FUEL CYCLE ANALYSIS OF THE SABR SUBCRITICAL TRANSMUTATION REACTOR CONCEPT

FUEL CYCLE AND MANAGEMENT

KEYWORDS: *transmutation fuel cycle, actinide burning fuel cycle*

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A fuel cycle analysis was performed for the SABR transmutation reactor concept, using the ERANOS fast reactor physics code. SABR is a sodium-cooled, transuranic (TRU)-Zr–fueled, subcritical fast reactor driven by a tokamak fusion neutron source. Three different four-batch reprocessing fuel cycles, in which all the TRUs from spent nuclear fuel discharged from light water reactors are fissioned to >90% (by recycling four times), was examined. The total fuel residence time in the reactor was limited in these three cycles by a radiation damage limit (100, 200, or 300 displacements per atom) to the cladding material. In the fourth cycle the fuel residence time was determined by trying to achieve 90% burnup in a once-through cycle without reprocessing.

I. INTRODUCTION

The global expansion of nuclear power leads to the issue of spent fuel disposal. Currently, the method in the United States and most of the world is to use the fuel once and then dispose of the spent fuel in temporary storage before sending it to a final geological repository. At the current nuclear power production rate in the United States, a new geological repository would be needed in 2018 (Ref. 1) according to the legislative limit of Yucca Mountain. If that limit is increased to the engineered limit, a new repository would be needed in 2043 (Ref. 1). This estimate assumes no expansion of the current reactor fleet. Assuming a nuclear expansion to maintain the current electric market share of 20% by the year 2100, 11 Yucca Mountain–sized repositories would be necessary by the end of the century.[2]

To reduce this growing requirement for long-term geological respositories, the concept of separation and transmutation has been introduced. Separation refers to separating the fission products, which emit high-energy decay products (alpha, beta, gamma), and storing them separately until their high level of radioactivity decays away. Transmutation refers to reprocessing the spent fuel discharged from light water reactors (LWRs) to separate the long-lived fissionable transuranics (TRUs) for use as fuel in fast reactors.

It seems likely that the system of fast transmutation (or “burner”) reactors will consist of a mixture of critical and subcritical reactors in order to achieve sufficient TRU burnup to significantly lessen geological repository requirements. The subcritical system allows for greater fuel cycle flexibility in that the fuel residence time in the reactor is no longer limited by criticality but rather by the radiation damage limit and external neutron source strength. Moreover, the small delayed neutron fraction of TRU fuel is no longer a safety limit on the TRU fraction of the fuel with a subcritical system because the subcriticality substantially increases the reactivity margin to prompt criticality.

This study investigates the fuel cycles available to the SABR subcritical fast reactor with a fusion neutron source, the concept for which was developed at the Georgia Institute of Technology.[3] The fusion neutron source is based on ITER physics and technology and is capable of generating up to 500 MW of fusion power, which would provide up to 1.8×10^{20} 14-MeV n/s to maintain the neutron chain reaction in the sodium-cooled, TRU-fueled fission core. The fuel cycle analysis reported in this paper updates the preliminary analysis reported in Ref. 3 by using the state-of-the-art ERANOS fast reactor fuel cycle code, by using a revised core and reflector

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design to achieve better neutron economy, and by specifically evaluating the effect of cladding radiation damage limits.

This paper is organized as follows: The SABR reactor system is summarized in Sec. II, and then Sec. III discusses the performance of several fuel cycles. Finally, Sec. IV provides a summary and conclusions of the work.

II. THE SABR DESIGN

SABR is a subcritical sodium-cooled fast reactor driven by a fusion neutron source[3] to produce 3000 MW(thermal) of fission power. SABR contains Zr40-TRU metallic fuel. Figure 1 shows a three-dimensional model of the reactor, and Fig. 2 shows the detailed *R*-*Z* cross-sectional model used for the neutronics calculations. The fusion neutron source is surrounded on the outside by an annular fission core. Outside of the fission core is a stainless steel reflector and tritium breeding blanket; there are also tritium breeding blankets on the top side of the fusion neutron source. Outside of the blankets is a multilayered shield to protect the superconducting magnets.

Fuel cycle calculations for SABR were performed using the code[4] ERANOS, which is able to calculate core reactivities, core flux profiles, and fuel depletion. Figure 2 shows the computational model used in ERANOS2.0.

II.A. Fuel Configuration

The annular fission core has been arranged in four vertical annular rings of fuel assemblies to facilitate a four-batch fuel cycle. The core height of 3.2 m includes an active fuel length of 2.0 m, a fission gas plenum of 1.0 m, and a top reflector of 20 cm. The fuel for SABR is a metallic TRU-Zr slug inside of fuel rods arranged in a hexagonal assembly. Each fuel rod is 7.26 mm in diameter, with an outer fuel diameter of 4 mm. The core contains a total of 918 fuel assemblies with 271 rods per assembly. The fuel pin is shown in Fig. 3, the arrangement of the 271 fuel pins in a fuel assembly is indicated in Fig. 4, and the annular arrangement of the 918 fuel assemblies in four annular rings is depicted in Fig. 5.

II.B. Fuel Cycle

The overall SABR fuel cycle is depicted in Fig. 6. TRU fuel from LWRs is used in SABR [the advanced burner reactor (ABR) in Fig. 6]. This fuel is burned in the reactor in a four-batch fuel cycle, then reprocessed, combined with fresh TRU, and refabricated and recycled in SABR (or another ABR). The fission products are separated from the TRU and sent to the geological repository.

The four-batch fuel cycle utilized in SABR is depicted in Fig. 7.

II.C. Neutronics

The neutronics calculations in ERANOS use JEFF2.0 cross sections in 33 energy groups from 20 MeV down to 0.1 eV. The cross sections are processed via the ECCO cell module. A lattice cell calculation using P1 transport theory is done on the assembly and the energy groups are collapsed from 1968 groups to 33, and the assembly is then homogenized. The two-dimensional flux calculation uses discrete ordinates theory with S8 quadrature with 91 mesh points in the radial direction and 94 mesh

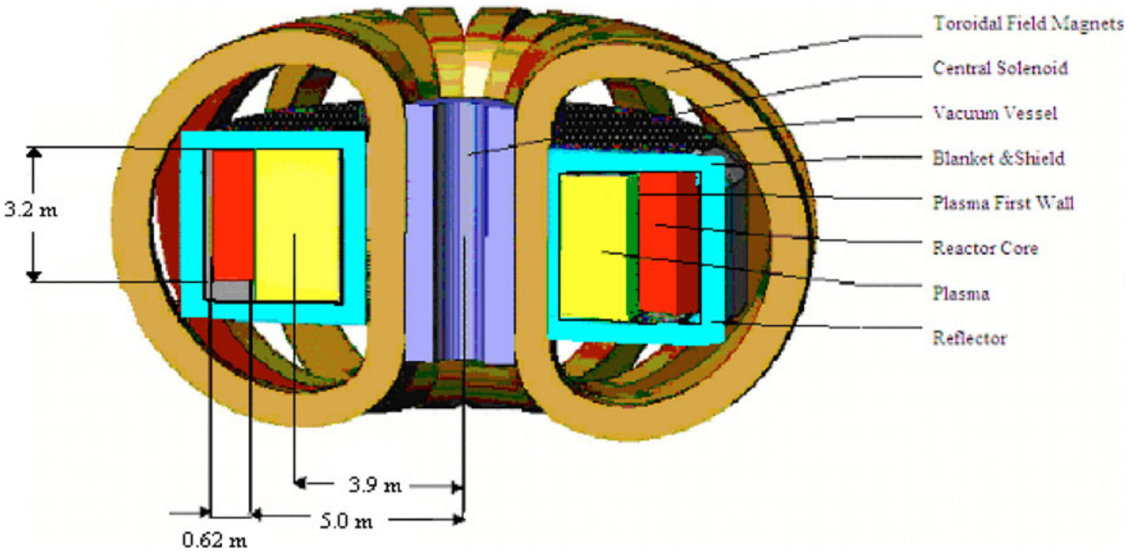

Fig. 1. Configuration of SABR.

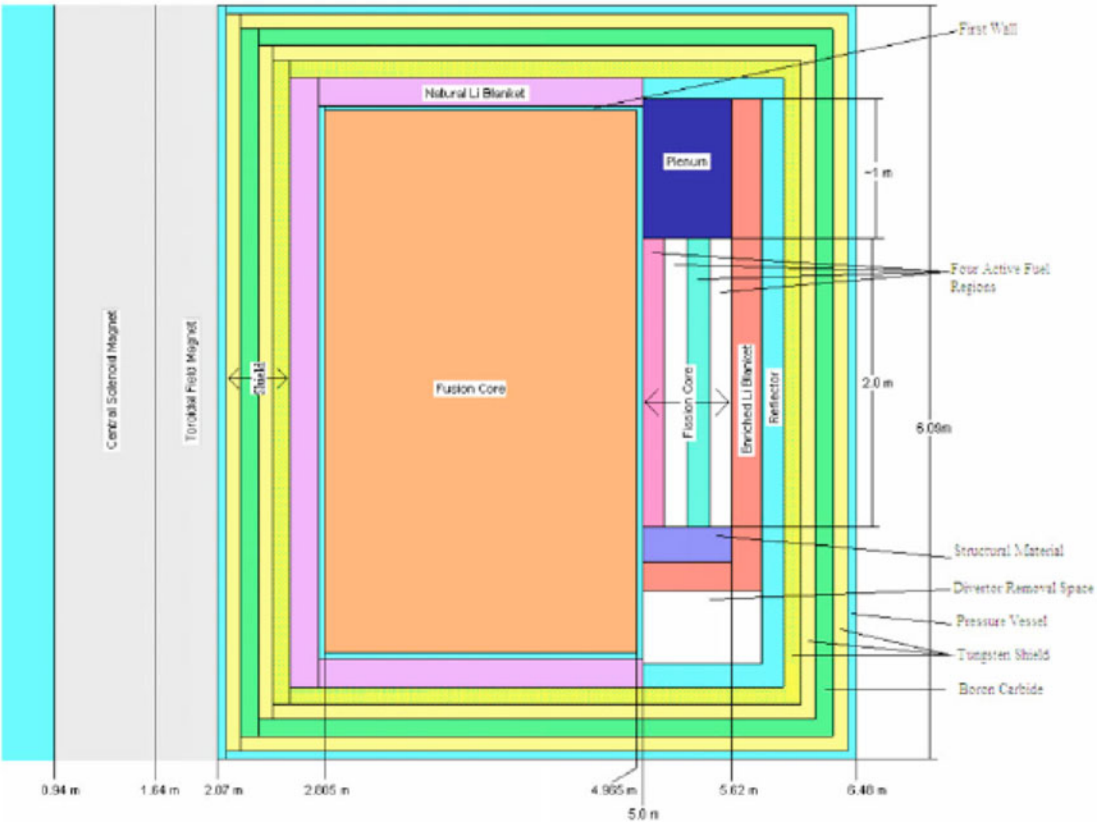

Fig. 2. Detailed *R-Z* cross-sectional model of SABR.

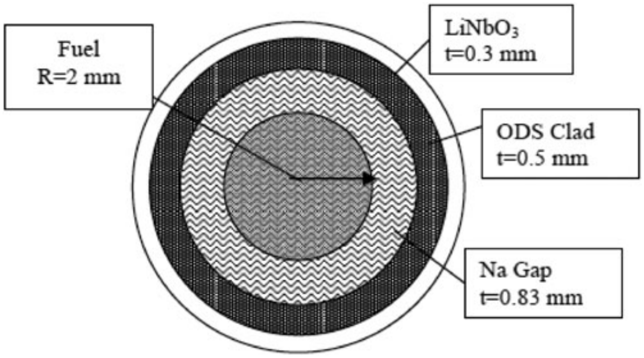

Fig. 3. Cross-sectional view of a fuel rod.[5]

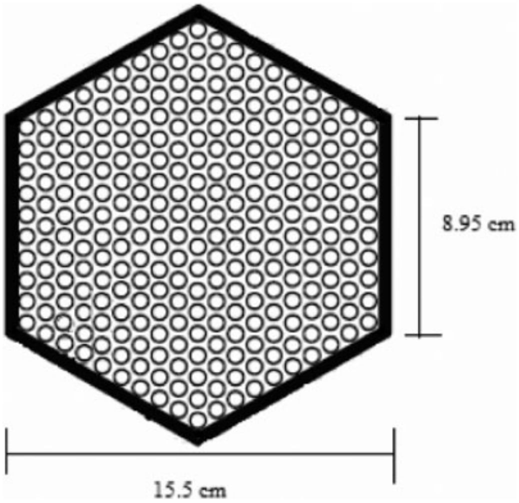

Fig. 4. Hexagonal fuel assembly of 271 pins.

points in the axial direction. A convergence criteria of 1×10^{-4} for inner iterations and 1×10^{-5} for the outer iterations is used.

II.D. Reprocessing

SABR employs the pyroreprocess being developed at Argonne National Laboratory[6] (ANL). Pyroreprocessing was chosen over aqueous reprocessing because of the metallic fuel used in the core. Pyroreprocessing eliminates an oxidation step that is necessary to convert metallic fuel into a form that is able to be reprocessed with an aqueous system.

The pyroreprocessing system has been tested only on a laboratory scale, not an industrial scale, so separa-

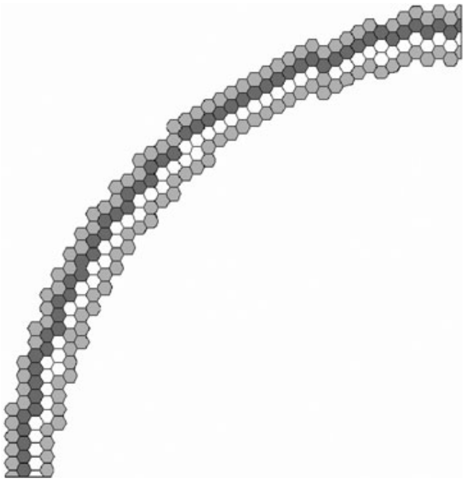

Fig. 5. Core configuration of 918 fuel assemblies in four rings.

tion and contamination factors have not been determined on the industrial scale. Separation efficiencies that have been achieved on the laboratory scale[7] are 99.85% for Np and Pu, 99.97% for Am, and 99.95% for Cm. The present study assumes industrial-scale recovery efficiency for the actinides of 99% and a contamination rate by fission products of 1% in the reprocessed fuel, and a 1% contamination of the TRUs going to waste storage with the fission products.

III. FUEL CYCLE PERFORMANCE

The fuel cycle of SABR, unlike a critical system, is not limited by the need to maintain criticality. The limitations on SABR's fuel cycle are the fusion neutron source strength of 500 MW and radiation damage to the fuel's cladding [reference radiation damage limit; 200 displacements per atom (dpa) assumed]. The SABR neutron source was designed to produce 500 MW, using ITER physics and technology, but could readily be extended to somewhat higher power. We find that a neutron source with 500 MW of fusion power would enable SABR to operate on a four-batch fuel cycle with 10.95-years fuel residence time in the reactor. This residence time would accumulate a radiation damage level of 294 dpa and a TRU burnup of 31.6% per residence time. Cladding materials currently under development are anticipated to be able to withstand a radiation damage level of 200 dpa. Based on these limitations, it would seem that SABR's fuel cycle would be limited by radiation damage to the core clad and structure, not by the maximum fusion neutron source strength of the neutron source.[8] So, it is important to determine the effect of the radiation damage limit on fuel cycle performance, which is one of the purposes of this paper.

III.A. The SABR Four-Batch Fuel Cycle

The chosen fuel cycle is a four-batch fuel cycle with an out-to-in shuffling pattern. Previous work has shown that the out-to-in pattern produces lower power peaking due to the less reactive fuel being in the inner assemblies near the plasma source. The four-batch cycle was chosen to increase the overall burnup of the fuel, while not requiring over-frequent refueling. The fuel is based on ANL (Ref. 9) metallic fuel that is composed of a 60-TRU 40-Zr. The initial beginning-of-life (BOL) TRU fuel composition is given in Table I.

The fuel is then irradiated in four batches through 700 full-power day (FPD) fuel cycles. The out-to-in fuel shuffling pattern was chosen for this work.[10] In the out-to-in shuffling pattern new fuel [a mixture of reprocessed previously burned TRU and "fresh" TRU from LWR spent nuclear fuel (SNF)] is placed in the outermost ring of assemblies farthest from the fusion neutron source. The fuel is burned for 700 FPD (for the 200-dpa cycle), then is moved to the next ring inward. The innermost ring of fuel assemblies next to the neutron source is removed and sent to the reprocessing facility, where the fission products are removed and the remaining TRU is mixed with fresh TRU (from LWR SNF) and refabricated into new fuel for SABR (or another ABR). After several fuel cycles, the compositions of the fuel loaded into the outer ring and removed from the inner ring reach equilibrium values. Figure 7 illustrates the out-to-in fuel movement sequence in SABR.

TABLE I

TRU BOL Composition

Isotope	Mass Percent BOL
^{237}Np	17.0
^{238}Pu	1.4
^{239}Pu	38.8
^{240}Pu	17.3
^{241}Pu	6.5
^{242}Pu	2.6
^{241}Am	13.6
^{243}Am	2.8

SABR's fuel cycle was evaluated based on the following criteria: overall TRU burnup, reactivity decrement, necessary fusion power, power peaking, radiation damage, and decay heat. All of these criteria depend on the fuel residence time in the reactor. The overall burnup will be greater with a greater fuel cycle length, as will the fusion power (neutron source strength) needed to sustain the fission power level at 3000 MW(thermal) and the

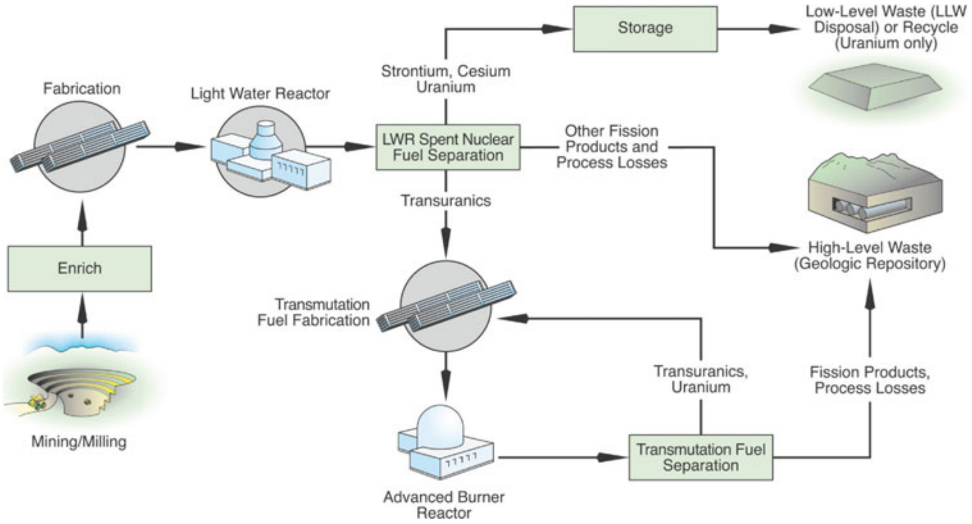

Fig. 6. Multistep fuel cycle employed with SABR (Ref. 5).

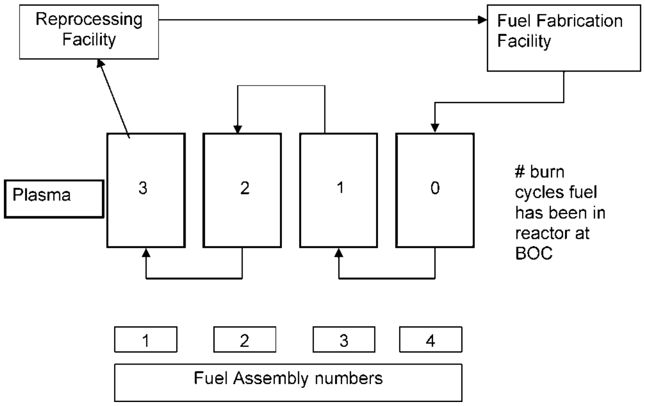

Fig. 7. Out-to-in reprocessing fuel cycle.

radiation damage to the clad. The required end-of-cycle (EOC) (end of 700-FPD fuel cycle) fusion power increases with residence time because the decreased reactivity of the system—or more specifically, the multiplication of the source neutrons—decreases as more fuel is burned.

The neutron spectrum will be harder, and the power profile will become more peaked as the residence time of the fuel is increased. A highly peaked power profile is undesirable in terms of the thermal-hydraulic design of SABR. The neutron spectrum hardening over time in SABR is beneficial in regard to fissioning of the TRU fuel since the fission-to-capture ratio of the TRU is higher in a harder spectrum. A harder neutron spectrum increases radiation damage, reducing the allowed residence time of the fuel in the reactor.

The composition of the fresh fuel initially loaded into the core is listed in Table I for all four fuel cycles considered in this work. This composition results in a BOL k_{eff} equal to 0.972 for all of the fuel cycles considered. The length of each fuel cycle is determined by the fuel residence time in the reactor, which is limited by radiation damage to the clad. This study evaluates three different radiation damage limits (100, 200, and 300 dpa), which correspond to three different fuel cycle lengths and three different fuel residence times. A fourth fuel cycle is also considered that assumes radiation damage limits sufficiently large so that the residence time is limited only by the neutron source strength needed to maintain 3000-MW(thermal) fission power.

Although the BOL fuel composition is the same for all four fuel cycles, the fuel burnup and hence the equilibrium beginning of cycle (BOC) and EOC fuel compositions and k_{eff} vary among the four fuel cycles. The fusion neutron source strength, hence the fusion power level, required to maintain 3000-MW(thermal) fission power level increases with longer fuel residence times (higher radiation damage limits). The average TRU compositions in the reactor for each of the four fuel cycles at BOC and EOC are shown in Tables II and III. The BOL composition listed in Table I is all fresh fuel. On the other hand, BOC composition in Tables II and III are the average core compositions at the beginning of the equilibrium cycle, composed of fresh fuel in ring 4, once-burned fuel in ring 3, twice-burned fuel in ring 2, and three-times-burned fuel in ring 1. The EOC compositions are an average of once-burned fuel in ring 4, twice-burned fuel in ring 3, thrice-burned fuel in ring 2, and four-times-burned fuel in ring 1. In the reprocessing fuel cycle, the fresh fuel referred to above is a combination of fresh TRU from LWR SNF and reprocessed fuel from SABR. The amount of fresh TRU is

TABLE II

SABR Fuel Compositions at BOC and EOC for the 100- and 200-dpa Cycles

Isotope	100-dpa Cycle BOC (wt%)	100-dpa Cycle EOC (wt%)	200-dpa Cycle BOC (wt%)	200-dpa Cycle EOC (wt%)
^{235}U	0.02	0.02	0.2	0.3
^{238}U	3.0E−5[a]	4.0E−5	1.0E−4	2.0E−4
^{237}Np	13.3	12.6	8.6	7.5
^{239}Np	2.0E−6	2.0E−6	2.0E−6	2.0E−6
^{238}Pu	8.3	9.3	13.8	14.2
^{239}Pu	29.8	28.0	20.7	18.5
^{240}Pu	20.9	21.2	25.7	25.7
^{241}Pu	5.09	4.9	5.2	5.1
^{242}Pu	3.91	4.1	6.1	6.4
^{241}Am	11.7	11.1	8.4	7.6
^{242m}Am	0.5	0.6	0.7	0.7
^{243}Am	2.6	2.5	2.7	2.6
^{242}Cm	0.4	0.4	0.3	0.3
^{243}Cm	0.04	0.05	0.07	0.07
^{244}Cm	0.8	0.9	1.9	2.0
Fission products	2.64	4.33	5.63	9.03

[a] Read as 3.0×10^{-5}.

TABLE III

SABR Fuel Compositions at BOC and EOC for the 300-dpa and the Once-Through Cycles

Isotope	300-dpa Cycle BOC (wt%)	300-dpa Cycle EOC (wt%)	Once-Through BOC (wt%)	Once-Through EOC (wt%)
^{235}U	0.2	0.3	0.2	0.2
^{238}U	1.0E−5[a]	1.0E−4	1.0E−4	1.0E−4
^{237}Np	8.6	7.0	8.3	7.3
^{239}Np	2.0E−6	2.0E−6	1.0E−6	2.0E−6
^{238}Pu	13.4	13.9	8.1	8.3
^{239}Pu	20.6	17.3	19.3	17.0
^{240}Pu	24.8	24.8	17.9	17.6
^{241}Pu	5.1	4.9	4.1	4.0
^{242}Pu	5.9	6.2	4.2	4.3
^{241}Am	8.3	7.2	7.7	6.8
^{242m}Am	0.7	0.7	0.4	0.4
^{243}Am	2.6	2.5	2.2	2.0
^{242}Cm	0.3	0.3	0.1	0.3
^{243}Cm	0.07	0.07	0.02	0.04
^{244}Cm	1.8	2.0	1.1	1.3
Fission products	7.83	12.83	26.38	30.46

[a] Read as 1.0×10^{-5}.

dependent on the level of a particular fuel cycle's burnup and is calculated using

$$\text{Fresh TRU} = 7.89 \times (1 - 0.99 \times \text{FIMA}) \ .$$

For the 200-dpa case, 6.03 tonne of fresh TRU is added to the reprocessed fuel. Appendix A contains the heavy metal content for each batch of SABR's 200-dpa equilibrium cycle.

The "once-through" fuel cycle differs from the other three fuel cycles not only in that the burn cycle length is longer but also in that the new fuel loaded into the outer ring is always fresh TRU from LWR SNF since there is no reprocessing in this cycle. The cycle length was chosen so that the four-burn cycle residence time achieved ~90% TRU burnup.

III.B. Fuel Cycle Performance Parameters

The principal results of the four fuel cycle calculations are summarized in Table IV.

The current design of the fusion neutron source can accommodate the fusion powers needed for the three reprocessing fuel cycles. The source would need to be extended to accommodate the once-through cycle, but this fuel cycle is not realistic because of the high-clad dpa and is shown simply for illustration.

The power peaking is calculated as the ratio of the maximum volumetric power density to the average volumetric power density in the reactor.

The TRU burned per residence is given in FIMA and is calculated by taking the amount of TRU in the initial loading, subtracting from that the TRU that is going to the reprocessing facility after each burn cycle, and dividing that by the initial TRU loading.

The TRU burned per residence or percent burnup is important in this study because the repository capacity is determined by the long-term heat load. The long-term heat load is a function of the amount of TRU in the repository. The greater the burnup percentage, the fewer reprocessing steps are necessary to destroy all of the TRU from the SNF. Those fewer steps reduce the amount of TRU in the repository because of the inherent losses of TRU to the waste stream in the reprocessing treatment.

The LWR support ratio in SABR is defined as the amount of TRU destroyed by SABR to the amount of TRU produced by a 1000-MW(electric) LWR. On average, a 1000-MW(electric) LWR produces ~250 kg (Ref. 11) of TRU, which may be compared to the 1.05 tonne burned in SABR's 200-dpa cycle, resulting in a support ratio of 3.54 LWRs for every SABR built. This LWR support ratio assumes that the shutdown for refueling is 60 days and that, in addition, the facility is unavailable for 10% of the time during the operating period because of unscheduled shutdowns.

The SNF "denatured" (by having its long-lived TRU fissioned) per year is about 100 times the TRU fissioned per year. At the current rate of SNF production, 2000 tonne per year and assuming the 200-dpa SABR fuel cycle, 30 SABRs would fission the TRU from all current LWRs in the United States.

The dpa is a measure of radiation damage. It is calculated in ERANOS using 33-group neutron fluxes and dpa cross sections from JEFF2.0.

III.C. Power Distribution

The power distributions for all four fuel cycles are shown in Fig. 8.

The three reprocessing fuel cycles all display the same basic shape in their power profiles. There is a large power spike in the inner ring of fuel assemblies adjacent to the plasma neutron source, which is only somewhat greater at EOC than BOC. The highest power peaking occurs in the 300-dpa fuel cycle, the cycle with the longest residence time and fuel burnup. All three reprocessing fuel cycles

TABLE IV

Fuel Cycle Performance Parameters for Four-Batch Fuel Cycles*

Parameter	Cycles			
	100 dpa	200 dpa	300 dpa	Once Through
Burn cycle length time (FPD)	350	700	1000	4550
Four-batch residence time (FPY)[a]	3.83	7.67	10.95	49.8
k_{eff} (BOC/EOC)	0.940/0.916	0.894/0.868	0.887/0.834	0.784/0.581
Pfus (BOC/EOC) (MW)	155/218	240/370	286/461	1012/1602
TRU content (BOC/EOC) (tonne)	29.6/28.6	29.0/27.1	28.3/25.4	22.6/9.5
Power peaking (BOC/EOC)	1.68/1.78	1.80/1.98	1.82/2.04	1.97/1.59
TRU burned per residence (%)	16.7%	23.8%	31.6%	87.2%
TRU burned per year (tonne/FPY)	1.04	1.05	1.05	1.05
LWR support ratio	3.27	3.54	3.62	3.82
Average core flux across cycle ($n/cm^2 \cdot s$)	6.34E15[b]	6.59E15	7.25E15	2.16E16
Average fast (>0.1 MeV) flux ($n/cm^2 \cdot s$)	4.73E15	4.81E15	5.28E15	1.82E16
Clad radiation damage (dpa)	97	203	294	1381

*3000 MW(thermal) and power density = 93.75 kW/kg (BOL Pu loading 32 tonne, $k_{eff} = 0.972$).

[a] FPY = full power year

[b] Read as 6.34×10^{15}.

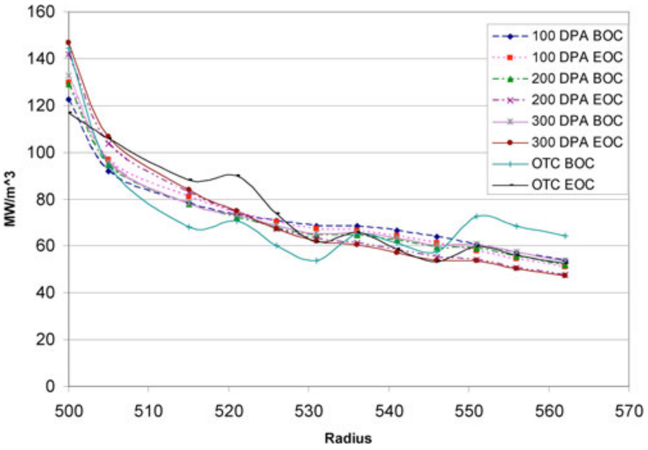

Fig. 8. Power distributions for the different fuel cycles analyzed in SABR.

have large power gradients in the first fuel region and then are flatter for the remaining three fuel regions. There are several possibilities that we plan to explore for flattening the power distributions.

The once-through cycle is calculated in the same manner as are the reprocessing fuel cycles. The four fuel regions are loaded with fresh fuel and then are shuffled every 4550 days in an out-to-in pattern. The once-through cycle exhibits completely different behavior from the reprocessing fuel cycles. First, the BOC and EOC power distributions do not exhibit the same behavior as in the reprocessing fuel cycles. In the once-through cycle, the BOC power peaking is significantly higher than the EOC power peaking. This is caused by the innermost fuel ring being 87% depleted and thus not creating as much power at EOC.

III.D. Radiation Damage

The radiation damage calculation was done using the dpa cross sections in ERANOS2.0. As stated earlier, 200 dpa is the limiting factor on radiation damage for the reference fuel cycle. Radiation damage is produced by high-energy neutrons, thus a softer neutron spectrum produces lower damage. SABR has a very hard spectrum (73% of the flux is >100 keV in the 200-dpa fuel cycle), thus radiation damage is higher in SABR than traditional sodium-cooled fast reactors. The normalized neutron spectrum for all of the fuel cycles is shown in Fig. 9 for the innermost ring of fuel assemblies. The spectrum was normalized versus the peak value of the neutron flux.

The variation of the neutron spectra within SABR is indicated in Fig. 10. Note the relatively small peaking effect of the 14-MeV fusion neutrons in ring 1 nearest the neutron source. Note also the larger fraction of lower-energy neutrons in ring 1 that have been reflected across the plasma after scattering of the inboard side of the plasma.

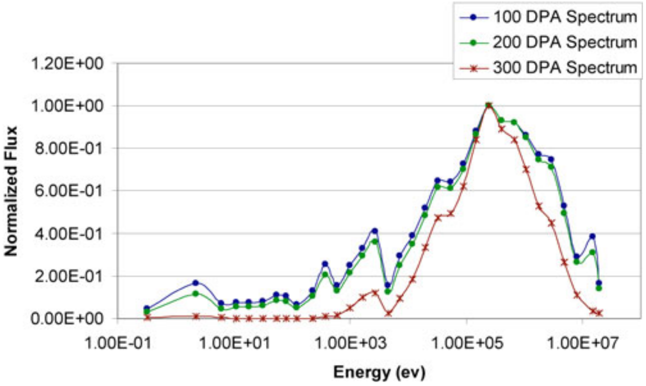

Fig. 9. SABR neutron spectra at BOC in the innermost fuel ring #1 for the reprocessing fuel cycles.

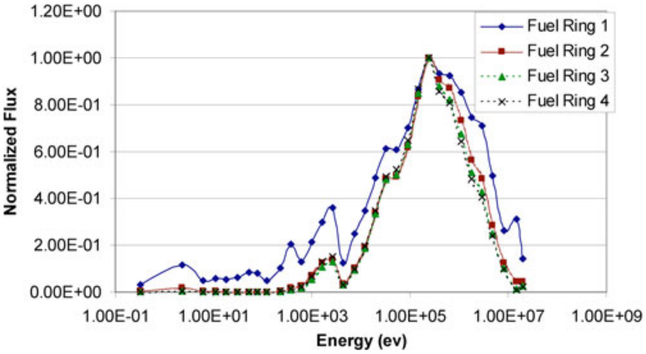

Fig. 10. Flux spectra for the 200-dpa cycle.

III.E. Effects of Transmutation on the Geological Repository

The material from SABR that is ultimately stored in the geological repository is the waste stream from the reprocessing facility. In this study the waste stream is assumed to be 1% of the transmuted TRUs and 99% of the fission products discharged from SABR. This is a conservative assumption when compared to the separation efficiencies (greater than 99%) that have been obtained on the laboratory scale.[7] The transuranic composition in kilograms for each of the fuel cycles that goes to the geological repository is shown in Table V.

Table V shows that in the 200-dpa fuel cycle 10.84 kg of ^{239}Pu are put into the repository after every reprocessing step. For the 200-dpa fuel cycle, 60.2 kg of TRU is in the waste stream per full-power year (FPY) and therefore will be interned at a Yucca Mountain–type repository after each reprocessing step. This equates to 31.39 kg of TRU per full calendar year for the 200-dpa cycle. The amount of TRU per calendar year interned in a geological repository is shown in Table VI.

Table VI shows that as the cycle length of the reprocessing fuel cycle increases, the amount of TRUs that

TABLE V

Transuranic Waste in Kilograms to the Repository After Each Reprocessing Step for SABR

Isotope	100-dpa Cycle (kg)	200-dpa Cycle (kg)	300-dpa Cycle (kg)	Once-Through Cycle (kg)
^{235}U	0.022	0.178	0.20	12.4
^{238}U	3.15E−5[a]	1.0E−4	1.1E−4	8.8E−3
^{237}Np	8.088	4.28	3.28	8.45
^{239}Np	1.47E−6	1.45E−6	1.34E−6	6.7E−5
^{238}Pu	7.21	10.2	9.68	77.1
^{239}Pu	18.05	10.84	8.83	53.1
^{240}Pu	15.13	17.27	16.01	322.7
^{241}Pu	3.32	3.42	3.28	100.8
^{242}Pu	2.99	4.32	4.18	216.3
^{241}Am	7.22	4.41	3.49	19.8
^{242m}Am	0.469	0.49	0.45	2.52
^{243}Am	1.71	1.64	1.50	68.9
^{242}Cm	0.42	0.35	0.30	3.02
^{243}Cm	0.039	0.06	0.07	1.2
^{244}Cm	0.77	1.49	1.51	119.9
^{245}Cm	0.08	0.32	0.36	47.9
Total	65.8	60.2	54.0	1090

[a] Read as 3.15×10^{-5}.

TABLE VI

TRU to Geological Repository

Fuel Cycle	Kilograms to Repository Per Year
100 dpa	67.68
200 dpa	31.39
300 dpa	19.71
Once-through cycle	87.44

needs to be stored in the repository is smaller. Increasing the radiation damage limit is a key factor in limiting the amount of TRU stored in the repository. The once-through cycle sends significantly more TRU to the repository because after the cycle all of the TRU is sent to the repository, as opposed to the reprocessing fuel cycles where only the TRU in the waste stream is sent to the repository.

The repository capacity is determined by the long-term decay heat produced in the repository. The long-term heat production is a function of the amount of long-lived TRUs in the reprocessing waste stream. There are two possibilities to decrease the amount of TRUs in the waste stream. The first is to burn the fuel to higher levels of burnup in SABR, resulting in fewer reprocessing steps and therefore less TRU in the fission products sent to the respository as indicated in Table VI. The second possibility is to decrease the TRU in the fission product waste stream by increasing the separation efficiency in the reprocessing procedure. Figure 11 shows the decay heat of the material in the waste stream that is sent to the repository for final storage.

IV. CONCLUSIONS

A four-batch reprocessing fuel cycle for the SABR transmutation reactor concept, in which all the TRU from SNF is fissioned to >90%, was examined using the ERANOS fast reactor physics code. The total fuel residence time in the reactor was limited in the first three cycles by a set radiation damage limit (100, 200, and 300 dpa) to the cladding material. In the fourth cycle the fuel residence time was determined by trying to achieve 90% burnup in a once-through cycle. The reference cycle for this study was chosen to be the 200-dpa fuel cycle because of expected future radiation damage limits of the clad.

SABR contains 32 tonne of "fresh" TRU at BOL, corresponding to a k_{eff} of 0.972. An out-to-in shuffling scheme was utilized where at the end of a 700-day burn cycle (in the reference cycle) the fuel in the innermost fuel ring (next to the plasma) is removed from the core and sent to reprocessing, the fuel in the other rings is shifted inward by one ring, and new fuel is loaded into the outermost ring. The fuel removed from the reactor is separated pyrometallurgically into fission products and TRUs. The fission products are sent to a geological

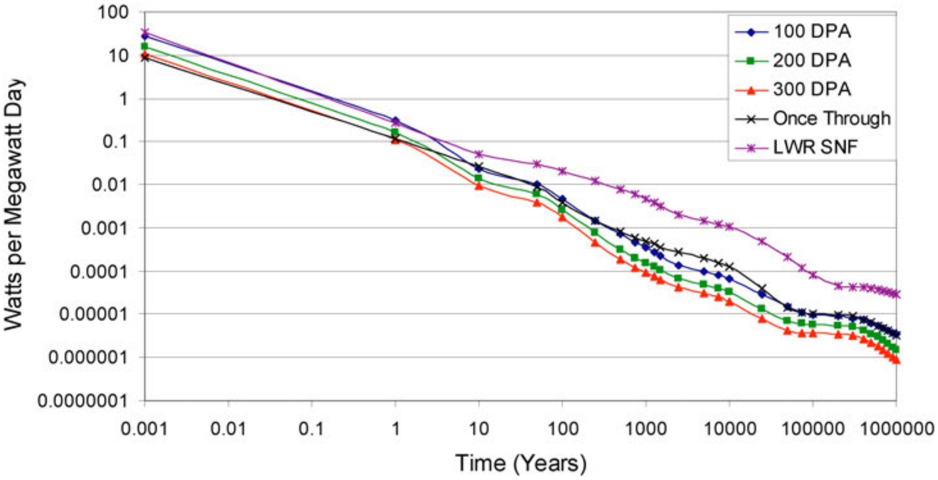

Fig. 11. Decay heat of material sent to repository for reprocessing fuel cycles.

repository, and the TRUs are mixed with "fresh" TRU from SNF, fabricated into fuel, and recycled into the outermost ring of the SABR. After several burn cycles, an equilibrium is established for the compositions at the BOC and EOC. The reference fuel cycle contains 29.0 tonne of TRU at BOC, which corresponds to a k_{eff} of 0.894, and 27.1 tonne of TRU at EOC corresponds to a k_{eff} of 0.868. The neutron source strength required to maintain 3000 MW of fission power is 75 MW at BOL, 240 MW at BOC, and 370 MW at EOC. For the fuel cycles with residence times limited by radiation damage limits of 100 and 300 dpa to the structural materials, the EOC fusion powers are 220 and 460 MW, respectively. Thus, it seems appropriate to design the fusion neutron source to produce up to 500 MW of power. If the radiation damage limits could be overcome, TRU burnup of >90% could be achieved in a once-through cycle by leaving the fuel in the reactor until k_{eff} is <0.6. This would require a fusion neutron source strength greater than 500 MW to maintain the fission power of 3000 MW.

The TRU fission rate in SABR is 1.05 tonne per FPY of operation. Allowing for 60 days downtime for refueling and shuffling after each burn cycle and 10% unavailability during the burn cycle, SABR could achieve 84% overall availability, which allows SABR to fission all the TRUs in the SNF discharged annually from 3.5 1000-MW(electric) LWRs. For a given batch of fuel that resides in the reactor for the four burn cycles between reprocessing steps, 23.8% of the TRU is fissioned.

We note that even though we have attempted to use a realistic model of the SABR core and surrounding zones for this fuel cycle analysis, the SABR design is at a conceptual stage, and many details that may affect the fuel cycle analysis have not yet been developed.

APPENDIX

MASS BALANCES IN SABR

TABLE A.I

Heavy Metal Mass Content in SABR at BOC

	Ring 1	Ring 2	Ring 3	Ring 4
^{235}U	1.61E+01[a]	2.38E+01	2.30E+01	2.23E+01
^{238}U	1.18E−02	1.51E−02	1.37E−02	1.21E−02
^{239}Pu	1.31E+03	1.42E+03	1.62E+03	1.78E+03
^{240}Pu	1.83E+03	1.97E+03	2.04E+03	2.07E+03
^{241}Pu	3.33E+02	3.79E+02	4.25E+02	4.76E+02
^{242}Pu	4.48E+02	5.03E+02	5.05E+02	5.02E+02
^{241}Am	5.63E+02	5.98E+02	6.54E+02	6.82E+02
^{237}Np	5.50E+02	5.73E+02	6.51E+02	7.13E+02
^{245}Cm	2.87E+01	3.62E+01	3.71E+01	3.74E+01
^{233}U	1.42E−09	1.59E−09	1.95E−09	2.24E−09
^{243}Am	1.84E+02	2.05E+02	2.15E+02	2.23E+02
^{238}Pu	1.04E+03	1.04E+03	1.05E+03	1.03E+03
^{242m}Am	5.04E+01	4.78E+01	4.76E+01	4.67E+01
^{242}Cm	1.62E+01	1.41E+01	1.46E+01	3.24E+01
^{243}Cm	4.61E+00	4.88E+00	5.55E+00	6.17E+00
^{244}Cm	1.38E+02	1.55E+02	1.56E+02	1.57E+02
^{242f}Am	7.81E−02	6.82E−02	6.77E−02	1.56E−01
^{234}U	9.57E+01	1.14E+02	1.05E+02	9.30E+01
^{236}U	5.64E+00	8.86E+00	8.04E+00	7.24E+00
^{239}Np	1.59E−04	1.77E−04	1.86E−04	1.46E−04
Fission products	6.45E+02	3.96E+02	1.69E+02	1.04E+01

[a] Read as 1.61×10^1.

TABLE A.II

Heavy Metal Mass Content in SABR at EOC

	Ring 1	Ring 2	Ring 3	Ring 4
^{235}U	2.13E+01[a]	1.61E+01	2.38E+01	2.30E+01
^{238}U	1.25E−02	1.18E−02	1.51E−02	1.37E−02
^{239}Pu	1.05E+03	1.31E+03	1.42E+03	1.62E+03
^{240}Pu	1.75E+03	1.83E+03	1.97E+03	2.04E+03
^{241}Pu	3.36E+02	3.33E+02	3.79E+02	4.25E+02
^{242}Pu	4.52E+02	4.48E+02	5.03E+02	5.05E+02
^{241}Am	4.37E+02	5.63E+02	5.98E+02	6.54E+02
^{237}Np	4.08E+02	5.50E+02	5.73E+02	6.51E+02
^{245}Cm	3.56E+01	2.87E+01	3.62E+01	3.71E+01
^{233}U	9.79E−10	1.42E−09	1.59E−09	1.95E−09
^{243}Am	1.69E+02	1.84E+02	2.05E+02	2.15E+02
^{238}Pu	1.02E+03	1.04E+03	1.04E+03	1.05E+03
^{242m}Am	4.80E+01	5.04E+01	4.78E+01	4.76E+01
^{242}Cm	2.59E+01	1.62E+01	1.41E+01	1.46E+01
^{243}Cm	5.47E+00	4.61E+00	4.88E+00	5.55E+00
^{244}Cm	1.52E+02	1.38E+02	1.55E+02	1.56E+02
^{242f}Am	1.25E−01	7.81E−02	6.82E−02	6.77E−02
^{234}U	9.76E+01	9.57E+01	1.14E+02	1.05E+02
^{236}U	7.00E+00	5.64E+00	8.86E+00	8.04E+00
^{239}Np	1.49E−04	1.59E−04	1.77E−04	1.86E−04
Fission products	9.58E+02	6.45E+02	3.96E+02	1.69E+02

[a] Read as 2.13×10^1.

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