PLUTONIUM SEQUESTRATION WITH DISTRIBUTED NUCLEAR ISLANDS

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ABSTRACT

Nuclear Islands, which are integrated power production sites, could effectively sequester and safeguard the US stockpile of plutonium. A Nuclear Island, an evolution of the Integral Fast Reactor, utilizes all the Tranuranics {TRU (Pu plus minor actinides)} produced in power production, and eliminates all spent fuel shipments to and from the site. This latter attribute requires that fuel reprocessing occur on each site and that fast reactors be built on site to utilize the TRU. All commercial spent fuel shipments could be eliminated by converting all LWR nuclear power sites to Nuclear Islands.

Existing LWR sites have the added advantage of already possessing a license to produce nuclear power. Each could contribute to an increase in the nuclear power production by adding one or more fast reactors. Both the TRU and the depleted uranium obtained in reprocessing would be used on site for fast fuel manufacture. Only fission products would be shipped to Yucca Mountain for storage.

The Nuclear Island concept could be used to alleviate the strain of LWR plant sites currently approaching or exceeding their spent fuel pool storage capacity. Consider an LWR plant site with two 1000 MWe LWR's nearing their 40 year license with spent fuel pools reaching saturation. A reprocessing plant of 100 MTHM/yr would be added to the site. The site would have sufficient spent fuel to supply plutonium for the initial loading of two fast reactors, the first of which would be built in seven years. The fast reactor would be designed with a desired conversion ratio and in one example, a breeding (conversion) ratio of 0.5 is investigated. Fuel for the second plant will take longer (fourteen years) to produce because the fuel from the first fast reactor plant must also be reprocessed to keep it running. Alternatively, if a breeding ratio of 1.0 is designed into both fast reactors, at the end of year 21, the two thermal reactors, assuming each has a 21 year extension, will have produced enough spent fuel to supply plutonium for a third fast reactor. If one of the now 60-year-old thermal spectrum plants were retired, the third fast reactor could replace it. Continued operation would complete the site conversion to fast reactors. If desired, thermal reactors could be kept on site and as many as four thermal plants could coexist with two fast reactor plants at steady state operation with no build up of TRU on site and no spent fuel shipped off-site.

Changing existing plant sites to Nuclear Islands could proceed at a reasonable pace by converting sites as they reach (some have reached) their spent fuel storage capacity. To keep plutonium from being stored in Yucca Mountain, it must be sequestered in fast reactors since even a 1000 MWe pure burner could only burn 0.8 tonnes Pu/yr. This pales in comparison to the approximate 1600 tonnes Pu worldwide now in spent fuel with 80 more tonnes produced each year. Fast reactors can be designed for breeding ratios most conducive to either reducing plutonium or to producing power, to convert existing sites to all fast reactors or to keep the majority thermal. Examples are included, BR=0.5, BR=1.0, and BR=1.3 to bracket all these objectives. The conversion to all fast reactors is recommended and may be the most cost effective.

INTRODUCTION

Nuclear Islands, which are integrated power production sites, could effectively sequester and safeguard the US stockpile of plutonium. A Nuclear Island, an evolution of the Integral Fast Reactor [1], utilizes all the Tranuranics {TRU (Pu plus minor actinides)} produced in power production, and eliminates all spent fuel shipments to and from the site. This latter attribute requires that fuel reprocessing occur on each site and that fast reactors be built on site to utilize the TRU. The most straightforward way to eliminate all commercial spent fuel shipments would be to convert existing LWR nuclear power sites to Nuclear Islands since all the commercial spent fuel is currently stored on these sites.

These existing sites have the added advantage of already having a license to produce nuclear power which should allow easier licensing of added on-site nuclear plants. Assuming that nuclear power would increase with at least the same rate as the increase in electrical power in the US, these sites could contribute to this an increase in the nuclear power production by adding two or more fast reactors to each site. Doubling the electrical power over the next 40 years could easily occur [2]. Just a 2% increase in electrical power requirements per year would result in over double the power in 35 years. The study shows how an existing nuclear site with sufficient room and two thermal reactors nearing the end of an initial 40 year license but with a 20 year extension could be converted to a four reactor fast reactor site within a 40 year time frame with no spent

fuel shipments off-site. The waste form will only include fission products resulting in a 300 year storage project rather than a 10,000 year one. The fision product waste forms developed [3] are the only products to be shipped to a waste repository. Several other options are investigated with lower and higher power increases, and with complete conversions to fast reactors or with retaining several thermal reactors but all have the characteristic of no spent fuel shipments off-site.

The power history at a site depends upon the Breeding Ratios of the fast reactors, the throughput of the reprocessing plant added to the site, and how long the thermal reactors continue to operate with license extensions. Both the TRU and the depleted uranium obtained from reprocessing would be used on site for fast fuel manufacture. Only fission products would be shipped to Yucca Mountain for storage. Both the thermal spent fuel and the fast reactor spent fuel will be processed.

To minimize the nuclear proliferation threat, the model here assumes that reprocessing of oxide spent fuel from the thermal reactors will be reduced to metal and then the Argonne developed electrochemical process [4] will be used to separate the spent fuel into fission products, Transuranics, and Depleted Uranium. Since each Nuclear Island would have reprocessing capability, nuclear proliferation could become an important issue and would make use of a chemical separation process for like Purex less likely to be accepted because plutonium is separated as an individual product. Plutonium is susceptible to diversion because of its low radioactivity. The Argonne electrochemical process is only able to separate out the Transuranics (which contains 90% Pu and are often spoken of as Pu) as a group which has lethal amounts of radioactivity and is not a candidate for diversion. Processing of these metallic transuranics into fast reactor fuel must be done in a hot cell environment with its attendant five foot thick walls for radiation protection and the difficulty and high probability of personal demise in diverting this material. Central station reprocessing using the same non-proliferation technology has also been studied [5]. The Nuclear Island concept could be used to alleviate the strain of those LWR plant sites currently approaching their spent fuel storage limit or which have exceeded it and are now installing dry storage racks. Five scenarios are presented, each starts with a Light Water Reactor (LWR) plant site with two 1000 MWe LWR's nearing their 40 year license with spent fuel pools reaching saturation. A reprocessing plant of 100 MTHM/yr would be added to the site. The site would have sufficient spent fuel to supply plutonium for the initial loading of two fast reactors, the first of which would be built in four years. The fast reactors would be designed with a specified breeding ratio. Three different breeding ratios are studied in these scenarios, 0.5, 1.0 and, 1.3. The objective of using a breeding ratio of 0.5 would be to convert all the spent fuel from the thermal spectrum plants but not increase the power output. Designing a fast reactor with a higher breeding ratio would increase the number of reactors and thus the power at the site. Reactors with breeding ratios of 0.5 would not use blanket assemblies and would be designed to lose neutrons. Enough DU exists in the fuel rods themselves for a 0.5 breeding ratio. The higher breeding ratio reactors would include blanket assemblies and more efficient geometries to capture more neutrons.

The purpose of this paper is to investigate different scenarios for the Nuclear Island development in terms of increasing power with breeding ratio, size of reprocessing plant on each site, and length of operation of the thermal plants. The following section briefly describes the model used to estimate these scenarios. This is followed by a results section which investigates these scenarios. Within 40 years from now, all nuclear power plant sites in the US could be on their way to becoming Nuclear Islands and to doubling or tripling their power output.

DESCRIPTION OF MODEL

Each site is assumed to start out with two 1000 MWe thermal spectrum plants. All the results can be applied to any other site by scaling the results by the ratio of actual to the 2000 MWe assumed here.

The heavy metal in the annual spent fuel product from a 1000 MWe thermal spectrum plant is 20.7 MT/Yr.

$$D_{TR} = \frac{3000\ MW * 365\ days * (capacity\_factor = 0.85)}{45{,}000\ MWd / MTHM} = 20.7\ MTHM / GW \qquad \text{(Eq.1)}$$

The reactors are assumed to operate for 40 years producing the 20.7 MT of heavy metal (HM) each year. A processing plant of 100 MT/Yr is assumed to start operation in Year 41 of reactor years and Year 1 of reprocessing. It is assumed that construction of this plant began four years before. Results in Section 3 are presented in reprocessing years.

Transuranics approximately make up 1% of the spent reactor fuel. Transuranics are made up of 90% plutonium and 10% of the minor actinides americium, Curium, and neptonium. Therefore the TRU harvested annually from 100 MT/Yr reprocessing plant is 0.01 * 100. When enough TRU has been harvested in reprocessing to fabricate fuel for a fast reactor

core, a fast reactor is loaded and started up. It is assumed that plant construction was started five years before that time and is now complete. The amount of TRU fuel needed to fuel a fast reactor core is 4 MT. Two reloads are needed in addition to the initial core load before new TRU fuel can be assigned to the second fast reactor. A core reload is 1/3rd of an initial core. One third of the core is replaced every 1.5 years so that a complete core changeout occurs every 4.5 years. The 1/3rd of the core taken out and replaced by the reload is referred to as an xload. The first xload must decay for at least one year after being taken out of the reactor before it can be processed. To simulate the above in a model with year to year increments of time, it is assumed that the 4 MT/4.5 Yr = 0.889 MT/Yr spent fuel is removed from a fast reactor. Then a two year delay is assumed before it can be processed.

The net amount of TRU which must be supplied annually to fuel a fast reactor is 0.889 * (1 – BR). In this model, 0.889 MT of TRU is taken from the TRU fuel reservoir as input to the reactor and the 0.889 * BR MT is added to the TRU reservoir after the fast fuel is processed (two years after). The TRU which is fissioned in a year can also be estimated by

$$M_{TRU} = \frac{3000\ MW_t * 365\ days * (capacity\ \ factor = 0.85)}{MW_t d / 0.95\ gm} = 0.889\ MTTRU / GW \quad \text{(Eq.2)}$$

Spent fuel from both thermal and fast reactors (referred to here as thermal and fast spent fuel) are processed in the same facility so that in a 100 MT/Yr facility, if 9.3 MT/Yr of fast spent fuel is processed, then only 90.7 MT/Yr of thermal spent fuel can be processed. For each operating fast reactor, 9.3 tonnes of HM are produced as spent fuel annually. This contained the 0.889 MT of TRU when it was loaded into the core.

$$D_{FR} = \frac{3000\ MW * 365\ days * (capacity\ \ factor = 0.85)}{100{,}000\ MW_t d / MTHM} = 9.31\ MTHM / GW \quad \text{(Eq.3)}$$

The fuel downloaded from a fast reactor each year that must be processed is 9.3 MT/Yr is assumed independent of the amount of TRU in it (i.e., the breeding ratio). This is actually true only for BR=0.5 because it will not have blanket assemblies. For larger breeding ratios greater than 0.5, they will have blanket assemblies which must be processed also to get the TRU that is produced in them. [4] For BR=1, this is approximately an increase of 25%. This effect has not been included in the model but should not change the conclusions drawn.

Reprocessing of fast fuel takes precedence over processing thermal fuel because less fast fuel needs to be processed to produce a unit of TRU fuel than thermal fuel. So 9.3 tonnes of spent fuel from the fast plant must be processed to produce 0.889*BR MT of TRU. For BR=0.5, 20.9 tonnes of this spent fuel must be processed to produce one tonne of TRU fuel. For BR=1.0, 10.46 tonnes of this spent fuel must be processed to produce 1 tonne of TRU fuel. From a thermal plant 100 tonnes must be processed to produce one tonne. In addition, the front end oxide reduction process is not performed to process the metallic spent fuel from the fast reactors. Thus, it is less expensive to reprocess the fast fuel.

The change in the amount of non processed spent thermal fuel NPF (that is, the thermal fuel left to process) is equal to the amount added from the number of thermal reactors (GWT) that year minus the amount of thermal fuel processed last year, THMP.

$$NPF_{i+1} = NPF_i + GWT_{i+1} * 20.7 - THMP_i \quad \text{(Eq.4)}$$

The reprocessing plant throughput (HMP) is limited by the size of the plant (RPS) as well as the amount of spent fuel available to process, that is, the Fast Reactor Fuel to process (FRFP) plus the non processed thermal fuel. In a given year:

HMP = MIN (RPS, FRFP + NPF) (Eq.5)

Most of the thermal spent fuel will be aged at least several years before it is processed. In the cases where the thermal reactors are shut down several years before all the thermal fuel has been processed, all the fuel will be aged. In some scenarios where the thermal plants continue to run, this is not true in the later years. In the later years in scenarios where thermal plants continue to run, thermal spent fuel is processed in the year it is produced. Although there should be a delay in reprocessing this fuel, his effect has been neglected in this model but including the effect would not affect the conclusions.

The annual change in TRU fuel in the reservoir is equal to 0.01 times the thermal fuel reprocessed each year minus the amount used to fuel a fast reactor core minus the amount used in core reloads plus the amount harvested from reprocessing fast reactor fuel. In mathematical notation, this change is represented in Equation 6. Each term mentioned above corresponds to each of the terms in Equation 6 as

$$TRU_{i+1} = TRU_i + THMP_{i+1} * 0.01 - (GWF_{i+1} - GWF_i) * 4 - GWF_{i+1} * 0.889 + GWF_{i-1} * 0.889 * BR \quad \text{(Eq.6)}$$

The TRU reservoir is used to estimate when to start a new fast reactor plant. If starting causes the TRU to go negative, then the plant is delayed a year or more until the TRU does not enter into negative territory.

RESULTS

Fast reactors can be designed to produce the breeding ratio most conducive to either reducing plutonium or to producing power, to convert existing sites to all fast reactors or to keep the majority thermal. Three scenarios are described using, BR=0.5, BR=1.0, and BR=1.3 to convert 2 thermal plant sites to Nuclear Islands resulting respectively in 2, 4, or 6 fast reactors. In addition, two scenarios are presented where sites are converted to two thermal reactors, two fast reactor Nuclear Islands or to four thermal reactors, two fast reactor Nuclear Islands. The scenario chosen in the US will depend upon the future power increase needed from nuclear reactors and what percentage of fast reactors will be allowed. It must be a minimum of 33%. Without the fast reactors, there can be no Nuclear Island.

Site Conversion from Two Thermal to Two Fast Spectrum Plants (BR=0.5)

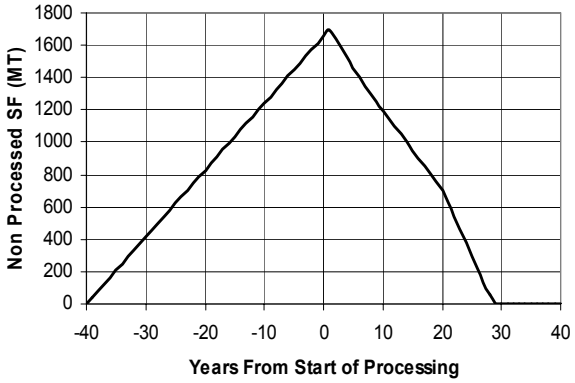
A breeding ratio of 0.5 used in the fast reactors added to a reactor site will allow it to be converted from a two thermal reactor site to two fast reactor sites over a 40 year time frame. As in all these examples, the site initially contains two 1000 MWe unit thermal reactors. Construction of a 100 MT/Yr reprocessing plant construction begins 36 years after initial operation of the thermal plants. The reprocessing plant is completed in year 40 and begins reprocessing spent fuel. Simultaneously with the start of reprocessing, construction on a 1000 MWe fast reactor plant is begun. The processing consists of reducing spent oxide fuel to metal and electrorefining the metal to produce TRU, DU, and fission products. The TRU and DU are processed to produce metallic fast reactor fuel of the type developed in EBR-II and the fission product waste form is sent to Yucca Mountain for 300 year storage. [5] The fission product waste form has one fifth the heat and volume of the original spent fuel and only uses one fifth the space.

At the end of four years of operation, enough fuel has been processed to fuel a fast reactor. The fast reactor is assumed to be built, to be ready to accept this core, and to begin operation. Another three years is required to produce the two reloads (each 1/3 core) needed for operation. The first reload is needed after 1.5 years of operation, at which time, it is inserted in the core and the first xload is removed from the core to allow it to cool for one to two years before reprocessing can occur. Since an electrochemical process is being used, only one or two years of cooling are required before reprocessing can occur. After another 1.5 years, the second reload is inserted in the core and the second xload is removed. The first xload is now added to the reprocessing line since it has cooled long enough. It produces more TRU/MT of spent fuel processed than the thermal fuel and the amount depends on the breeding ratio designed into the fast reactor. Since the same reprocessing facility is used for both fast and thermal spent fuel, the spent fast reactor fuel processed reduces the amount of thermal fuel which is processed. The fast fuel has an advantage in processing in that it does not have to be reduced to metallic fuel since it is already metallic. Some of the thermal fuel which is processed at this time will be used to fuel the second fast reactor. The rate of TRU production which is allotted to the second reactor is reduced by the amount of TRU needed for reloads in the first reactor which is high in this case because the breeding ratio is 0.5.

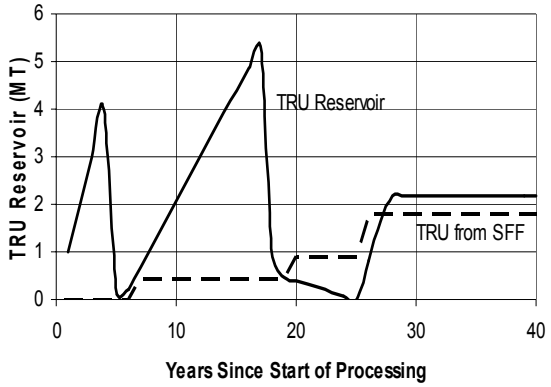
The time history of non-processed spent fuel is shown in Figure 1a for this case. The spent fuel is seen to build up for the first 40 years of plant operation and to begin to decrease with the operation of the reprocessing plant. The rate of decrease is the largest during the fabrication of the first core load and two reloads which takes seven years after the reprocessing plant commences operation. After that, the decrease in the non processed fuel per year lessens because the fuel from the fast reactor must be processed and cuts down on the thermal fuel reprocessing. Eighteen years after processing begins, manufacture of the fuel for the second fast reactor is completed so the slope changes again. Two years after that, the two thermal plants are assumed to run out their license extension and are shut down. With no additional thermal spent fuel being generated, the stockpile of this spent fuel reduces to zero within another seven years. At that time, the supply of TRU fuel to

the fast reactors becomes insufficient and the breeding ratio must be increased to one for continued operation of the reactors. For any scenario, such as this one, which ends up with only fast reactors, the breeding ratio must be adjusted to one.

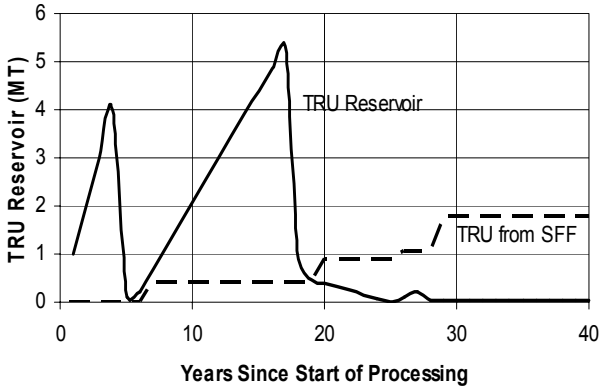
The time history of the TRU fuel reservoir is shown in Figure 1b. The first two precipitous drops are due to the new fast reactors coming on line when the core inventory of four metric tonnes of TRU is loaded. A delay of two years in the loading of the second reactor was taken in order to prevent a negative TRU inventory to occur due to additional fuel needed for reloads. The TRU inventory would have become negative in the year 26. To prevent having to bring in TRU from an outside source, the breeding ratio of the fast reactors was changed to one at Year 26. This change was adequate and caused the TRU reservoir to increase to about 2.2 metric tonnes and to stay at that value. All the archived spent fuel had been processed by year 29. Thereafter, the TRU reservoir becomes constant because there are only two fast reactors which use as much TRU as they produce. The excess in the TRU reservoir can be easily be reduced. For example, increasing the breeding ratio to 0.6 in Year 26 for three years until all the archived spent fuel is processed and then to 1.0 yields the time history for TRU in Figure 1c which is almost zero after year 28. The TRU from Spent Fast Fuel (SFF) is also shown in 1b and 1c.



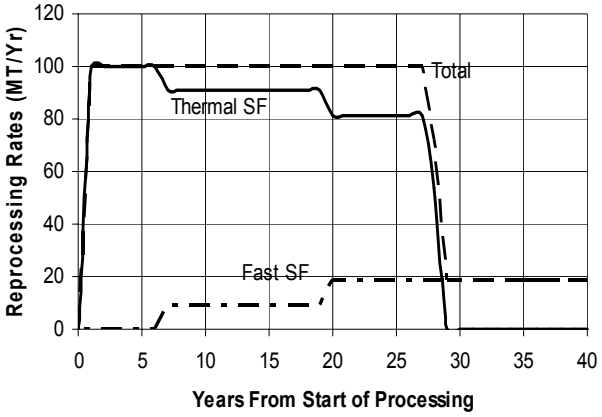
a. Thermal Reactor Spent Fuel Inventory.



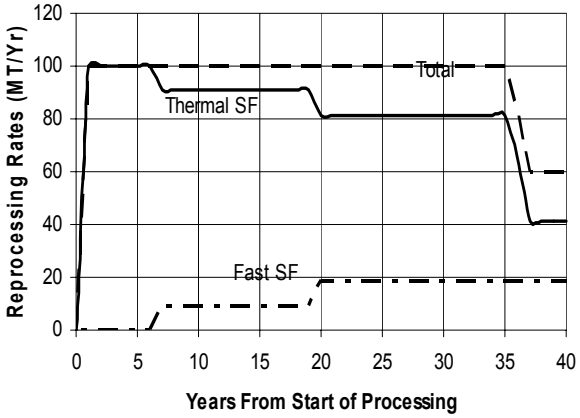
b. Time History of TRU Reservoir.



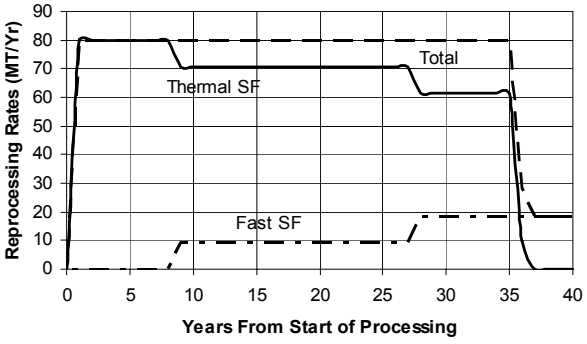
c. TRU Reservoir with Modified Increase in Breeding Ratio.



d. Time History of the Reprocessing.



e. Reprocessing Rates Needed for Continued Thermal Plant Operation.



f. Effect of Reducing Reprocessing Plant Size.

Fig. 1 Site Conversion from Two Thermal to Two Fast Spectrum Plants (BR=0.5)

Two problems are noted with this scenario. The first is that the total reprocessing rate shown in Figure 1d drops to the reprocessing rate for the fast reactor fuel in Year 28 which means that the reprocessing plant is only used at 19% of capacity soon after the thermal plants are shut down when the thermal fuel has all been processed. The power output from the site is also a problem if an increasing power is desired since the power goes from 2000 MWe to 3000 Mwe in year five, to 4000 Mwe in year 18, and back to 2000 Mwe in year 21 when the thermal plants are shut down.

Several possibilities exist for resolving these problems. The first would be to extend the license of the thermal plants by another 20 years and change the breeding ratio to 0.6 at year 26. This increased breeding ratio and the extra thermal spent fuel supplies enough TRU until the reservoir of spent fuel drops to just the amount added each year and then the breeding ratio must again be increased, say to 0.75 for the last four years. The reprocessing rate for this case is shown in Figure 1e where it is seen that the total reprocessing rate remains at 100% until the year 35, which is not a benefit since it will cost more to run the plant at 100% for more years. A benefit is that the power remains constant until the year 40 since the thermal plants continue to operate. However, this scenario also has its drawbacks since the thermal plants will probably have to be replaced at year 40 but there are only two fast reactors on the site with insufficient TRU to fuel more so that it may be necessary to replace the thermal plants with new thermal plants with the consequent requirement to supply fresh thermal reactor fuel. There is a trade off on cost with fast reactor plants being more expensive than thermal plants but supplying reload fast reactor fuel from reprocessing fast reactor spent fuel would be less expensive than from spent thermal reactor fuel.

Effect of Reprocessing Plant Size (BR=0.5)

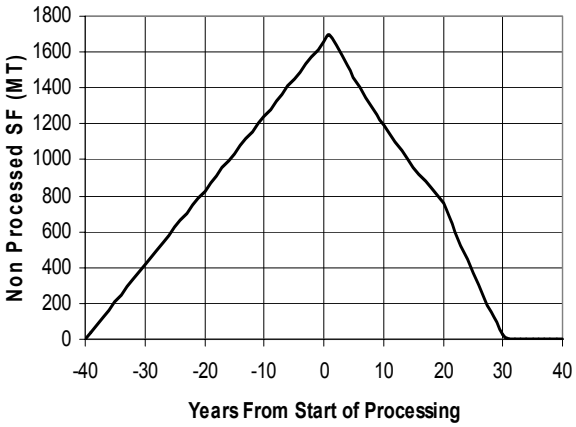
Capital costs would be less if the reprocessing plant on each Nuclear Island were smaller but this section shows that reprocessing plants on the order of 100 MT/Yr are close to ideal for Nuclear Islands. Much larger plants are appropriate if the decision is made to use central reprocessing [6] but would not work here. Much smaller would not work either. This section investigates a slightly smaller plant size and shows that it is just barely adequate. Figure 1f illustrates the effect on reprocessing when the plant size is reduced to 80 MT/Yr.

It is seen that processing produces sufficient TRU fuel for the first fast reactor to begin operation in Year 7 and the second to begin operation in Year 26. The breeding ratio is increased to 0.7 at the same time as the second plant starts up to supply sufficient TRU fuel. The spent fuel is completely reprocessed by Year 36 and the breeding ratio must be increased to 1.0 at that time. The processing plant is used at full capacity out to year 35. If the plant has reached its end-of-life at this time, it could be replaced by a smaller plant which only reprocesses the fast reactor spent fuel. A problem with this scenario is that when the thermal reactors are shut down in Year 21, there is only 1000 MWe being generated at the site until Year 26 when the second fast reactor is started. If the thermal plants are extended to run to Year 26 to provide more power, the thermal spent fuel will still all be processed by Year 39. Thus the smaller reprocessing plant size is practical but tends to delay when the conversion occurs to the fast reactors so is dependent upon being able to get a further plant life extension for the thermal plants.

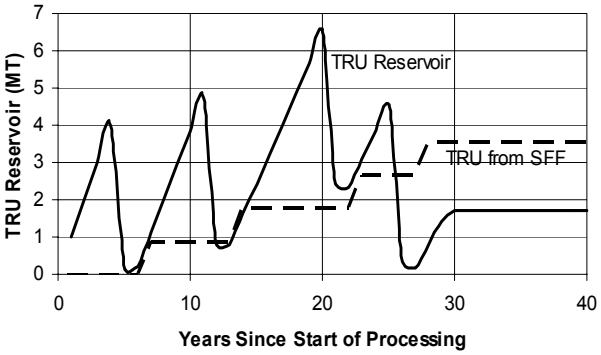
Both this and the previous scenario with breeding ratios of 0.5 do not increase total site power but do convert the site from two thermal reactors to two fast reactors over 36 years. The breeding ratios of the fast reactors must eventually be increased to one toward the end of the first forty years of operation.

Site Conversion from Two Thermal to Four Fast Spectrum Plants (BR=1.0)

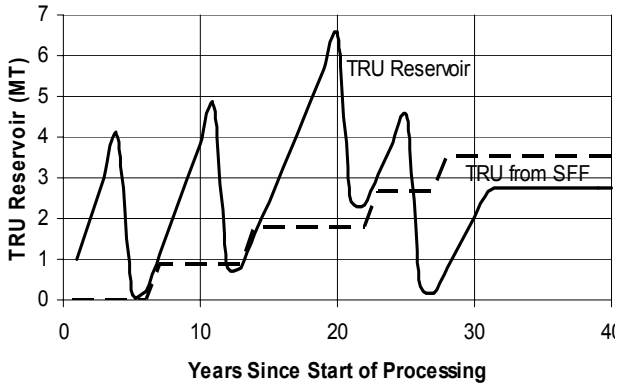
This case increases power from two thermal plants to four fast reactor plants and begins with the same assumptions as the previous section; however, the fast reactors utilize a breeding ratio of 1 in their design. Due to the quicker build up of TRU fuel, the fast reactors are brought on line more quickly. The non processed spent fuel inventory is shown in Figure 2a. It takes slightly longer to process all the spent fuel in this case than the breeding ratio 0.5 case because more fast fuel must be processed to operate the fast reactors.



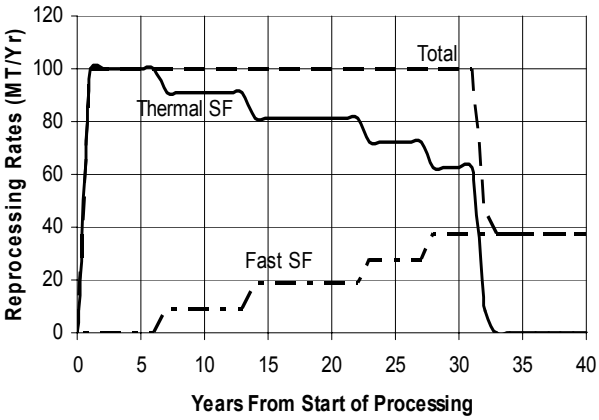
a. Thermal Reactor Spent Fuel Inventory.



b. TRU Fuel Inventory, Thermal Plants 60 Years Service.



c. TRU Fuel Inventory, Thermal Plants 60, 65 Years Service.



d. Processing Rates, Thermal Plants 60, 65 Years Service.

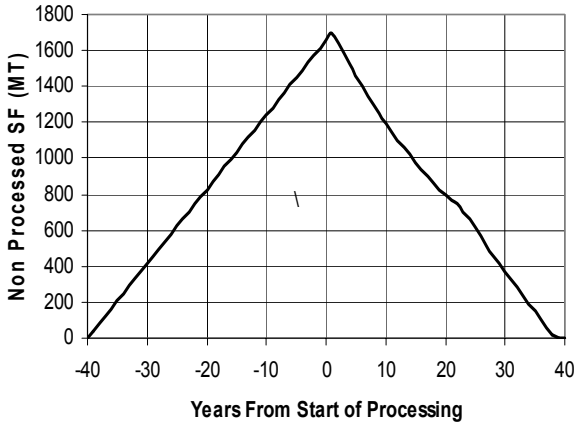
Fig. 2 Site Conversion from two thermal to four fast spectrum plants (BR=1.0)

The TRU fuel inventory is shown in Figure 2b. The large decreases again indicate when new fast reactor plants are brought on line. Breeding ratio doesn't affect the initial plant, so, as before, it starts in Year 5. The second plant comes on much earlier at Year 12. In year 21, the two thermal reactors will have produced enough spent fuel to supply plutonium for a third fast reactor. Even though the thermal plants are shut down at this time, there is still enough spent thermal fuel to process to produce enough TRU metallic fuel for a fourth fast reactor in Year 26. There may be some logistic difficulty in replacing one of the thermal reactors in Year 21 with a fast reactor which could cause some delay in starting this reactor. This could cause additional TRU reservoir buildup in the steady state (i.e., after the fourth fast reactor is started up in Year 26). If that buildup is undesirable or if the steady state value shown in Figure 2b (1.8 MT) is too high or too low, the breeding ratio can be adjusted temporarily to bring the reserve into desired compliance. This scenario has a steady output of 4000 MWe after the second fast reactor plant is started except for a five year period from Year 21 to 26 when both thermal plants have been shut down and only three fast reactor plants are operating. Only one of the 60-year-old thermal spectrum plants should be retired from service at age 60 and the other operated until the fourth fast reactor comes into service. The TRU Inventory is shown in Figure 2c. The steady state inventory is higher since more thermal spent fuel was processed. Again, this could be lessened by using a lower temporary breeding ratio.

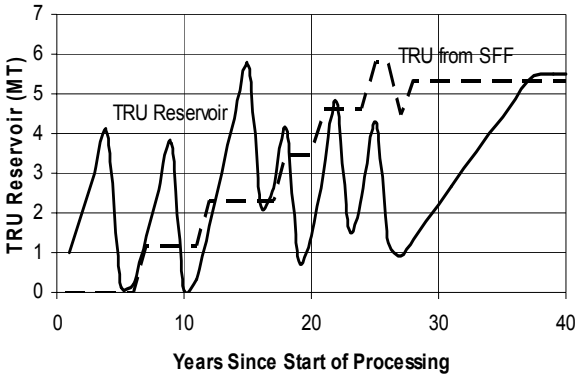
The reprocessing rates for this constant 4 GWe power profile is shown in Figure 2d. The reprocessing plant is utilized out to Year 32 at 100% capacity and afterward at 40%. The processing plant may only have a plant life of 32 years and would be replaced by a smaller 40 MT/Yr plant to process only the metallic fast reactor fast fuel.

Site Conversion from Two Thermal to Six Fast Spectrum Plants (BR=1.3)

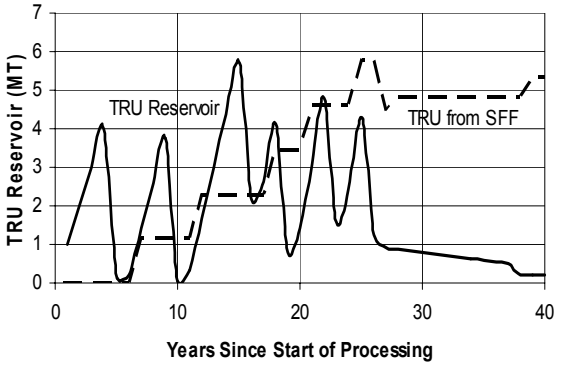
This breeding ratio has the capability of converting two thermal reactor sites to more than six fast reactor sites and would apply to sites with enough room for these additional reactors. The non processed fuel is shown in Figure 3a. Processing all the spent thermal fuel takes longer than previous cases because of the added fast reactor spent fuel processed to operate the fast reactors.



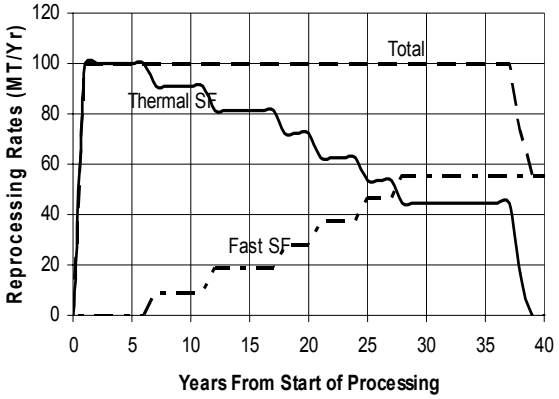
a. Non Processed Fuel Inventory (BR=1.3).



b. TRU Fuel Inventory (BR=1.3).



c. TRU Fuel Reservoir (BR=1.3 then reduced to 0.91).



d. Reprocessing Rates (BR=1.3 then reduced to 0.91).

Fig. 3 Conversion from two thermal to six fast spectrum plants (BR=1.3)

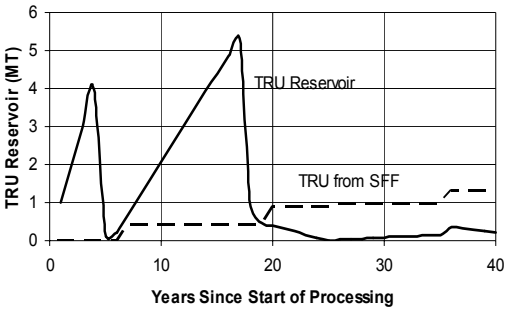
The TRU fuel inventory is shown in Figure 3b. The start of each fast reactor is indicated as before with drops in the TRU inventory of four MT. These reactors are started in Years 5, 10, 16, 19, 23, and 26 respectively. The increase in power at the site occurs steadily. The first thermal reactor is assumed shut down in Year 23 as the fifth fast reactor comes on line. Similarly, the second thermal reactor is shut down when the sixth fast reactor plant comes on line in Year 26. Thus the power output is kept constant at six GWe once the fourth fast reactor is brought on line.

In order to decrease the steady state TRU inventory, the breeding ratio may be reduced after the sixth fast reactor has been started. Figure 3c shows the effect of this reduction. The breeding ratio is reduced to 1 in Year 27, then to 0.91 in Year 28 where it is held constant until all the thermal fuel has been processed by Year 38. Then the breeding ratio is increased to 1.0 again in Year 39 and kept constant.

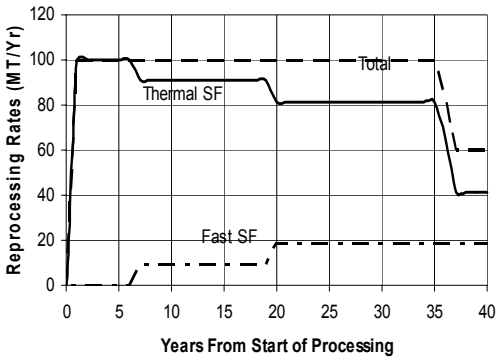
The reprocessing rate, shown in Figure 3d, runs at 100% out to Year 37 and then reduces to 58% when all the thermal spent fuel is completed. So the reprocessing plant is used much more effectively in this scenario.

Site Conversion to Two Thermal and Two Fast Spectrum Plants (BR=0.5)

Due to the additional expense of fast reactor plants over thermal plants, it may be more desirable to continue to use thermal plants even with no offsite shipments of spent nuclear fuel. The first two thermal plants are shut down after 60 years of operation but are replaced by two new thermal plants or the license extensions. Two fast reactors are added to the site in a similar manner as in the breeding ratio=0.5 scenario. The resultant TRU inventory is shown in Figure 4a. The fast reactor plants are started in Years 5 and 18. After the second fast reactor plant comes on line, the TRU inventory begins to decrease because of the additional demand for TRU from the second plant. It would go negative in Year 26 so the breeding ratio is increased to 0.55 in Year 26 to prevent this. The stockpile has been completely processed by Year 37so that the only source of thermal spent fuel is the thermal reactors discharge of 41.4 MT/Yr. To supply enough TRU, the BR is increased to 0.75 in Year 36.



a. TRU Fuel Reservoir.



b. Reprocessing Rates.

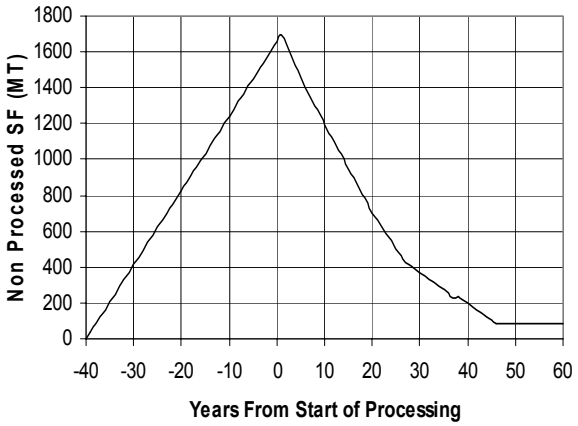
Fig. 4 Conversion to Two Thermal, Two Fast Spectrum Plants (BR=0.5, then to 0.55 and then 0.75)

The reprocessing rates are shown in Figure 4b. It decreases to meet the spent fuel available for reprocessing in Year 37. The site has reached a steady state of 60% reprocessing and will remain constant as long as two thermal reactors and two fast reactors operate at this site.

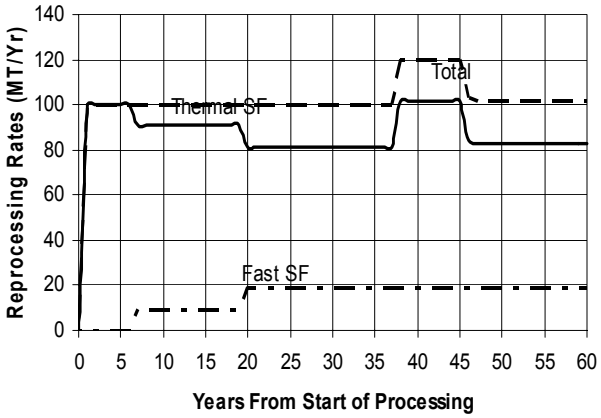
Site Conversion to four Thermal, Two Fast Spectrum Plants (BR=0.5)

The minimum practical breeding ratio is about 0.5[6]. Four thermal plants produce a total of 82.8 MT of heavy metal. The 1% TRU in this fuel produces 0.828 MT of TRU. Each fast reactor plant of breeding ratio 0.5 needs about 0.44 MT of replacement TRU/yr so two fast reactor plants burn 0.88 MT/Yr, a bit more than the four thermal plants produce. The added TRU needed at steady state can be obtained with a slight increase in breeding ratio above 0.5. Thus, this scenario represents the maximum ratio of thermal plants to fast reactor plants.

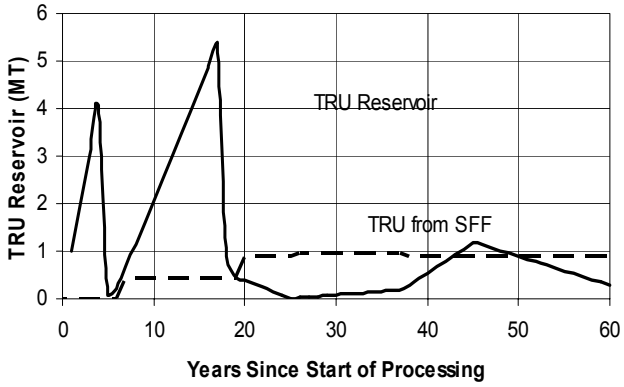
The non-processed fuel for this scenario is shown in Figure 5a. More than 40 years after the reprocessing plant startup is required to reach a steady state. The two fast reactors are started in Years five and 18. The fast reactors are built before the third and fourth thermal reactors to minimize transient TRU inventory. Thermal plants one and two operate throughout either by life extensions or replacing the plants. The timing of thermal plants three and four is not critical. In this study, the third thermal plant is started in Year 28, ten years after the second fast reactor plant. It causes a noticeable bend in the non processed fuel curve, Figure 5a, since it is adding 20.7 MT/yr. The fourth thermal plant is started in Year38, ten years after the third. The 100 MT/Yr reprocessing plant is now inadequate to process all the spent fuel so an additional 20 MT/Yr plant is added. Without this added capacity, the non processed fuel starts to climb but with it, the non processed fuel continues to decline. It declines until all the archived spent fuel has been processed. Then it becomes constant as the total reprocessing rate drops from the rated 120 MT/Yr to 101.4 MT/yr, the steady state output from the thermal and fast reactors.



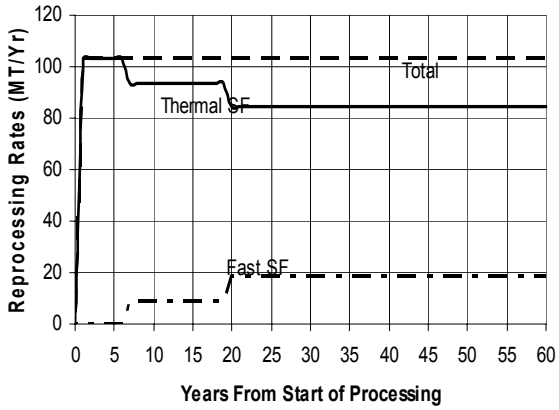
a. Non Processed Fuel.



b. Reprocessing Rate.



c. TRU Fuel Reservoir.



d. Increased Processing Rate of 103 MT/yr.

Fig. 5 Conversion to four thermal, two fast spectrum plants (BR=0.5, increased to 0.55 and then 0.5)

The reprocessing rate is shown in Figure 5b. The additional 20 MT/Yr, started in Year 38, is needed until processing of the archived fuel is finished (Year 45) when the reprocessing rate decreases to the steady state value of 101.4 MT/Yr. There is considerably more processing with this option and these costs plus continual new nuclear fuel costs must be weighed against the additional cost of fast reactors in the other scenarios.

The TRU reserve is shown in Figure 5c. The startups of the two fast reactor plants are evidenced by sharp drops in the level. A slow decline occurs after the second plant comes on line due to the decrease in the available thermal processing. To keep the TRU reserve positive, the breeding ratio is increased to 0.55 in Year 26 and kept at that value to Year 38 when it is returned to 0.5. The additional TRU needed then is supplied by the added 20 MT/Yr reprocessing plant. The TRU reserve then rises until Year 46 when the archive thermal spent fuel is depleted when it decreases slowly. After Year 46, BR can be increased slightly to get a constant TRU reserve when the reservoir decreases to the desired amount.

Alternatively, the reprocessing plant can be built initially for 103 MT/Yr to yield a reprocessing rate curve that remains constant, as shown in Figure 5d, until Year 59 then drops a small amount. In this modification, the reprocessing plant is used at almost 100% continuously. It was necessary to increase the breeding ratio to 0.55 between Years 42 and 46 to prevent having to transport TRU from off-site.

CONCLUSIONS

The conversion of existing plant sites to Nuclear Islands would eliminate the need for long term repository storage of plutonium. This conversion would not be done on a rush basis but over decades by beginning now with older sites reaching

or having reached spent fuel storage capacity. If the conversion is carried out when each site reaches this stage, over the next 40 to 100 years, all of the existing commercial nuclear sites can be converted to Nuclear Islands. The conversion would be initiated at any given site with the construction of a 100 MT/Yr reprocessing plant. Fast reactors can be designed to produce the breeding ratio most conducive to either maintaining current power levels or increasing power to match increased electrical demands, and to either convert existing sites to all fast reactors or to keep the majority thermal. Scenarios have been investigated using, BR=0.5, BR=1.0, and BR=1.3 to convert two thermal plant sites to Nuclear Islands with respectively two, four, or six fast reactors. In addition, scenarios were presented where two thermal reactor sites could be converted to two thermal reactors, two fast reactor Nuclear Islands or to four thermal reactors, two fast reactor Nuclear Islands. The latter case yields the 2/3rds thermal, 1/3rd fast reactor ratio and is close to the maximum thermal to fast reactor ratio possible and still meet the no spent fuel shipping requirement.

Fast reactors must be part of a Nuclear Island to first sequester the TRU which exists in the spent nuclear fuel on site and then to fission the annual production of spent fuel from thermal reactors and supply any additional TRU needed to run the fast reactors. Without the fast reactors, there can be no Nuclear Island. The criteria to select the best Nuclear Island conversion scenario would depend upon many factors but primarily economics and how effectively the US intends to use its total uranium supply. In all of these examples, no spent fuel would ever have to be shipped off site. Only fission products would be disposed of in Yucca Mountain. However the last scenario, four thermal and two fast reactors, would leave a lot of wasted depleted uranium. The author would like to see the scenario adopted which converts two thermal reactors to six fast reactors since this most fully uses uranium and triples the nuclear power. Hopefully, the additional nuclear plants would be in place of fossil fuel plants. Detailed cost estimates of each scenario are beyond the scope of this paper but the total cost of each may be similar per GWh. The all fast reactor options offer the advantage of reprocessing much less spent fuel than the two thermal reactor scenarios, but fast reactors are more expensive to build than thermal reactors (25%). Reprocessing also produces cost savings since it decreases the volume and heat load which must by handled in Yucca Mountain by a factor of 5.

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REFERENCES

1 Till, C. E., Chang, Y. I., and Hannum, W. H., "*The Inegral Fast Reactor-an Overview*," Progress in Nuclear Energy, Vol 31, Pp. 3-, 1997.

2 Nifenecker, H., et. al., "Scenarios with an Intensive Contribution of Nuclear Energy to the World Energy Supply," Global 2001, September 9-13, 2001.

3 Battisti, T. J., Goff, K. M., Bateman, K. J., Simpson, M. F., and Lind, J. P., "*Ceramic Waste Form Production and Development at ANL-West*," American Nuclear Society's Fifth Topical Meeting on Spent Nuclear Fuel and Fissile Materials Management, Charleston, SC, September 17-20, 2002.

4 Till, C. E., and Chang, Y. I., "*Evolution of the Liquid Metal Reactor: The Integral Fast Reactor (IFR) Concept*," American Power Conference, Chicago, IL, April 24-28, 1989.

5 Solbrig, C. W., Lineberry, M. J., and Benedict, R. W., "*Repository Storage Strategy with Central Station Reprocessing*," Proceedings of ICAPP'03, Cordoba, Spain, May 4.-7, 2003.

6 Hill, R., Wade, D., Liaw, J., and Fujita, E., "*Physics Studies of Weapons Plutonium Disposition in the Integral Fast Reactor Closed Fuel Cycle*," Nuclear Science and Engineering, 171:17-31, 1995.