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Optimization Studies for Seed-and-Blanket Unit (SBU) Fuel Assemblies in PWRs

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The objective of recent studies as part of a joint NERI project between Brookhaven National Laboratory and Massachusetts Institute of Technology was to develop a seed and blanket unit (SBU) fuel assembly (FA) for thorium utilization in pressured water reactors (PWR). This heterogeneous design utilizes enriched uranium seed and mixed uranium/thorium dioxide blanket fuel pins in physically separable sub-assemblies, and could be used as a one-for-one replacement of more conventional UO_2 FA's in PWRs. The seeds are used for three 18-month cycles in a 3-batch fuel core management strategy, while the blankets are used for six 18-month cycles before being removed for long-term storage; the concepts considered here assume a once-through fuel cycle consistent with current U.S. policy. The SBU should have improved proliferation, radiation safety, and comparable economic characteristics in comparison to existing PWR FA's. Optimization studies using the BOXER, COBRA-EN, and ORIGEN codes have led to an improved SBU FA design for PWRs that achieves high burnup (80 GWd/t over 3 cycles for SBU) with reduced proliferation and toxicity characteristics, while satisfying thermal-hydraulic safety limits (minimum departure from nucleate boiling ratio greater than 1.3 for 118% over-power). The SBU is an attractive fuel for existing and next-generation PWR.

KEYWORDS: thorium, seed-blanket, proliferation-resistance, high-burnup, fuel design, PWR

1. Introduction

The objective of recent studies, as part of a NERI project between Brookhaven National Laboratory and the Massachusetts Institute of Technology [1,2] was to develop a seed and blanket unit (SBU) pressurized water reactor (PWR) fuel assembly (FA) design utilizing enriched uranium and thorium dioxide fuel pins that would be capable of achieving high-burnup levels with reduced spent fuel toxicity, while meeting requirements imposed by thermal-hydraulic safety and proliferation limits. An optimized SBU could then be used as a replacement for all-uranium (in the form of UO_2) FA's in existing and future PWRs. An SBU-fuelled PWR would essentially

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be U-235 burner with supplementary production and in-situ burning of U-233 bred from the thorium. The SBU could develop a relatively high conversion ratio over its burnup period, ~0.70. Use of the SBU would produce less plutonium and would help exploit the energy potential available in the fertile fuel thorium. The SBU should have improved proliferation, waste, and comparable economic characteristics in comparison to existing UO2-based PWR fuel assemblies. Since an early design [1] for the SBU (baseline) had limitations in meeting thermal-hydraulic and proliferation requirements, a series of optimization studies were performed to develop an optimized SBU design from the baseline one.

2. SBU Design Specifications

The SBU has the same general dimensions of a standard 17x17 366-cm long Westinghouse PWR fuel assembly [3] with 264 fuel rods, and 25 locations for guide tubes for water holes, instrumentation, burnable poison rods, or control rods. The inner 11x11 seed sub-assembly (SSA) contains 108 UO_2 pins with ZrB_2/ZrO_2 poison plugs. The outer blanket sub-assembly (BSA) contains 156 pins, each of which is a mix of enriched UO_2 and ThO_2. In both the baseline and optimized SBU designs, the blanket and seed pins have the same outer diameter (0.95 cm), but there are differences in the size and composition of burnable poison plugs and central voids, as shown in Figure 1.

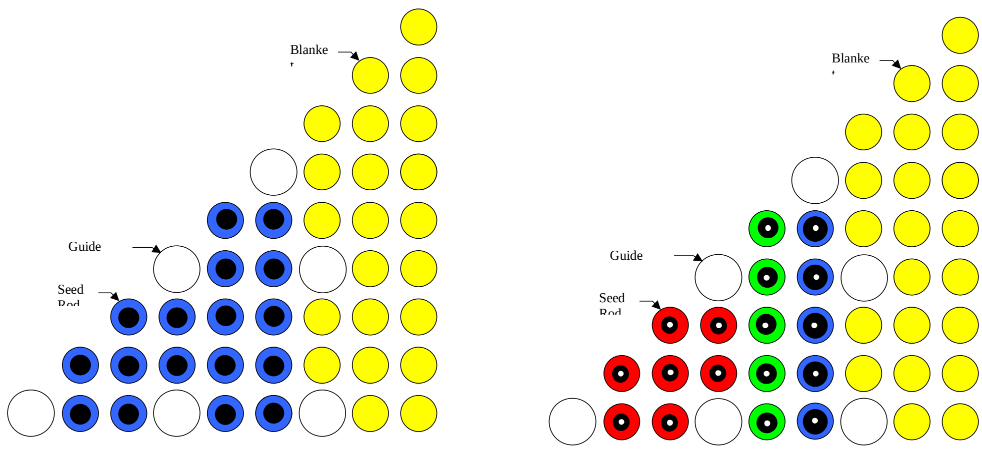

Fig. 1. Layout of Fuel Pins in 1/8th Baseline (left) and Optimized (right) SBU Designs

In the baseline design, all seed pins have the same dimensions and isotopic compositions for the fuel (20 w/o UO_2) and central poison plug (2.5% ZrB_2 in ZrO_2). The baseline blanket fuel pins are 13% by volume of 12.2 w/o UO_2 in ThO_2. In contrast, the optimized SBU design employs three different types of seed pins and a modified blanket pin composition. The inner seed pins have a slightly higher fuel volume, ~20% larger than the baseline. The middle seed pins have the same fuel volume as the baseline, while the outer seed pins have a slightly lower fuel volume, ~15% smaller than the baseline. The spatial gradient of fuel volume helps to reduce the radial power peaking while maintaining the reactivity needed for a long burnup. It is noted that the power tends to peak in one of the corner seed pins adjacent to the blanket and the corner guide tube / water hole. In addition, all seed pins in the optimized FA have a 0.4-cm diameter central void that allows space for fission product gases. The volume fraction of ZrB_2 in the annular poison plugs varies as well, ranging from 4.52% in the outer seed pin to 8.31% in the inner seed pins. The volume fraction of ZrB_2 in the middle seed is higher than that in the baseline case (2.5%) in order to conserve the number of boron atoms with the presence of a void. The fuel in all optimized seed pins has the same enrichment as the baseline: 20 w/o. The optimized blanket pin is slightly different in design. The number density for U-235 is the same, but the volume fraction and enrichment have been adjusted to 0.15 and 10.57 w/o (10.69 a/o) respectively. The higher fraction of UO_2 and hence U-238 is meant to improve proliferation resistance of the fissile uranium (U-235 and U-233) after high burnup levels.

3. SBU Nuclear Performance

The BOXER lattice-physics code developed at the Paul Scherrer Institute in Switzerland [4,5] was used for performing neutron transport and burnup calculations for the baseline and optimized SBU designs. The BOXER code has been designed primarily to analyze light water reactor (LWR) fuel assemblies.

Two sets of burnup calculations were performed with BOXER. In the first set, the baseline and optimized SBU designs, starting with fresh seed and fresh blanket, were burned out to 80 GWd/t, which is the desired burnup level of an SBU fuel assembly if it is to operate at a specific power of ~ 49 MW/t for a full 3 cycles, each 18 months, or ~540 days long. The specific power is such that the average power per 366-cm long assembly will be ~ 17.7 MW, and the total power generated in a 193-assembly core will be ~ 3400 MWth. In the second set of calculations, a fresh seed sub-assembly was inserted into the blanket from the previous 80 GWd/t SBU burnup. The isotopic composition of the blanket at an average burnup of ~80 GWd/t for the SBU was used as the initial isotopic composition in the blanket sub-assembly for the second three cycles of burnup with the next seed sub-assembly. This second set would emulate the second three cycles in a core calculation.

Results for these four sets of burnup calculations are shown in Figures 2 and 3. Figure 2 is a plot of the SBU infinite multiplication factor (K-Inf) versus the burnup level. The variation of K-Inf with burnup is almost identical for the baseline and optimized SBU designs for the first set and the second set. By the end of the second cycle (~53 GWd/t), the K-Inf for the first set is ~ 1.047, and the K-Inf for the second set is ~ 1.028. The multiplication factor drops 2 to 3% in the second set with the recycled blanket due to the depletion of U-235 and the buildup of fission products. If a 80-GWd/t discharge burnup is desired, then the 3-batch linear reactivity model [6] requires that K-Inf be greater than ~1.03 at 53 GWd/t (assuming a $\Delta k=0.03$ allowance for core leakage). Both the baseline and the optimized SBU designs meet this requirement for the first set, and almost for the second set. It may be necessary to slightly shorten the cycle length for the second set, or attempt to boost the reactivity by a multi-batch management scheme for the blanket sub-assemblies.

Figure 3 shows the relationship between the average burnup levels in the seed and blanket sub-assemblies with the average burnup in the optimized SBU for the first and second SSA loadings. The baseline case gives similar results. The average burnup in the SSA is almost twice that of the SBU while average burnup in the BSA is approximately 60% of the SBU burnup. At 80 GWd/t, the burnup in the SSA is ~ 154 GWd/t (first seed) and 149 GWd/t (second seed), while the burnup in the BSA is ~ 48.6 GWd/t (first seed) and 49.5 GWd/t (second seed). Spatial variation in the burnup occurs, not only because of differences in fuel enrichment, but also because of spatial variation in the neutron flux. Although the outer seed pins have a smaller volume of fuel, the thermal neutron flux is higher, causing greater burnup.

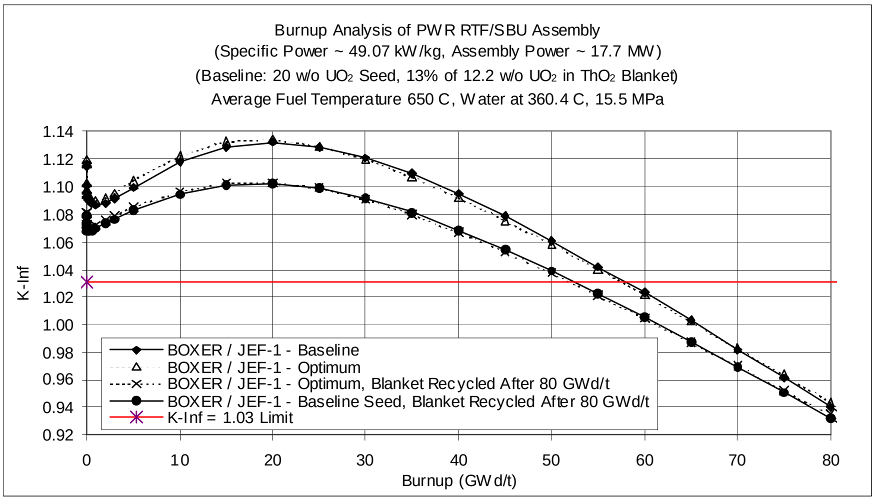

Fig. 2. BOXER Calculations of SBU Fuel Assembly Reactivity Variation with Burnup

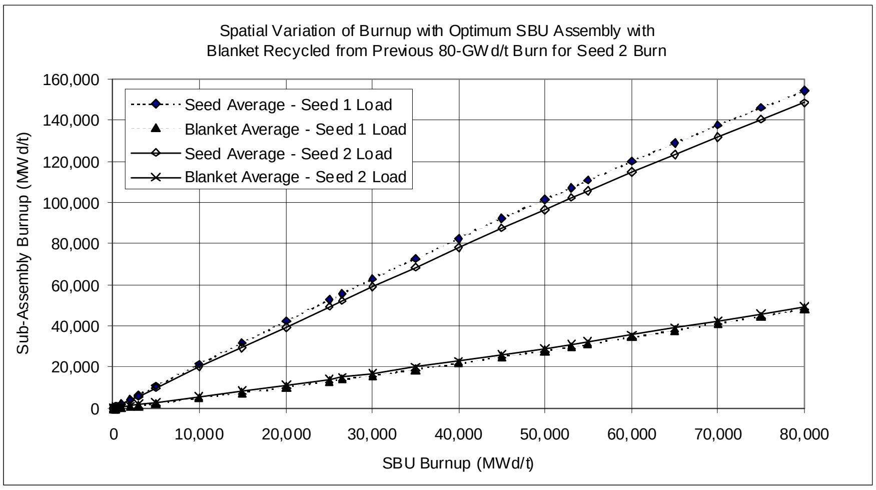

Fig. 3. Variation of Sub-Assembly Burnup Level with SBU Burnup

4. Thermal-hydraulics Issues

The COBRA-EN [7] sub-channel thermal-hydraulics code was used to compute the flow distribution, pressure drop, and departure from nucleate boiling ratios (DNBR) throughout the SBU assembly under various power conditions. The relative pin power distributions were extracted from the previous BOXER neutronic calculations for fresh seed sub-assemblies in fresh blanket sub-assemblies with zero burnup. The relative axial power distribution and the assembly peaking factor (F_{xy}) were taken from previous core calculations using the SILWER code [1,2]. Both axial power distributions and assembly power peaking factors can vary from cycle to cycle, but a typical one with a normalized axial peak of ~ 1.6 at 140 cm above the bottom of the 366-cm core, and a somewhat conservative assembly peaking factor of F_{xy}=1.5 were initially used in the COBRA calculations. The core-average linear rod power at full power was approximately 18.2 kW/m.

BOXER calculations demonstrated that the use of graded fuel and poison volume loading in the seed pins helps to reduce the pin peaking factor from 2.1 in the baseline case to less than 1.9 in the optimized case. As a result, COBRA-EN calculations demonstrated that the optimized SBU design always has a larger MDNBR than that for the baseline SBU. At full power conditions, only the optimized design has a MDNBR greater than 1.3. When the power level is increased to 112%, the MDNBR drops below 1.3, even for the optimized case with modified grid loss coefficients in the blanket and seed pins. Grid loss coefficients of K=0.86 were initially used, but it should be possible to introduce appendages and small flow divertors to reduce the loss coefficients in the seed pin sub-channels to K_{seed}~0.6, while increasing the loss coefficients in the blanket pin sub-channels to ~$K_{blanket}$~2.0 [1]. If the assembly peaking factor is reduced from 1.5 to 1.4, then even at 118% of full power, the optimized SBU assembly design will have an MDNBR greater than 1.3, while the baseline case remains below. At every power level, with modified grid loss coefficients, and a reduced assembly power peaking factor, the optimized SBU design has a larger safety margin than the baseline case.

It should be noted that as an assembly undergoes burnup, a greater portion of the assembly power is generated in the blanket due to the depletion of U-235 in the seed, and also due to buildup of U-233 in the blanket. The pin power peaking factor also drops, and this helps increase the MDNBR. If a fresh fuel assembly is inserted into a partially burned blanket, the pin peaking factor will drop as well. For example, the optimized SBU at beginning of cycle (BOC) with a fresh seed inserted in a blanket sub-assembly recycled from a previous 80-GWd/t SBU burn has a pin power peaking factor of ~ 1.64, which is significantly less than 1.85 initial value. Thus, the most severe situation that the SBU must be designed to handle is that with a fresh seed sub-assembly inserted into a fresh blanket sub-assembly.

In previous SBU core calculations with SILWER [2], the assembly peaking factor was found to go above 1.4, particularly during startup cycles. In some cases, there were once-burned assemblies that had peaking factor of almost 1.7. By the time the SBU core approaches equilibrium conditions, the assembly peaking factor is usually below 1.4. Additional core calculations are needed to check this possibility for the optimized SBU design. It must be stressed, however, that having an assembly peaking factor greater than 1.4 should not be considered desirable, for any fuel assembly design. Unless one is willing to accept a penalty in burnup capability and fuel cycle length, and use a fuel assembly design with highly reduced pin peaking factors, it is desirable to ensure that the core assembly peaking factor does not exceed 1.4. Incidentally, a typical PWR core [3,6] does not have an assembly peaking factor of more than ~1.3. One strategy that could be employed to ensure the assembly peaking factor does not go above 1.4 is inserting burnable poison rods in the guide tubes for the assemblies that do not have control banks. This approach could be particularly effective for the startup cycles.

5. Resource Utilization and Proliferation Issues

Data was taken from the BOXER calculations of the baseline and optimized SBU designs to evaluate the mass consumption and production of the various isotopes of concern for proliferation. The BOXER calculations for a single 366-cm (12 foot) assembly demonstrated that the mass of fissile uranium (U-235) in the SSA dropped by 16.6 to 17.4 kg over the course of three cycles (80 GWd/t burnup). The discharge U-235 enrichment was 4.6 to 4.9 w/o for the first seed, and to 5.2 to 5.4 w/o for the second seed. The optimized SBU had a slightly lower burnup of U-235.

One of the parameters of importance for the proliferation resistance of the SBU is the proliferation mass ratio (PMR= (mass of U-233 + mass of Pa-233 +0.6×mass of U-235)/(mass of U + mass of Pa-233)), which applies to the blanket, and must be less than 12%. The Pa-233 should be included in the calculation of the PMR because it will eventually decay to U-233 with a relatively short half-life. By the end of the sixth cycle, the optimized SBU design has a proliferation mass ratio of less than 12%. In contrast, the baseline SBU blanket exceeds 12%, even if the Pa-233 production is neglected. Even after 3 cycles (80 GWd/t) of burnup, the baseline blanket has a PMR greater than 12%. Thus, a slightly lower enrichment (10.57 w/o) and larger volume fraction (15%) of UO_2 in the blanket in the optimized case ensures that the proliferation limit is not exceeded. Total and fissile plutonium production in the SBU at discharge (3 cycles for the seed, 6 cycles for the blanket) for both designs were approximately the same, although the optimized design was slightly higher by a few hundred grams per assembly, due to the larger U-238 loading in the blanket.

Data from the BOXER calculations for both SBU designs were used to project resource utilization and isotope production characteristics for a full PWR core loaded with SBU assemblies under equilibrium conditions. The mass production of various isotopes was normalized to the production per GWe-year of electrical energy production, assuming a conversion efficiency of η~33%, and these extrapolated values were compared with sample data for a conventional PWR [1]. Compared to the baseline, the optimized SBU design has a slightly higher total production of plutonium (~1.4 kg/GWe-year higher) and the fraction of Pu that is Pu-239 is slightly higher as well (46.5 w/o in optimized vs. 45.7 w/o in baseline). However, plutonium production with either SBU design was 65% less than that in a conventional PWR core [1], and the weight fraction of Pu-239 was less as well (45 to 48 w/o for the SBU versus ~54 w/o for the PWR). Production of americium and curium isotopes in both SBU designs was comparable (~ 6.0 to 6.3 kg/GWe-year).

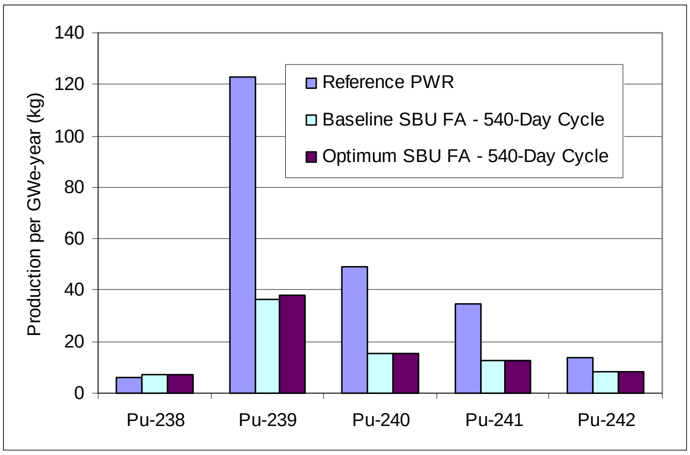

Figure 9: Plutonium Isotope Production per GWe-Year

6. Spent Fuel Characteristics

The populations of the various isotopes of actinides, fission products and poisons in the seed and blanket sub-assemblies after 3 cycles of burnup (6 cumulative cycles for the blanket) were extracted from the BOXER calculations of the baseline and optimized SBU designs and entered into ORIGEN [8] which is a zero-dimensional isotope production/depletion program. ORIGEN modeled the evolution of the isotope populations over 10 years of decay, and was used to compute the decay heat production, radioactivity, and the inhalation and ingestion toxicities of an SBU assembly. These data for two 3-cycle SSA burnup periods, and one 6-cycle BSA burnup period were extrapolated to obtain the characteristics for a full SBU core, normalized per GWe-year of electrical energy production. The blanket data for the first seed load was not used in the calculation since it had only burned for 3 cycles, and was not yet being discharged from the core for disposal or storage. These extrapolated data are shown in Table 1 along with sample PWR core data for comparison. The PWR results were based on data extrapolated from BOXER and ORIGEN calculations for a 417-cm long 17x17 4.2 w/o UO_2 fuel assembly [3] with a discharge burnup of ~50 GWd/t, which is typical for existing PWRs [3,6] operating on a 3-batch management scheme with a specific power of ~ 37 MW/t and a fuel cycle length of 14 to 15 months. As shown in Table 1, a core loaded with the baseline SBU will have a reduced heat load, radioactivity, and toxicities due to the actinides. Although the optimized SBU has a higher (~22%) heat load than the reference PWR, the radioactivity, inhalation toxicity, and ingestion toxicity are 56%, 14%, and 19% lower respectively, and the optimized SBU has better neutronic, thermal-hydraulic, and proliferation characteristics than the baseline design.

Table 1. Heat Load, Radioactivity and Toxicity per GWe-Year After 10-Year Decay Period

Data for Actinides Only (Some fission products are not tracked in BOXER)	Standard PWR (1)	Baseline SBU FA Data Extrapolated to PWR Core 540-Day Cycle	Optimum SBU FA Data Extrapolated to PWR Core 540-Day Cycle
Heat Load (Watts)	**10,077**	**8,844**	**12,248**
Radioactivity (Ci)	2.702E+06	1.039E+06	1.174E+06
Inhalation Toxicity (Sv)	**4.892E+11**	**3.667E+11**	**4.179E+11**
Ingestion Toxicity (Sv)	2.338E+09	1.636E+09	1.893E+09
(1) Values for Standard PWR are based upon calculations for an all-UO2 4.2 w/o enrichment fuel assembly burned to 50 GWd/t			

7. Conclusions

Recent computational studies with BOXER and COBRA-EN have lead to the development of an optimized seed and blanket unit (SBU) fuel assembly design. The optimized SBU design makes use of variable fuel and poison volumes to reduce pin power peaking. The optimized design has a 4-mm-diameter void in the seed pins to allow space for fission product gases. The blanket pins have a higher volume fraction of UO_2 and loading of U-238 to ensure that the proliferation mass ratio of 12% is not exceeded at high burnup levels, even if the production of Pa-233 is included in the calculation. With modified grid loss coefficients and an assembly peaking factor kept below 1.4, the optimized SBU will have a MDNBR greater than 1.3 at 118% over-power conditions. This is a major improvement over the baseline design. Production of plutonium isotopes will be low in comparison to a standard PWR fuel assembly, and the optimized design will be comparable to the baseline in other aspects. Although the heat load of the optimized SBU will be higher due to the higher population of radioactive actinides in the blanket sub-assemblies, the spent fuel characteristics will still be improved over that of a more conventional PWR because of the lower radioactivity and toxicity levels. The optimized SBU addresses thermal-hydraulic safety, proliferation, and toxicity issues while having the capacity to sustain a long burnup (80 GWd/t) for improved fuel cycle economics.

Further studies must investigate the radial power distributions in an SBU-loaded core. It may be necessary to employ burnable poison control rods or to devise alternative loading patterns to ensure that the assembly peaking factor does not exceed 1.4 during the startup cycles. It will also be necessary to perform full-core coupled neutronic and thermal-hydraulic calculations using reactivity data for the optimized SBU design to determine the safety characteristics of a PWR fuelled with such SBU assemblies.

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