms. The positive breeding gain is mostly from radioactive decay of ^{239}Np (0.52987) and neutron capture of ^{240}Pu (0.07819). The negative breeding gain is mostly due to loss (capture + fissions) of ^{239}Pu (-0.35764) and ^{241}Pu (-0.09094) as well as the neutron capture of ^{238}U (-0.20076). However, because the neutron capture of ^{238}U produces ^{239}Np that becomes ^{239}Pu, the neutron capture of ^{238}U can be eventually treated as a positive term (0.32909). It is obvious that the breeding gain is determined by the initial isotopic number density and transmutation flux. The effects of these parameters on the breeding gain (or ratio) were also estimated in terms of sensitivity coefficients.

For the reference core, the sensitivity of breeding ratio to the charge enrichment is -27.7%. Therefore in order to increase the breeding ratio (gain) further, the charge enrichment should be reduced. However this will be limited due to the criticality requirement of the core. One way to get around this will be to increase the fuel fraction in the core so that the charge enrichment can be reduced without losing core reactivity to a certain extent.

For the effect of neutron flux on the breeding ratio, the sensitivities can be divided into two groups. The high energy neutrons between 67 keV and 20 MeV (from group 1 to 11) have negative effects on the breeding ratio, while neutrons between 0.7 keV and 67 keV (from group 12 to 20) have positive effects. However the sensitivity itself is much smaller compared to that of isotopic number density. The sensitivity of breeding ratio to overall flux level is -0.56%. Therefore it is expected that the breeding gain will decrease if the power density increases, even though the magnitude of change is small.

3.4 Recycling Calculation

The breeding gain of the reference core is negative but very close to zero. In the GCFR fuel cycle proposed in this study, all actinides are recycled homogeneously after being mixed with feed material to make up for the mass loss due to depletion. In this fuel cycle, because uranium isotopes are continuously transmuted to higher actinides, the breeding capability of the core will increase as the fuel is recycled. Therefore simulations have been performed to assess the feasibility and core characteristics of the recycled GCFR core.

The recycling simulation can be performed based on the mass balance obtained from ERANOS depletion calculation. The main effort in the recycling simulation is to determine the fuel composition for the subsequent fuel cycle, which was done outside the ERANOS code in this study. The strategy used for recycling simulation is as follows:

- All actinides are recovered and fission products are removed from the spent fuel through a dry process after 5 years cooling period.
- Because the fuel is preferentially burned in the outer core while it is bred reasonably in the inner core, material transfer between the inner and outer core spent fuel is allowed to maximize the utilization of spent fuel.
- Natural uranium is used as fertile feed and REP2016 is used as fissile feed to control the enrichment.
- If the fissile breeding is too much from the core, surplus fuel material is sold after the dry process.
- The fissile contents of the inner and outer cores are adjusted to maintain the initial charge enrichment ratio.
- The target fissile content is searched to sustain the criticality of the core in the subsequent fuel cycle.

The amounts of feed material can be obtained from the mass balance of heavy metal and fissile isotopes. For the generality, the mass balance equation was developed to include the fission products content. In the mass balance equation, the initial total heavy metal is balanced with the residual heavy metal, fission products, fuel transfer, natural uranium feed and plutonium feed. The initial fissile content is also balanced with the residual fissile and feed fissile. The amount of feed material is determined by sweeping the fuel transfer from the lowest value to the highest value and minimizing total amount of plutonium feed. If a negative value is obtained for the feed material, the amount of surplus material (sold) is estimated by putting sold terms in the mass balance equations.

The recycling simulation has been successfully performed for the reference core up to 7 recycles (51.4 full power years including initial core fuel cycle) and the results are summarized in Table II. It can be seen that the breeding gain becomes positive from 2nd recycle. The initial reactivity and reactivity swing drop appreciably as the fuel is recycled (Fig. 1). As the fuel is recycled continuously, the higher actinide content increases and the safety-related parameters (void reactivity, Doppler reactivity, delayed neutron fraction and prompt neutron generation time) are deteriorated. However the power distribution, represented by the peak power densities of the BOL and EOL cores, is well controlled, because the reference charge enrichment ratio is maintained throughout the recycling simulation. The mass flow of the reference core is plotted in Fig. 2. It can be seen that the core requires plutonium feed up to 3rd recycle and discharges surplus actinides from 4th recycle, which is consistent with the breeding gain change.

Table II. Characteristics of the recycled reference core

Recycle	Breeding gain	$\Delta\rho_{BU}$	ρ_{Void} (BOL)	$\rho_{Doppler}$ (BOL)	β_{eff} (BOL)	Peak power density (W/cm^3)	Peak linear power (W/cm)
0	-0.04755	4344.4	168.8	2260.4	380.7	86.7	113.7
1	-0.00687	2261.4	191.2	2099.9	356.6	86.8	113.9
2	0.01163	1379.4	202.0	2033.3	346.7	86.8	113.8
3	0.02125	940.3	207.8	2001.1	342.2	86.5	113.4
4	0.02706	678.4	211.5	1981.7	339.9	86.0	112.8
5	0.03088	502.2	214.1	1966.9	338.5	85.5	112.1
6	0.03349	384.4	215.9	1955.7	337.6	84.9	111.3
7	0.03536	301.9	217.2	1946.8	337.0	84.4	110.6

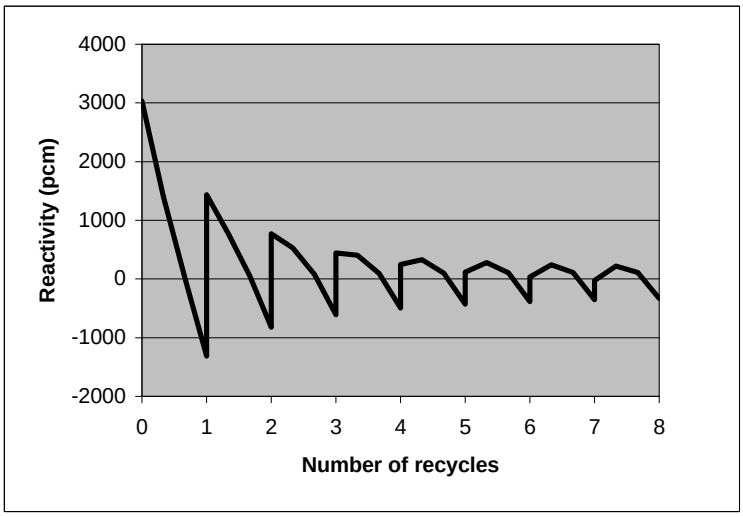

Fig. 1 Variation of reference core reactivity

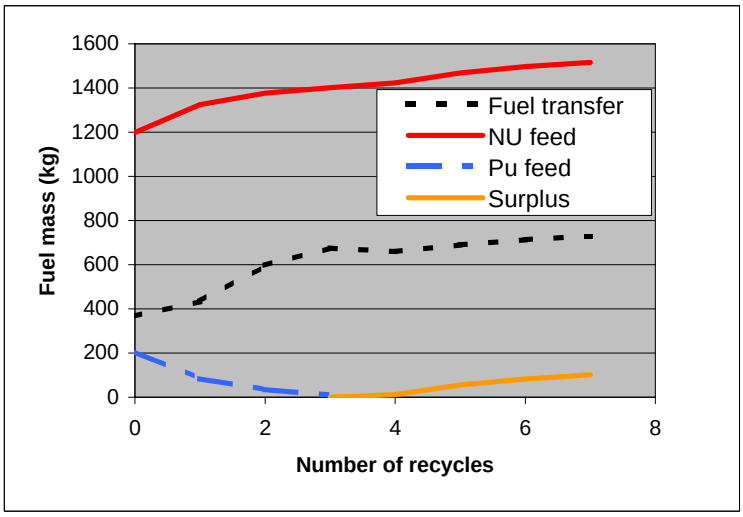

Fig. 2 Mass flow of the reference core

The characteristics of the recycled core are determined by the fuel composition change from the initial core. As the breeding capability of the core gradually increases through recycling, the fissile content of the fuel decreases as the fuel is recycled. However the amount of minor actinides (MA) increases as the fuel is continuously recycled. It was also found that the fraction of uranium isotopes decreases while that of plutonium (or higher actinides) increases as the fuel is recycled. For the fissile isotope, ^{235}U fraction is negligible after 7 recycles and ^{239}Pu remains as the dominant fissile isotope.

5. SUMMARY AND CONCLUSION

The neutronic and recycling characteristics of a 600 MWth GCFR core have been assessed. The recycling simulation has been performed under an assumption that the fuel is recycled through a dry process that removes only the fission products from the self-generated spent fuel. The results of simulation have shown that the initial breeding gain of -0.04755 is sufficient to breed the fissile material necessary for subsequent fuel cycles. For the reference core, the core

does not have any external discharge of spent fuel material except for fission products that are removed during the dry process.

REFERENCES

1. P. Fortescue and G. M. Schultz, "A 1000 MW(e) gas-cooled fast breeder reactors," GA-7823, General Dynamics, April (1967).
2. P. Fortescue, G. Melese-d' Hospital and L. Meyer, "Design studies for 1000 Mwe gas-cooled fast breeder reactors," GA-8581, Gulf General Atomic Inc., May (1968).
3. R. D. Vaughan, et al., "A design and assessment study of gas cooled breeder reactors," European Association for Gas Breeder Reactor, March (1972).
4. A. Vasile, et al., "Fast reactor fuel cycle core physics results from the CAPRA-CADRA programme," Proc. Int. Conf. on Back-End of the Fuel Cycle: From Research to Solutions (Global2001), Paris, Sept. 9-13 (2001).
5. E. L. Quinn, "New nuclear generation - in our life," Nuclear News, Oct. (2001).
6. C. W. Forsberg and K. L. Peddicord, "Hydrogen markets and futures for nuclear power," Transactions of American Nuclear Society, **85**, p.31, Nov. (2001).
7. J. E. Martin, *Physics for radiation protection*, John Wiley & Sons, Inc. (2000).
8. W. D. Magwood, IV, "Report to congress on small modular nuclear reactors," U.S. Department of Energy, May (2001).
9. K. Sawa, S. Suzuki and S. Shiozawa, "Safety criteria and quality control of HTTR fuel," *Nuclear Engineering and Design*, **208**, pp305-313 (2001).
10. S. Berrard, et al., "ERANOS: European Reactor Analysis Optimized System, Version: ERANOS 2.0, User's Manual: Catalogue of the functions," Commissariat à l' Energie Atomique.
11. R. C. Cochran and N. Tsoulfanidis, *The nuclear fuel cycle: Analysis and management*, American Nuclear Society, La Grange Park (1990).
12. H. Etherington, Ed., *Nuclear Engineering Handbook*, McGraw-Hill Book Co. (1984).