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Article

A Phased Development of Breed-and-Burn Reactors for Enhanced Nuclear Energy Sustainability

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Abstract: Several options for designing fast reactors to operate in the Breed-and-Burn (B&B) mode are compared and a strategy is outlined for early introduction of B&B reactors followed by a gradual increase in the fuel utilization of such reactors. In the first phase the fast reactor core will consist of a subcritical B&B blanket driven by a relatively small critical seed. As the required discharge burnup/radiation-damage to both driver and blanket fuel had already been proven, and as the depleted uranium fueled B&B blanket could generate close to 2/3 of the core power and will have very low fuel cycle cost, the deployment of such fast reactors could start in the near future. The second phase consists of deploying self-sustaining stationary wave B&B reactors. It will require development of fuel technology that could withstand peak burnups of ~30% and peak radiation damage to the cladding of ~550 dpa. The third phase requires development of a fuel reconditioning technology that will enable using the fuel up to an average burnup of ~50%—the upper bound permitted by neutron balance considerations when most of the fission products are not separated from the fuel. The increase in the uranium ore utilization relative to that provided by contemporary power reactors is estimated to be 20, 40 and 100 folds for, respectively, phase 1, 2 and 3. The energy value of the depleted uranium stockpiles ("waste") accumulated in the US is equivalent to, when used in the B&B reactors, up to 20 centuries of the total 2010 USA supply of electricity. Therefore, a successful development of B&B reactors could provide a great measure of energy sustainability and cost stability.

Keywords: fast reactors; breed-and-burn; stationary wave; travelling wave; seed-and-blanket; sustainability; depleted uranium; thorium

1. Introduction

Present day commercial nuclear power reactors, mostly Light-Water-Reactors (LWRs), utilize less than one percent of the natural uranium feed: the uranium enrichment level presently preferred by the industry is approximately 4.5% ^{235}U. As natural uranium contains only 0.72% of ^{235}U, it takes 8 to 10 tons of natural uranium to make 1 ton of 4.5% enriched uranium. The remaining 7 to 9 tons of depleted uranium, typically containing 0.2% to 0.3% ^{235}U, is discarded as a waste. Of the enriched uranium that is loaded into the core, only about 5% is actually fissioned, making the overall uranium utilization only ~1/9 of 5% or, approximately, 0.6%.

The amount of natural uranium that has been mined so far for fueling the fleet of commercial LWRs that presently generates close to 20% of the U.S. electricity consumption is approximately 700 thousand tons. Out of these, more than 60,000 tons ended up as used nuclear fuel (UNF)—the enriched uranium fuel that was fed into the LWRs and discharged after few percent of the uranium has been fissioned. More than 600,000 tons ended up as depleted uranium "waste". Additional depleted uranium has been accumulated from the military programs.

By using fast breeder reactors it is possible, in principle, to fission close to 100% of the depleted uranium "waste". However, this high uranium utilization cannot be achieved in a single irradiation campaign because neutron-induced radiation damage effects constrain the burnup level the fuel can withstand to the order of 10% to 15% FIMA (Fissions per Initial heavy Metal Atom), depending on the core neutron spectrum. Consequently, attainment of high uranium utilization also necessitates multiple fuel recycling. Traditionally, fuel recycling includes removal of the fuel cladding, removal of most of the fission products, addition of some depleted uranium make up fuel, fabrication of new fuel elements and reloading them into the reactor core for another irradiation cycle. Although technically feasible, there is a significant objection in the U.S. and other countries towards fuel reprocessing due to economic viability and proliferation concerns.

Fast breeder reactors (FBR) could, in principle, also operate without fuel recycling; that is, using a once-through fuel cycle as do all of the LWRs presently operating in the USA. Although a discharge burnup of 10% to 15% FIMA is 2 to 3 times higher than that of contemporary LWRs, the uranium utilization from a once-through FBR is not significantly different from that of a once-through LWR because the uranium enrichment required to fuel the FBR is more than twice that required to fuel the LWR.

Nevertheless, it may be possible to realize a significant increase in the uranium utilization without fuel reprocessing using a special class of fast reactors, referred to as "breed-and-burn" (B&B) or "travelling wave" reactors, such as the TWR under development by Terra-Power [1–3]. The unique feature of a B&B reactor is that it can breed plutonium in depleted uranium feed fuel and then fission a significant fraction of the bred plutonium, without having to reprocess the fuel. In order to initiate the chain reaction, the B&B core must first be fed with an adequate amount of fissile fuel such as enriched uranium. Plutonium or TRU extracted from UNF could also be used for this "starter". Thereafter, the B&B core is capable of continued operation while being fed solely with depleted uranium. Eventually, the uranium utilization will approach the fraction of the loaded uranium that has been fissioned.

The principles and concepts of B&B reactors had been proposed in the past; [3–11] is a partial list of references. These references describe either one of two basic variants of B&B reactors—one is the

Travelling-Wave-Reactor (TWR) like the highly published CANDLE reactor concept [11,12] and the TWR concept initially pursued by Terra-Power [1,8]. The other is the Stationary-Wave-Reactor (SWR) like the concepts proposed in [2,3,5,7,13] that is also presently pursued by Terra-Power [2,3]. However, in order to sustain the chain reaction in the B&B mode of operation it is necessary to fission, on the average, approximately 20% of the depleted uranium fed (see section 2). This corresponds to a peak discharge burnup of close to 30% FIMA. This peak burnup corresponds to peak radiation damage to the fuel rod cladding material of about 550 displacements per atom (dpa). The experimental and demonstration fast reactors that operated in the past have proven that the HT-9 fuel clad can maintain its mechanical integrity up to 200 dpa, corresponding to a burnup of ~10% FIMA in a hard-spectrum core such as required for a B&B reactor. It is likely that the fuel could have withstood higher burnup without losing its mechanical integrity but there is no experimental evidence that this, indeed, is the case. Moreover, a combination of the development of improved structural materials, improved fuel materials, and improved core design is likely to increase the acceptable burnup.

The minimum of 20% average burnup pertains to large volume SWR cores. The situation is aggravated in TWR cores because a smaller fraction of the excess neutrons can be used for building up the fissile content in the depleted uranium feed—as will be elaborated upon in Section 3.

Alternatively, it might be possible to establish the B&B mode of operation with limited fuel "reconditioning" [13–19]. The functions of the fuel re-conditioning are to remove a portion of the fission products, primarily the gaseous ones, and replace the fuel clad prior to fuel re-use in the reactor. This procedure overcomes material performance limits in a way that cannot be used to extract plutonium and that is, hopefully, not as expensive as conventional fuel reprocessing. The re-fabricated fuel can either be re-introduced into the reactor core for additional burnup, or be used as the "starter" fuel for a new core. The latter option, to be referred to as the "spawning" mode of operation, offers a significant savings in the amount of enriched uranium and, therefore, natural uranium that is required to deploy a fleet of B&B reactors.

However, significant R&D is required before an acceptable fuel reconditioning process will be developed, and it is not certain today whether or not such a process will be acceptable. Likewise, the accumulation of experimental evidence that HT-9 or another structural material can maintain its integrity up to 550 dpa is a long campaign that will take significant time to complete and, although likely to succeed, success is not certain.

The objectives of the present paper are to describe and compare several options for designing fast reactors to operate in the B&B mode and to suggest a strategy for phased commercialization of B&B reactors that could provide a significant measure of energy sustainability significantly sooner than otherwise possible.

Section 2 gives an estimation of the minimum burnup required for establishing the B&B mode of operation as well as the maximum burnup that is attainable in such B&B reactors when fuel reconditioning can be used for recycling the fuel in the B&B reactor as long as the fuel has sufficient reactivity to maintain criticality. The feasibility of spawning new B&B reactors using fuel discharged from previous generation B&B reactors is also discussed in this section. Section 3 explains the difference between a TWR and a SWR in terms of the minimum burnup required for sustaining the B&B mode of operation. Section 4 introduces the concept of a subcritical B&B blanket driven by a critical seed and suggests an approach for phased development of the technology required for B&B

reactors while Section 5 gives a brief summary of the impact B&B reactors and fuel reconditioning could have on energy security and economic stability.

2. Minimum Required and Maximum Attainable Burnup

2.1. Neutron Balance Analysis

The minimum burnup required for sustaining the B&B mode of operation, as well as the maximum burnup that can be achieved if fuel reconditioning could be implemented, were established in previous studies [15,17–21]. It is insightful to estimate these values using a simple neutron balance analysis that counts the number of neutrons that are absorbed and that are generated by fissions in a unit volume of fuel as a function of burnup in the core, starting from the fresh feed fuel. The minimum required burnup is the lowest burnup (BU_m), other than zero, for which Equation (1) is satisfied where the maximum attainable burnup is the largest BU_m for which Equation (1) is satisfied [15,17–21].

$$N_{HM}\int_0^{BU_m}\left[P_{NL}*P_{NRC}-\frac{1}{k_\infty(\mathrm{BU})}\right]\bar{\nu}(\mathrm{BU})*d\mathrm{BU}=0 \tag{1}$$

In the above, N_{HM} is the Heavy Metal (HM) atom density, BU is expressed in FIMA, $\bar{\nu}(\mathrm{BU})$ is the average number of neutrons emitted per fission, P_{NL} (= 1 − P_L) is the non-leakage probability and P_{NRC} (= 1 − P_{RC}) is the probability that a fission-born neutron will escape capture in the control elements used to compensate for the burnup reactivity swing over the equilibrium cycle. In the above we ignored the contribution of (n,2n) and (n,3n) reactions. The values of P_L and P_{RC} are deduced from 3-D analysis of a representative core; the other parameters that go into Equation (1) can be deduced from a batch-by-batch neutron balance analysis in the specific core being analyzed; they can also be well approximated from a much simpler unit cell analysis [15,17].

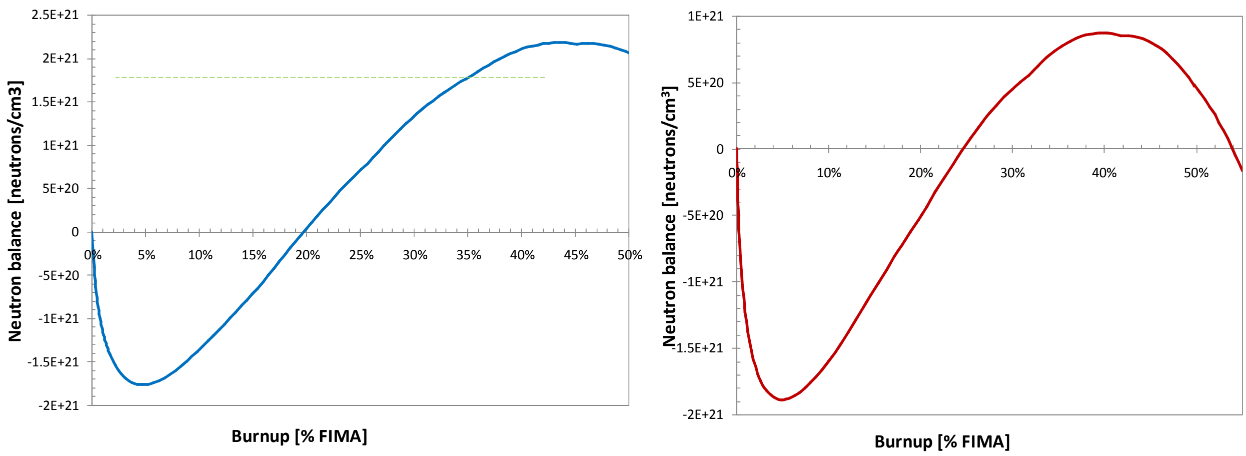
A quantitative analysis performed at the University of California, Berkeley (UCB) for a large sodium-cooled fast reactor B&B core [17] is briefly summarized. This core uses a ternary metallic fuel U-Pu-Zr with 10 wt% zirconium, a fuel density of 15.85 g/cm^3 and a smear factor of 75%—to accommodate the fuel swelling with burnup. The assumed volume fraction of fuel, initial gap, HT-9 clad and Na coolant is, respectively, 37.5%, 12.5%, 22% and 28%. These correspond to a hexagonal lattice pitch-to-diameter ratio of 1.122—near the lower limit used in liquid sodium cooled reactors. The active core height is 209 cm and its diameter is 402 cm. The core is divided into 8 radial batches. At the end of an equilibrium cycle the highest burnup batch is discharged, the other batches are shuffled in a predetermined optimal pattern and a fresh depleted uranium fuel batch is loaded at the outermost core zone.

When a fuel batch reaches its radiation damage limit, it undergoes a melt-refining process like that developed for metallic fuel in the Experimental Breeder Reactor II project [13,25]. The melt-refining involves loading the decladded fuel into a zirconia crucible and melting it at ~1300 °C for several hours under argon atmosphere. The gaseous and volatile fission products are released and certain solid fission products are partially removed by oxidation with the zirconia of the crucible. Based on [25] it is assumed that this process can remove 100% of Br, Kr, Rb, Cd, I, Xe and Cs, and 95% of Sr, Y, Te, Ba and the rare earths (lanthanides). Thorium and americium are also oxidized with zirconia, and 95% of these two elements are assumed removed from the fuel. In fact, in the melt-refining" process experimented with in the EBR-II program, several percent of the plutonium and other actinides remained in the crud of the zirconia crucible. However, experts think that it is likely possible to develop a modified process that does not involve significant loss of actinides and, yet, can efficiently remove the gaseous and certain fraction of the volatile fission products. Although the results of this study are somewhat affected by the fraction and type of actinides and solid fission products that are removed in the fuel recycling process, the overall conclusions of this work are not expected to vary by assuming an ideal process with no loss of actinides other than americium and thorium.

The minimum required average burnup deduced from a detailed search for the equilibrium cycle was found [17,18] to be 19.4% FIMA. This core features an average neutron leakage probability of P_L = 4.4% and a fraction of neutrons absorbed in the control systems of P_{RC} = 2.2% [17,18]. The maximum possible average burnup, also deduced from a detailed search for the equilibrium cycle, was found to be 55% FIMA [17,18]. The P_L and P_{RC} values pertaining to this core are, respectively, 6.95% and 2.1%. The leakage probability of the maximum discharge burnup core is higher than that of the minimum required burnup core since the radial power distribution in the high burnup core peaks closer to the outer core periphery than in the minimum burnup core.

Figure 1a shows the burnup-dependent neutron balance evolution in a core that features the P_L and P_{RC} values of the minimum required burnup core. Shown in the figure is a plot of the left hand side integral of Equation 1, using the above mentioned values of P_L and P_{RC} and the burnup-dependent k_∞ values derived from the full core analysis [17,18]. The minimum required average burnup inferred from Figure 1a is close to 20%—slightly larger than the value obtained from the batch-wise full core analysis [18]. Likewise, Figure 1b shows the burnup-dependent neutron balance evolution in a core that features the P_L and P_{RC} values of the maximum attainable burnup core. The maximum attainable average discharge burnup inferred from Figure 1b is 54% FIMA—very close to the 55% calculated from the detailed fuel shuffling and burnup analysis [18].

Figure 1. Neutron balance *versus* burnup in large hard spectrum Stationary-Wave-Reactor (SWR) core designed to sustain the Breed-and-Burn (B&B) mode of operation at **(a)** the minimum required average burnup (P_L = 4.4%; P_{RC} = 2.2%) and **(b)** at the maximum possible average burnup (P_L = 6.95%; P_{RC} = 2.1%).



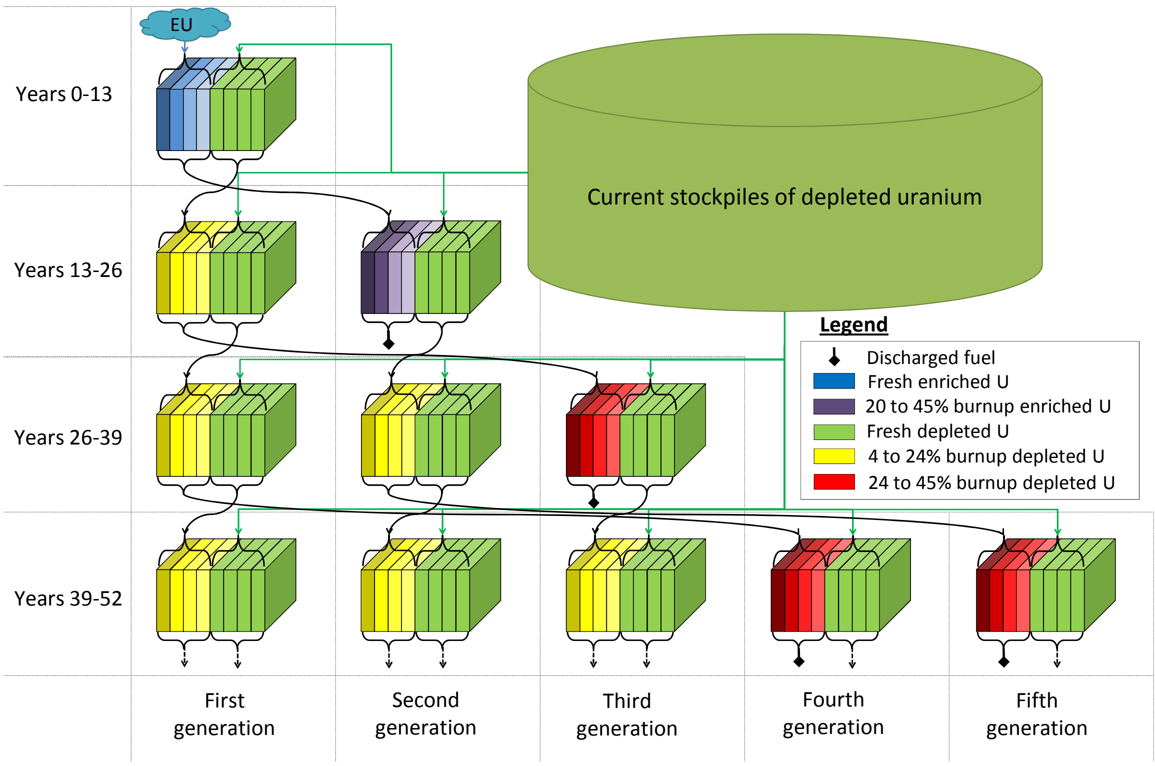
(a) **(b)**

Figure 1a shows that the fuel discharged at an average burnup of 19.4% FIMA has sufficient excess reactivity to provide a total of additional 2.2E + 21 excess neutrons per cm^3 of fuel—reached at a cumulative average discharged burnup of 42.5% FIMA. This is more than the ~1.8E + 21 neutrons that need to be provided per cm^3 of depleted uranium feed in order to turn it into a net neutron producer—corresponding to the minimum of Figure 1a curve. That is, the fuel discharged at 19.4% FIMA can serve, after reconditioning (aimed at relieving the radiation damage constraints) as the starter fuel for a new B&B core as described in the following sub-section.

2.2. Spawning Feasibility

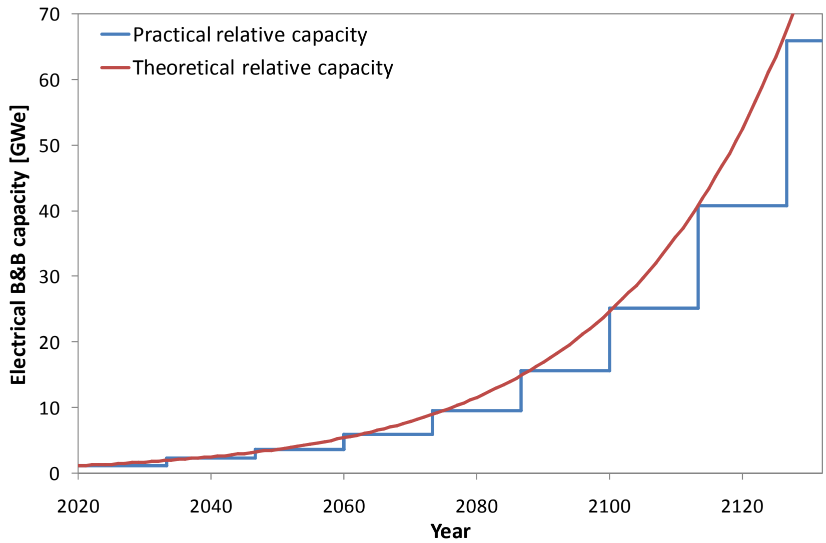
The spawning mode of operation of B&B reactors is illustrated schematically in Figure 2. The number of B&B cores at generation "i" equals the number of B&B cores at generation "i-1" plus the number at generation "i-2". Fissile fuel needs to be purchased only for the first core; thereafter, depleted uranium is the only fuel supply required for the growing fleet of B&B reactors.

Figure 2. Schematic illustration of the spawning mode of B&B reactors.



The doubling time of such a spawning fleet of B&B reactors is defined as the time it takes to accumulate 50% of the core volume worth of discharged fuel—an amount found sufficient [17,18] to make a "starter" for a new core. As the equilibrium cycle lasts 2.05 years and there are 12 fuel batches in the B&B core analyzed, the doubling time is 12.3 effective full-power years (EFPY). Assuming a capacity factor of 90%, the doubling time is approximately 13.5 years. Figure 3 shows the resulting installed capacity evolution; the asymptotic B&B reactors capacity growth rate is 3.86% per year. This capacity growth rate is larger than even that of the most optimistic scenario for nuclear energy expansion rate forecasted by the IIASA—3.6% per year. If a single 3000 MW_{th}/1.2 GW_e B&B core is started in 2020 and will be operated in the spawning mode featuring the 3.86(%)/y capacity growth rate, the total installed B&B capacity will be 25.2 GW_e by 2100 and 40.8 GW_e by 2120. Except for the several tons of enriched uranium or plutonium or TRU required for establishing initial criticality in the first ("Mother") core, this expanding fleet of B&B reactors requires only depleted uranium for its fuel feed.

Figure 3. Electrical capacity evolution due to one large B&B reactor deployed in 2020 and operated in the spawning mode.



3. Travelling-Wave *versus* Stationary-Wave

3.1. Neutron Balance Considerations

The minimum burnup required for sustaining the B&B mode of operation is highly sensitive to the number of excess neutrons available for converting fertile into fissile fuel. For a given fuel type the number of excess neutrons tends to increase with the hardening of the neutron spectrum—due to increase in the average value of the fuel, and tends to decrease with enhanced parasitic neutron capture and enhanced neutron leakage probability.

The neutron balance in a TWR core is significantly different from that of a SWR core. Figure 4 presents a schematic illustration of the "fission wave" propagation along the core of a TWR like the CANDLE reactor developed by Professor Hiroshi Sekimoto *et al.* [11,12,22–24]. The "fresh fuel" (sometimes referred to as the "blanket") is typically depleted uranium. Neutrons that leak from the "burning region" (sometimes also referred to as the "fission wave") in the direction of the wave propagation have high probability of being captured in the blanket fuel and increase its fissile fuel concentration by, primarily, converting ^{238}U into ^{239}Pu. This process is illustrated in Figure 5 that shows, among other things, the ^{239}Pu concentration distribution along the core axis. When the ^{239}Pu concentration in a blanket zone gets high enough to make this blanket zone k_∞ larger than 1.0, this blanket zone becomes a net neutron producer. While k_∞ at a given location in front of the wave keeps increasing with time, the value of k_∞ at a given location at the tail of the fission wave goes down with time due, primarily, to accumulation of fission products but also due to depletion of uranium and, correspondingly, plutonium. A typical axial distribution of k_∞ along a TWR core is illustrated in Figure 6. This k_∞ evolution is responsible for the propagation of the fission wave in the direction of the blanket.

Due to enhanced probability for parasitic neutron capture in fission products, neutrons that leak from the high fission density zone in the backward direction have a smaller probability of contribution to the B&B process than neutrons that leak from the same high fission density zone in the direction of the wave propagation. Moreover, neutrons that leak-out from the core in the radial direction and are not scattered back do not contribute to the B&B process.

Figure 4. Schematic illustration of the Travelling-Wave-Reactor (TWR) core evolution with burnup. Courtesy of Hiroshi Sekimoto [11,12,22–24].

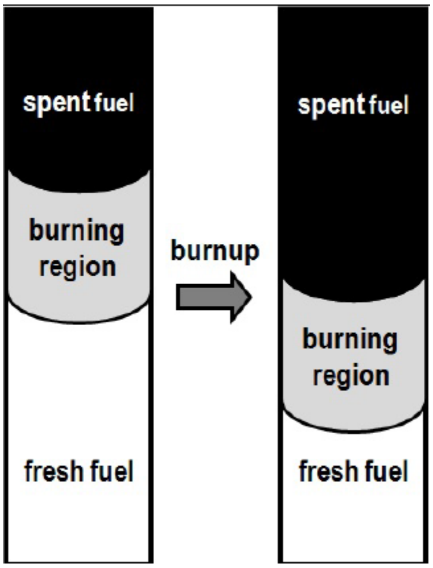


Figure 5. A snap shot of the concentration of selected fuel isotopes and of the neutron flux along the axis a TWR core. The fission wave propagates to the left. Courtesy of Hiroshi Sekimoto [11,12,22–24].

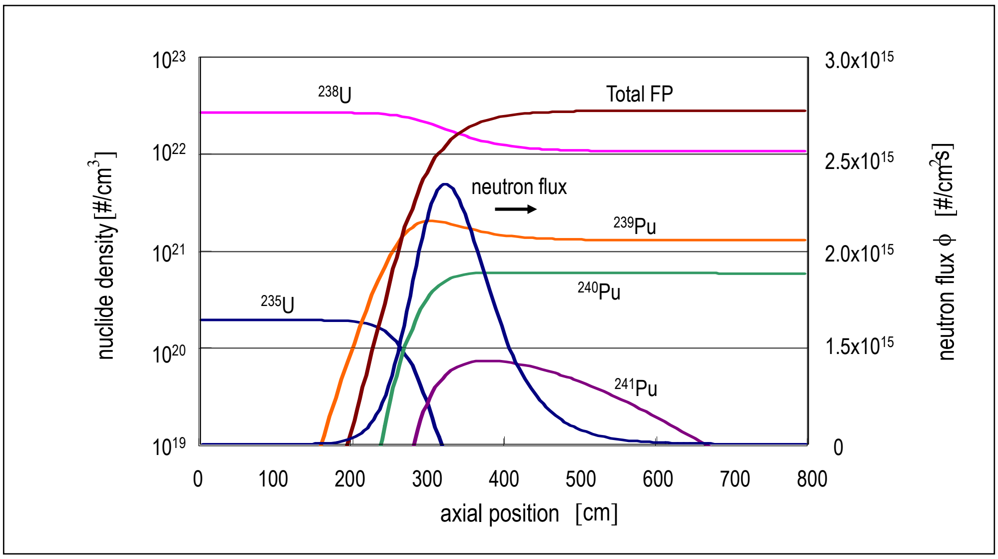
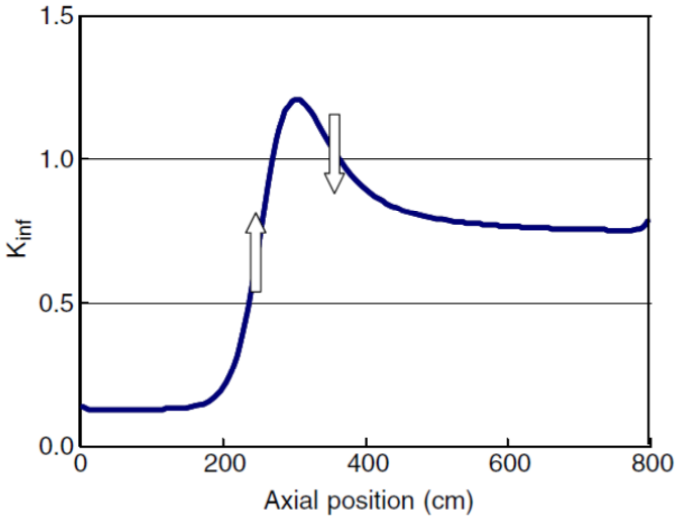


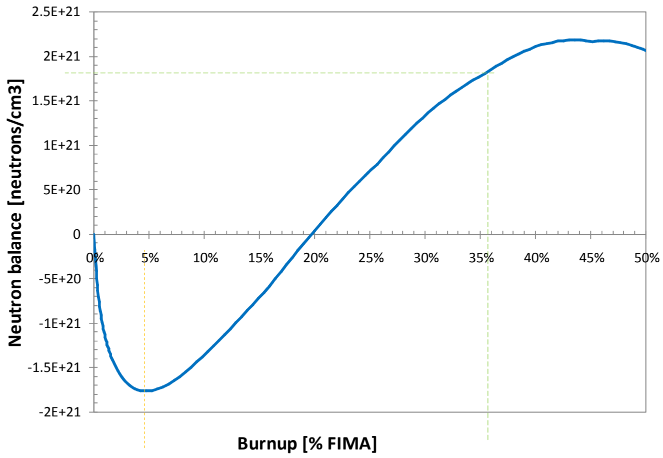
Figure 6. A snap shot of the k_∞ distribution along the axis a TWR core. The fission wave propagates to the left. Courtesy of Hiroshi Sekimoto [11,12,22–24].



The situation is different in a SWR; the blanket, typically made initially of depleted uranium, radially surrounds the fission zone and is shuffled inward when accumulating adequate amount of fissile isotopes. Consequently, neutrons that leak from the fission zone in the radial direction have a high probability to contribute to the B&B process while neutrons that leak in the axial direction do not. In the minimum burnup B&B core designed at UCB [18] and briefly described in Section 2, the axial neutron leakage probability is 0.7% while the probability that neutrons will leak out from the radial blanket and, therefore, will not contribute to the B&B process is ~3.7%. As a typical TWR core diameter is similar to that of a SWR core diameter, the TWR net radial leakage probability is expected to be larger since a TWR core does not have an effective radial blanket as SWR cores typically have. Based on the above considerations it is concluded that the fraction of the neutrons that are in excess of the number required for sustaining the chain reaction that can contribute to the B&B process is significantly smaller in a TWR than in a SWR of a comparable power level.

It is difficult to accurately estimate the fraction of the excess neutrons that do contribute to the B&B process in TWR and SWR cores without performing detailed 3-D core burnup analyses. It is possible, nevertheless, to get a rough estimate of the burnup implications of the difference in the wave propagation mode by assuming that the number of excess neutrons per unit burnup that are available for building up the fissile content in the blanket fuel in a TWR is only half that in a SWR core. This assumption is based on the simplified supposition that neutrons that leak in the backward 2 directions do not contribute to the buildup of fissile fuel in the TWR blanket. Factoring this assumption into the neutron balance analysis performed in Section 2, the total number of excess neutrons that need to be generated per cm^3 of TWR blanket fuel in order to turn it into a net neutron producer is twice the 1.8×10^{21} n/cm^3 value inferred from Figure 1a for the SWR fuel. Figure 7 shows that the minimum burnup required for providing this number of excess neutrons is ~36% FIMA. In fact, the burnup of many of the CANDLE cores designed by Sekimoto *et al.* [11,12,22–24] feature an average burnup level that is in the vicinity of 40% FIMA—nearly twice that required for sustaining a B&B mode of operation in a SWR.

Figure 7. Plot of the left hand side of Equation 1 *versus* burnup for a large SWR core designed [17] to operate at the minimum burnup required for sustaining a B&B mode of operation.

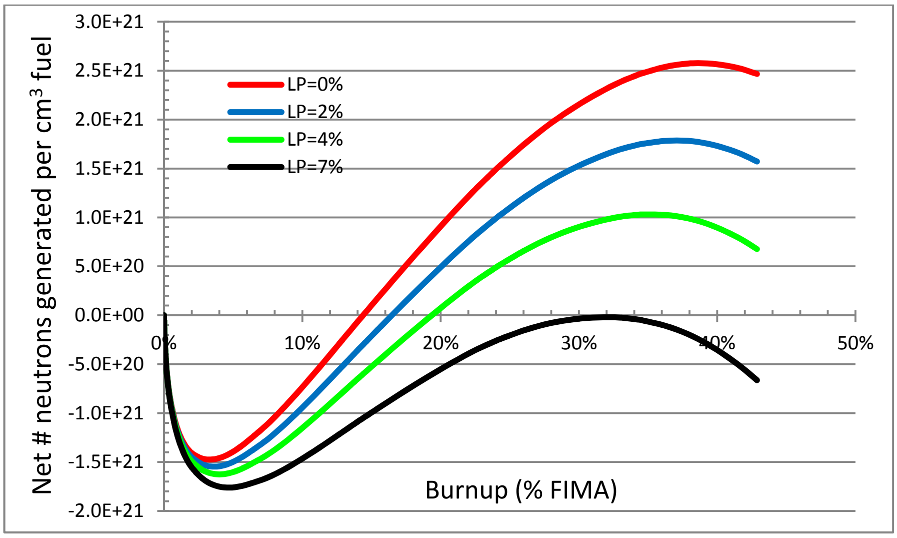


3.2. Practical Considerations

Perhaps the most challenging practical design feasibility issue for the SWR and, even more so, TWR is the ability of the fuel clad to maintain its mechanical integrity over the extended burnup required for sustaining the B&B mode of operation. The peak fuel burnup corresponding to a minimum required SWR batch average burnup of 20% FIMA is close to 30% FIMA. The corresponding radiation damage to an HT-9 clad is in the vicinity of 550 dpa. This is more than double the maximum value of 200 dpa HT-9 structure was subjected to so far. It is possible that future irradiation experiments along with innovative design of the fuel rods will prove that clad made of HT-9 or, more likely, of an improved structural material will be able to safely accommodate ~550 dpa. It is most unlikely, though, that a TWR core could reach its minimum required burnup without fuel reconditioning. This is one of the reasons that make SWR more practical than TWR for a near-term implementation of the B&B mode of operation. As suggested in Section 4, it is possible to start introducing the stationary wave type B&B mode of operation using already proven technology.

Another unique challenge is to design the SWR to be inherently safe. Most conventional fast reactor cores are designed to be oblate—having a relatively small height-to-diameter ratio so as to enhance the neutron leakage probability in the axial direction. The primary objective of this design approach is to reduce the typical positive reactivity effect of coolant density reduction—either by temperature increase or voiding. The neutron leakage probability in typical fast reactor core designs is close to 20%—significantly larger than the 4.4% of the B&B SWR core designed at UCB for which the results of Figure 1a and associated discussion in Section 2 pertain. In fact, neutron balance analysis performed using the simplified approach presented in Section 2 suggests that, as illustrated in Figure 8, it is not feasible to establish a sustainable B&B mode of operation when the neutron leakage probability exceeds ~7%. Detailed 3-D B&B core design performed at UCB [26] extends the maximum feasible leakage probability to up to 9% or, possibly, 10%.

Figure 8. Plot of the left hand side of Equation 1 *versus* burnup for several values of the neutron leakage probability. $P_{CR} = 1\%$.



It has been proposed [8,27,28] to passively compensate for the relatively large positive coolant temperature reactivity coefficient by insertion into the active core region of ^{6}Li neutron poison in a way that is passively actuated by coolant temperature increase. Recent analysis [28] shows that such ^{6}Li injection systems can be designed to provide a strong negative reactivity feedback without significantly impairing the neutron economy, reactor operation and cost, while giving safety margins that equal or exceed those of smaller and leakier fast reactor core designs. Nevertheless, detailed time-dependent simulation and experimental verification of the feasibility and license-ability of such passive ^{6}Li injection systems are yet to be performed.

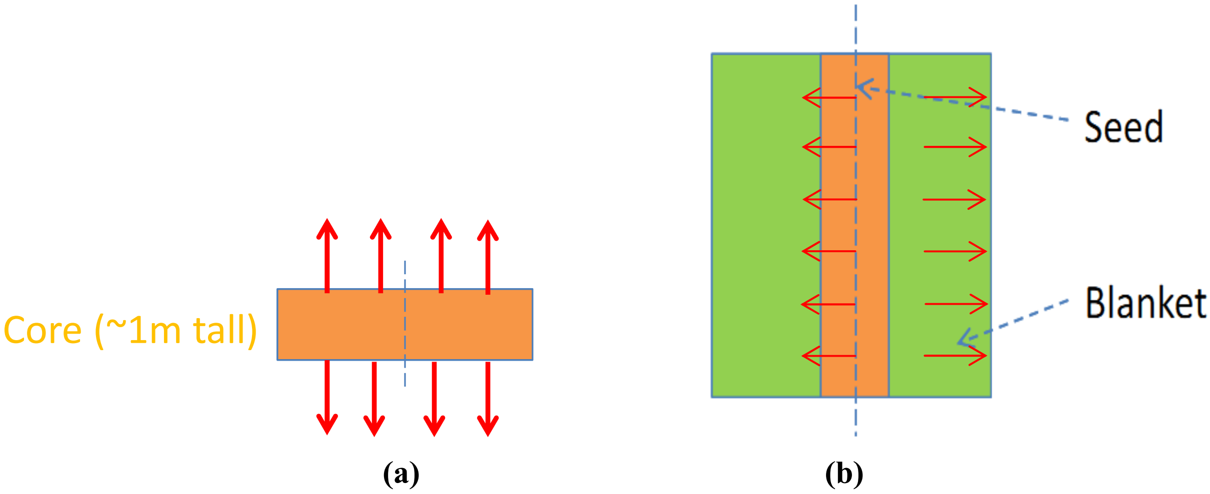
4. Phased Commercialization of Breed-and-Burn Reactors

4.1. Concept Introduction

Fast sodium-cooled critical reactors (SFR), such as the Advanced Recycling Reactor (ARR) and the Advanced Burner Reactor (ABR), are designed to have an oblate ("pancake" shape) core the dominant neutron leakage from which is in the axial direction, as schematically illustrated in Figure 9a [29–32]. A typical neutron leakage probability from such an SFR core is on the order of 20%; the majority of the neutrons leak in the axial direction and do not have any constructive usage. The relatively high neutron leakage probability helps designing the core to have a smaller positive (and seldom, negative) coolant temperature and coolant voiding reactivity effect. ABR cores are sometimes designed to have an even larger neutron leakage probability in order to reduce their conversion ratio (typically CR = 0.5 to 0.75).

Instead of designing the SFR core to be oblate with the dominant neutron leakage being in the axial direction, it is proposed [33,34] to design the SFR core to be of a prolate ("cigar" like) shape for which the majority of the neutron leakage is in the radial direction, and to make use of the leaking neutrons to "drive" a subcritical B&B blanket that radially surrounds the core, as illustrated in Figure 9b.

Figure 9. Schematic layout of **(a)** a conventional fast reactor core and **(b)** the proposed core having a "cigar shape" seed surrounded by a blanket. Not to scale.



The composition of the driver fuel will be similar to that of a conventional SFR core; it can use TRU from LWR UNF and can be designed to have a low conversion ratio as in an ABR—in case there is interest in LWR TRU transmutation, or to be TRU self-sustaining, as in ARR cores. It is envisioned that the driver fuel will be multi-recycled, as is the case for conventional SFR—typically when the fuel accumulates ~100 GWD/tHM corresponding to 200 dpa in an HT-9 fuel clad, or to a fast neutron fluence constraint of 4×10^{23} n/cm^2 [29–32]. The blanket can be fueled with depleted uranium, thorium or another type of low fissile content fuel such as reprocessed LWR UNF. The blanket is to operate on the once-through fuel cycle; when a blanket fuel assembly reaches its irradiation induced design constraint—initially assumed to be 200 dpa in the fuel clad, it will be discharged and a fresh fuel assembly will be loaded into the blanket. In order to maximize the neutron economy, it is desirable to load the fresh blanket fuel in the outer part of the blanket and gradually shuffle it inward as it builds up more fissile fuel.

The proposed seed (driver)-and-blanket core and fuel cycle concept could facilitate the development and early introduction of depleted uranium-fed B&B reactor technology by designing the B&B blanket to be subcritical and "driving" it by the excess neutrons leaking out from the TRU driver—initially up to the licensable 200 dpa for HT-9 cladding (average burnup ~10% FIMA). The blanket fuel discharge burnup will be progressively increased as fuel/cladding materials that are licensable to higher FIMA/dpa level become available; up until, hopefully, reaching a level of ~30%FIMA/550 dpa that enables sustainment of the B&B mode of operation in a critical stationary-wave core.

The proposed seed-and-blanket core is likely to significantly reduce the SFR fuel cycle cost and, thus, to improve the SFR economic viability. This is because the cost of a depleted uranium fuel assembly required for the blanket is significantly smaller than the cost of a TRU-containing fuel assembly required for the driver, while the amount of energy to be generated per unit weight of blanket fuel and driver fuel is comparable; it is limited by similar radiation damage constraints. The larger the fraction of the core power to be generated by the blanket is, the smaller need be the installed capacity of UNF reprocessing and recycling plants per unit of electricity generated in the seed-and-blanket core and, hence, the smaller will be the fuel cycle cost.

4.2. Depleted Uranium B&B Blankets

A study recently initiated at UCB [35] indicates that it is possible to generate nearly 2/3 of the total core power from a subcritical B&B blanket fueled with depleted uranium without exceeding 300 dpa. Both seed and blanket use an IFR type metallic fuel made of depleted uranium alloyed with Zr and, in case of the seed fuel, also TRU. The HT-9 ferritic-martensitic steel is used for the cladding and sodium for the coolant and bonding material (filling the initial fuel-clad gap).

The preliminary design analysis assumed that the metallic fuel contains 10 weight % Zr; that its smear density is 68% and that the hexagonal lattice pitch to fuel outer diameter ratio is 1.24. The corresponding fuel, structural material and sodium volume fractions are, respectively, 43.0%, 16.9% and 40.2%. The core height is 250 cm, the seed outer diameter is 54.7 cm and the blanket outer diameter is 179.4 cm. The TRU loading in the seed fuel is adjusted so as to be TRU self-sustaining as in an ARR core and the seed diameter is the minimum required for generating a total of 800MW$_{th}$ in the core without exceeding thermal-hydraulic design constraints.

Table 1 presents selected characteristics of a very preliminary seed-and-B&B blanket equilibrium core conceptual design recently arrived at [35]. The seed has a couple of batches; each cycle, that lasts 1150 EFPD (3.15 EFPY), the inner seed batch is discharged, the outer seed batch is shuffled inward, and a recycled seed fuel is loaded at the outer seed batch location. The blanket is made of 16 batches. Each cycle the innermost blanket batch is discharged, the other blanket fuel batches are shuffled inward, and a fresh blanket fuel is loaded at the outermost blanket batch location. The discharged blanket fuel is not recycled. The small burnup reactivity swing will facilitate the design of the control and safety systems of such a core.

Table 1. Selected performance characteristics of an illustrative seed-and-blanket core *.

Characteristic	Value
Number of seed batches	2
Number of blanket batches	16
Seed/Blanket batch number	2/16
Fuel cycle length (EFPD)	1150
Seed/Blanket total resident time (EFPD)	2300/18400
BOEC/EOEC k_{eff}	1.00242/1.00580
Discharged seed fuel peak/average burnup (%)	16.37/12.30
Discharged blanket fuel peak/average burnup (%)	14.36/9.56
Peak DPA in seed/blanket fuel clad at discharge	280/293[a]
Power fraction from blanket (%)	60.3

* Design is far from optimal.

The above fuel management scheme is far from optimal and is not the most practical; it is desirable to reduce the number of blanket batches and the need for fuel shuffling. It is likely possible to halve the number of blanket batches and to double the blanket batch cycle time without significantly degrading the overall core performance. It is also possible to eliminate seed fuel shuffling with little penalty on the core performance. Optimal seed-and-blanket core designs will be thoroughly explored in the framework of the NEUP project [34] that is soon to be initiated.

The time required for the blanket to reach an equilibrium composition exceeds (16 batches × 3.15 EFPY =) 50.4 EFPY. It is possible, nevertheless, to initially load the inner part of the blanket with enriched fuel so as to get the blanket to generate from day one a similar fraction of the total core power as the blanket generates in the equilibrium core. The total amount of TRU in the preliminary equilibrium core described above is 1.22 tons in the seed and 3.33 tons in the blanket. Instead of TRU, it is possible to use for the initial blanket enriched uranium. After the first fuel loading, only depleted uranium (or other fertile fuel) will be fed into the blanket. Optimal strategies for the approach to the equilibrium core performance will be explored as part of the NEUP project [34].

4.3. Thorium B&B Blankets

A recent study found [17] that critical B&B cores cannot be designed using pure thorium feed fuel. This is so because, in the SFR spectrum, (a) (^{233}U) < (^{239}Pu) and (b) the fast fission probability of ^{232}Th is significantly smaller than that of ^{238}U.

Nevertheless, thorium can be used as the feed-fuel for a subcritical B&B blanket that is driven by neutrons that leak out from a critical seed. In fact, there is a unique synergism between an ABR-type seed and a thorium blanket; rather than just incinerating TRU in ABR cores, the proposed core concept will convert part of the fissioned TRU into ^{233}U. This ^{233}U may be valuable for starting in the future a self-sustaining ^{233}U-Th energy system (a number of which are being proposed). If and when ^{233}U is a commercial commodity, its value will further improve the economic viability of the TRU driver—Th blanket SFR concept. No ^{233}U/Th fuel recycling capability is required for utilization of thorium for nuclear energy generation in the seed-and-blanket reactor.

A preliminary analysis indicates [33,36] that it is possible to generate in thorium-fueled B&B blankets at least 1/3 of the total power of the seed-and-blanket core while fissioning up to 15% of the fed thorium without exceeding the cladding 200 dpa constraint. The amount of energy thus obtained per kg of mined Th is more than 30 times the amount of energy extracted in the once-through LWRs per kg of natural uranium mined. This is because about 90% of the mined U turns into depleted U and only ~5% of the enriched U is fissioned; also, the efficiency of converting thermal energy to electricity in SFR is expected to be ~40% *versus* ~32% in LWR.

4.4. Other B&B Blanket Options

It may be possible to use for the blanket reconditioned LWR used nuclear fuel. The required functions of the LWR UNF reconditioning are removal of the gaseous fission products and zircaloy cladding and fabrication of fuel rods and fuel assemblies of the dimensions and design that is suitable for the SFR blanket, using HT-9 or another acceptable type of cladding material. There is no need to remove from the LWR UNF any of the actinides or solid fission products and there is no need to convert the fuel from an oxide to a metal alloy. Whereas oxide fuel cannot establish a sustainable B&B mode of operation in a critical core [17], it can generate a significant amount of extra energy in a subcritical B&B blanket—possibly more than twice the amount of energy it generated in the LWR. An AIROX or DUPIC-like process can be used for decladding the LWR UNF and removing the gaseous fission products [37–41].

Alternatively, a cermet-type fuel similar to that recently proposed by Walters and Wade [42] might be used. Walter and Wade are proposing to replace the depleted uranium, that is the commonly used makeup for recycled SFR fuel, by an equivalent amount of LWR used nuclear fuel in the form of crushed oxide particles. For their application, Walter and Wade are suggesting that the "crushed U/Pu/MA/fission product oxide particles, that can be generated in an AIROX-like process described above, would be well blended with the uranium/transuranic metal alloy particles recovered by the pyro-recycle process of the SFR fuel and then the mixed powder would be vibropacted into the fuel cladding. The processes would all be done remotely. After return to the reactor, and upon ~1 atom % burnup, the mixed particle bed will swell under fission gas production and restructure into a solid cermet fuel form comprised of oxide particles embedded in a metallic fuel alloy matrix—containing interconnected porosity and filling the interior radius of the cladding at a smear density of 70–75%" [42]. For the once-through B&B blanket, we envision mixing as much crushed U/Pu/MA/fission-product oxide particles from reconditioned LWR UNF with metallic particles made of depleted uranium alloyed with Zr or with metallic thorium particles. The implications of such options will be studied in a later stage of the NEUP project [34].

5. Impact on Energy Sustainability and Economic Stability

Table 2 compares the estimated uranium utilization that could be achieved with B&B reactors that are designed and/or operated in either one of the following five modes, all using depleted uranium for the blanket fuel feed:

(a) A seed-driven subcritical B&B blanket the fuel of which is discharged at an average burnup of 10% FIMA. No fuel reconditioning is required.
(b) A critical stationary-wave B&B core using a fuel that can maintain its integrity up to an average burnup of at least 20% FIMA. No fuel reconditioning is required unless the discharged fuel is to be used for spawning new B&B reactors.
(c) Like "b" along with a successful development of the technology for a single fuel reconditioning at ~20% burnup. Spawning new SWR is possible.
(d) A critical SWR or, possibly, TWR with 2 or more fuel reconditioning steps that will enable to achieve the maximum attainable burnup of ~50% FIMA (*versus* 55% obtained in the UCB large B&B core analysis [18]) without separation of most of the solid fission products.
(e) Traditional fast breeder reactor approach in which fuel is reprocessed many times (every 10% FIMA or so). It assumes extraction of all of the fission products and addition of depleted uranium makeup fuel at each recycle. There is no limit to the number of fuel recycles.

Also given in Table 2 is the uranium utilization in the reference scenario of contemporary LWRs that operate with the once-through fuel cycle and discharge their fuel at 50 GWD/T.

The relative uranium utilization values given in Table 2 are per unit of electrical energy generated. In converting thermal energy to electrical energy it is assumed that fast reactors convert thermal energy into electricity at 20% higher efficiency than LWRs.

The rightmost column in Table 2 gives the number of years the B&B reactors could supply electricity at present day USA total annual consumption rate from all sources (assumed 4200 million

MW_eh/year) if they are to be fueled only with the depleted uranium stockpiles ("waste") that will be accumulated in the US from the fueling of LWRs (~1.3×10^6 tons) and B&B reactors (~0.5×10^6 tons) until the end of deployment of the first generation of B&B reactors—assumed in the second half of the 21st century.

Table 2. Estimated uranium utilization limits and energy value of depleted uranium when used in B&B reactors and in Light Water Reactors (LWR).

Mode of operation	Uranium utilization	Relative U utilization	No. of years at present supply
Light Water Reactors (LWRs)—reference	0.6%	1	0
(a) subcritical B&B blanket; no reconditioning	10%	20	400
(b) SWR; 20% average discharge BU	20%	40	800
(c) SWR, 1 reconditioning @ 20%; spawning possible	40%	80	1600
(d) SWR or TWR, with >1 fuel reconditioning	50%	100	2000
(e) Fast reactor with continuous recycling	>95%	>190	3900

It is observed that using practically proven fuel technology (except for the length of the fuel rods which is envisioned to be 2 to 3 meters versus ~1 meter for conventional SFR and ~4 m for LWR) in subcritical B&B blankets it is possible to achieve a uranium utilization that is 20-fold that offered by LWR. A successful development of B&B reactors that can achieve 20% average fuel burnup which, hopefully, could be achieved without fuel reconditioning, will offer 40-fold increase in the uranium ore utilization *versus* that presently achieved. A successful development of a fuel reconditioning technology could increase the attainable uranium utilization to close to 100-fold that achieved in contemporary LWRs. This corresponds to extraction of approximately 50% of the nuclear energy worth of depleted (and natural) uranium. All the above options do not require separation of most of the solid fission products from the actinides. For the utilization of the remainder 50% it will be necessary to develop economically viable and societal acceptable fuel reprocessing technology that will separate the fission products from the actinides. Such a reprocessing could be deferred, though, by several centuries, as the existing stockpiles of depleted uranium can provide all our electricity needs for between 400 to 2000 years (rightmost column of Table 2). Basically, the same SFR technology can be used for implementing the different options.

6. Conclusions

A successful development of metallic fuel and cladding that can maintain the fuel rod integrity up to a peak burnup of ~30% FIMA and peak radiation damage of ~550 dpa will enable the operation of stationary-wave fast reactors in a sustainable Breed-and-Burn (B&B) mode using depleted uranium for the feed fuel. Such SWR reactors will offer 40-folds increase in the uranium ore utilization relative to contemporary LWR while operating in a once-through fuel cycle. A successful development of a fuel reconditioning technology could enable an increase in the attainable uranium utilization of SWR to 100-folds its present value without separation of actinides from most of the fission products. It will also enable the use of reconditioned B&B fuel to provide the initial fissile fuel loading required to spawn new SWR without the need for external supply of fissile fuel. The growth rate of the installed capacity of SWR possible to achieve using such a spawning mode of operation is estimated to be nearly 4% per year. A successful development of a fuel reconditioning technology could also enable deployment of traveling-wave fast reactors.

As it may take significant time and R&D effort to develop the fuel technology that is required for operating a sustainable SWR that is fed with depleted uranium, it is proposed to start benefiting from the B&B mode of operation by deploying seed-and-blanket fast reactors in which a subcritical B&B blanket is driven by neutrons leaking from a critical seed, without exceeding ~100% FIMA/200 dpa; that is, relying on proven fuel technology. Such seed-and-blanket reactors are expected to be more economically viable than conventional fast reactors and can facilitate the phased commercialization of critical B&B reactors. When using depleted uranium for its feed fuel, the subcritical B&B blanket could generate close to 2/3 of the total core power without exceeding the radiation damage constraints. The amount of fuel reprocessing and TRU fuel re-fabrication required for the seed fuel of such a seed-and blanket core is only ~1/3 that required for a conventional fast reactor core, when measured on per unit of electricity generated by these cores. As a result, the fuel cycle cost of the seed-and-blanket reactor is expected to be significantly smaller than that of a conventional fast reactor. As fuel designs that can be certified to operate at higher than ~100% FIMA/200 dpa become available, the seed-and-blanket core could be designed to discharge the fuel at higher burnups and to offer higher uranium utilization.

The B&B blankets of seed-and-blanket cores can also be fed with thorium. The amount of energy that can be generated per kg of mined thorium is estimated to be more than 30 times the amount of energy extracted in the once-through LWRs per kg of natural uranium mined.

An additional interesting option for the feed fuel of the B&B blanket is reconditioned LWR used nuclear fuel. This may enable the generation of additional energy from the UNF without reprocessing; possibly close to twice the amount of energy it generated in the LWR.

The energy value of the depleted uranium stockpiles ("waste") to be accumulated in the USA until the middle of the present century is equivalent, when used in the B&B reactors, to the total 2010 USA supply of electricity up to 8 centuries without fuel reconditioning and up to 20 centuries with fuel reconditioning. Therefore, a successful development of B&B reactors could provide a great measure of energy security and cost stability.

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Conflict of Interest

The authors declare no conflict of interest.

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