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S-PRISM Fuel Cycle Study

For Session 3: Future Deployment Programs and Issues

Allen E. Dubberley*
GE Nuclear Energy
175 Curtner Avenue, San Jose, CA 95125-1006
Phone (408) 925-2145, Fax (408) 925-3991
E-mail: Allen.Dubberley@gene.ge.com

Charles E. Boardman
GE Nuclear Energy

Douglas G Carroll
GE Nuclear Energy

Chester Ehrman
Burns and Roe
(retired)

Carl E. Walter
Lawrence Livermore National Laboratory
(retired)

Abstract – *This paper assesses the environmental and economic impact of introducing S-PRISM reactors to the U.S. grid during the first quarter of the 21st Century. The study predicts the number and timing of new fuel cycle facilities that will be required to an expanding fleet of S-PRISM based Liquid Metal Fast Reactors (LMRs). The calculated fuel cycle cost of less than 5 mills/kW-hr when combined with a plant capital cost of less than 1300 \$/kWe*[1-4] *assures that the busbar cost will be competitive with other energy generating systems. The fuel cycle cost is based on the required rate of return from the construction and operation of the reprocessing facilities divided by the number of kWhr/year produced by the expanding fleet of S-PRISM based fast reactors. The capital cost and operating costs of the reprocessing facilities are based on a detailed conceptual design developed by Burns and Roe during the DOE sponsored ALMR program* [5-7].

Two introduction scenarios are compared. In both scenarios S-PRISM power blocks are built at a rate that adds 1520 MWe per year to the generating system. Both scenarios arbitrarily assume that the construction continues for 25 years at which point 38,000 MWe of S-PRISM based fast reactors have been added to the system. The first scenario assumes that the S-PRISM cores operate with a breakeven breeding ratio. In this scenario, the fuel derived from reprocessing spent S-PRISM fuel maintains the existing plants. The fissile material required for new (startup cores) must be extracted from spent LWR fuel. The second scenario evaluates the use of a core with a breeding ratio of 1.22. This option requires less LWR-derived fuel and thus would allow more LMRs to be started, or at a faster rate, than is possible in the first scenario. However, the mass of LWR spent fuel that must be processed to launch 38,000 MWe of S-PRISM based fast reactors decreases from 70,000 MTHM for the breakeven cores to 56,000 MTHM with the high breeding ratio cores.

The results also show that the present 40,000 tonne inventory of spent LWR fuel will be processed and conditioned for disposal within 35 years or less. The capacity of a heat load limited repository like Yucca Mountain would be increased by a factor of 4 or more, and the period that the repository’s LWR based spent fuel waste would remain more toxic than the original ore would be reduced from millions of years to less than 500 years significantly reducing the long term risk to the environment while making future repositories more acceptable to the public. If larger three block plants rated at 2,280 MWe were built on the same 25 year schedule, the total inventory of spent LWR fuel that will be produced by the present U.S. fleet of LWRs during their operating lifetime (86,000 tonnes) would be processed, the residual energy recovered, and the fission product waste conditioned for disposal. This approach would postpone the time when an additional repository like Yucca Mountain would be needed. An additional finding was that the risk of proliferation would be reduced by replacing the need for additional LWR enrichment facilities with proliferation resistant dry pyroprocessing facilities where the spent and new fuel must be handled in heavily shielded and inerted hot cells and transfer casks at all times.

I INTRODUCTION

S-PRISM is an advanced Fast Reactor plant design that utilizes compact modular pool-type reactors sized to enable factory fabrication and an affordable prototype test of a single Nuclear Steam Supply System (NSSS) for design certification at minimum cost and risk. Based on the success of the previous DOE sponsored Advanced Liquid Metal Reactor (ALMR) program GE has continued to develop and assess the technical viability and economic potential of an up rated plant called SuperPRISM (S-PRISM) [1-4].

S-PRISM retains all of the key ALMR design features including passive reactor shutdown, passive shutdown heat removal, and passive reactor cavity cooling that were developed under the earlier DOE program. The reference S-PRISM plant is made up of three power blocks, each of which contain two independent 1000 MWt reactor systems. Since each of the three power blocks has a net output of 760 MWe the total rating of a three power block site is 2280 MWe; however, the size of the site could be limited to 760 MWe until the utility decides to add the additional power blocks.

II. DESCRIPTION OF SCENARIO AND COSTING BASIS

The Fast Reactor (LMR) power generation cycle is assumed to be started by reprocessing spent LWR fuel to extract the fissile material required to fabricate the initial startup cores and initial reloads. Once the LMR fuel production capability reaches breakeven, all fuel is supplied by recycling spent LMR fuel. Until fissile breakeven is reached, a mixture of LWR-sourced fuel and LMR-sourced fuel is required to maintain the LMR power generation cycle. Figure 1 illustrates the fuel and waste flows during the introduction of LMRs to the US power grid.

The initial startup cores for the LMRs are obtained by processing spent LWR fuel in LWR Spent Fuel Recycle Facilities (LWR-SFRF). As shown in Figure 2, this facility receives spent LWR fuel, reduces the oxide fuel to metallic form and then uses a dry pyroprocess that is being developed by Argonne National Laboratory (ANL)[5,6,7] to separate the spent fuel into three process streams. Transuranic elements are fabricated into startup cores for newly constructed S-PRISM based fast reactors, uranium is used for S-PRISM fuel and breeder blanket assemblies, and the fission products and other process wastes are conditioned for waste disposal. A small fraction (0.1%) of the transuranics are assumed to pass through to the waste stream due to process inefficiency

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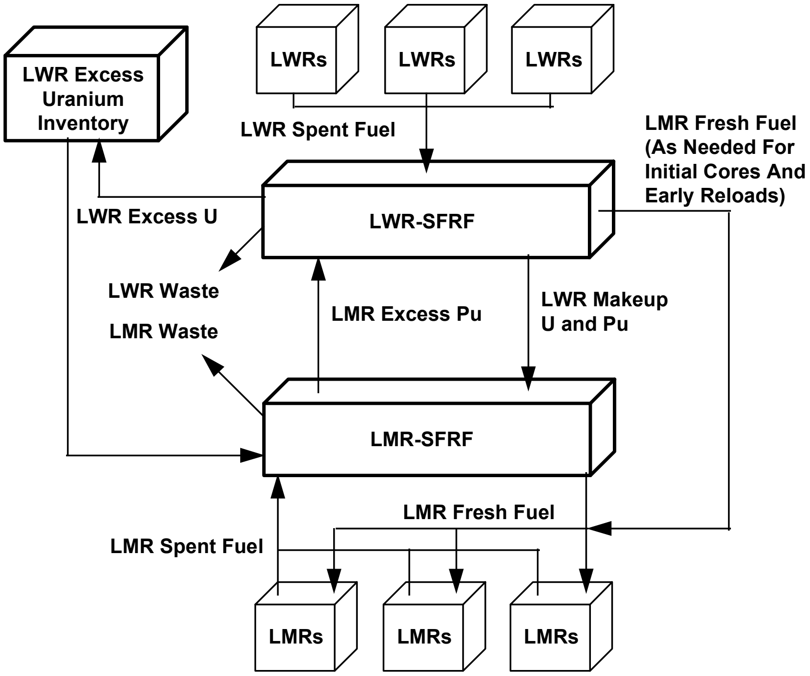

Figure 1 Fuel and Waste Flows During LMR/S-PRISM Introduction

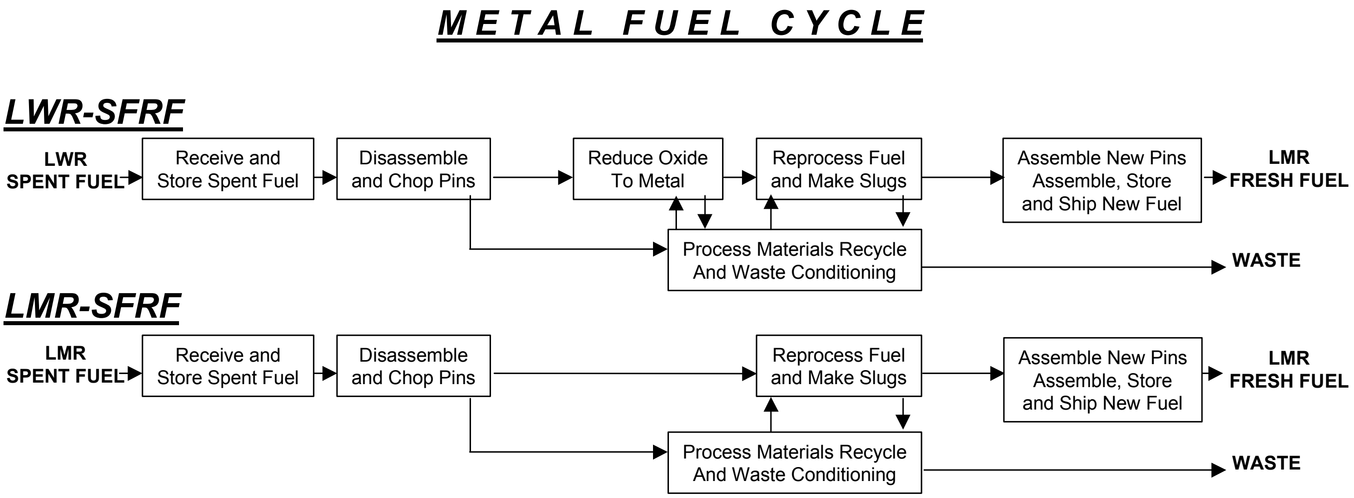

Figure 2 S-PRISM/LMR Spent Fuel Recycle Facility (SFRF) Functions

One of the advantages of utilizing spent LWR fuel as the fissile source for the initial (startup) LMR cores is that the fissile and fertile materials (Pu and minor actinides as well as the fertile uranium) are extracted for reuse and only the fission products, which amount to less than 3% of the material in spent LWR fuel, are sent to the repository. Since the fission products have short half-lives compared to the plutonium and minor actinides that are recycled, the length of time that the waste remains more toxic than the original ore is reduced from millions of years to less than 500 years as illustrated in Figure 3 reducing the risk of releasing highly radioactive materials to the environment.

Table 1 provides an estimate of the inventory of LWR generated spent fuel that was generated by the end of 2000 40,000 tonnes. Processing this fuel would produce enough fissile material to startup twenty-two 1520 MWe S-PRISM plants with a total output of 33,440 MWe.

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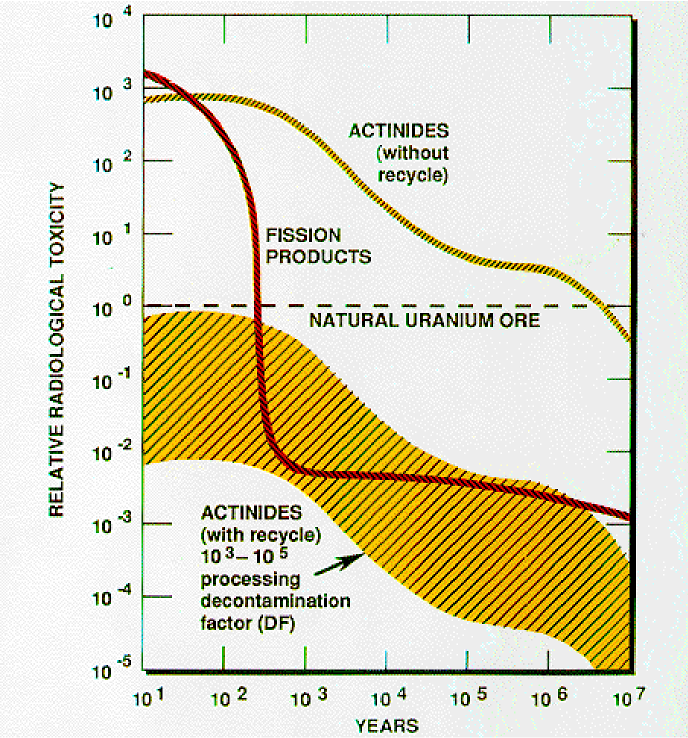

Figure 3 Time Phased Relative Waste Toxicity In Spent LWR Fuel

Table 1 Approximate U.S. Inventory of Depleted Uranium and Spent LWR Fuel (year 2000)

Total Generating Capacity	~ 103 GWe
Number of Operating Plants	103
Depleted Uranium In Storage, tonnes	700,000
Spent LWR Fuel In Storage, tonnes	40,000
Plutonium Contained In Spent LWR Fuel, tonnes	400
Minor Actinides In Spent LWR Fuel, tonnes	40
Total electrical generating capacity of S-PRISM plants who's startup cores and initial reloads can be obtained by processing the 40,000 tonnes of spent LWR in storage at the end of 2000, MWe	22,000.

Table II illustrates the impact that the operation of various reactor types would have on the need for uranium and spent fuel storage and disposal. A 1000 MWe LWR will produce about 1000 tonnes of spent fuel and require the production of about 11,000 tonnes of depleted uranium over its operating lifetime. While the S-PRISM based fast reactor produces very little waste and consumes less than 1 tonne of uranium-238 per year. By the time that the present U.S. fleet of LWRs complete their operating life the amount of fertile material (depleted uranium) and fissile material (Pu and minor actinides) that will be available to use as a secure long-term energy resource dwarfs all the other U.S. energy reserves as illustrated in Figure 4.

Table II Nuclear Material Use and Inventories by 1000 MWe Plants

Reactor Type	Thermal Efficiency (%)	Spent fuel / year (tonnes)	Depleted uranium produced / year (tonnes)	Natural uranium/year (tonnes)
LWR	33	18	200	215
PBMR[4]	45	8	195	200
S-PRISM	38	1[1]	-1 [2]	0[3]

(1) Fission products sent to the repository.

(2) Fast Reactors consume depleted uranium rather than producing it as a byproduct of the enrichment process.

(3) No additional uranium will need to be mined for hundred years because S-PRISM based fast reactors will be able to extract over 2100 TWy from the depleted uranium stock piles and spent LWR fuel (Figure3).

(4) Pebble Bed Modular Reactor.

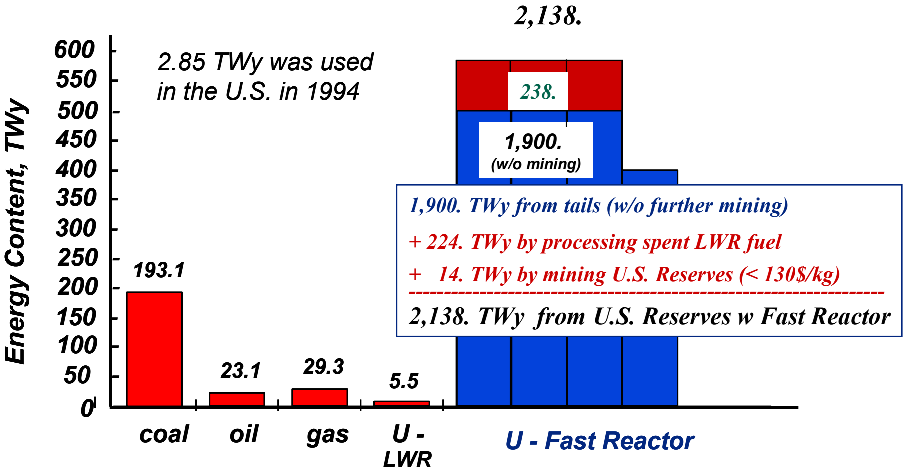

Figure 4 United States Energy Resources

Once sufficient spent S-PRISM fuel becomes available, LMR Spent Fuel Recycle Facilities are constructed to reprocess this source of fissile fuel. As shown in Figure 2, the LMR-SFRF is identical to the LWR-SFRF except for the initial step which reduces the spent oxide fuel to a metallic form to feed into the pyroprocessing equipment is omitted.

The cost of the processing facilities is based on a detailed conceptual design of the recycle facility developed by Burns and Roe in 1995[7] using information available from Argonne National Laboratory on pyrometallurgical fuel reprocessing, remote operations, material handling considerations, and detailed time and motion studies. Minor actinides (MA) are recycled with the fuel and returned to the reactor for continued transmutation. The current best-estimate facility costs were adjusted in accordance with the facility throughput. Both types of fuel cycle facilities are assumed to be centrally located plants serving a number of S-PRISM plants.

Table III summarizes the cost elements of the LWR-SFRF and LMR-SFRF. The two facilities are similar in design and function and have about the same fissile mass throughput. However, the difference in enrichment (about a factor of 10) between LWR and LMR fuel results in a large difference in total heavy metal throughput for the two reprocessing plants. The study applies non-inflated values, so interest and earnings rates are net of inflation and the costs are in 1997 dollars.

Table III Scenario Assumptions

	LWR-SFRF	**LMR-SFRF**
Capacity (MTHM per Year)	1000	100
Closure Basis	Decommissioned at end of life	Refurbishment over a 30 year period, not closed
Financial Cost Parameters		
Depreciation - Months	180	180
Monthly Interest Rate Paid on Debt (Annual %)	6.0	6.0
Income Tax Rate (%)	20.0	20.0
Property Tax Rate (%)	1.0	1.0
Financial Income Parameters		
Interest Rate Received on Savings (Annual %)	15.0	15.0
Required Internal Rate of Return (Annual %)	15.0	15.0
Facility Cost Parameters		
Year of Cost Definition	1997	1997
Facility ($)	127,000,000	127,000,000
Equipment ($)	107,000,000	82,000,000
Design ($)	57,000,000	57,000,000
Decommissioning ($)	29,100,000	
Operating Consumables ($/yr)	17,900,000	6,100,000
Average hardware ($/yr)	52,400,000	25,600,000
Maintenance ($/yr)	8,025,000	3,416,667
Refurbishment ($/yr)		5,325,000
Property taxes ($/yr)	2,910,000	2,660,000
Staff (Person-shifts)		
Exempt	210	176
Non-exempt	242	205

III KEY FUEL CYCLE MODEL ASSUMPTIONS

III A LMR Startup and Operation

The first S-PRISM power block begins operation on the first day of 2020 with an additional 760 MWe power block added every six months, until a total of 50 power blocks and 100 cores are installed. Since each two module power block is rated at 760 MWe both scenarios assume that 1520 MWe is added to the system every year.

Fuel for new cores is required at the S-PRISM plant 12 months before reactor startup. Reload fuel is required 6 months before cycle restart. Spent fuel is assumed to be stored in-reactor for two years before it is shipped to the LMR-SFRF.

Due to the relatively low fuel cycle cost, the S-PRISM plants are assumed to operate at full capacity once they are brought on line. Phased startup or load following are not considered.

The scenarios associated with break even and high breeding ratio core designs employ a common S-PRISM plant except that axial blankets are needed to achieve the higher breeding ratio. The axial blankets increase the processing throughput associated with the high breeding ratio cores.

III B SFRF Startup and Operation

The plutonium needed for initial S-PRISM cores and reloads is supplied by processing spent LWR spent fuel. The supply of LWR spent fuel is assumed to be inexhaustible.

The value of spent LWR fuel is assumed to be zero. As a result, the cost of plutonium in S-PRISM based fast reactor fuel is determined by the extraction costs from spent fuel.

Recycle processes are assumed to lose 0.1% of uranium and plutonium throughput to the waste stream.

The shipping time between the reactor and the processing plants and back is assumed to be 3 months in all cases.

Spent LWR fuel is assumed to be at the LWR-SFRF at the time it is required. The reprocessing and fresh fuel fabrication time is assumed to be 12 months at both the LMR and LWR-SFRFs.

The LMR-SFRF facilities are assumed to have a lifetime greater than the period of the study. This assumption is based on a continuous repair approach in which maintenance includes equipment replacement. Equipment replacement permits technology improvements to be incorporated into the existing facility, as the recycle technology grows more mature. The buildings and process cells do not require replacement, and in effect, the SFRFs are continuously replaced.

It is assumed that when new SFRFs are first started up that they are loaded in a linear ramp from 0% to 100% of capacity in 18 months.

The startup timing and operating strategy of the LMR-SFRFs is set to maintain an input spent fuel inventory sufficient to permit the SFRF to operate at maximum capacity at all times.

IV BASE CASE SCENARIO – 2 LMR POWER BLOCKS USING FISSILE BREAKEVEN CORES STARTED PER YEAR

The manner in which the inventories of spent LWR fuel is utilized and the rate that LWR-SFRF waste and LMR-SFRF waste is accumulated depends on the rate at which the S-PRISM plants are constructed. Once the construction rate and SFRF capacities are defined, the timing of SFRF construction is determinable. The only additional assumptions necessary are: a) that the LMR-SFRFs will not be constructed until there is sufficient spent fuel inventory available to operate them at full capacity, and b) that the initial LWR-SFRF is started at the latest date possible while meeting demand for the initial core of the first LMR.

The base case assumes that one 760 MWe S-PRISM power block will be completed and started every six months. The startups begin in 2020 and continue for 25 year to 2045. During this period a total of 50 power blocks or 38,000 MWe of S-PRISM capacity is added to the system. After 2045, the power generated by the 50 power blocks is assumed to remain constant while the scenario calculation continues to the year 2100. Since the reactor modules are limited to a 60 year life, the initial LMRs begin closure and decommissioning in 2080; however, new power blocks are constructed and started as required to offset the closures so that the total power generated by the S-PRISM reactors remains constant after 2045. The extra mass flow of fuel required to decommission old LMRs and to load new cores into the replacement reactors has a minor impact on the need for fuel cycle facilities and/or spent fuel inventory. Figure 5 plots the number of S-PRISM power blocks and fuel cycle facilities operating each year.

Figures 6 through 9 plot fuel cycle mass flows and inventories for the metal fuel cycle. The period covers 2010 through 2100, inclusive. The period before the first S-PRISM plant in 2020 is required to permit the LWR-SFRF startup and operation and thus supply the fuel required for the first reactors.

Figure 6 plots the reprocessing capacities of the LWR-SFRFs and LMR-SFRFs. Because the facilities are operated at the full capacity, as allowed by number of facilities and startup rates, the plots of capacity are also plots of the masses of spent fuel that are recycled. Capacity is shown in kg of heavy metal input into the facility and do not include the mass of fission product waste included with the input spent fuel.

Three LWR-SFRFs are required for startup and early reload fuel. The first SFRF reaches full production in 2017. The second and third SFRFs reach full capacity two years later. All three operate for 22 years and are then shutdown. The lifetimes are defined to supply only the minimum fissile fuel required to support the LMR fuel system until fissile breakeven. Note that this is a conservative assumption with respect to the calculated fuel cycle cost since the LWR-SFRFs can be used to process spent S-PRISM fuel simply by skipping the oxide to metal reduction step since the remaining equipment is the same in both types of fuel cycle facilities.

The first LMR-SFRF reaches full production in 2027. Subsequent LMR-SFRF startups are given in Table IV. The startup of each facility is delayed until sufficient spent fuel inventory and production is available to keep it fully loaded and thus operating at 100% of capacity.

Table IV SFRF Startups – Base Case 2 Power Blocks Per Year With Fissile Breakeven Cores

LWR-SFRF	LMR-SFRF
2017	2027
2019	2033
2019	2040
	2053
	2083
	2095

The combination of LWR-SFRFs and LMR-SFRFs provide fuel together until 2044, assuming LWR-sourced fuel is the preferred source. The transition from LWR-sourced fuel to LMR-sourced fuel is shown in Figure 7. The transition spans the period from 2031 to 2044.

The transition interval is controlled by the choice of a preferred fuel source. If S-PRISM based fast reactor fuel is the preferred source, the LWR-sourced fuel is used as makeup until the LMR fuel system reaches fissile breakeven in about 2054. The choice of using LWR-sourced fuel in preference to LMR-sourced fuel is made based on an assumed desire to reduce the inventory of spent LWR fuel as quickly as possible. This choice a) ties up LWR sourced fissile material in new LMR cores and makes the material unavailable for other uses at the earliest date, b) reduces the peak total fissile inventory in the LMR fuel system and c) contains the major fissile inventory at the LMR-SFRFs in a more diversion-resistant form. By using LWR-sourced fissile as rapidly as possible, the large and early output from the LWR-SFRFs is moved into reactors at the earliest date. The slower and later buildup of LMR-sourced fissile is allowed, but the maximum out-of-core inventory is smaller because the early, large buildup from the LWR-SFRFs is avoided. Finally, using LWR-sourced fuel in preference to LMR-sourced fuel allows the LWR-SFRFs to be closed earlier, 2044 compared to 2054, while producing the same amount of total fuel.

Overall fuel cycle inventories are plotted in Figure 8. Note that the plot is semi-log so that the large inventories of spent LWR fuel reprocessed and the resulting uranium inventory do not render the much smaller fissile and waste inventories unreadable.

The fissile inventory from LWR recycle initially increases to about 29.9 MT in 2024 during the early build up of excess fuel. This inventory is rapidly depleted and the LWR-SFRFs are shut down in 2043.

The LMR-sourced fissile inventory grows initially as it is not fully used for re-supply each year. The maximum processed fissile inventory at the LMR-SFRF reaches 73.9 MT in 2041; about the time the LWR-SFRFs are shutdown. The fissile inventory then drops to a low of 3.6 MT in 2053, at the time fissile breakeven is reached in the LMR fuel system. After that time, a recovery in fissile inventory is made possible and overall inventories can be controlled through changes in the core-breeding ratio.

Figure 8 also plots waste inventories and the amount of spent LWR fuel removed from the waste stream. Waste from the LWR-SFRF increases from start until closure and then remains constant. The LMR-SFRF waste increase rate grows with each added LMR-SFRF.

The inventory of spent LMR fuel stored at the LMR-SFRF tends to grow as LMRs are built, until sufficient inventory and annual flow are available to support another LMR-SFRF. The new LMR-SFRF then adds to the system recycle capacity and reduces inventory until new LMRs again provide enough excess spent fuel to justify another SFRF. After 2080, LMR decommissioning adds whole core discharges to the recycle system and the inventory of unprocessed spent fuel increases. Additional LMR-SFRFs are needed to accommodate this extra mass flow.

The heavy metal in fuel being shipped between the SFRFs and the reactors shows distinct steps in mass flows as reactors are started, reloaded and then decommissioned.

Figure 9 compares the mass of LWR fuel removed from the nuclear waste stream with the waste created by the LMR fuel cycle. About 70,125 MTHM of LWR spent fuel are reprocessed by the LWR-SFRFs and removed from the waste stream. The total waste from the LWR-SFRFs and LMR-SFRFs reaches about 4851 MTHM by 2100. The ratio of spent LWR fuel removed from the waste stream compared to the wastes and spent fuel inventories created varies from about 26-to-1 early in the LMR startup to a low of about 14-to-1 at the end of the study interval. This measure of the value of reprocessing and LMR power generation would be much more dramatic if the waste reduction were computed in terms relative to the total power generated and credit were given to reducing the period the waste remains more toxic than the original ore from millions of years to less than 500 years.

V ALTERNATE SCENARIOS COMPARISONS

Table V and Figures 10 and 11 show the impact of the LMR mission on the fuel cycle system. The base case scenario assumes a desire to remove LWR spent fuel from the waste stream. The alternative scenario assumes a desire to conserve the fissile content of spent LWR fuel in order to increase the number of startup cores that can be created through the processing of spent LWR fuel. The key difference is in the breeding ratio of the cores placed into the S-PRISM plants. The total fissile mass in each core is similar, but the addition of axial blanket zones to increase breeding adds considerable non-fissile metal mass to the high breeding ratio core.

Fissile breakeven cores, with a breeding ratio of 1.05 require about 70,125 MTHM of spent LWR fuel to reach system fissile breakeven as plants are being added. In comparison, using high breeding ratio cores reduces the LWR spent fuel requirement to about 55,875 MTHM. The cycle scenario based on fissile breakeven cores reaches system fissile breakeven in 2054. In comparison, the high breeding startup scenario reaches system fissile breakeven in 2045.

On the other hand, the higher total metal and fissile metal inventories of the high breeding ratio cores requires the LWR-SFRFs to start operation earlier to meet initial demand. The increased fuel mass also requires more LMR-SFRFs and also requires that these facilities start earlier to minimize spent fuel inventories. These differences indicate an increased fuel cost for the high breeding cores.

Fuel cycle cost (FCC) is calculated by the price that the SFRFs must sell fresh LMR fuel for to make a desired rate of return (IRR) on the investment and expenses involved in each fuel business. The IRR is computed over the first 30 years from start of SFRF construction and is thus lower than would be computed if the "levelizing interval" were taken as the full 100 years of the scenarios.

As shown in Table V, the fuel cycle cost for S-PRISM plants is not very sensitive to the core mission. The FCC for the breakeven core scenario is 4.63 mills/kW-hr, while the FCC with high breeding cores is 4.65 mills/kW-hr.

The fuel supplied from the LWR-SFRFs is priced considerably higher than the fuel from LMR-SFRFs to achieve the desired IRR. The differences in SFRF capital and operating costs, decommissioning versus refurbishment and fissile produced per unit of capacity contribute to the higher cost of LWR-sourced fuel.

While the FCC for high breeding cores is slightly higher than for breakeven cores, the fuel price quoted in dollars per kg-HM is considerably lower. The mass of non-fissile metal in the breeding core axial blanket zones biases the cost when quoted in this manner. The breeding core contains only 5% more fissile metal, but 39% more total metal, compared to the breakeven core. A more useful and consistent normalization basis would be cost per kg of fissile HM; however, the historical basis is used here for consistency with the past.

VI CONCLUSIONS AND OBSERVATIONS

The fuel cycle cost (FCC) for S-PRISM plants is insensitive to core mission and is about 4.6 mills/kW-hr. The total fissile inventories in fissile breakeven and breeding cores are nearly equal, so only a small difference in FCC should be expected.

FCC increases with breeding cores because axial blankets add a large HM mass to the input stream of the SFRF for only a small increment in fissile materials output from the SFRF. An extra LMR-SFRF is required to reprocess the greater total heavy metal from the breeding cores.

The LWR spent fuel required for startup fissile increases with low breeding ratio cores because the LMR recycle output from early LMR plants contributes less to initial loading of later plants. This study estimates that 56,000 to 70,000 MTHM are needed to start up the 100 cores. The study is simplified to use only a single characterization of spent LWR fuel, consistent with older LWR fuel in the spent fuel inventory. A more accurate assessment of the number of S-PRISM reactors required to tie up the entire fissile inventory from all spent fuel requires a more accurate specification of the spent LWR fuel and its residual fissile content.

The reduced cost of LMR fuel in terms of \$/kg-HM with breeding core fuel compared to burner core fuel is that the axial blankets add a large mass of non-fissile HM to each assembly and thus reduce cost per kg-HM.

The capacity of a heat load limited repository like Yucca Mountain would be increased by at least a factor of 4, and the period that the repository's LWR based spent fuel waste would remain toxic would be reduced from millions of years to less than 500 years.

The risk of proliferation would be reduced by replacing the need for additional LWR enrichment facilities with proliferation resistant dry pyroprocessing facilities where the spent and new fuel would always be so radioactive that it would always need to be handled in heavily shielded and inerted hot cells and transfer casks.

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Table V   Fuel Cycle Scenario Comparisons

Parameter	Scenario 1 Fissile Breakeven LMR Cores	Scenario 2 Fissile Breeder LMR Cores
Key LMR Core Configuration Difference	No Axial Blanket Zones	Upper and Lower Axial Blankets
Core Breeding Ratio	1.05	1.22
Core Inventory – Total (MTHM)	26.09	36.25
Core Inventory – Fissile (MTHM)	2.34	2.46
LWR Spent Fuel Required To Start LMRs (MTHM)	70125	55875
LWR-SFRFs Required	3	3
LMR-SFRFs Required	6	7
Economics Levelizing Interval (Years from start of construction)	30	30
Price of LMR Fuel from LWR-SFRFs	4255	3145
Price of LMR Fuel From LMR-SFRFs	2749	2182
Average Fuel Cycle Cost	4.63	4.65

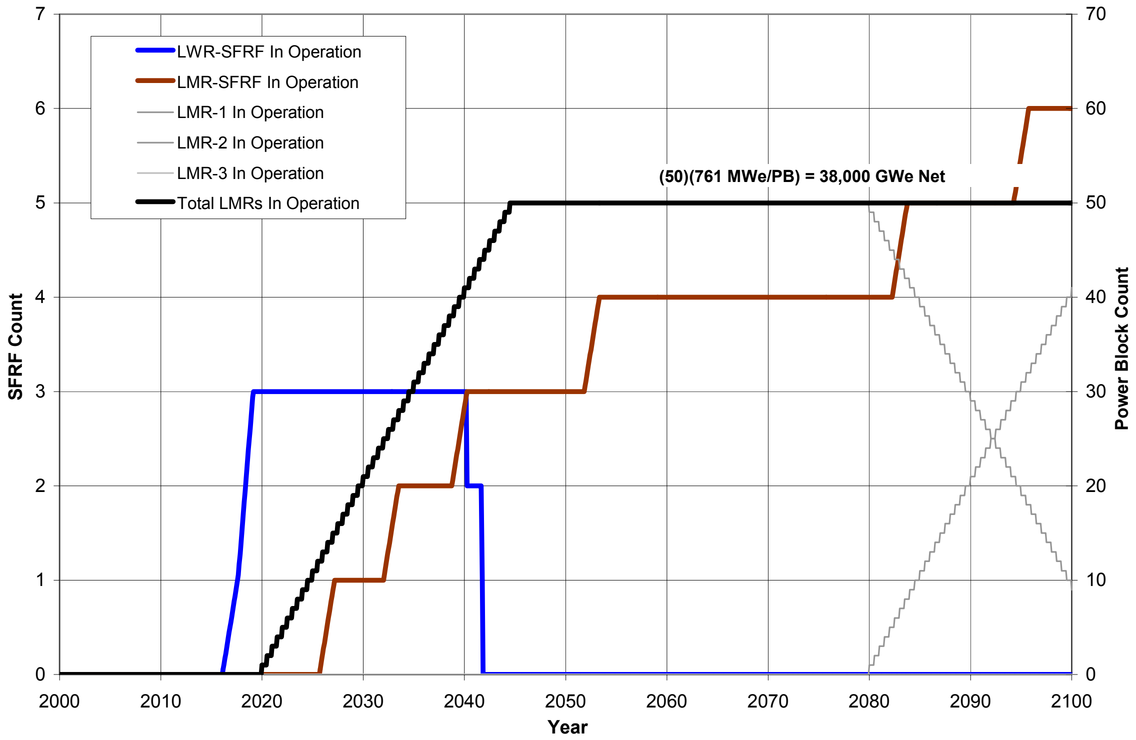


Figure 5 Base Case – Power Blocks & Fuel Cycle Facilities In Operation

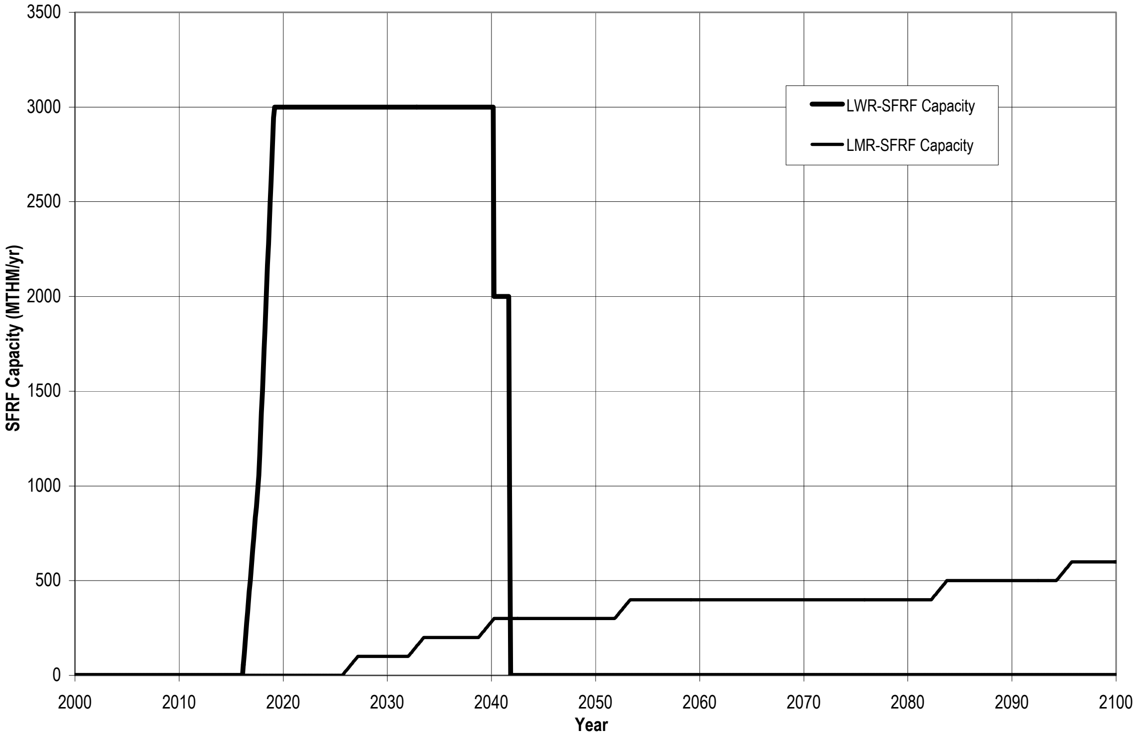


Figure 6   Base Case - Fuel Cycle Facilities Capacities

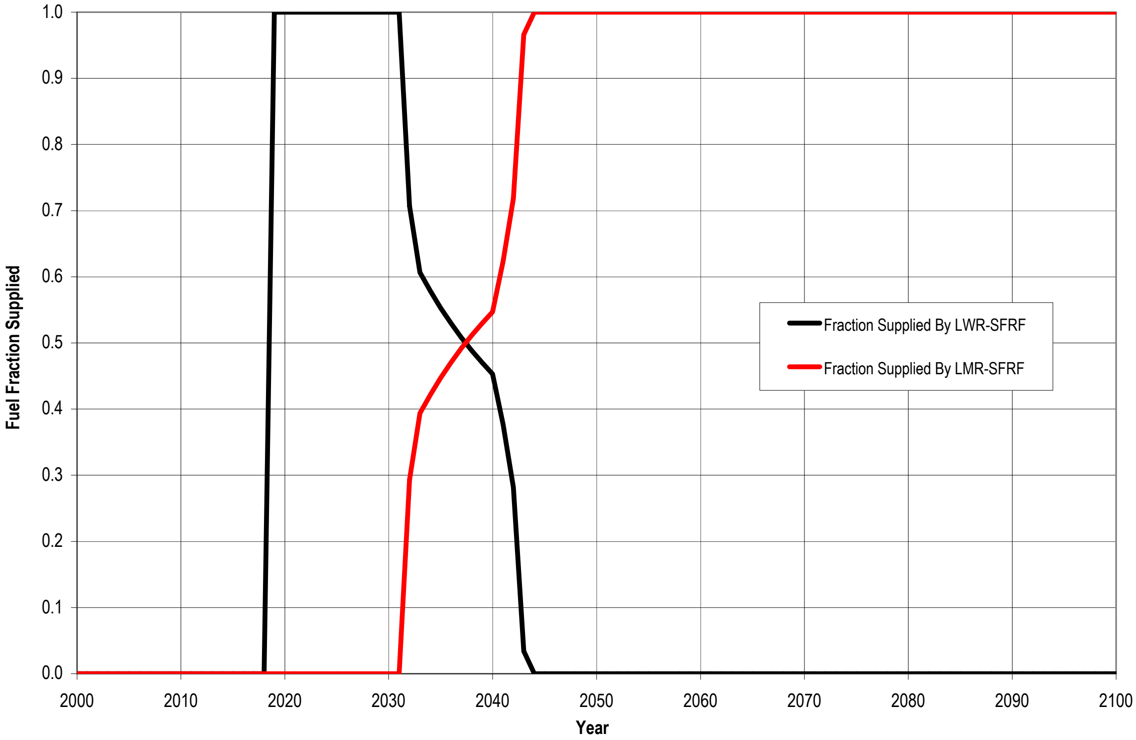


Figure 7 Base Case – Annual Average Fuel Supply Source Fraction

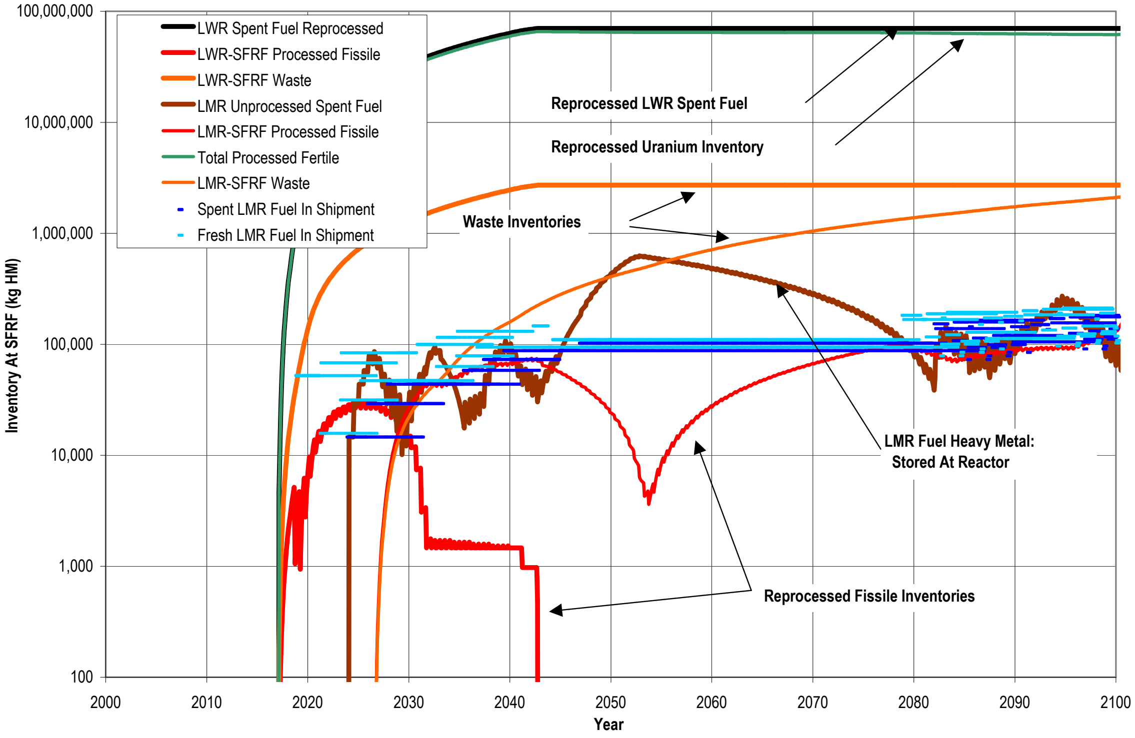


Figure 8 Metal Cost Optimized Core - Fuel Cycle Inventories

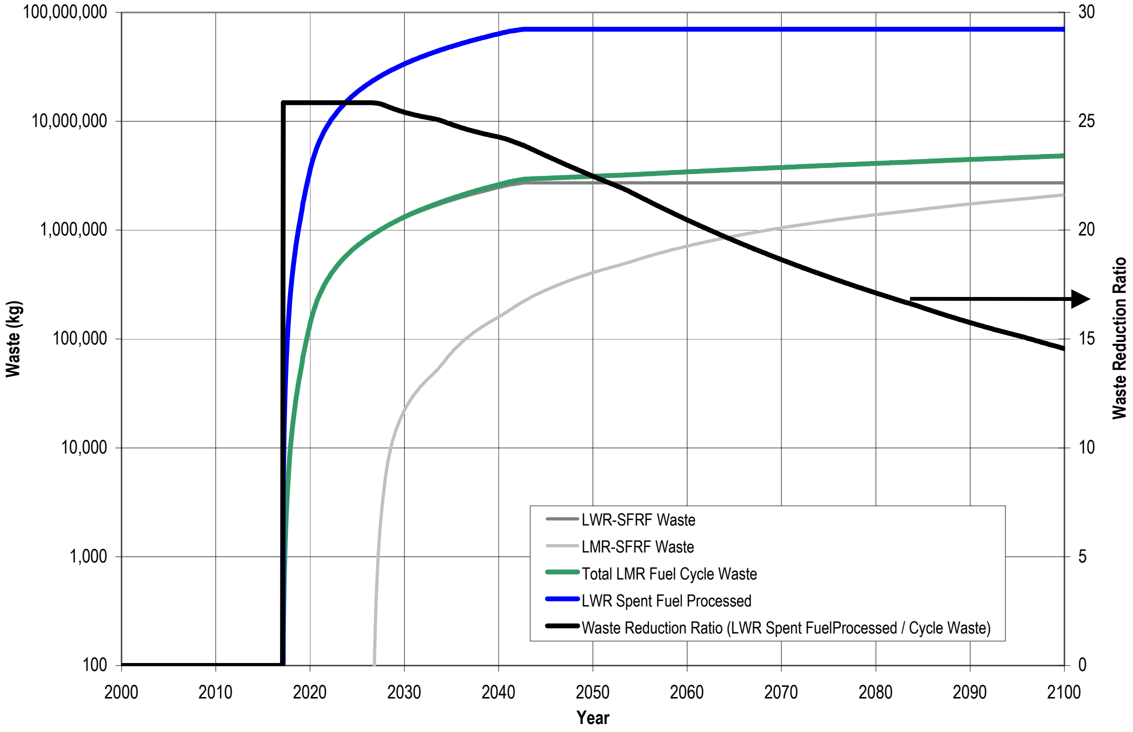
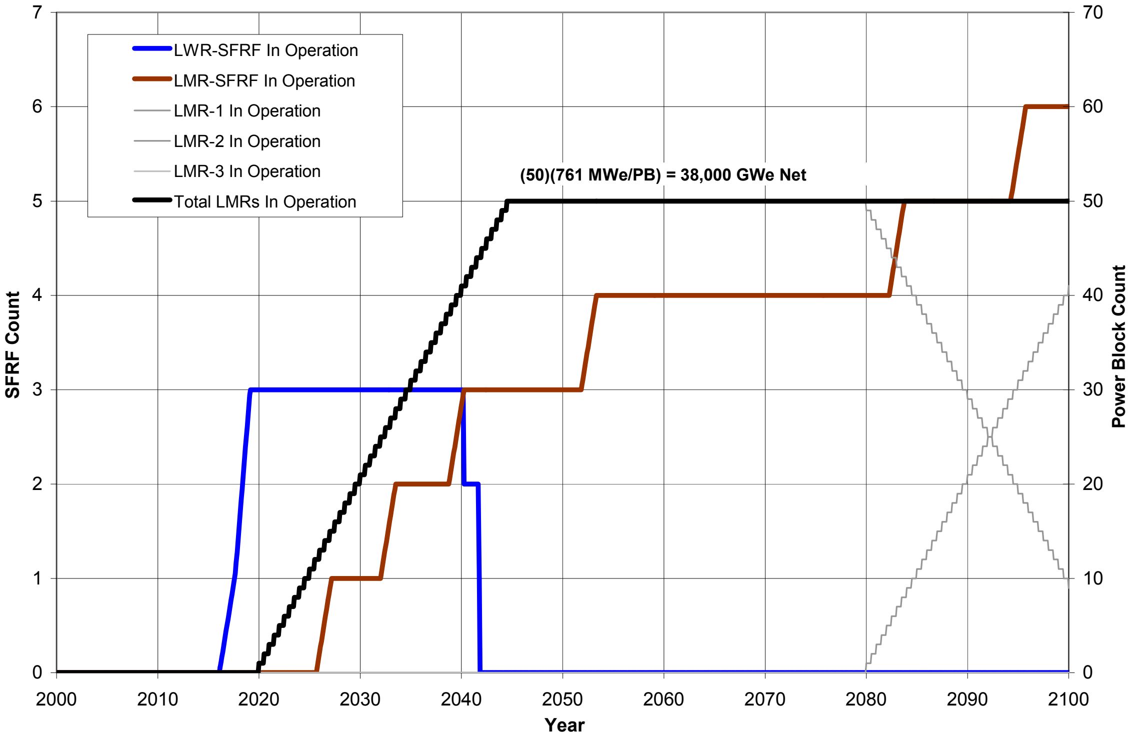
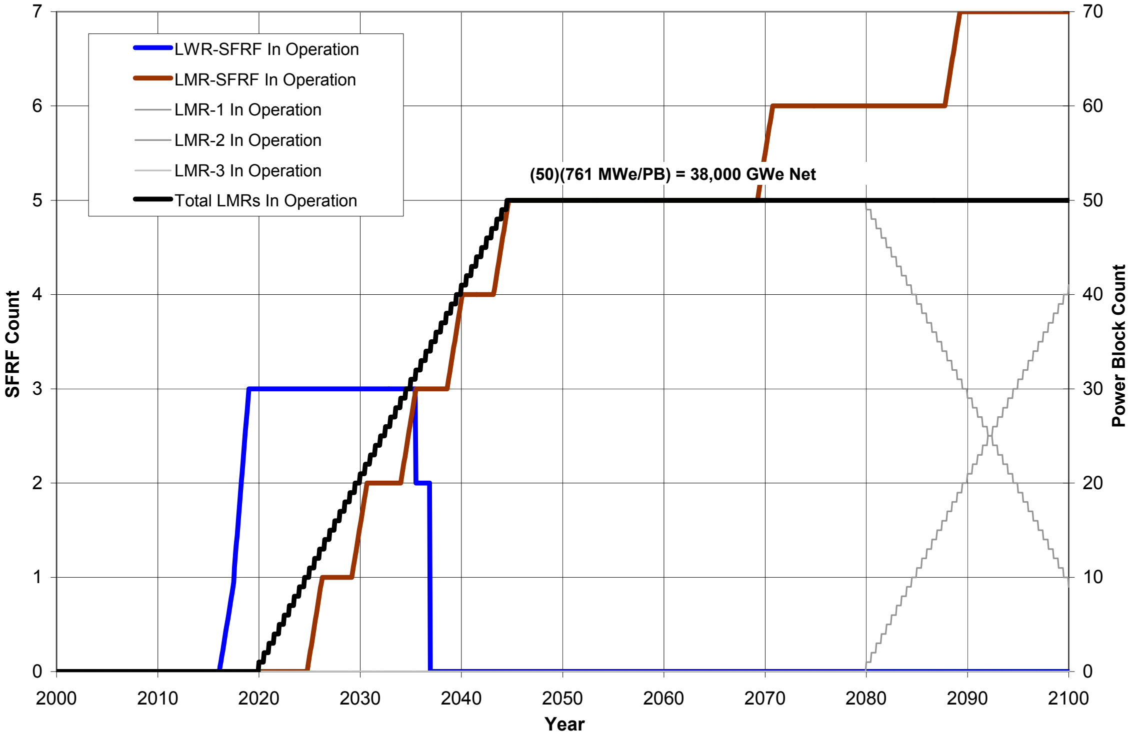


Figure 9 Base Case - LWR Spent Fuel Consumed vs.’ Waste Produced

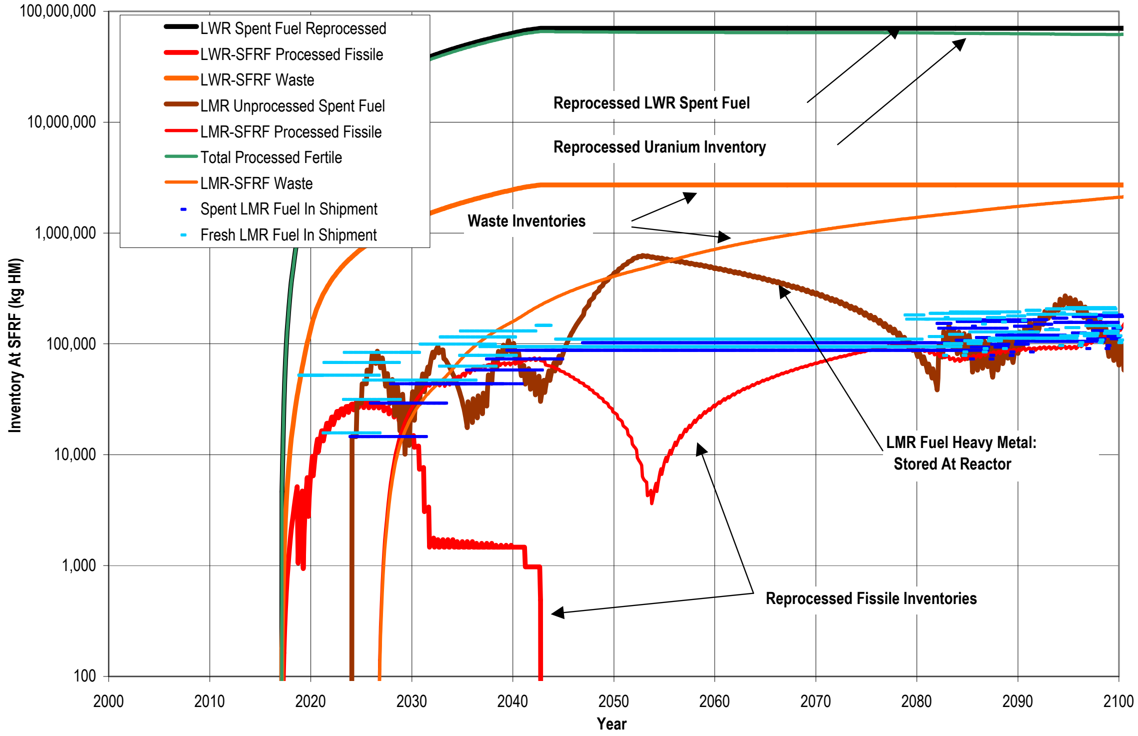


Scenario 1 - Fissile Breakeven Cores

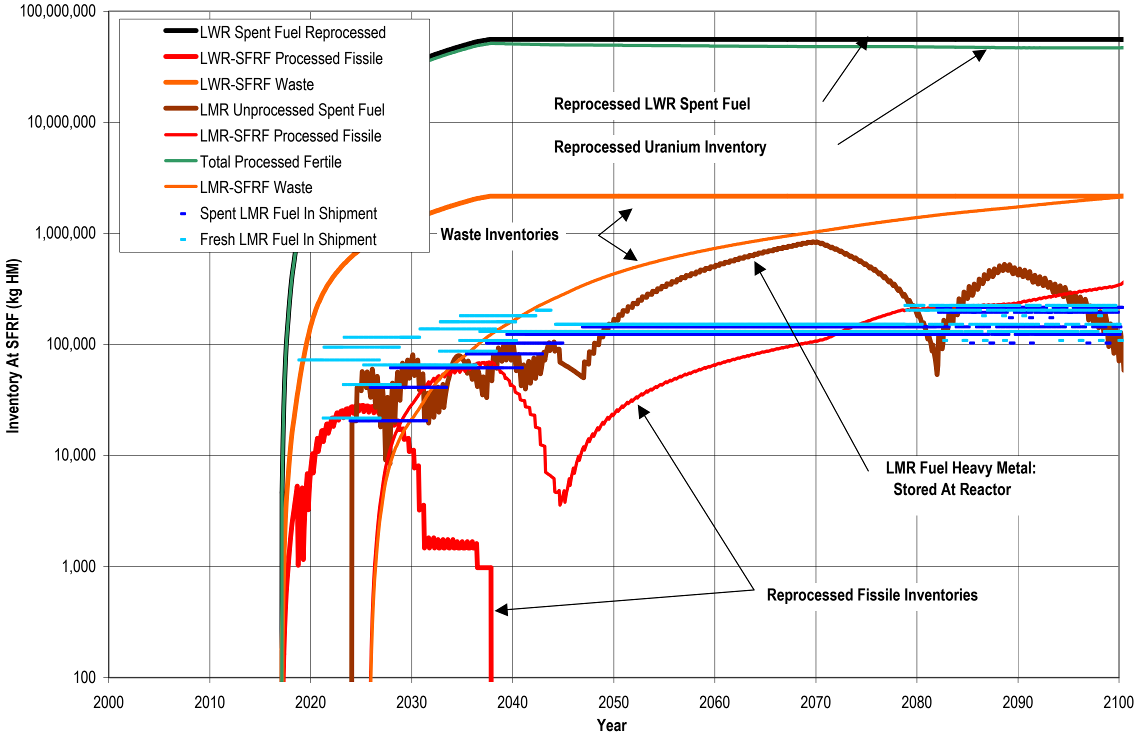


Scenario 2 - Fissile Breeding Cores

Figure 10 Fuel Cycle Facilities Operation Comparison



Scenario 1 - Fissile Breakeven Cores



Scenario 2 - Fissile Breeding Cores

Figure 11 Fuel Cycle Mass Flows and Inventories Comparison