Utilization of Used Nuclear Fuel in a Potential Future US Fuel Cycle Scenario - 13499

Andrew Worrall
Oak Ridge National Laboratory*, P.O. BOX 2008 MS6172, Oak Ridge, TN, 37831-6172
worralla@ornl.gov

ABSTRACT

To date, the US reactor fleet has generated approximately 68,000 MTHM of used nuclear fuel (UNF) and even with no new nuclear build in the US, this stockpile will continue to grow at approximately 2,000 MTHM per year for several more decades. In the absence of reprocessing and recycle, this UNF is a liability and needs to be dealt with accordingly. However, with the development of future fuel cycle and reactor technologies in the decades ahead, there is potential for UNF to be used effectively and efficiently within a future US nuclear reactor fleet.

Based on the detailed expected operating lifetimes, the future UNF discharges from the existing reactor fleet have been calculated on a yearly basis. Assuming a given electricity demand growth in the US and a corresponding growth demand for nuclear energy via new nuclear build, the future discharges of UNF have also been calculated on a yearly basis. Using realistic assumptions about reprocessing technologies and timescales and which future fuels are likely to be reprocessed, the amount of plutonium that could be separated and stored for future reactor technologies has been determined. With fast reactors (FRs) unlikely to be commercially available until 2050, any new nuclear build prior to then is assumed to be a light water reactor (LWR).

If the decision is made for the US to proceed with reprocessing by 2030, the analysis shows that the UNF from future fuels discharged from 2025 onwards from the new and existing fleet of LWRs is sufficient to fuel a realistic future demand from FRs. The UNF arising from the existing LWR fleet prior to 2025 can be disposed of directly with no adverse effect on the potential to deploy a FR fleet from 2050 onwards. Furthermore, only a proportion of the UNF is required to be reprocessed from the existing fleet after 2025. All of the analyses and conclusions are based on realistic deployment timescales for reprocessing and reactor deployment. The impact of the delay in recycling the UNF from the FRs due to time in the core, cooling time, reprocessing, and re-fabrication time is built into the analysis, along with impacts in delays and other key assumptions and sensitivities have been investigated.

The results of this assessment highlight how the UNF from future reactors (LWRs and FRs) and the resulting fissile materials (U and Pu) from reprocessing can be effectively utilized, and show that the timings of future nuclear programs are key considerations (both for reactors and fuel cycle facilities). The analysis also highlights how the timings are relevant to managing the UNF and how such an analysis can therefore assist in informing the potential future R&D strategy and needs of the US fuel cycle programs and reactor technology.

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INTRODUCTION

The United States (US) currently operates 104 commercial nuclear power reactors with a combined installed capacity of approximately 107 GWe.[1] These LWRs [pressurized water reactors (PWRs) and boiling water reactors (BWRs)] generated approximately 20% of the US electricity demand in 2011. The current and historic US reactor fleet (of which an additional 28 commercial plants were once operated but are now permanently closed) has to date generated approximately 68,000 MTHM (metric tonnes of heavy metal) of used nuclear fuel (UNF).[2] Even with no new nuclear build in the US, this stockpile will continue to grow at approximately 2,000 MTHM per year for at least two more decades.

Although the UNF inventory continues to be stored and managed safely, it remains a liability and needs to be dealt with accordingly; when and how is yet to be decided. The two major options available for management of the UNF are (i) geological disposal and (ii) reprocessing and recycle, but as of today, neither of these two options is currently underway while policy, technological, and regulatory challenges continue to be addressed. Although the objective of this paper is not to discuss the benefits and detriments of disposal versus reprocessing and recycle, it is necessary to consider some of the potential drivers as this will determine the effectiveness of the fuel cycle scenario developed in this analysis.

Until the last few years, direct disposal has been considered the only viable option in the US and as such, employing an open, or once-through, fuel cycle has led to the production and need to store the UNF. However, since the 2001 national energy policy[3] recommendation from the National Energy Policy Development Group that the US "develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant" a number of programs are now underway that look to underpin and answer these challenges for both of the major UNF management options.[4] Nevertheless, one question that remains is whether one of these options could foreclose the other. For example, is there a realistic and financially viable future fuel cycle in which the current inventory needs to be retained for reprocessing and re-use? And if the UNF generated to date were to be disposed of and therefore the potentially useful plutonium and uranium thrown away, would that prevent the start-up of future advanced reactors such as FRs?

To answer this question, it is necessary to consider how nuclear demand in the US could potentially grow in the future. The US Energy Information Administration (EIA) recently reported that the expected electricity demand would grow at approximately 1% from around 2020 to 2035.[5] Applying this plateaued growth expectation year on year for the remainder of this century and assuming nuclear maintains its 20% share of total electricity production, this will mean that the nuclear fleet will need to grow from 107 GWe today to approximately 210 GWe by 2100. If all of this nuclear energy were to be produced by LWRs similar to those operating or being built today, the UNF discharged per year would double to approximately 4,000 MTHM per year. Over a 60 year operating lifetime, this fuel would consume approximately 2.5 million tons of uranium ore. Based on current spot market prices, this represents approximately 50% of the world's economically recoverable uranium resource[6].

However, this increased demand from the US combined with demands from around the world (as other nations also expand their nuclear programs or new ones start) does not necessarily result in a shortage of uranium within this century as the amount of known resource will continue to grow as uranium prospecting continues in earnest as it has since around 2007. But it is likely that the increased uranium demand will drive up the price of uranium; to what extent is unknown at this time. The US currently ranks ninth in the world for known economically recoverable uranium resource (with approximately 210,000 tons), and as a result almost all of the uranium used today in US commercial reactors is imported, with around half of that material coming from down-blended weapons-grade highly enriched uranium (HEU) from Russia. This means that the US will be as sensitive to uranium price increases as other nations as the indigenous uranium reserves are not sufficient to buffer the US from price fluctuations.

This also points to the need for the US to consider security of supply and sustainability as well as the economics of uranium-based fuels and therefore the need to make the most of the existing uranium resource and utilize the fissile material in the UNF (i.e., reprocessing and recycle of the plutonium and the reprocessed uranium). Furthermore, the US currently has additional uranium resource in the form of more than 700,000 MTHM[7] of depleted uranium tails, the waste product from the enrichment of the LWR fuels. Although currently a liability that will need to be processed and placed in the geological disposal facility, this tails material could equally be used as the major component of the fuel to be loaded along with the plutonium in future FRs. Whether there is sufficient tails material to fuel the potential future FR fleet is also considered in this study.

It is clear that there are a number of short- to medium-term challenges (e.g., management of UNF, increasing U ore prices) as well as future challenges (e.g., sustainability, deployment of advanced technologies) facing the nuclear industry today, and there are several key programs underway to underpin the strategies and assessments required.[8] One such study has proposed a US strategy in which the vast majority of the total UNF generated to date should be permanently disposed of, without the need to make fuel retrievable from disposal for reuse or research purposes.[9] That assessment does not assume any decision about future fuel cycle options or preclude any potential options, including those with potential recycling of commercial UNF. However, the assessment states that the ~2,000 MTHM of UNF that is generated annually in the future would be sufficient to provide the feedstock needed for deployment of alternative fuel cycles and the fueling of FRs. The analysis presented below was completed as part of that assessment[9] and analyses and underpins that statement and assesses whether such a strategy would fit in with the longer-term and advanced reactor demands for fuel.

Ideally, any solution should be compatible with both the near- and longer-term challenges and enable an effective transition from one to the other on the way to a sustainable, equilibrium future fuel cycle. Many scenarios and options have looked at an assumed equilibrium situation. However, this assessment goes one step further, looking at how a liability today could be managed through a growth transition period based on actual closure dates before reaching equilibrium in the decades ahead and applies realistic industrial constraints and timescales to the analysis.

ANALYSIS

As stated above, the US currently operates a fleet of 104 LWRs. Based on recent experience, it is reasonable to assume that all of these LWRs could expect to achieve lifetime extensions and be allowed to operate for up to 60 years. Of those reactors operating today, this would result in the first closure of the existing fleet in 2029 (Oyster Creek) and the last closure of the existing fleet in 2056 (Watts Bar-1), although is it noted that some reactors may be taken out of service earlier than allowed by the operating license. Against this closure schedule, there is the expected electricity demand increase of approximately 1%.[5] Therefore, if nuclear is to maintain its electricity share of approximately 20%, a new build program will be required to not only address the closure of the existing fleet, but also match the expected growth. On the basis that FR technology will not be ready for commercial deployment in the US until 2050, it is reasonable to assume that any reactors built prior to that will most likely be LWRs of some description [e.g., ABWR, AP-1000, EPR, ESBWR, or Small Modular Reactors (SMRs)].

Based on a detailed year-by-year closure of the existing 104 reactors taken from Power Reactor Information System (PRIS),[1] Figure 1 shows the closure of the existing fleet against the backdrop of the potential growth in the demand for nuclear in the remainder of the century. The figure also shows the cumulative number of reactors required to meet the future demand, assuming, for simplicity, reactors of 1300 MWe per unit (an average of the larger reactor designs proposed in the US today). As can be seen, a significant new build program of approximately 150 reactors will be required before the end of the century. In the analysis, no accounting is attempted for the capacity factors for any of the reactors, although it is recognized that this is likely to increase for new LWRs but be lower for new FRs.

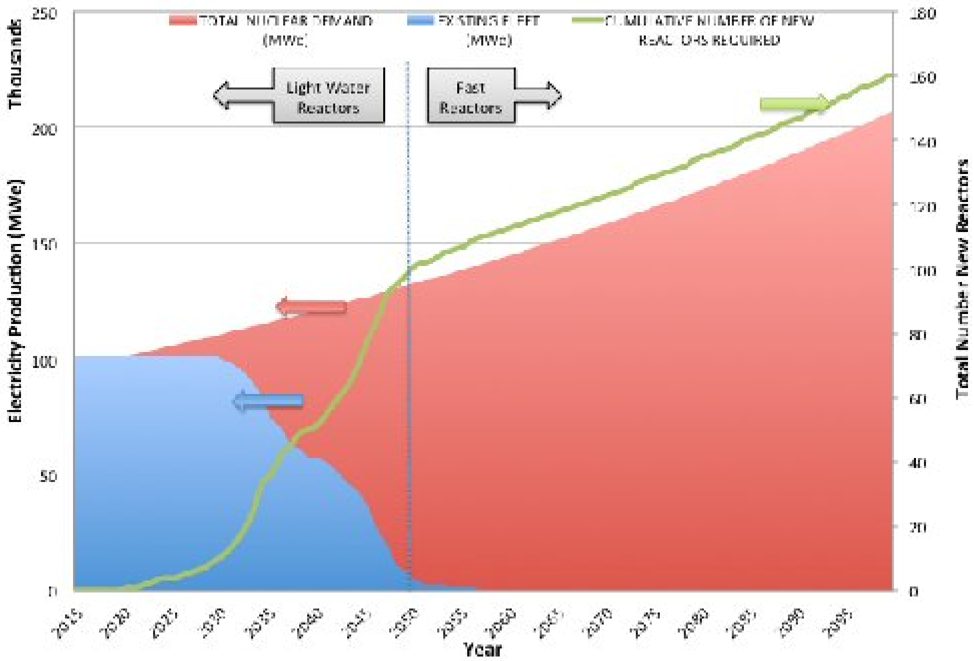

Fig. 1. Predicted nuclear electricity production and demand and associated number of new reactors required.

Fig. 2 breaks this down further and highlights the number of either LWRs or FRs required on a year-by-year basis; the detailed assessment of the reactor closure dates has allowed this level of detail to be generated and assessed. Of course the reactors may not be built to exactly coincide with the demand; the build schedule is most likely to be determined by the economics and business case for the utility at that time. But the figure is useful for illustrating the specific construction and demand profile. In the case of the deployment of the new LWRs, it is clear that they are required as and when the existing LWRs are retired. A trend in which the number of replacement LWRs increases around 2030 onwards can clearly be seen and coincides with the closure of several LWRs built in the early to mid-1970s (e.g., Peach Bottom, Browns Ferry, etc.). The maximum number of new LWRs required to match the closure of the existing LWRs is nine around 2035. Similarly, 60 years later (circa 2095), 10 FRs are required to replace the closing 9 new LWRs; this ramp-up in FR deployment is something that is returned to later in the paper.

The assumption in the analysis is that if the US decides to build FRs rather than LWRs in the mid-part of the century, then the drivers for this will be such that any further reactors built will also be FRs and no more LWRs will be built after 2050. This means that in the early years of FR deployment, only one or two are required each year, and these are needed to simply match the electricity demand increase (the 1% per year). Since the FRs will be a new technology at that time, deployment on such a conservative basis aligns with the approach that the regulators, utilities, and investors are most likely going to want to see (i.e., build up confidence in the technology in terms of the build schedule, costs, and operational performance - not just of the new reactor but also the associated new fuel cycle technology). However, in the latter part of the century (around 2090 onwards), the demand for FRs increases notably to between four and ten per year. The assumption in the analysis is that the new build LWRs will also operate for 60 years, and so in the latter part of the century, the FR demand is not only to match the 1% per year growth (which in real terms is a greater MWe demand) but also to replace the new build LWRs that have reached the end of their operating life. The breakdown of the electricity production from the existing LWRs, new LWRs, and new FRs is shown in Fig. 3 and shows how there is a potential gradual growth in FR construction, ideally suited to deployment of a new technology and how the FR ramp-up is required as the new LWRs begin to retire. It should also be noted that since the last LWR comes on line in around 2050, the US fleet will not be an all-FR fleet until 2110.

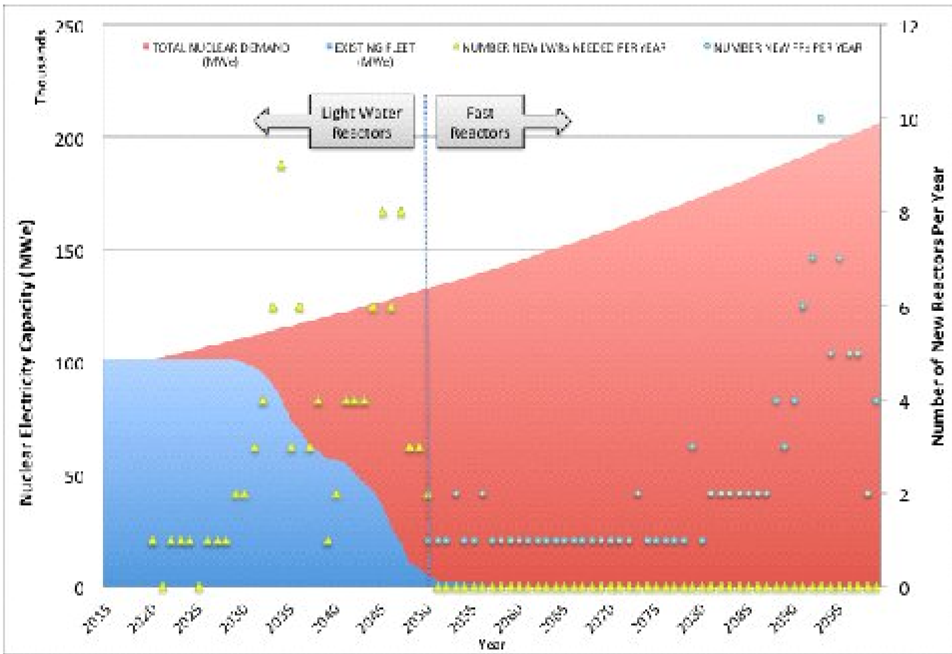

Fig. 2. Predicted number of light water reactors and fast reactors required to match potential nuclear growth scenario.

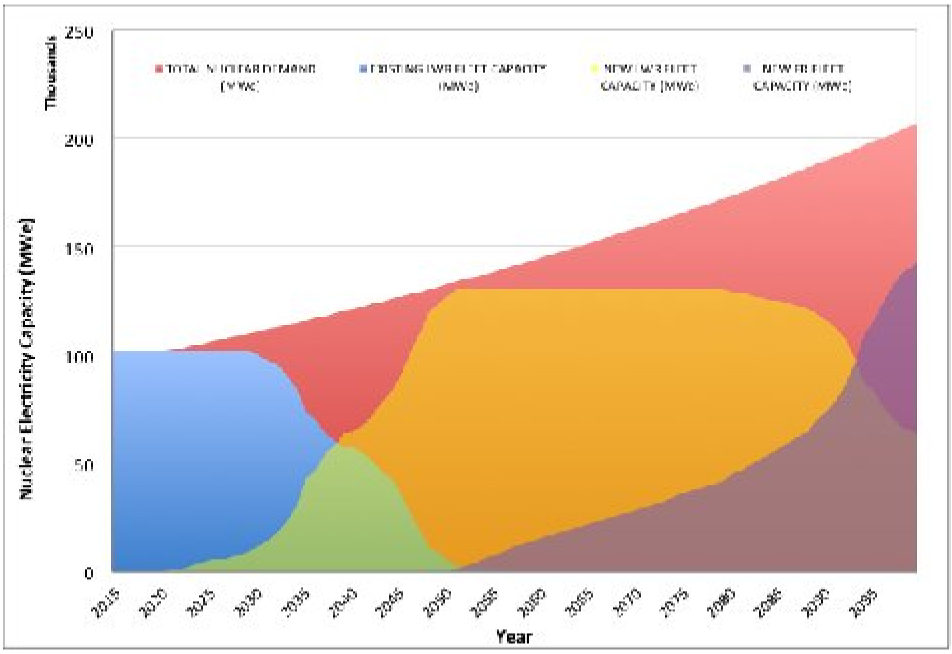

Fig. 3. Electricity capacity from the various nuclear generation types.

As outlined above, one of the major reasons for moving to a FR fleet in the middle of the century would be the potential shortage of uranium, resulting in price increases and the need to address security of supply and sustainability since the US will have to import the majority of its uranium at that time. Therefore, it is important to determine how much plutonium is needed to sustain the FR deployment presented above. The advantage of FRs is that once they are operating, they can become self-sustaining, producing enough plutonium to fuel themselves and eventually even producing enough excess plutonium to start up other units. However, initially to start up each of the FRs, another fuel source will be required, and this is where the reprocessing of the UNF from LWR operations (either the historic or the future fleet) becomes vital.

The above growth scenario and the associated assumptions for FR deployment result in approximately 150 GWe of FRs by the end of the century. Assuming typical core sizes and plutonium loadings for FRs, this size of fleet will require ~1,000 MTHM of plutonium for the start-up cores alone (i.e., this does not include the fuel required for subsequent fuel reloads). The plutonium needed for the reload fuel comes from the FRs as they are assumed to become self-sufficient and produce enough plutonium to fuel themselves. However, the start-up cores will require plutonium either from UNF from the current or future LWR fleet.

Based on detailed inventory analyses, for every fuel assembly in the ~68,000 MTHM of UNF discharged to date,[10] the average plutonium content has been calculated to be 1.18 wt % plutonium for PWR fuel and 1.28 wt % plutonium for BWR fuel, the differences being due to the fuel management operated for those fuels. However, for fuel discharged from the new LWR fleet, it can reasonably be assumed that the burnup of the UNF would be more typically 55 GWd/tHM compared with the historic average of ~35 GWd/tHM, and as such the plutonium content will be more typically 1.1 to 1.2 wt %, with approximately 20 MTHM of UNF arising per GWye produced.

In this assessment, all of the current inventory of UNF from the existing fleet is assumed to be disposed of, therefore only leaving the future LWR UNF (from the existing and new build reactors) available for recycle and reuse. The above LWR deployment scenario results in approximately 140,000 MTHM of UNF from the new build LWRs by the end of the century, which equates to ~1,500 MTHM of plutonium. This means that there is clearly sufficient plutonium in the new fleet of LWRs to fuel the start-up of a new FR fleet and the UNF from the existing LWR fleet is not required for reprocessing and recycle. However, the key question remains as to whether this material is available as and when required by the FRs, allowing for FR UNF cooling, reprocessing, re-fabrication into new fuel, and all of the associated transportations steps. If the plutonium is not available on the required timescales, then how much of the UNF from the existing fleet also needs to be reprocessed?

The key properties of the FR and start-up program are shown in Table 1.[11] The capacity of the LWR reprocessing plant(s) was varied in the analysis and is discussed in more detail below. The LWR reprocessing start-up date is a realistic timescale to allow policy decisions, licensing applications, construction, and commissioning to be completed. The capacity of the FR reprocessing plant was unconstrained and allowed to reflect the demand placed upon it. The FR start-up date is consistent with the estimated commercial deployment of that technology (i.e., 2050).

TABLE 1. Properties and Assumptions of Key Components of Fuel Cycle

LWR Fuel Cycle	
Electrical capacity per reactor (GWe)	1.3
Reactor lifetime (years)	60
UNF discharge per year (MTHM/GWye)	20
Reprocessing operations begins	2030
Reprocessing capacity (MTHM)	Variable
% Pu in LWR UNF	1.1
FR Fuel Cycle	
Electrical capacity per reactor (GWe)	1.3
Deployment starts	2050
Core size (MTHM)	123.8
Reprocessing operations begins	2050
Reprocessing capacity (MTHM)	Unconstrained
Pu content in unirradiated fuel (wt %)	9
UNF discharge per year (MTHM/GWye)	14.1
Cycle length (years)	2.25
Pu discharged-to-charge mass ratio	1.2

Based on the build profile shown in Fig. 2 and the data in Table 1, the amount of UNF from the current and future fleets (LWR and FR) was calculated. Fig. 4 shows the UNF for the three different reactor fleets versus time as well as some key dates assumed in the analysis. As can be seen, this puts the maximum discharged UNF from the LWRs (current and/or new build) at a little over 2,500 MTHM per year and provides a very useful indication as to the likely maximum size of an LWR reprocessing plant that would be needed to manage all of the future US LWR UNF. With LWR reprocessing not realistically likely to start before 2030, only the UNF discharged from the reactors from 2025 onwards will be reprocessed; this allows for 5 years of cooling prior to reprocessing.

Fig. 4 also illustrates the lag between LWR reprocessing (starting in 2030) and the start-up of FRs (in 2050). This 20 year lag not only allows for the ramp-up of the reprocessing facility to reflect commissioning and gradual scale-up to full throughput, but it is also necessary in order to build up sufficient stocks of plutonium for the FR start-up cores. Although the FRs will eventually become self-sufficient, there is a lag of several years from the time the FR UNF is discharged, cooled, transported, reprocessed, and the resulting plutonium (and also potentially minor actinides) then fabricated into new fuel and transported back to the FR for re-use. During this period, the FR will still require refueling. Until equilibrium is reached, this shortfall while the material is held up in the fuel cycle will have to be accommodated by using plutonium from LWR reprocessing. This highlights a key sensitivity to the sustainability of any FR program: the delay time between discharging UNF from FRs and the time to be able to re-use the resulting plutonium, and this is considered further below. The plutonium from the LWR reprocessing is therefore not only required for the FR start-up cores, but also for the reload fuels during the early years of FR operation.

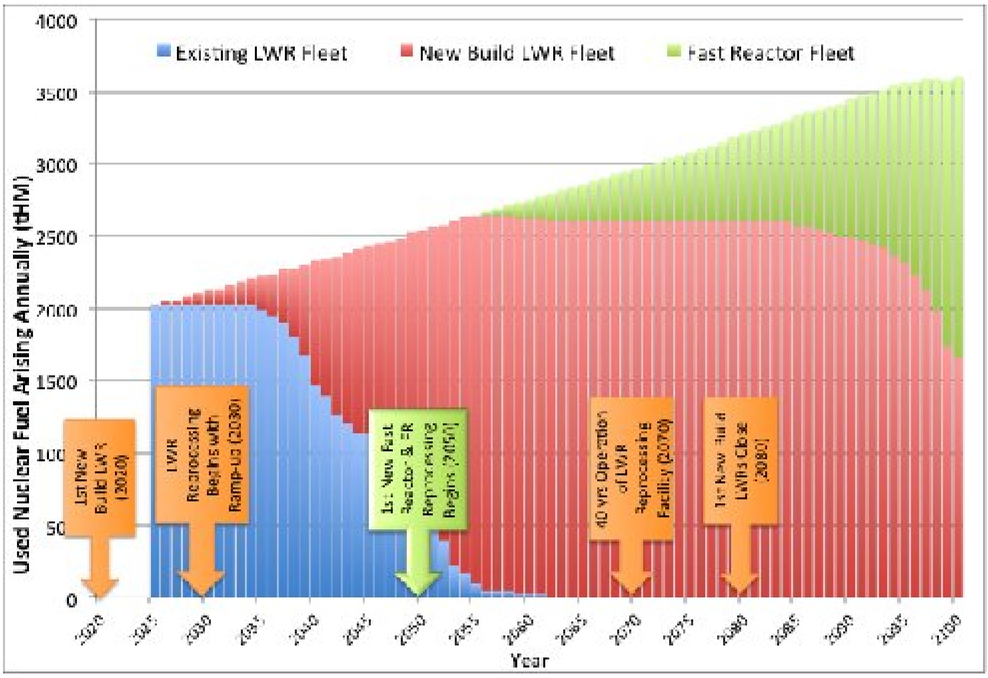

Fig. 4. UNF arising from the LWR and FR fleets (with key dates shown).

An LWR will produce approximately 0.2 MTHM of plutonium per GWye[†]. If this is compared with a FR that discharges approximately 1.5 MTHM of plutonium per GWye[‡], it appears that the LWR can contribute very little to the start-up of any new FR. However, the FR that generated that plutonium also needs ~1.3 MTHM of plutonium to fuel itself in the following cycle of operation, therefore only leaving ~0.2 MTHM of plutonium to assist in the start-up of a new FR (i.e., approximately the same as that arising from the LWR UNF reprocessing).

Another way to consider the plutonium balance and demand is that if a FR requires ~8 MTHM of plutonium for the start-up core, this equates to approximately 30 to 40 reactor years of operation of either an LWR or a FR. The major difference is that there is a potential store of LWR UNF reflecting a large number of reactor years of operation that is available to build up the buffer for FR re-use, which is not the case for the FR fleet until many decades into the FR fleet operation.

On the basis outlined above, the amount of plutonium separated and utilized in FRs was calculated as shown in Fig. 5, taking into account all of the parameters in Table 1 as well as the cooling and recycling lag times (5 years for LWR fuel and 6 years for FR fuel). This is a detailed but important element of the assessment and is discussed further below.

Since the reprocessing plant is assumed to not come on line until 2030, it is assumed that only the UNF arising at that time (from the new LWR fleet and the remaining current fleet) will be reprocessed and the remaining historic UNF from the current fleet will go directly to disposal. Not all of the UNF arising after 2025 from the existing LWRs is required to be reprocessed to achieve the scenario in Fig. 5. Only approximately 40% (17,000 MTHM) of the UNF (discharged after 2025) from the existing LWRs is needed. However, this 40% is vital to achieve this FR growth program on the timescales shown as there is insufficient UNF available from the new build LWRs in the early years and, therefore, insufficient plutonium would be available to fuel the FR fleet.

[†] 1.1 wt % in LWR UNF and ~20 MTHM discharged per GWye = 1.1% × 20 = 0.22 MTHM per GWye
[‡] 1.2 × 9 wt % in FR UNF and ~14 MTHM discharged per GWye = 1.2 × 9% × 14 = ~1.5 MTHM per GWye

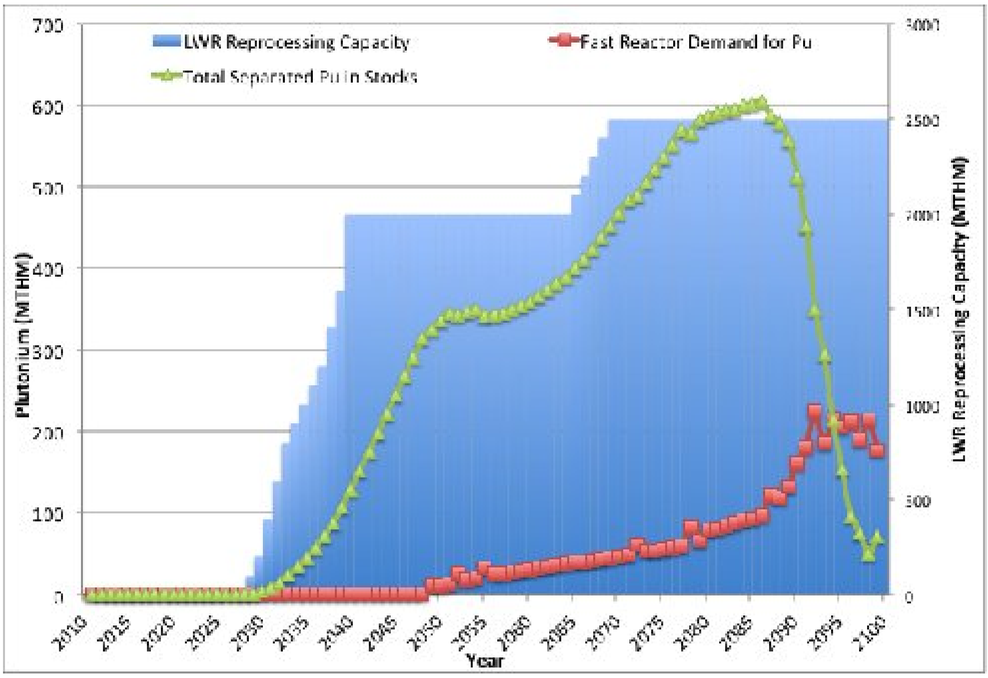

Fig. 5. LWR reprocessing capacity and plutonium demand based on FR deployment scenario.

The mass of plutonium separated in a given year is driven by the reprocessing capacity. The gradual ramp-up of the reprocessing plant throughput was deliberately chosen to reflect the introduction of a new technology and fuel cycle facility into the US. The capacity was deliberately capped at 2,000 MTHM to not only be consistent with the capacity experience in Europe (e.g., at La Hague in France) but was also chosen to provide sufficient plutonium for the FR program. As can be seen, as the gradual ramp-up in reprocessing increases, so does the amount of separated plutonium in storage, until 2050 when the first FRs come on line and the rate of increase in the stockpile slows. After 40 years of operation (in 2070), which is typical for a commercial reprocessing facility, an additional reprocessing line was introduced (which could also potentially be a refit of the existing facility) as additional plutonium was anticipated for the faster introduction of FRs in 2080 onwards. The proportion of plutonium from LWR and FR reprocessing (with an additional capacity of ~2,000 MTHM) can be seen in Fig. 6, where the plutonium from the FRs is the dominant source of material.

As can be seen in Figure 5, there is sufficient plutonium available in this scenario up to and including 2100, even allowing 6 years from discharge of the FR UNF to the new fuel being reloaded. This scenario has not been optimized, but some of the key parameters are worth exploring to assess the sensitivity to such an assessment and deployment scenario for the US. These sensitivities include (i) lag time in FR fuel recycle, (ii) LWR reprocessing plant capacity and timescales, and (iii) FR deployment rate.

If the lag time (the time taken from discharging the FR UNF until the time the separated plutonium from that fuel is reloaded into a FR) increases by only 2 years (to 8 years), then with all of the other assumptions remaining the same, there will be insufficient plutonium available to fuel the more rapid FR deployment in the latter part of the century. This FR deployment schedule could still be achieved by increasing the percentage of UNF from the existing LWRs to be reprocessed, and this in turn would require an increase in the reprocessing capacity to more than 3,500 MTHM per year, or reprocess more UNF earlier. Both of these options will result in the need to store more separated plutonium.

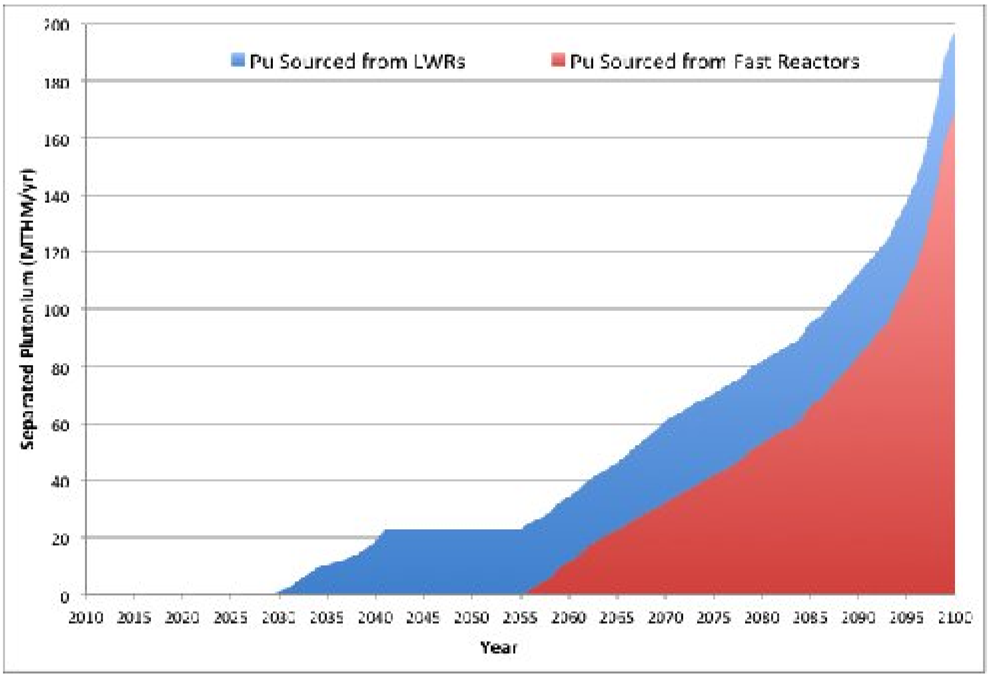

Fig. 6. Plutonium used in fast reactor fleet from LWR and fast reactor reprocessing.

However, if the lag time was reduced by 2 years (for example by needing less cooling time, as is the case in pyro-reprocessing), then there would need to be less plutonium separated per year from the LWR UNF and the reprocessing plant capacity could be reduced to ~1800 MTHM throughout the program compared with 2000 ramping up to 2,500 MTHM.

As noted above, the likelihood is that the FR deployment rate would not coincide exactly with the demand curve shown in Fig. 2. To even out the rate of deployment, particularly at the end of the century, more FRs could be built early and fewer at the end of the century. By doing this, although the LWR reprocessing plant capacity would not change, the amount of separated plutonium in storage would reduce to ~400 MTHM. If this is combined with reducing the lag time to 4 years, then the LWR reprocessing capacity can be reduced to ~1600 MTHM, and this also further reduces the amount of separated plutonium in storage, as shown in Fig. 7.

The timescales presented here, although long, do not show the complete phaseout of LWRs in the US. Since the last LWR would be deployed around 2050, then even with no lifetime extension, the last LWR will still be operating in 2110. This co-existence of the LWR and FR fleet could therefore also be considered as a potential symbiotic option where the LWRs produce plutonium for the FR start-up and transition cores and then the FRs produce high quality plutonium to feed the LWRs in the form of MOX fuel later in the reactor life. This would be particularly relevant if, as speculated, uranium becomes a more sought after and therefore expensive commodity. Nevertheless, the use of FRs as outlined in this paper will save the US nuclear industry approximately 2 million metric tons of uranium ore over their lifetime. If the uranium that is separated from the LWR UNF was also recycled and used as enriched reprocessed uranium, this could save a further 10% of the uranium ore. At current uranium market prices, this equates to more than $100 billion of reduced import costs.

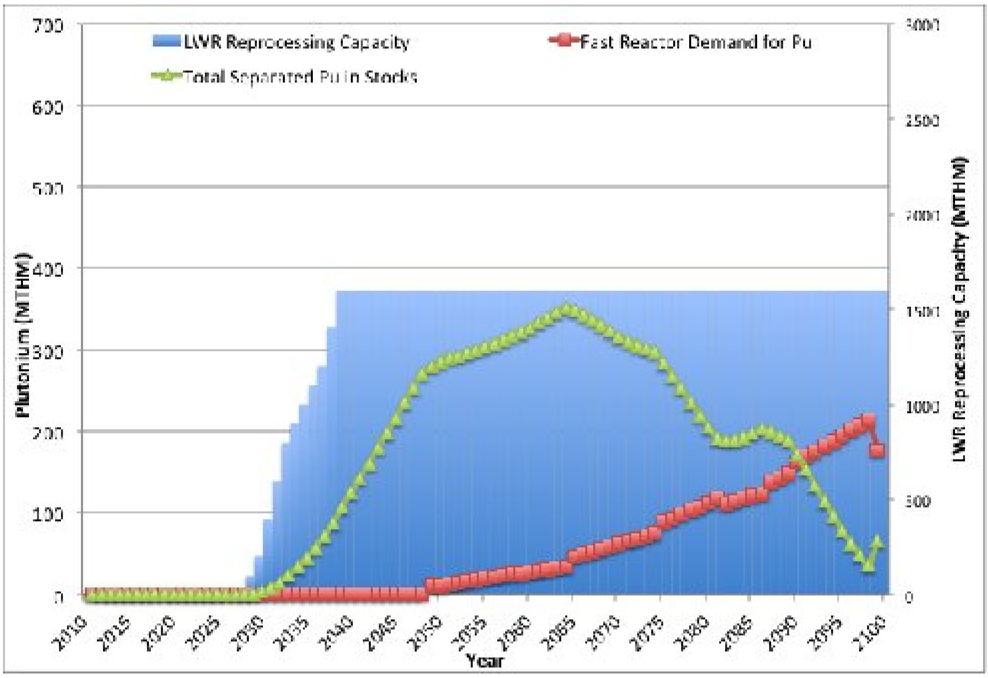

Fig. 7. "Optimized" deployment scenario.

The total FR fuel required in the above scenario is approximately 50,000 MTHM. This means that the current US stock of more than 700,000 tons of uranium tails is more than enough to fuel the FR fleet more than ten times over. In other words, the use of FRs at this (or even much higher deployment rates) would mean that that US would not need to mine or purchase any more uranium ore (or any other fertile material) once a full FR fleet was deployed, therefore not only saving on the import costs but also reducing the environmental impact from mining, ensuring security of the fuel stock supply and buffering the US from future uranium ore price fluctuations.

CONCLUSION

An analysis of a potential future US nuclear fuel cycle has been completed in which the UNF from the existing and future LWRs has been reprocessed and the resulting plutonium recycled to fuel a fleet of FRs. Assuming a 1% per year growth in electricity and nuclear demand in the US for the remainder of the century, a detailed analysis based on realistic deployment timescales and plant throughputs was completed. The assessment demonstrated that there is sufficient plutonium available in the LWR UNF arising from 2025 onward to fuel the FRs required from 2050 onwards. This also means that the UNF arising from the existing LWR fleet prior to 2025 can be disposed of directly with no adverse effect on the potential to deploy a FR fleet of approximately 150 GWe by 2100. Furthermore, only ~40% of the UNF from the existing fleet after 2025 will be required for reprocessing and recycle in addition to all of the UNF from a future LWR fleet. Reprocessing at the level assumed in this assessment would reduce the amount of UNF destined for disposal by ~150,000 MTHM by the end of the century.

However, the analysis has demonstrated the importance of the availability of the plutonium on appropriate timescales to start up and then continue to deploy new FRs. The start-up cores are the most limiting as they require substantially more plutonium than the fuel reloaded each cycle. Even with a relatively high breeding ratio, the FRs are unable to provide sufficient plutonium to fuel their next cycle of operation and at the same time be able to provide enough plutonium for the start-up of additional, new FRs on the timescales considered in this study. In effect, the FRs provide the same *excess* plutonium per GWye as an LWR because the majority of plutonium is reloaded in the subsequent FR operating cycle of the existing reactors. This means that the UNF from LWRs (current and new build fleet) has to be recycled for FRs to be deployed, even at a modest rate. Too fast a deployment rate has been shown to result in the need to have a larger LWR reprocessing capacity and necessitate the storage of more separated plutonium in order to have sufficient fuel for the start-up cores. The use of enriched uranium could be considered as an alternative FR start-up fuel. However, if the major driver for FR deployment is due to uranium ore availability and associated high uranium prices, then this option would prove expensive, particularly for a large number of FRs.

The study has also highlighted the importance of minimizing the lag time between discharging the fuel from the FRs and being able to recycle the plutonium as new fuel. By reducing the lag time and making the gradual transition to FRs, the capacity of the LWR reprocessing facility can be reduced to less than 2,000 MTHM and the amount of separated plutonium that is needed to be stored in preparation for the FR deployment can be reduced by ~200 MTHM.

The FR deployment assumed here and the associated reprocessing of the LWR UNF would save more than 2 million tons uranium ore, saving the US more than $100 billion in import costs (based on current ore prices), and would consume approximately 10% of the tails uranium currently destined for disposal. If the reprocessed uranium from the LWR UNF was recycled in LWRs, an additional 10% of uranium ore could also be saved.

This analysis did not consider the transition to a thermal MOX program in LWRs prior to moving to a fully closed fuel cycle using FRs. Any LWR MOX program introduced prior to a FR program that also used the plutonium from LWR recycle (rather than the former weapons plutonium) will affect the conclusions of this study. In particular, the effective "holdup" of the plutonium in the LWR MOX UNF and fuel cycle will be key, as will the destruction of the plutonium in LWR MOX fuel (typically 1/3 of the plutonium is destroyed in LWR MOX irradiation). Nevertheless, other studies have concluded that this impact is manageable.[11]

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