Deployment Scenarios for Nuclear Waste Management

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ABSTRACT

A major objective of the DOE Advanced Fuel Cycle Initiative, AFCI, is to explore technologies that may reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials. In this work, the potential impact of the AFCI technology and its beneficial effects on waste management and its ability to meet waste management objectives are demonstrated. In addition, practical scenarios to improve permanent disposal utilization and/or reduce the temporary spent nuclear fuel (SNF) storage inventory by closing the fuel cycle through transition to fast reactor (FR) converters are also discussed.

INTRODUCTION

Recently, simulation of the dynamic behavior of the nuclear fuel cycle scenarios [1,2] has taken increasing importance as a tool for the assessment of the integrated nuclear energy systems options and its development pathways. In the U.S., this tool is being used extensively in the evaluation of the US-DOE Advanced Fuel Cycle Initiative (AFCI) options.[3] The simulation initiative is part of the DOE’s integrated nuclear research approach that address the numerous issues facing the future of nuclear energy. Those issues include management of the spent nuclear fuel, proliferation risk associated with nuclear materials, and avenues for improving the prospects of nuclear power in the US. AFCI dynamic scenarios evaluate the possible benefit to the waste disposal system in the U.S. given deployment choices [4] timelines, with focus on the geologic repository at Yucca Mountain (YM).

The improvements in waste management through advanced fuel cycle strategies can benefit geologic disposal, where the waste will be stored permanently, and the temporary storage where the spent fuel will be stored until disposal in a geologic repository or transfer to separations facilities. The possible benefits of waste transmutation to geologic disposal are identified as follows: a) increasing its capacity through minimization of the waste volume and improvement of the repository thermal loading; and, b) reduction of the long-term waste radiotoxicity and dose rate. In addition, the implementation of the advanced strategies will reduce the waste volume in temporary storage through the following: a) use of high burnup fuel including high burnup UOX, MOX, or IMF; b) the reprocessing of spent fuel; and, c) the recycling in fast transmuter systems.

The reduced proliferation risk goal can be achieved through selection of a fuel cycle system that prevents material diversion at all points in the nuclear fuel cycle and avoids fissile material discharge to waste. Reasonable economics and excellent safety must be retained with improved waste management and reduction of the proliferation risk to ensure future prospects for nuclear power in the U.S.

All of the above goals can be achieved through the use of a transmutation system that consumes the problematic transuranic (TRU) isotopes (actinide burning) while keeping the remaining TRU inventory in the fuel cycle and out of the waste. For this strategy, key isotopes are the Pu-241 to Am-241 to Np-237 decay chain, which are responsible for the majority of the long-term heat, radiotoxicity, and dose in a geologic repository like YM.

The current work considered different scenarios of spent nuclear fuel management strategies in the U.S. to respond to various projections of future nuclear energy demand. The general fuel cycle strategies considered include once-through (OTC), limited recycle using MOX (Mixed-OXide) fuel or IMF (Inert Matrix Fuel), and transitional and sustained recycle (using fast transmutation systems). Extensive dynamic analyses of the full range of nuclear deployment scenarios were conducted using a systems dynamics model developed for the U.S. nuclear energy park, DYMOND-US (DYnamic Model of Nuclear Development) – U.S.).[5] For different recycle scenarios, the efficacy in meeting the AFCI waste management goals is evaluated using this model. Comparisons were made between the recycling strategies and the current LWR once-through strategy. The comparison shows that there is a significant impact of the different recycling strategies under consideration, compared to OTC, on limiting the number of geologic repositories needed in this century in a nuclear energy growth scenario. The first part of the work is intended as a broad comparison between the different transmutation systems and the possible range of benefits that those systems can shed on the nuclear energy development in the U.S. In addition to those general scenarios, a more practical set of scenarios that deals with the dynamics of the waste allocations are also presented. Those are intended to represent a more specific and possible situation of transition to fast converter transmutation systems, which is given in the second part of the work.

ADVANCED FUEL CYCLE SCENARIOS

The current work considered different scenarios of future nuclear energy demand and different spent nuclear fuel management strategies to respond to those demands. As mentioned before, three general fuel cycle strategies were considered:

- Once-through fuel cycle;
- Limited recycle (using MOX or IMF fuel);
- Transitional and sustained recycle (using fast reactor systems).

More details about those scenarios and its data and assumptions are provided in reference [5]. The base nuclear growth scenario considered here is a continuing market share generation scenario where replacement plants and additional plants are built to maintain nuclear energy’s ~20 percent electricity market share. The total capacity grows at the same rate as electricity demand (1.8 percent growth). Other scenarios considered are continuing level energy generation (no growth), and growing market share generation where nuclear market share grows, both for electricity and for hydrogen production (3.2 percent growth).

The analysis assumed that ultra-high burnup fuels (e.g., 100 GWd/t) are deployed in 2010 and AFCI recycle technologies are deployed in 2025 to process both existing and newly generated spent fuel. The use of such high burnup fuel is intended as a demonstration of the possible range of benefits that are achieved from the its use, where 100 GWd/t represents an upper limit on how much the UOX fuel burnup can be increased. The capacity of the proposed YM repository is measured by the accumulated long-term decay heat from the key isotopes that include Pu-238, Pu-239, Pu-240, Pu-241, and Am-241.[6] These integrated values have been implemented in the DYMOND-US system dynamics calculations [7], which are given by the integral over 1500 years of the long-term decay heat of those key isotopes. The results of the calculations are summarized in Figure 1.a and 1.b. In those figures, the area between the high-burnup and conventional burnup curves represents the possible range of benefits achieved through increasing the conventional LWR UOX fuel burnup. The other area in the figures, which is shaded, represents the range of benefits achieved through limited recycling using MOX or IMF fuel.

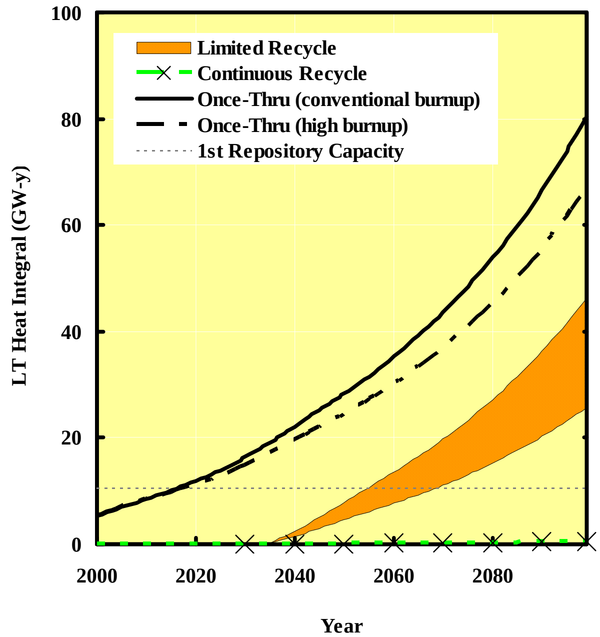

Fig. 1a. Long-term heat load in permanent disposal waste for once-through, limited recycle, and sustained recycle strategies

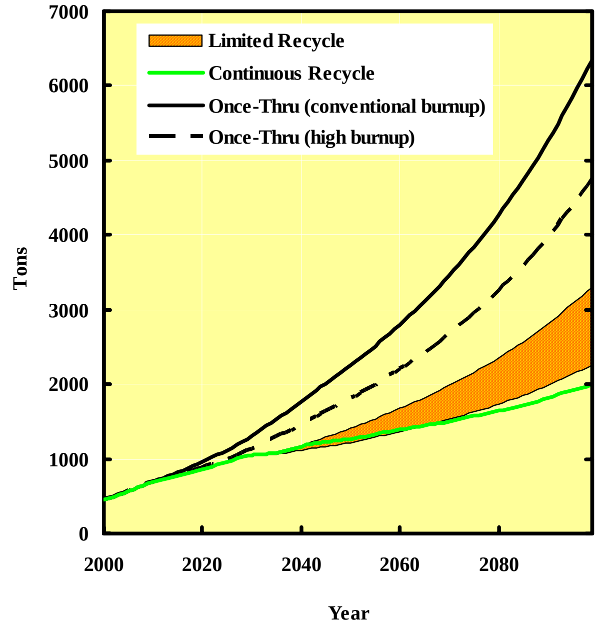

Fig. 1b. Plutonium inventory for once-through, limited recycle, and sustained recycle strategies

In terms of the AFCI waste management goals, Figure 1.a shows the impact of the fuel cycle strategies on limiting the number of geologic repositories needed in this century. The figure compares the accumulated long-term integrated decay heat associated with the waste from the different strategies. Notice that the shaded range in the figure corresponds to the range of MOX/IMF scenarios. The long-term integrated heat load shown in the figure corresponds to materials that are destined for disposal in a geologic repository. In the case of fast reactor recycling, these materials are the fission products and the TRU losses from separations, as the remaining TRU are recycled back into the reactors. The dotted line in the figure corresponds to the statutory capacity at Yucca Mountain, which is legislated at 70,000 metric tons. As shown in the figure, the introduction of advanced nuclear fuel cycle technology may significantly postpone the technical need for additional repositories. As mentioned before, the 100 GWd/t integrated decay heat line bounds the range of repository benefits that can be achieved from increasing the UOX burnup in the context of an OTC scenario.

The comparative evaluation of the AFCI proliferation goals for the different scenarios is shown in Figure 1.b. In this figure, the key material diversion concerns are related to the plutonium that is produced from uranium fuel in a reactor and is present in conventional spent fuel. This plutonium is recycled and transmuted in all advanced fuel cycle strategies. All recycle strategies will reduce the plutonium inventory compared to the Once-Through fuel cycle, where the out-of-reactor Pu inventory behavior is illustrated in Figure 1.b. For this analysis, the bulk of the nuclear power generation continues to be conventional reactors with enriched uranium fuel (producing plutonium), offset by plutonium destruction in the recycle fuels. A more aggressive implementation of recycle technology could be employed to stabilize or decrease the plutonium inventory.

Uranium resource projections are uncertain, but are not expected to be limiting for many decades under any scenario, though short-term shortages may occur if relatively low prices continue to inhibit exploration and development of new mines. For the two growth scenarios (1.8% and 3.2%), natural uranium supplies may become constrained toward the end of the century, especially if there is rapid international expansion. In Sustained Recycle, the deployment of fast reactors to generate fuel from waste uranium will ensure long-term energy security.

PRACTICAL DEPLOYMENT SCENARIOS

The general spent fuel recycling scenarios discussed in the previous section illustrated the general range of benefits that are achieved through implementation of possible AFCI strategies. This section presents a set of practical scenarios that serve as examples of the complexity of the “real-world” scenarios focusing on transitioning to converter fast reactor (CFR) systems. The scenarios discussed here focus on improving permanent geologic disposal utilization and/or reducing the inventory of spent fuel in temporary storage. In the case of limited or transitional recycling scenarios, it is assumed that the repository accepts only high-level waste from reprocessing or MOX or IMF spent fuel (in the case of continuous recycling, only HLW goes to repository). Thus, it was assumed that direct disposal of LWR spent fuel does not proceed as long as recycling is taking place. This leads to the accumulation of large quantities of spent fuel in temporary storage and requires the continuation of the common, safe practice of maintaining large quantities of spent fuel in dry or wet temporary storage. In practice, the YM repository might accept LWR spent fuel, and perhaps even emplace it for later retrieval, although the policy decision to start recycling has already been made. In addition, the delay in introducing continuous recycling in fast reactors through the implementation of a succession of different technologies might not be needed. To avoid these delays an alternative strategy with rapid parallel deployment of separations and fast reactor technology has been considered as discussed in the next sub-sections.

General Assumptions and Timelines

Again, the current scenarios explored different energy growth projections, including the baseline growth case (1.8% per year), 0% growth, and 3.2% growth. The analyses assumed that ultra-high burnup fuels (e.g., 100 GWd/t) replace existing fuel with time and the deployment of reprocessing capacity is dependent on the energy growth rate. Finally, all TRU’s from UOX SNF is transmuted by a converter fast reactor (CFR), and the deployment of CFR’s is limited to about 1.6 GWe/yr (correspond to 5 CFR’s of about 0.320 GWe each), beyond 2030.

The timeline for these scenarios is as follows:

- Starting 2010, demand grows at different rates (0%, 1.8%, or 3.2%).
- Starting 2015, use ultra-high burnup, 100 GWd/t fuel in all reactors
- Starting 2025, SNF reprocessing starts using an 800 MT/yr commercial plant followed by an upgrade to 2,000 MT/yr in 2035 and 3,000 MT/yr total capacity in 2055.
- FR deployment starts with a first of a kind plant (FOAK) FR , followed by full deployment of FR’s 5 years later, at a maximum rate of 1.6 GWe/yr (5 FR burners/yr)
- Starting 2028, replace retiring LWR’s with FR’s to meet new energy demand if possible. If there is not enough TRU for FR’s, build new ALWR’s
- SNF transfer to the repository starts in 2012 and follows the acceptance rates for commercial SNF at YM per the DOE contract with the utilities [8] (ramp up acceptance rate of spent fuel to repository as follows: 2012=400MT, 2013=600MT, 2014=1200MT, 2015=2000MT, 2016 and beyond = 3000MT)

Scenarios Results

The base scenario is 1.8% growth rate with implementation of high burnup fuel starting in 2015. Figure 2 shows the dynamic deployment of both LWR's and FR's according to this growth rate, where the CFR contribution to the total energy generation is as high as about 18%. The limited reprocessing capacity of LWR spent fuel does not limit the deployment of FR systems. The limitations here on the deployment of FR's are instead caused by the constraint of maximum deployment rate of 1.6 GWe/yr FR capacity per year, which is imposed to limit the number of FR burners to be deployed per year. FR percent of total capacity increases gradually to about 18%, and a significant decline starts 2090 because of the retirement of FR's built in 2030 (given 60 years of reactor lifetime), while the TRU inventory is not large enough to make up for those reactors and also respond to increase in demand. However, this can be avoided by increasing the reprocessing capacity a few years earlier, or deployment of breeder reactors. Figure 3 shows the deployment rates of the FR's and LWR's as new energy capacity per year. While the FR capacity additions are limited to a maximum value, the LWR capacity additions show large fluctuations with time in order to compensate for loss of capacity due to reactor retirements.

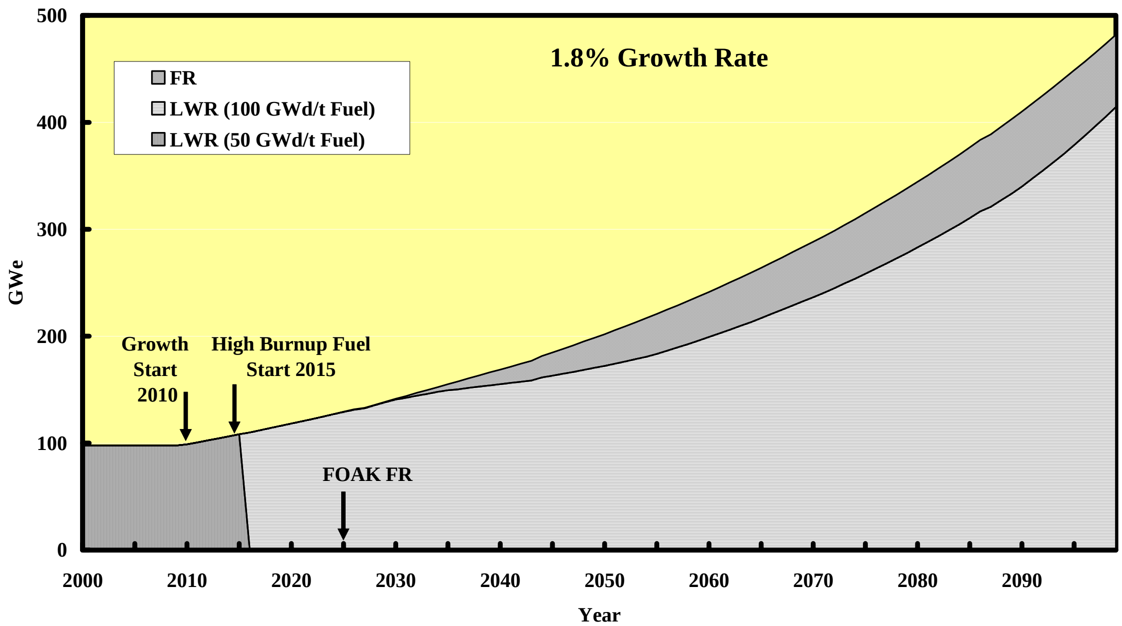

Fig. 2. Dynamic deployment of the different nuclear energy systems for 1.8% growth rate

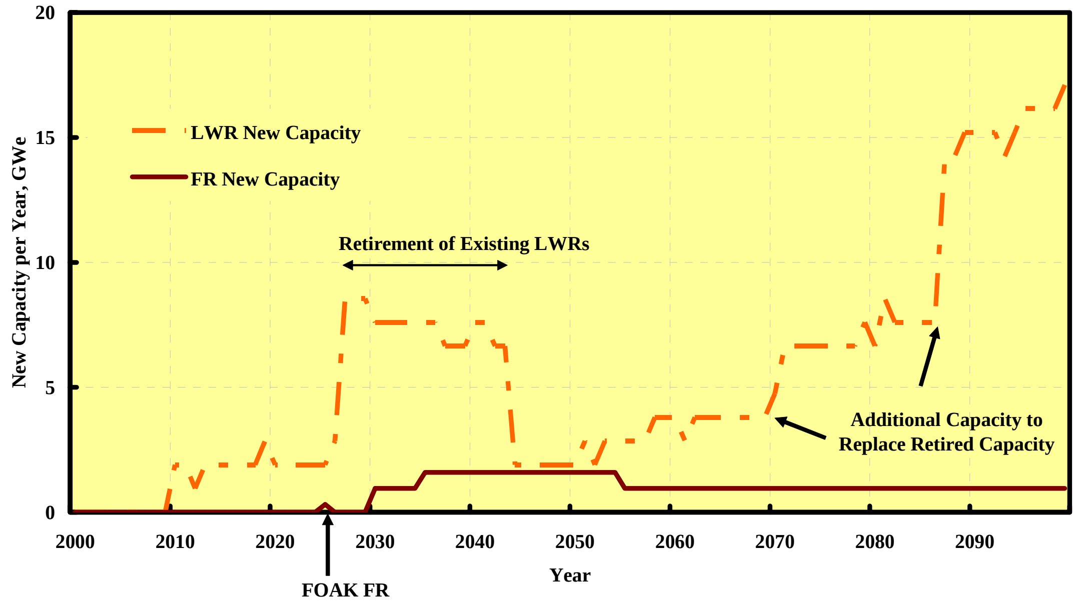

Fig. 3. Capacity additions rates for the different nuclear energy systems for 1.8% growth rate

Key scenario results are shown in Figures 4, where the volume of spent fuel in temporary storage is minimized. With reprocessing and transfer of spent fuel to a geologic repository, temporary storage requirements decline, and by about 2030, storage requirements are less than the storage requirements in 2000. Eventually storage requirements start to increase after a 2043 minimum; however, by the end of the century, the temporary storage requirements remain below the year 2000 values. Direct disposal of large amounts of spent fuel in a geologic repository is realized in this scenario. By 2028, all year 2000 legacy spent fuel (LSF) is transferred to the repository, and by 2043, all spent fuel production goes to reprocessing, with no more transfer of spent fuel to the repository until ~ 2088, when the available spent fuel exceeds the reprocessing needs. Spent fuel in the repository reaches ~ 94,000 MT by 2043 (including military & DOE spent fuel – inventory of 7000 MT). Note that the out-pile SF shown in the figure represents the sum of spent fuel in temporary storage and the SF in repository (in addition to SF in the pipelines of the fuel cycle including SF at reprocessing facilities and fabrication plants). The fission products inventory and the inventory of heavy metal (HM) losses from the reprocessing facilities are also shown in the figure.

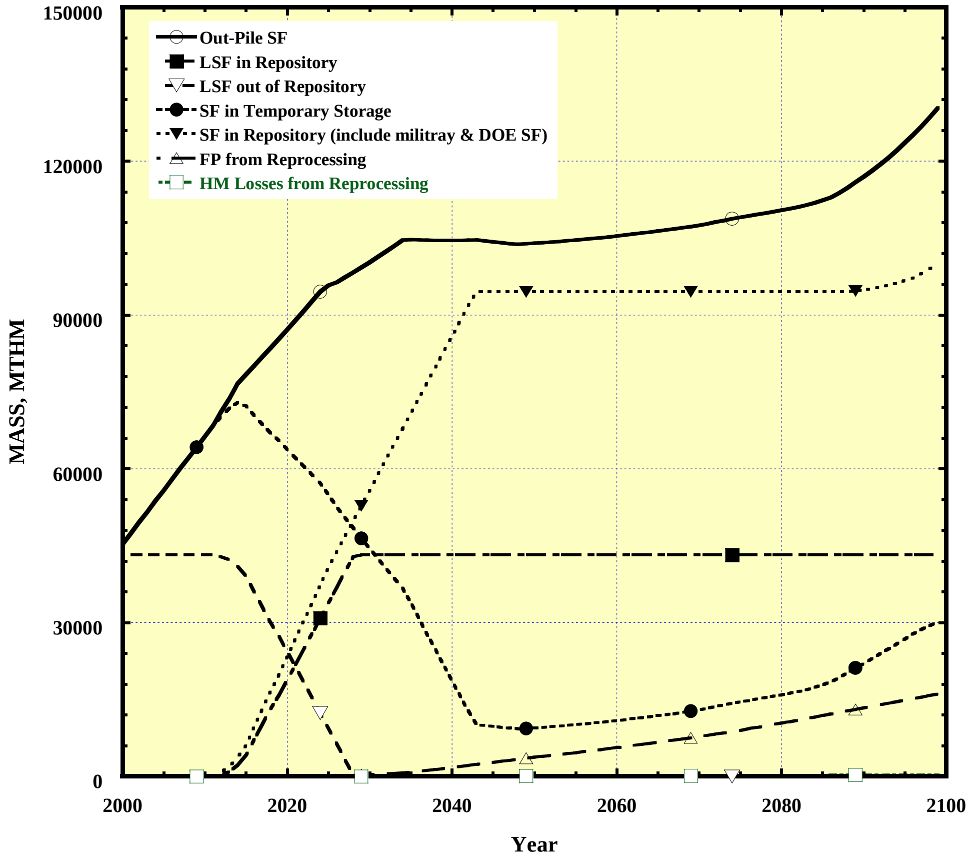

Fig. 4. Dynamics of waste accumulation in both temporary and permanent storage for 1.8% growth rate

In a recycling scenario such as the one presented here, the Pu inventory from separations that is waiting in the pipeline for utilization in reactors, represents a key parameter related to proliferation resistance. This parameter is shown in Figure 5, where the Pu inventory remains less than the current worldwide inventory at all times (150 MT). As shown in the figure, the initial peaks in the Pu inventory are associated with the increase in separations capacities, which cause a temporary build-up that are eventually depleted by Pu consumption as new FR’s are introduced. Moreover, the Pu inventory coinciding with FR converters demand for Pu beyond year 2050 leads to an overall decline even with the increase in separations capacity to 3000 MT per year. Given the reduction in the Pu inventory by the year 2090, and the start of retirement of FR’s, there will be insufficient Pu to startup new FR’s. For this scenario, this will lead to the replacement of retiring FR’s with ALWR’s, and eventually will lead to reduction in Pu consumption and build up of Pu inventory. This Pu inventory will continue to increase as shown in the figure, but it remains below the 150 MT value at the end of this century. Further overall minimization of Pu inventory in this scenario can be achieved by optimization of the deployment of FR’s and separations plants combined with retrieving LWR spent fuel from the repository.

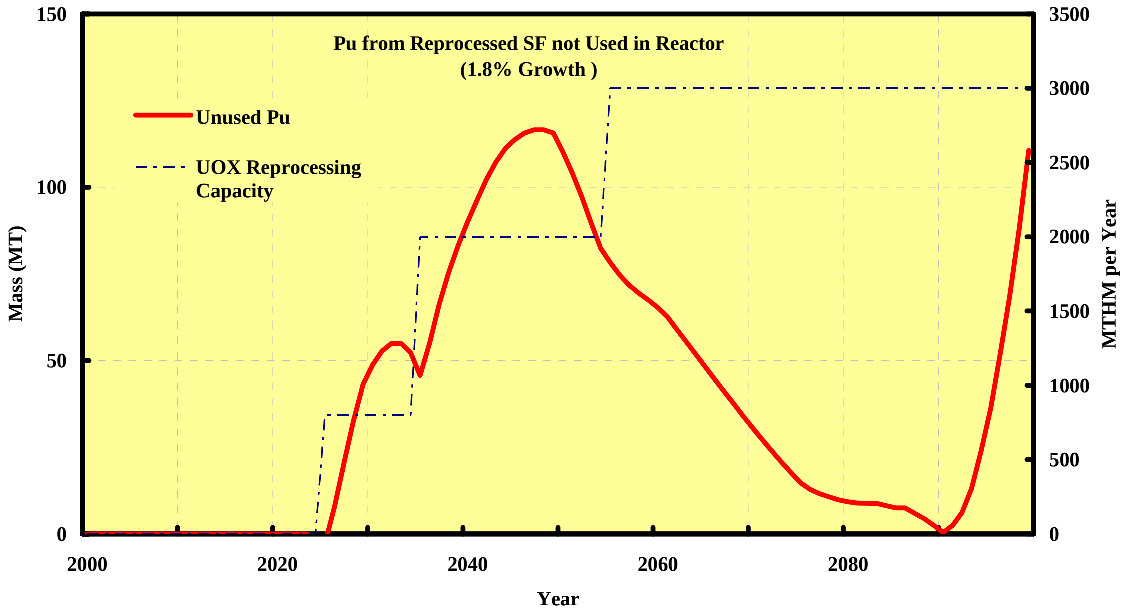

Fig. 5. Inventory of Pu from reprocessed SF that is out of reactors for1.8% growth rate

A final note on this specific scenario is related to the uranium utilization compared to the once-through scenario. The recycling of TRU’s in FR’s, combined with the reduced need for enriched uranium to be used in conventional LWR’s, leads to a reduction in the overall use of natural uranium. For this scenario, there is about a 14% reduction by the end of this century.

Figures 6 and 7 show results for the 0% growth rate scenario (“business-as-usual” scenario). The limitation on growth of nuclear energy constrains the deployment of FR’s as shown in Figure 6 and limits it to the period between 2028 and 2043 to replace retiring LWR’s, until the next wave of retirement of ALWR’s in 2087. The retiring ALWR’s correspond to those reactors built starting in 2027 (the retirement rate of existing LWR’s with a capacity of about 97 GWe is assumed to be linear between 2027 and 2043, including license extensions of 20 years). By 2043, the percent of FR’s reaches about 22.5%, and remains constant until 2087, when ALWR’s start to retire. Those ALWR’s retired in 2087 are replaced by FR’s, which increase the FR% to about 28% by 2090.

In this scenario, the SNF temporary storage requirements are also minimal. With reprocessing and transfer of spent fuel to the repository, storage requirements decline, and by about 2028, storage requirements are less than the storage requirements in 2000. Direct disposal of large amounts of spent fuel in the repository is also realized here. By 2028, all the year 2000 LSF is transferred to the repository. By 2041, all spent fuel goes to reprocessing, and no more spent fuel is transferred to the repository until year 2100. Spent fuel in the repository reaches ~ 86,000 MT by 2041 (including military & DOE spent fuel - 7000 MT). Again, the Pu inventory (from reprocessed spent fuel) at any point in time remains less than the current worldwide inventory.

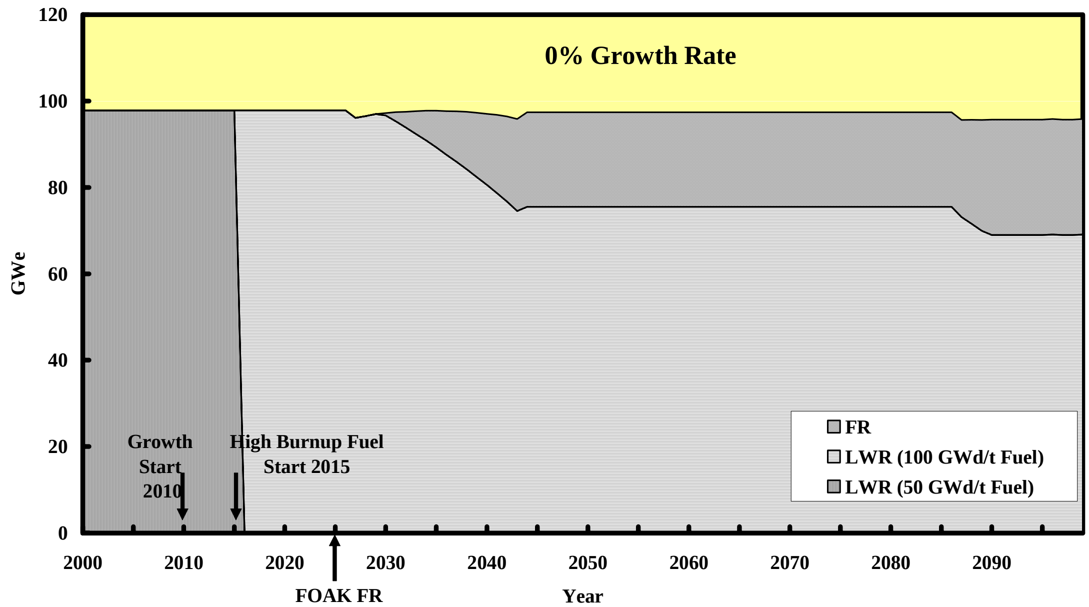

Fig. 6. Dynamic deployment of the different nuclear energy systems for 0% growth rate

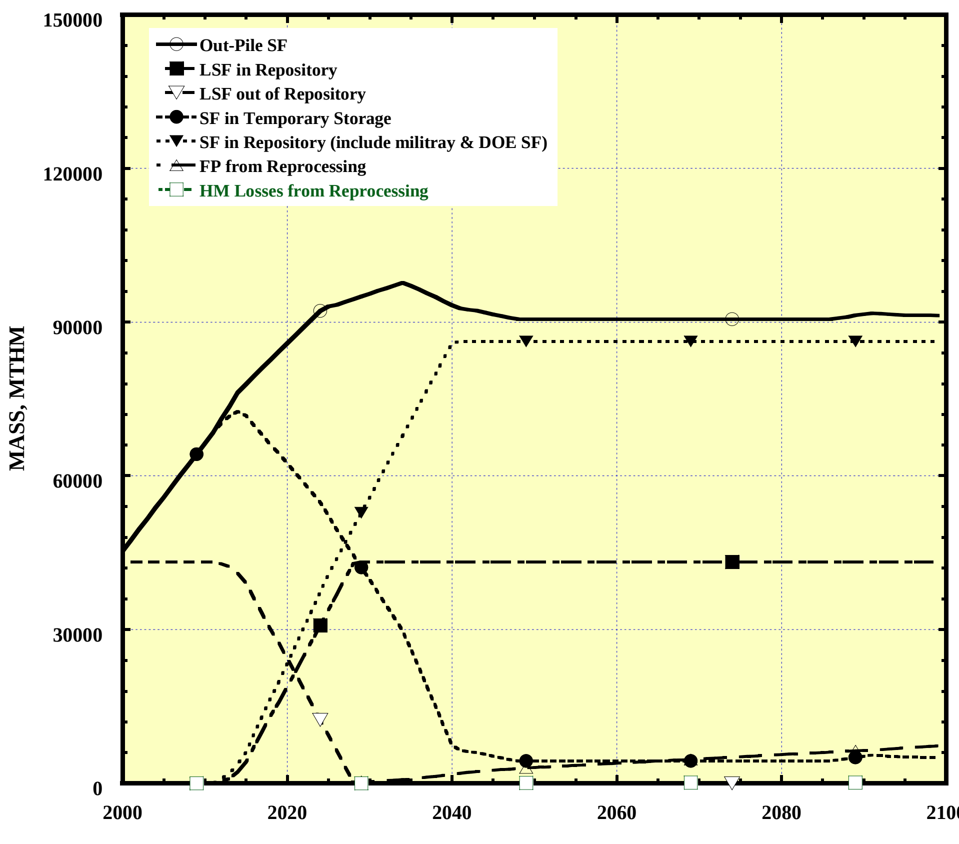

Fig. 7. Dynamics of waste accumulation in both temporary and Permanent storage for 0% growth rate

The case of 3.2% growth is similar to the 1.8% growth rate case. However, the separations capacities are different, where larger separations capacities are needed to accommodate the increase in spent fuel production in this case. Until the year 2055, separations capacity is assumed to be the same as the 1.8% scenario, but beyond 2055 it increases rapidly to catch up with the high spent fuel production rate (2000 MT/yr capacity is added every 4 years until the year 2087. The build-up of FR's/year increases gradually from 1.5 GWe/year in 2055 to about 7.3 GWe by 2095. The FR% reaches about 14% (lower than the 1.8% growth rate because of the faster growth rate and the lack of enough TRU's to fuel FR's under increased demand). With separations and transfer of spent fuel to the repository, temporary storage requirements decline, and by about 2035, storage requirements are less than the storage requirements in 2000. Eventually, storage requirements start to increase after a minimum in 2045. Direct disposal of large amounts of spent fuel in repository is also achieved. By 2028, the entire year-2000 LSF is transferred to the repository, and by 2062, all spent fuel goes to reprocessing with no more transfer to the repository through 2100. The spent fuel inventory in the repository reaches ~ 118,000 MT by 2062 (including military & DOE spent fuel - 7000 MT). Again, the Pu inventory (from reprocessed SNF) at any point in time remains below 150 MT.

CONCLUSIONS

The continuation of the current once-through fuel cycle should be re-evaluated as the demand for nuclear energy increases in the U.S. Potential consequences of the once-through cycle include substantial increase in the number of geologic repository sites, continued accumulation of weapons-usable materials, and inefficient use of uranium resources. However, advanced fuel cycles can limit spent fuel storage and direct disposal; with continuous recycle, significant reduction in waste volume, toxicity, and dose rate are possible. A closed fuel cycle approach, where separations, recycling, and geologic disposal form a comprehensive waste management strategy provide the optimal approach to future sustainable nuclear energy.

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