Simulation of the Nuclear Fuel Cycle With Recycling: Options and Outcomes

by

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Submitted to the Department of Nuclear Science and Engineering and to the Engineering Systems Division in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Science and Engineering, and Master of Science in Systems Engineering

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Abstract

A system dynamics simulation technique is applied to generate a new version of the CAFCA code to study the mass flow in the nuclear fuel cycle, and the impact of different options for advanced reactors and fuel recycling facilities on the accumulation of the transuranics (TRU) inventory. Several aspects of the nuclear fuel cycle are studied for the US and for Brazil. This includes the impact of advanced nuclear technologies' introduction, under a prescribed industrial construction capacity, on uranium resources, the need for uranium enrichment, demand for fuel reprocessing facilities, and total cost of electricity over the next one hundred years. Introduction of fuel recycling can reduce the growing demand for uranium, and the long-term need for storage of radioactive spent fuel. However, the timing of introduction of recycling is important for proper technology development, and that is reflected in the assessments.

The nuclear fuel cycle is modeled as a *high level structure diagram,* which provides an overview of the interconnections among its blocks without showing all the details, and as a *structure-policy diagram* which details the decision rules applied to the structure. The *high level structure diagram* represents the nuclear fuel cycle; the fleet of thermal and fast reactors; the separation and reprocessing plants; the waste repository; the spent fuel storage; and the paths for the fuel and waste mass transfer. In addition, an economic model is added to study different cases under the same assumptions. The economic model is based on the forecasted need for advanced reactors and recycling facilities, assuming that all costs are recovered within the nuclear energy system.

Different recycling technology options are included in the code: (1) Thermal recycling in LWRs using *Combined Non-Fertile and UO_2 Fuel* (CONFU), (2) Recycling of TRU in fertile-free fast cores of *Actinide Burner Reactors* (ABR); and (3) Fast recycling of TRU with UO_2 in self-sustaining *Gas-cooled Fast Reactors* (GFR). Case studies for different advanced technology introduction dates and for distinct TRU depletion rates are examined. In particular, the code is equipped to simulate the introduction of two recycling technology options with a prescribed allocation of the TRU supply between them.

The simulation results show that early introduction of the GFR recycling scheme leads to the most significant reduction in uranium consumption, and enrichment requirements, thus delaying the depletion date of uranium ore. The GFR technology requires less uranium resources due to U recycling and near unity fissile conversion ratio. However, in a non-breeding reactor system, the consumption of U continues to grow, and the TRU needed to start fast reactors will be growing at a constrained rate. On the other hand, the CONFU recycling scheme keeps the TRU inventory in the entire system well below other schemes, and guarantees equilibrium between the generation and consumption of transuranics without investments in fast reactors. Also, it reduces the TRU sent to the repository for disposal by orders of magnitude. The ABR scheme does the same but requires the introduction of fast reactors. Nevertheless, the CONFU and ABR schemes have no significant impact on the amount of uranium resources consumption or enrichment requirements. CONFU incinerates more TRU than the GFR and ABR schemes during the simulation period.

Economic analysis indicates that the CONFU technology is more attractive at current uranium prices, and that fast recycling becomes as attractive as thermal recycling at higher uranium prices. The results also show that if a nuclear *fuel cycle state/reactor state* collaboration with Brazil is started, there will be a significant impact on the U.S. cumulative TRU inventory at interim storage, enrichment requirements, uranium consumption, and number of advanced fuel facilities. The results show that a nuclear partnership without the introduction of advanced nuclear technologies would not have advantages for the U.S. Furthermore, a nuclear collaboration allows a higher ratio of fast reactors to total installed nuclear electric capacity in the U.S.

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1 Introduction

1.1. Motivation

In the last decade, many countries had to intensify national discussions about energy, its source, market, regulatory structure and environmental impact. In 2006, the introduction of the *Global Nuclear Energy Partnership* (*GNEP*) program by the U.S. started an international discussion on the deployment of advanced nuclear technologies, for both fresh fuel and spent fuel, among countries to "develop worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy to meet growing electricity demand" [1]. With the deployment of advanced technologies, the market for the front- and back-end of the fuel cycle will become more competitive. In addition, the demand for uranium should increase and, at least until the deployment of fast reactors, its supply assurance could become an issue.

GNEP assumes that many countries, for different reasons, are going to fulfill their electricity growth demand by improving their energy supply portfolio focusing on nuclear power. However, the carbon-free characteristic of nuclear power is not enough to assure the public's attitude in support of nuclear power expansion. The public would also want that the new nuclear plants be environmentally friendly, and that the nuclear waste be treated, the long-term waste is reduced to a reasonable amount, and stored in a suitable geological repository.

Several options for advanced nuclear technologies are able to reduce the amount of transuranics inventory, and fulfill the power demand. Applying system dynamics tools to simulate the nuclear fuel cycle, we will evaluate the repercussion of the deployment of new technologies on the global energy market. Therefore, a central issue in this study is the simulation of the nuclear fuel cycle for different scenarios, using an innovative system dynamics version of the *Code for Advanced Fuel Cycles Assessment* (CAFCA) [2], for the deployment of advanced reactors and fuel facilities. Moreover, the impact of the introduction of these technologies on uranium resources, on SWU requirements, on TRU inventory, on the rate of construction of reactors and fuel facilities, on the fuel cycle cost, and on the total cost of electricity over a one hundred years period is evaluated.

1.2. Review of Previous Work

Efforts have been made to develop flexible tools to simulate the nuclear fuel cycle. Previous work at MIT addressed three different schemes for recycling spent fuel, to make the nuclear energy system sustainable from the waste standpoint: [2]

- Thermal recycling in LWRs using *Combined Non-Fertile and UO_2 fuel* (CONFU) technology;
- Fast recycling of TRU in fertile-free fast cores of *Actinide Burner Reactors* (ABR); and
- Fast recycling of TRU with UO_2 in self-sustaining *Gas-cooled Fast Reactors* (GFR).

To understand such studies, the Center for Advanced Nuclear Energy Systems (CANES) at MIT has been developing a code for simulating the deployment of these advanced technologies for closing the nuclear fuel cycle. CAFCA (Code for Advanced Fuel Cycles Assessment) is designed to simulate the impact of the introduction of advanced technologies on the nuclear market, focusing on the rate of construction of reactors and fuel facilities to fulfill the nuclear power demand, and to keep the TRU inventory below reasonable levels. CAFCA has three versions developed in the MATLAB simulation environment. The first version was used to simulate the deployment of two technologies, one thermal (CONFU) and one fast (ABR) recycling schemes [3]. The second version of CAFCA introduced one more fast recycling strategy (GFR), and the option for a minimum loading mass factor for advanced treatment facilities [2]. The last version of CAFCA, released in June 2007, introduced the capability of tracking the isotopic composition through the fuel cycle in order to assess the radioisotope decay in the system [4]. The system dynamics version of CAFCA described in this work, i.e. CAFCA-SD, introduces the capability of simultaneous deployment of up to three recycling technologies, and the flexibility of using more than one option for TRU depletion. Moreover, an innovative modeling strategy, with *structure-policy diagrams* for the estimation of the mass flow in the system, is developed. Nevertheless, several nuclear fuel cycle codes are undergoing active development at the U.S. and other locations. For example, the *Commelini-Sicard* (COSI) code, developed by the *French Atomic Energy Commision*; the *Dynamic Analysis of Nuclear Energy System Strategy* (DANESS) code, developed by *Argonne National Laboratory*; and the *Verifiable Fuel Cycle Simulation* code (VISION), which is the *United States Department of*

Energy's (DOE) *Advanced Fuel Cycle Initiative's* (AFCI) nuclear fuel cycle systems code, are a non comprehensive list of few nuclear fuel cycle codes found in reference [5].

The use of system dynamics to model and simulate the nuclear fuel cycle is motivated by the growing complexity of the system; by the necessity of adding the capability to include policies to the task of fulfilling the power demand; by the need to inject uncertainty analyses, such as *construction times* and *transportation delays,* in the code; and to have a code that should facilitate further development using the modular system dynamics tools. Moreover, closing the nuclear fuel cycle with different technologies towards a sustainable nuclear energy market introduces the need for a more detailed mass-flow and economics analysis that can be easily assembled to CAFCA-SD. In addition, the demand for modeling *information* and *material delays*, and the *non-linear* behavior of the system, increase the complexity of the code, and justify the use of system dynamics. It is noticeable that VISION and DANESS both employ System Dynamics as their development language.

In general, for the renaissance of the nuclear energy, the inventory of stored spent fuel should be kept at reasonable levels and for assuring maximum recovery of energy from the fuel. In addition, TRU inventories, such as plutonium and minor actinides (primarily neptunium and americium), should be used as fuel that can be recycled several times, possibly in advanced fuel, to burn the long-term radioactive elements and to make the system sustainable from the waste standpoint. Thus, the inventory of TRU elements should be controlled and limited by appropriate reactors serving as transuranic element burners. The *Advanced Fuel Cycle Initiative (AFCI)* and GNEP program focuses in fast reactors for that purpose [6]. Nevertheless, the world is not expected to eliminate Light Water Reactors (LWRs). Therefore, the system dynamics model of the nuclear fuel cycle assumes that LWRs operate in conjunction with advanced reactors.

1.3. Scope of the work

To summarize, this work presents a system dynamics model of the nuclear fuel cycle, and analyzes results from a set of simulations for different scenarios. The mass transferred among nuclear facilities is tracked during the simulation, and both traditional and advanced technologies interact. Furthermore, an economic model is applied to estimate the capital costs, the operating and maintenance (O&M) cost, the fuel cycle cost, and the total cost of electricity. The impact of the introduction of advanced technologies on the U.S. nuclear energy market, and on the Brazilian nuclear energy market, is assessed using the new code CAFCA-SD. The U.S. is the advanced nuclear country with the largest fleet of reactors. Its electricity market relies on nuclear power (20% share currently), and advanced reactors and fuel facilities are planned to meet the electricity demand in the future decades. Moreover, the U.S. will be a *fuel cycle state* providing fuel for the *reactors states*. On the other hand, Brazil is one of the few countries outside the *Organization for Economic Cooperation and Development (OECD)* with large economies, so called BRIC (term used to refer to the combination of Brazil, Russia, India, and China). It is expected to play an important role in the market in the next few decades [7]. Although the electric power system in Brazil is hydro dominated, the country has been improving its energy supply portfolio through nuclear power, and has been investing in R&D facilities. According to the 2003 MIT study "*The Future of Nuclear Power*," Brazil is expected to have a nuclear energy annual growth of 7.8% until 2050 [8].

The deployment of the three recycling strategies listed in Section 1.1 is examined using CAFCA-SD. Moreover, the components of a nuclear fuel cycle system are described as a set of physical and information interconnections, and the behavior of the system over time is considered to analyze the impact of the introduction of recycling schemes in different dates, and with different rates of TRU depletion on the nuclear market. Also, the model includes an economic analysis, which consists of the estimation of the capital cost, O&M costs, cost of the fuel cycle, and the total cost of electricity.

In the first part of the study, the system is described using structure-policy diagrams. All significant relationships and variables that describe the behavior of the system are considered. In addition, the model is implemented using the system dynamics coding platform *Vensim*[*]. The code tracks the mass transferred through the system, and applies economics to calculate the cost of fuel cycle, and the total cost of electricity. Therefore, Chapter 2 presents the modeling strategy and applications, Chapter 3 presents the recycling strategies, and Chapter 4 describes the economic model analysis and assumptions.

[*] The Ventana simulation environment for Windows

In the second part of the study, the impact of the introduction of advanced technologies on uranium resources is evaluated. Also, the economic impact of uranium prices on the fuel cycle cost, and on the total cost of the electricity, is evaluated for the U.S. nuclear market. The economics of various rates of TRU consumption and the earlier deployment of fast recycling technologies are evaluated, including the cost of electricity of simultaneous recycling technologies. Therefore, Chapter 5 and Chapter 6 present the assessment of the U.S. nuclear market.

In Chapter 6.4, information about the Brazilian nuclear energy market and about the electric power system in Brazil is presented. Also, the impact of the introduction of advanced technologies on uranium resources in Brazil considering a sensitivity analysis of uranium prices is performed. Last, the impact of a U.S and Brazil nuclear partnership in the U.S. nuclear market is considered. Therefore, Chapter 6.4 presents the assessment of the Brazilian nuclear market.

2 Modeling Strategy and Implementations

2.1. Introduction

This chapter describes the modeling strategy adopted in this study, and provides an overview of system dynamics. The model of the nuclear fuel cycle is presented here as a *high level structure diagram*, and details of the system are presented as *structure-policy diagrams*. A *high level structure diagram* provides an overview of the model, highlighting interconnections among blocks of the system, without showing all the details for the computer simulation. A *structure-policy diagram* reproduces the structure of the system, and the decision rules applied to the structure.

2.2. System dynamics overview

System dynamics is a methodology invented at Massachusetts Institute of Technology (MIT) in the mid-1950s by Jay W. Forrester [9]. In the last sixty years, the technique has been applied in almost every field, from management, economic, and environmental issues, to medical, biological, and complex non linear dynamics problems. Moreover, system dynamics has been used in the public and private sectors for design and strategic energy planning for more than twenty-five years [10].

System dynamics is a process for modeling and understanding the behavior of complex "feedback systems" over time. By taking advantage of computer simulation, a set of physical and information interconnections describes the comportment of the system. The term "feedback system" refers to a situation where *X* affects *Y*, and *Y* in turn affects *X*, through a chain of causes and effects [11].

The technique is based on nonlinear dynamics and control theories [12]. First, the dynamics of the system considering feedback interactions that represent self-reinforcing (or self-correcting) process, stock (states variables), and flow (rates of changes) structures are modeled. The modeling goal is to identify the system variables which shape the patterns of behavior. Next, a computer model able to simulate a similar behavior is built. Last, the computer model is used to test policies designed to change the system's behavior as desired [10].

2.3. High level structure diagram

The *high level structure diagram* of the system is shown in Figure 2-1. The high level structure diagram represents:

- the nuclear fuel cycle;
- the fleet of thermal and fast reactors;
- the separation and reprocessing plants;
- the waste repository;
- the spent fuel storage; and
- the paths for mass transfers.

The nuclear fuel cycle is the sequence of nuclear fuel through a series of different stages, and it consists of front- and back-ends steps. The front-end stages are mining, milling, conversion, enrichment, and fuel fabrication. As seen in Figure 2-1, the progression of nuclear fuel through the front-end takes place in five steps: first, the amount of uranium (U) ore mined is calculated based on the thermal and fast reactor demand. Next, the amount of "yellowcake," processed from mined uranium, which is sold on the market as uranium oxide (U_3O_8), is evaluated. Then, uranium oxide is converted to uranium hexafluoride (UF_6), which is needed by commercial uranium enrichment facilities. Following, uranium hexafluoride from mined and recycled uranium (from separation plants) are sent to enrichment facilities. Last, enriched uranium is sent to traditional fuel fabrication plants and to CONFU fabrication plants, and natural or depleted uranium is sent to the self-sustaining GFR. In addition, losses are calculated at each front-end step, and sent to a radioactive waste disposal site.

The *light water reactor* (LWR) fleet is fed with UO_2 batches from traditional fabrication fuel plants, or from *young* and *old Combined Non-Fertile and UO_2 fuel* (CONFU) (see Chapter 3 for details) batches from FFF fabrication fuel plants. After burning in LWR, UO_2 spent fuel is sent, after six years in cooling storage, to the UO_2 interim storage facility. In addition, *young* and *old* CONFU batches are sent, after six and eighteen years in cooling storage respectively, to the CONFU interim storage facility.

Next, spent fuel from the UO_2 fuel interim storage is sent to separation plants (SP), where transuranic elements (TRU) are separated from the uranium, and losses are sent to the waste repository. Then, TRU available for fuel fabrication feeds FFF fabrication plants and *gas-cooled fast reactors (GFR)* fuel fabrication plants. FFF is used to produce young and old CONFU batches. FFF is also used to produce FFF batches for *actinide burner reactors* (ABR). Following, the ABR spent fuel is sent, after six years in cooling storage, to the ABR interim storage repository, as can be seen in Figure 2-1.

After a short cooling time, ABR and CONFU spent FFF fuel are sent to the FFF *reprocessing plants* (RP), and losses at reprocessing plants are sent to the waste repository. Then, reprocessed TRU is sent to the TRU available for fuel fabrication repository. Next, recycled U is mixed with TRU for fabrication of U/TRU fuel. After burning in gas-cooled fast reactors, and sitting for six years in cooling storage, U/TRU spent fuel is sent to the GFR interim storage facility. At the GFR reprocessing plants, U/TRU is separated from *fission products* (FP) and sent back to fuel fabrication. During all processes, losses are calculated waste, and sent to a radioactive waste disposal site.

2.4. Structure-policy diagrams

Figure 2-1 is a set of connected system blocks. The system-output of one block is the system-input for another connected block. There are user-outputs, i.e. SWU requirements, number of advanced fuel facilities, uranium needs, TRU inventory at interim storage, mass loading factor, incinerated TRU, fuel cycle cost and cost of electricity, which can be accessed anytime. Therefore, the model is a chain of coupled *structure-policy diagrams* with feedback interactions among blocks, as presented in Figure 2-2. Each structure-policy diagram is a single-input single-output (SISO) system that consists of two subsystems: system-structure and policy-structure. The first subsystem describes the structure, and the second one defines decision rules. The complete nuclear fuel cycle, including three recycling schemes, can be simulated by implementing structure-policy diagrams that relates system-inputs and system-outputs throughout system's variables.

The fleet of reactors and facilities are modeled as system-structure diagrams, and the policy-structure sets decision rules based on the state of the system. As soon as rules are applied, and the state of the system changes, information about the new state is fed back to the system-structure. Then, new decision rules are applied closing the loop inside the block. This behavior occurs at every time step of the simulation.

Four different structure-policy diagrams are defined. The first one is the *LWRs structure-policy diagram* for construction and decommissioning of LWRs. The system-input for this diagram is the nuclear annual growth rate, and the system-output is the number of LWRs under commercial operation (the "fleet" of LWRs). However, the number of LWRs starting commercial operation per year, the number of LWRs decommissioned per year, the number of decommissioned LWRs, the nuclear power demand, and the installed electric capacity can be accessed anytime by the user. The second one is the *back-end structure-policy diagram* for construction and decommissioning of fast reactors (FR), separation and reprocessing plants. The system-input for this diagram is the nuclear fuel available for fast reactors, or the mass available for partitioning. The system-output is the number of fast reactors under commercial operation, or the number of facilities to treat spent fuel. The following systems are modeled as back-end structure-policy diagrams: the construction of UO_2 separation plants (SP), the construction of FFF reprocessing plants, the construction of ABRs, the construction of GFR reprocessing plants, and the construction of GFRs.

The next diagram is the *front-end structure-policy diagram.* The system-input is the number of LWR loaded with UO_2 fuel. The mass transferred through the front-end steps of fabrication, enrichment, conversion, milling and mining, is calculated based on the fuel loaded in the LWRs fleet per year. The system-output is the amount of spent fuel discharged per year. The time lag between uranium mining and U fuel introduction in a reactor is ignored. In reality, this time lag is of the order of one to two years. Nevertheless, the cumulative UO_2 spent fuel, the cumulative natural Uranium needed, and the SWU requirements, as well as the amount of plutonium, minor actinides, fission products and uranium in the spent fuel can be accessed anytime by the user. The last diagram is the *CONFU technology structure-policy diagram.* The system-input is the TRU available for fuel fabrication, i.e. the separated TRU from separation plants, and reprocessed TRU from FFF reprocessing plants. Separated TRU is used for fabrication of young CONFU batches, and reprocessed TRU is used for fabrication of old CONFU batches. The system-output is the number of LWRs loaded with CONFU batches.

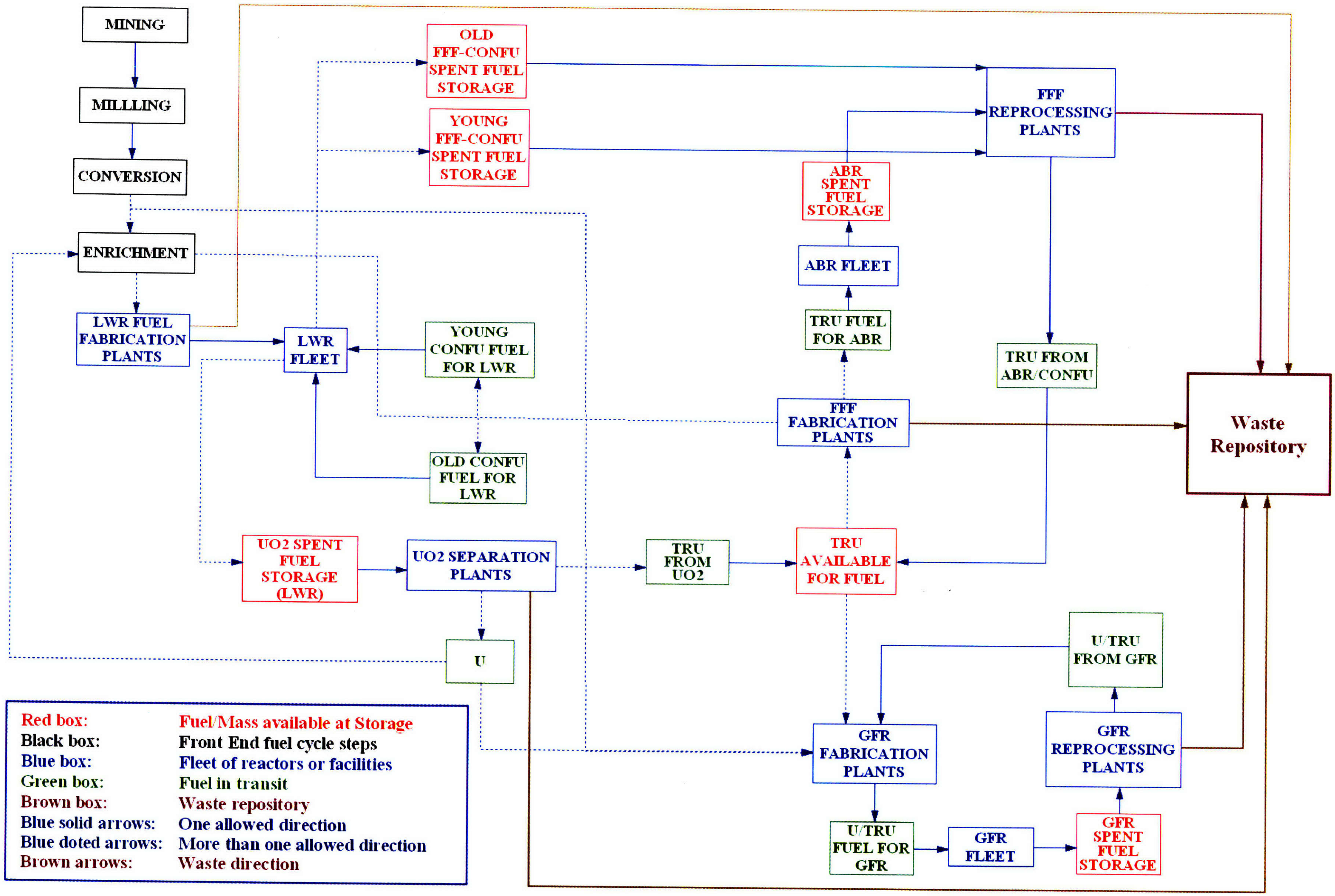

Figure 2-1 - High level structure diagram of the model

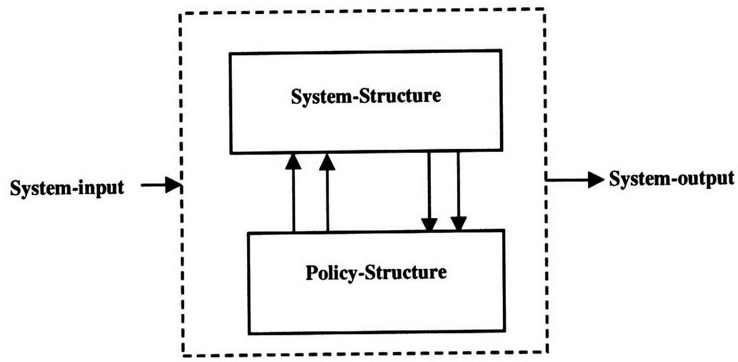

Figure 2-2 – Structure-policy diagram of the system

2.4.1. LWRs structure-policy diagram

The LWRs structure-policy diagram, presented in Figure 2-3, is a power-demand driven system. The system-input must be the expected nuclear annual growth rate, i.e. the power demand. The forecasted LWR fleet to fulfill electricity demand is calculated based on the system-input, and on the LWR and fast reactors net electrical outputs, as detailed in equation 2.2. The number of reactors under commercial operation is represented by one stock, or state variable, and it increases by the construction rate and decreases by the decommissioning rate. The decommissioning rate changes only due to end of the reactor lifetime. LWRs are built accordingly to pre set constraints, and only integer numbers of LWRs are built.

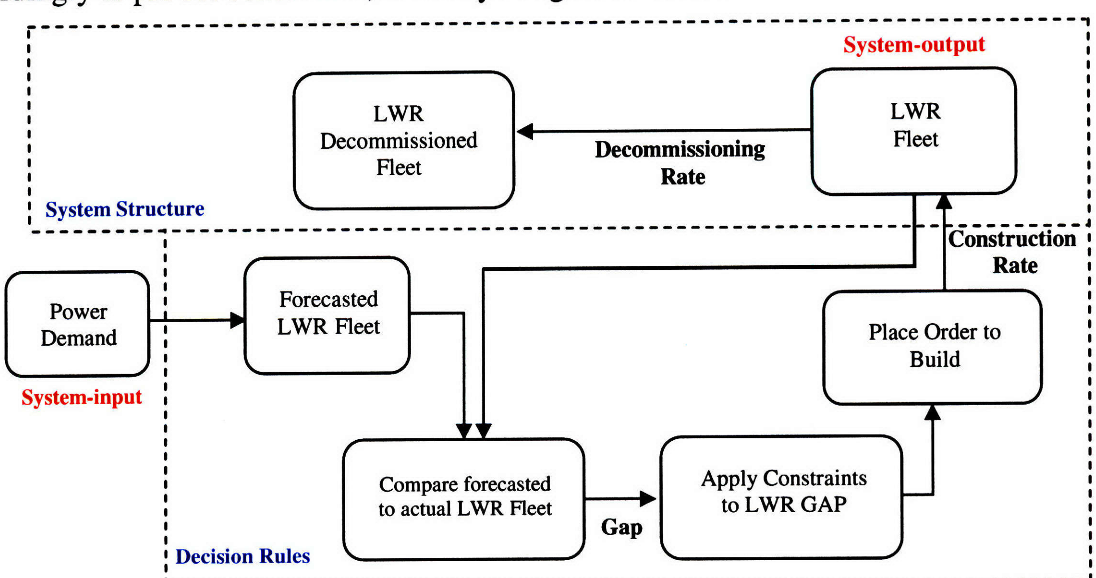

Figure 2-3 – LWRs structure-policy diagram of the system

The *LWRs structure-policy* considers the aging distribution of LWRs under commercial operation. One approach [12] to aging distribution is to make use of coflows structures. Coflows are system structures that track attributes of various items as they travel through the stock and flow structures. One assumption behind this approach is that all items in each coflow are perfectly mixed, and the order in which their attributes change is not relevant compared to the net change in the stock. Sixty coflow structures capture the aging distribution of the LWR fleet. The initial condition for each coflow is the number of LWRs with the same age multiplied by the one year duration pulse function, i.e. the simulation sampling time.

Next, the dynamics of the LWRs structure-policy will be described. First, the *nuclear power demand*, $P_N(t)$, is calculated considering the *initial nuclear power demand*, P_o, and the *nuclear power growth rate*, *g*:

$$P_N(t) = P_o \cdot e^{g \cdot t}. \tag{2.1}$$

Then, the *forecasted LWR fleet*, $F_{EST}^{LWR}(t)$, is evaluated as

$$F_{EST}^{LWR}(t) = \frac{P_N(t) - \left(F_{ABR}(t) \cdot P_{ABR}(t) \cdot CF_{ABR} + F_{GFR}(t) \cdot P_{GFR}(t) \cdot CF_{GFR}\right)}{CF_{LWR} \cdot P_{PWR}(t)}, \tag{2.2}$$

where $F_{ABR}(t)$ is the *number of ABRs*, $P_{ABR}(t)$ is the *ABR net electrical output*, CF_{ABR} is the *ABR capacity factor*, $F_{GFR}(t)$ is the *number of GFRs*, $P_{GFR}(t)$ is the *GFR net electrical output*, CF_{GFR} is the *GFR capacity factor*, CF_{LWR} is the *LWR capacity factor*, and $P_{LWR}(t)$ is the *LWR net electrical output*.

Then, the *forecasted LWR fleet* is compared to the *LWR fleet under commercial operation*, $F_{LWR}(t)$. The discrepancy, i.e. the gap, between $F_{EST}^{LWR}(t)$ and $F_{LWR}(t)$ is divided by the *LWR fleet adjustment time*, $\tau_{LWR}(t)$. The *adjustment time* is the time constant in which the discrepancy would be corrected, and it represents the industrial time to accommodate changes in the actual number of reactors. The correction action causes the shortfall between the inflow and outflow to diminish, and reduces the net inflow. Therefore, the *adjustment for fleet of LWR*, $ADJ_{LWR}(t)$, is modeled as

$$ADJ_{LWR}(t)=\frac{F_{EST}^{LWR}(t)-F_{LWR}(t)}{\tau_{LWR}}. \qquad (2.3)$$

For immediate implementation of changes in the number of reactors under commercial operation, the *LWR fleet adjustment time* must be equal zero. $\tau_{LWR}(t)=0$ means no lead time for new plants, and a nonlinear function that performs division except when that division would be by zero, in which case it returns a pre set argument, is applied. Here, the return value is $F_{EST}^{LWR}(t)-F_{LWR}(t)$. Also, there is no meaning for negative adjustment in the actual reactor fleet: LWRs can leave the stock of reactors under commercial operation only by decommissioning. This limits CAFCA-SD to simulation of constant growing demand for nuclear power. So, the non integer number of thermal reactors to be build to fulfill power demand, i.e. the *fractional LWR construction order rate,* $R_{CO}^{LWR}(t)$, is defined as equal to the maximum between zero and the $ADJ_{LWR}(t)$ plus the *LWR decommissioning rate,* $R_{DR}^{LWR}(t)$, at each time step:

$$R_{CO}^{LWR}(t)=Maximum[0,ADJ_{LWR}(t)+R_{DR}^{LWR}(t)]. \qquad (2.4)$$

The *fractional number of LWRs ordered* is modeled as

$$\frac{dF_{FRAC}^{LWR}(t)}{dt}=R_{CO}^{LWR}(t)-R_{FO}^{LWR}(t),F_{FRAC_0}^{LWR}, \qquad (2.5)$$

where $R_{FO}^{LWR}(t)$ is the integer number of LWR that can be built at every time step, i.e. *LWR fulfilled order rate*, and $F_{FRAC_0}^{LWR}=F_{FRAC}^{LWR}(t=0)$. The $R_{FO}^{LWR}(t)$ is defined as

$$R_{FO}^{LWR}(t)=\frac{I_{LWR}(t)}{TimeStep}, \qquad (2.6)$$

where $I_{LWR}(t)$ is the *integer number of reactors ready to start commercial operation*

$$I_{LWR}(t)=Integer[F_{FRAC}^{LWR}(t)]. \qquad (2.7)$$

Next, the LWR fleet, $F_{LWR}(t)$, is modeled as the sum of sixty coflows, $F_i^{LWR}(t)$, which are implemented by the use of subscripts (matrices)

$$F_{LWR}(t)=\sum_{i=1}^{60} F_i^{LWR}(t), \tag{2.8}$$

each coflow is modeled as

$$\frac{dF_i^{LWR}(t)}{dt}=R_{CR\ i}^{TRA}(t)-R_{DR\ i}^{TRA}(t),\ F_{i_0}^{LWR}, \tag{2.9}$$

where $R_{CR\ i}^{TRA}(t)$ is the *transition LWR construction rate,* $R_{DR\ i}^{TRA}(t)$ is the *transition LWR decommissioning rate,* and $F_{i_0}^{LWR} = F_i^{LWR}(t=0)$ at each coflow *i.* $R_{CR\ i}^{TRA}(t)$ is modeled as

$$R_{CR\ i}^{TRA}(t)=R_{FO}^{LWR}(t) \quad \text{if} \quad i=1, \tag{2.10}$$

$$R_{CR\ i}^{TRA}(t)=R_{DR\ i-1}^{TRA}(t) \quad \text{if} \quad i=2 \text{ to } 60, \tag{2.11}$$

and $R_{DR\ i}^{TRA}(t)$ is modeled as

$$R_{DR\ i}^{TRA}(t)=R_{LWRi}^{TRA}+R_{INT\ i}^{TRA}, \tag{2.12}$$

where R_{LWRi}^{TRA} is the *transition rate for LWR.* R_{LWRi}^{TRA} is a fixed delay with delay time equal to one year, and $R_{IN\ i}^{TRA}$ is the *transition rate for initial number of LWRs.* $R_{IN\ i}^{TRA}$ is modeled as the *initial number of reactors,* $F_{i_0}^{LWR}$, multiplied by the one year duration pulse function. The *decommissioned LWR fleet,* $F_{DEC}^{LWR}(t)$, is modeled as

$$\frac{dF_{DEC}^{LWR}(t)}{dt}=R_{DR}^{LWR}(t),\ F_{DEC_0}^{LWR}, \tag{2.13}$$

where $F_{DEC_0}^{LWR}=F_{DEC}^{LWR}(t=0)$. Last, the *number of LWR starting commercial operation per year,* $F_N^{LWR}(t)$, is modeled as

$$\frac{dF_N^{LWR}(t)}{dt} = R_{FO}^{LWR}(t) - O_{LWR}(t)\,,\ F_N^{LWR}{}_0, \tag{2.14}$$

where $F_N^{LWR}{}_0 = F_N^{LWR}(t=0)$, and $O_{LWR}(t)$ is a one year fixed delay applied to the fulfilled order rate.

2.4.2. Back-end structure-policy diagram

The back-end structure-policy diagram, shown in Figure 2-4, is a mass-demand driven system. The following systems are modeled in back-end structure-policy diagrams: the construction of UO_2 separation plants from spent LWR fuel, the construction of FFF reprocessing plants, the construction of ABRs, the construction of GFR reprocessing plants, and the construction of GFRs. The system-input for this diagram must be the nuclear fuel available for fast reactors, or the mass available for partitioning. The system-output is the number of fast reactors or separation/reprocessing facilities under commercial operation.

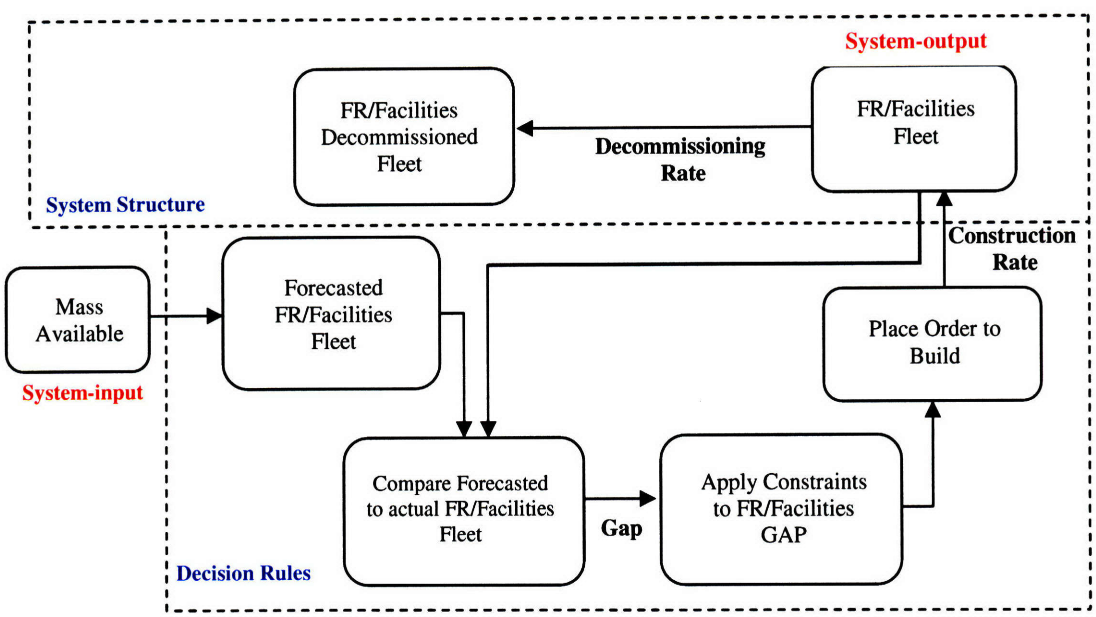

Figure 2-4 – Back-end structure-policy diagram of the system

The fleet to deplete the mass inventory is forecasted based on the mass inflow, the mass inventory, the nominal capacity, the plant lifetime, and on user specified instantaneous depletion time, as detailed in equations 2.18, 2.19, 2.20 and 2.21. The construction rate is calculated considering the gap between the actual and forecasted fleet, and the nominal and industrial capacity for construction of new plants. In addition, only integer numbers of FR or facilities are built. At the beginning of the simulation, there are no advanced facilities under commercial operation. For this reason, only one stock is used to represent the fleet of separation and reprocessing plants, or fast reactors. Also, the aging rate is modeled as a fixed delay with duration equal to the facilities lifetime.

In the system, the mass inventory is evaluated as the accumulation of material due to the mass inflow and to the mass utilization rate, i.e. the mass outflow. The mass inflow is a function of the system-input. The mass utilization rate is a function of the actual fleet and its nominal capacity. The development of the mass inventory should follow a desired state, and the mass utilization rate should counteract any disturbance that moves the actual state away from the goal. The goal is to burn or treat the mass inventory to keep it at a minimum level. In addition, the instantaneous and cumulative mass loading factor are evaluated. Next, each back-end structure-policy diagrams will be detailed.

2.4.2.1 UO2 separation plants structure-policy diagram

Initially, the system-input of the UO_2 separation plants structure-policy diagram is the amount of UO_2 spent fuel discharged from LWRs loaded with traditional or CONFU fuel, as presented in Figure 2-5. The amount of *spent fuel discharged per year*, $SF(t)$, is modeled as

$$SF(t) = SF_{UO_2}(t) + SF_{Young}(t) + SF_{Old}(t), \tag{2.15}$$

where $SF_{UO_2}(t)$ is the *LWR spent fuel discharged per year*, $SF_{Young}(t)$ is the *young CONFU UO_2 spent fuel discharged per year,* and $SF_{Old}(t)$ is the *old CONFU UO_2 spent fuel discharged per year* (see Chapter 3 for details). The *UO_2 spent fuel inventory*, $S_{SP}(t)$, is modeled as

$$\frac{dS_{SP}(t)}{dt} = R_{IR}^{SP}(t) - R_{UR}^{SP}(t), \ S_{SP_0}, \tag{2.16}$$

where $S_{SP_0} = S_{SP}(t=0)$. The *UO_2 spent fuel inflow rate,* $R_{IR}^{SP}(t)$, is modeled as

$$R_{IR}^{SP}(t) = (1 - L_{SP}) \cdot SF(t), \tag{2.17}$$

where L_{SP} is the *separation plants losses.*

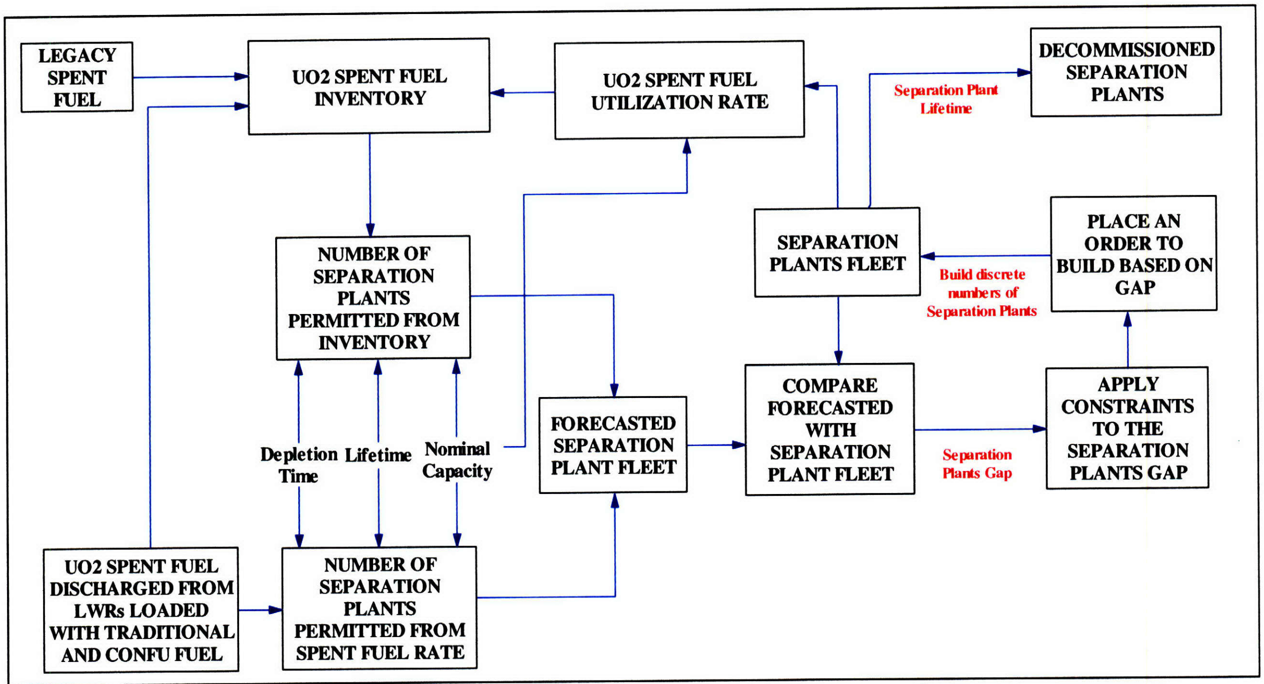

Figure 2-5 - UO_2 separation plants structure-policy diagram of the system

The *forecasted fleet of separation plants,* $F_{EST}^{SP}(t)$, is assumed as

If *time* $t < D_{SP}$: $$F_{EST}^{SP}(t)=0, \text{ or} \tag{2.18}$$

If *time* $t > D_{SP}$: $$F_{EST}^{SP}(t)=F_{INV}^{SP}(t)+F_{SUS}^{SP}(t), \tag{2.19}$$

where the *number of separation plants permitted from inventory,* $F_{INV}^{SP}(t)$, and the *number of separation plants permitted from spent fuel rate,* $F_{SUS}^{SP}(t)$, are modeled as

$$F_{INV}^{SP}(t)=\frac{S_{SP}(t)}{DT_{SP}}\cdot\frac{1}{NC_{SP}} \tag{2.20}$$

$$F_{SUS}^{SP}(t)=\frac{SF\ (t)}{NC_{SP}}\cdot\frac{LT_{SP}}{DT_{SP}} \tag{2.21}$$

where NC_{SP} is the *separation plant nominal capacity,* LT_{SP} is the *separation plants lifetime,* and DT_{SP} is the *instantaneous separation plant depletion time.* DT_{SP} is the time to deplete the current mass inventory if there is no change in the net inflow, and if no constraints are applied to the shortfall. The default value for DT_{SP} is the separation plants lifetime. However, the depletion time can be changed to alter the rate of adjustment in the mass inventory. Changes in the instantaneous depletion time imply changes in the number of separation plants under commercial operation, and changes in the mass loading factor. The *introduction date for separation plants*, D_{SP}, is modeled as the minimum among four introduction dates: *introduction date for ABR technology*, D_{ABR}; *introduction date for GFR technology*, D_{GFR}; *introduction date for CONFU technology*, D_{CONFU}; and *introduction date for U recycling*, D_U.

$$D_{SP} = Minimum[D_{ABR}, D_{GFR}, D_{CONFU}, D_U]. \tag{2.22}$$

Next, *the forecasted LWR fleet*, $F_{EST}^{SP}(t)$, is compared to the *total fleet of separation plant*, $F_{SP}(t)$. The *adjustment for the fleet of separation plants*, $ADJ_{SP}(t)$, is modeled as

$$ADJ_{SP}(t) = \frac{F_{EST}^{SP}(t) - F_{SP}(t)}{\tau_{SP}}, \tag{2.23}$$

where τ_{SP} is the *separation plant adjustment time* (the same assumptions made for the *LWR fleet adjustment time* are applied here). In addition, separation plants can leave the stock of plants under commercial operation only by decommissioning. So, the *fractional SP construction order rate*, $R_{CO}^{SP}(t)$, is defined as equal to the maximum between zero and the minimum between the *adjustment for the fleet of separation plants*, $ADJ_{SP}(t)$, and the *separation plants maximum construction starting rate*, $R_{MAX}^{SP}(t)$, at each time step

$$R_{CO}^{SP}(t) = Maximum[0, Minimum[ADJ_{SP}(t), R_{MAX}^{SP}(t)]]. \tag{2.24}$$

The *fractional number of SP ordered* is modeled as

$$\frac{dF_{FRAC}^{SP}(t)}{dt} = R_{CO}^{SP}(t) - R_{FO}^{SP}(t), F_{FRAC_0}^{SP}, \tag{2.25}$$

where $R_{FO}^{SP}(t)$ is the *SP fulfilled order rate*, and $F_{FRAC_0}^{SP} = F_{FRAC}^{SP}(t=0)$. The $R_{FO}^{SP}(t)$ is defined as

$$R_{FO}^{SP}(t)=\frac{I_{SP}(t)}{TimeStep},\tag{2.26}$$

where $I_{SP}(t)$ is the *integer number of separation plants ready to start commercial operation*

$$I_{SP}(t)=Integer[F_{FRAC}^{SP}(t)].\tag{2.27}$$

The *maximum construction rate*, $R_{MAX}^{SP}(t)$, is modeled to be the ratio between the *nominal capacity*, NC_{SP}, and the *industrial capacity*, $IC_{SP}(t)$

$$R_{MAX}^{SP}=\frac{IC_{SP}}{NC_{SP}(t)}.\tag{2.28}$$

In addition, $IC_{SP}(t)$ is modeled as

If *time* $t < D_D^{SP}$: $\quad IC_{SP}(t)=IC_i^{SP}$, or (2.29)

If *time* $t > D_D^{SP}$: $\quad IC_{SP}(t)=IC_f^{SP}$, (2.30)

where IC_i^{SP} is the *initial separation plant industrial capacity*, IC_f^{SP} is the *final separation plant industrial capacity*, and D_D^{SP} is the date when the industrial capacity changes.

The number of separation plants under commercial operation is represented by one state variable, $F_{SP}(t)$. The fleet of separation plants increases by the *separation plants construction rate,* $R_{CR}^{SP}(t)$, and decreases by the *separation plants decommissioning rate,* $R_{DR}^{SP}(t)$. Separation plants are built and stay under commercial operation for a fixed period of time. The only way that one plant can leave the system is for decommissioning. Therefore, $R_{CR}^{SP}(t)$ can not be negative, i.e. the destruction of a separation plant can not be ordered. The fleet of separation plants is modeled as

$$\frac{dF_{SP}(t)}{dt}=R_{CR}^{SP}(t)-R_{DR}^{SP}(t),\ F_0^{SP},\tag{2.31}$$

$$R_{DR}^{SP}(t)=Delay[R_{CR}^{SP}(t),LT_{SP}].\tag{2.32}$$

$$R_{CR}^{SP}(t) = R_{FO}^{SP}(t), \tag{2.33}$$

where $F_0^{SP} = F_{SP}(t=0)$. The *total recycled uranium per year,* $U_{SP}(t)$, is calculated based on the fleet of separation plants, on the nominal capacity, on the uranium percentage in the UO_2 spent fuel , and on the uranium percentage in CONFU batches

$$U_{SP}(t) = \frac{F_{SP}(t) \cdot NC_{SP}}{SF(t)} \cdot \left(P_U^{UO_2} \cdot SF_{UO_2}(t) + P_U^{Young} \cdot SF_{Young}(t) + P_U^{Old} \cdot SF_{Old}(t)\right), \tag{2.34}$$

where NC_{SP} is the *separation plant nominal capacity,* $P_U^{UO_2}$ is the *uranium percentage in the UO_2 fuel,* P_U^{Young} is the *uranium percentage in the young CONFU fuel,* $SF_{UO_2}(t)$ is the *UO_2 spent fuel discharged per year,* $SF_{Young}(t)$ is the *young CONFU spent fuel discharged per year,* $SF_{Old}(t)$ is the *old CONFU spent fuel discharged per year,* and P_U^{Old} is the *uranium percentage in the old CONFU fuel.* Consequently, the total separated TRU per year is modeled as

$$TRU_{SP}^{FUEL}(t) = \frac{F_{SP}(t) \cdot NC_{SP}}{SF(t)} \cdot \left(\left(P_{MA}^{UO_2} + P_{PU}^{UO_2}\right) \cdot SF_{UO_2}(t) + \left(P_{MA}^{Young} + P_{PU}^{Young}\right) \cdot SF_{Young}(t) + \left(P_{MA}^{Old} + P_{PU}^{Old}\right) \cdot SF_{Old}(t)\right), \tag{2.35}$$

where $TRU_{SP}^{FUEL}(t)$ is the *separated TRU per year,* $P_{MA}^{UO_2}$ is the *minor actinides percentage in the UO_2 fuel,* $P_{PU}^{UO_2}$ is the *plutonium percentage in the UO_2 fuel,* P_{MA}^{Young} is the *minor actinides percentage in the young CONFU fuel,* P_{Pu}^{Young} is the *plutonium percentage in the young CONFU fuel,* P_{MA}^{Old} is the *minor actinides percentage in the old CONFU fuel,* and P_{Pu}^{Old} is the *plutonium percentage in the old CONFU fuel.* Next, the *spent fuel utilization rate,* $R_{UR}^{SP}(t)$, is calculated to be the minimum between the *maximum spent fuel utilization rate due to inventory,* $R_{PR}^{SP}(t)$, and the *desired spent fuel utilization rate,* $R_{DU}^{SP}(t)$:

$$R_{UR}^{SP} = Min[R_{PR}^{SP}, R_{DU}^{SP}]. \tag{2.36}$$

Then $R_{DU}^{SP}(t)$ is modeled as

$$R_{DU}^{SP} = NC_{SP} \cdot F_{SP}(t), \tag{2.37}$$

and the *maximum spent fuel utilization rate due to inventory,* $R_{PR}^{SP}(t)$, is the ratio between $S_{SP}(t)$ and the simulation time step:

$$R_{PR}^{SP} = \frac{S_{SP}}{TimeStep}. \tag{2.38}$$

Then, the *instantaneous mass loading factor,* $LF_{SP}(t)$, is modeled as

$$LF_{SP}(t) = \frac{R_{UR}^{SP}}{R_{DR}^{SP}}, \tag{2.39}$$

and the *cumulative mass loading factor,* $LF_{CUM}^{SP}(t)$, is modeled as

$$\frac{dLF_{CUM}^{sp}(t)}{dt} = LF_{SP}(t). \tag{2.40}$$

Then, the *number of SP starting commercial operation per year,* $F_N^{SP}(t)$, is modeled as

$$\frac{dF_N^{SP}(t)}{dt} = R_{FO}^{SP}(t) - O_{SP}(t),\ F_{N\ 0}^{SP}, \tag{2.41}$$

where $F_{N\ 0}^{SP} = F_N^{SP}(t=0)$, and $O_{SP}(t)$ is a one year fixed delay applied to the fulfilled order rate.

Finally, the *TRU inventory at interim storage,* $TRU_{INV}(t)$, is calculated as

$$TRU_{INV}(t) = \frac{S_{SP}(t)}{SF(t)} \cdot \left(\left(P_{MA}^{UO_2} + P_{PU}^{UO_2} \right) \cdot SF_{UO_2}(t) + \left(P_{MA}^{Young} + P_{PU}^{Young} \right) \cdot SF_{Young}(t) + \left(P_{MA}^{Old} + P_{PU}^{Old} \right) \cdot SF_{Old}(t) \right). \tag{2.42}$$

The amount of TRU used for the fuel fabrication for each technology is defined by the ratio of TRU for ABR, for CONFU, and for GFR fuel fabrication, i.e. the first load into the GFR core. The percentage of TRU for each technology is a user input. TRU plus U from GFR reprocessing plants is used as fuel for GFRs already under commercial operation due to self-sustaining properties of the gas-cooled reactors.

2.4.2.2 Construction of ABRs structure-policy diagram

The system-input of the construction of ABRs structure-policy is the separated TRU discharged from separation plants, and the reprocessed TRU discharged from FFF reprocessing plants, as presented in Figure 2-6. The system-output is the ABR fleet. ABRs are built as soon as there is enough fuel for the first core, and the mass loaded at equilibrium is considered for calculating the fuel utilization rate.

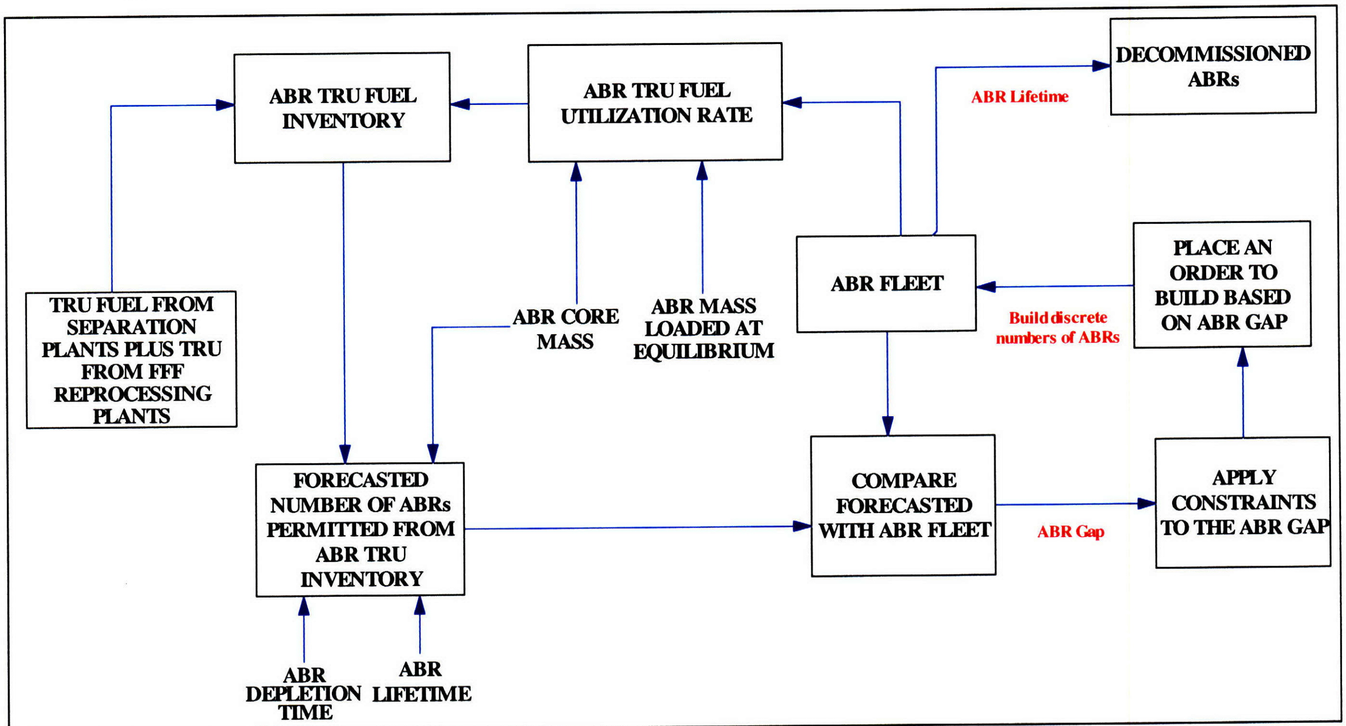

Figure 2-6 – Construction of ABRs structure-policy diagram of the system

First, the *TRU available for fuel fabrication per year*, $TRU_{FUEL}(t)$, is modeled as

$$TRU_{FUEL}(t) = TRU_{SP}^{FUEL}(t) + TRU_{FFF}^{FUEL}(t), \tag{2.43}$$

where $TRU_{SP}^{FUEL}(t)$ is the amount of *separated TRU per year*, and $TRU_{FFF}^{FUEL}(t)$ is the amount of *reprocessed FFF TRU per year*. The *TRU available for fabrication per year*, $TRU_{FUEL}(t)$, should be used for CONFU, ABR and GFR fuel fabrication. Therefore, the amount of *TRU available for ABR fuel fabrication per year*, $TRU_{ABR}^{FUEL}(t)$, is modeled as

$$TRU_{ABR}^{FUEL}(t) = P_{ABR}^{TRU}(t) \cdot TRU_{FUEL}(t), \tag{2.44}$$

where the *percentage of TRU for ABR fuel fabrication*, $P_{TRU}^{ABR}(t)$, is modeled as

$$\text{If } time\ t < D_{ABR}: \qquad P_{ABR}^{TRU}(t) = 0, \text{ or} \tag{2.45}$$

$$\text{If } time\ t > D_{ABR}: \qquad P_{ABR}^{TRU}(t) = \overline{P}_{ABR}^{TRU}, \tag{2.46}$$

where $\overline{P}_{ABR}^{TRU}$ is an user input defined as the *percentage of TRU for ABR fuel after introduction of technology*. The *ABR TRU Fuel*, $S_{ABR}(t)$, is modeled as

$$\frac{dS_{ABR}(t)}{dt} = R_{IR}^{ABR}(t) - R_{UR}^{ABR}(t),\ S_{ABR_0}, \tag{2.47}$$

where $S_{ABR_0} = S_{ABR}(t=0)$, and the *ABR TRU inflow rate is*

$$R_{IR}^{ABR} = (1 - L_{ABR}) \cdot TRU_{ABR}^{FUEL}, \tag{2.48}$$

and L_{ABR} is the *ABR fuel fabrication losses.*

Next, the *forecasted ABR fleet*, $F_{EST}^{ABR}(t)$, is modeled as

$$\text{If } time\ t < D_{ABR}: \qquad F_{EST}^{ABR}(t) = 0, \text{ or} \tag{2.49}$$

$$\text{If } time\ t > D_{ABR}: \qquad F_{EST}^{ABR}(t) = \left(\frac{S_{ABR}(t)}{CM_{ABR}}\right) \cdot \frac{LT_{ABR}}{DT_{ABR}}, \tag{2.50}$$

where LT_{ABR} is *ABR lifetime*, CM_{ABR} is the *ABR core mass*, and DT_{ABR} is the *ABR instantaneous depletion time* which has the same definition that DT_{SP}. Next, the *forecasted ABR fleet* is compared to the current ABR fleet. The *adjustment for the ABR fleet*, $ADJ_{ABR}(t)$, is modeled as

$$ADJ_{ABR}(t) = \frac{F_{EST}^{ABR}(t) - F_{ABR}(t)}{\tau_{ABR}}. \tag{2.51}$$

where τ_{ABR} is the *ABR adjustment time* -- the same assumptions made for the *LWR fleet adjustment time* are applied here. The *fractional ABR construction order rate*, $R_{CO}^{ABR}(t)$, is defined as the maximum between zero and the *adjustment for the ABR fleet* at each time step

$$R_{CO}^{ABR}(t) = Maximum[0, ADJ_{ABR}(t)]. \tag{2.52}$$

Following, the *fractional number of ABR ordered* is modeled as

$$\frac{dF_{FRAC}^{ABR}(t)}{dt} = R_{CO}^{ABR}(t) - R_{FO}^{ABR}(t), F_{FRC_0}^{ABR}, \tag{2.53}$$

where $R_{FO}^{ABR}(t)$ is the *ABR fulfilled order rate*, and $F_{FRAC_0}^{ABR} = F_{FRAC}^{ABR}(t=0)$. The $R_{FO}^{ABR}(t)$ is defined as

$$R_{FO}^{ABR}(t) = \frac{I_{ABR}(t)}{TimeStep}, \tag{2.54}$$

where $I_{ABR}(t)$ is the *integer number of reactors ready to start commercial operation*

$$I_{ABR}(t) = Integer[F_{FRAC}^{ABR}(t)]. \tag{2.55}$$

The number of ABR under commercial operation increases by the ABR construction rate and decreases by the ABR decommissioning rate. The assumptions for the $F_{SP}(t)$ are considered for the fleet of ABRs, which is modeled as

$$\frac{dF_{ABR}(t)}{dt} = R_{CR}^{ABR}(t) - R_{DR}^{ABR}(t),\ F_0^{ABR} \tag{2.56}$$

where $F_0^{ABR} = F_{ABR}(t=0)$. The $R_{CR}^{ABR}(t)$ and $R_{DR}^{ABR}(t)$ are modeled as

$$R_{CR}^{ABR}(t) = R_{FO}^{ABR}(t), \tag{2.57}$$

$$R_{DR}^{ABR}(t) = Delay(R_{CR}^{ABR}(t), LT_{ABR}). \tag{2.58}$$

Next, the *ABR TRU utilization rate,* $R_{UR}^{ABR}(t)$, is calculated as the minimum between the *maximum ABR TRU utilization rate due to inventory,* $R_{PR}^{ABR}(t)$, and the *desired ABR TRU utilization rate,* $R_{DU}^{ABR}(t)$:

$$R_{UR}^{ABR} = MIN(R_{PR}^{ABR}, R_{DU}^{ABR}), \tag{2.59}$$

and $R_{DU}^{ABR}(t)$ is modeled as

$$R_{DU}^{ABR} = EM_{ABR} \cdot F_{ABR}(t) + CM_{ABR} \cdot F_N^{ABR}(t), \tag{2.60}$$

where EM_{ABR} is the *ABR mass loaded at equilibrium*, and $F_N^{ABR}(t)$ is the *number of ABRs starting commercial operation per year.* The *maximum ABR TRU utilization rate due to inventory,* $R_{PR}^{ABR}(t)$, is the ratio between the $S_{ABR}(t)$ and the time step:

$$R_{PR}^{ABR} = \frac{S_{ABR}(t)}{TimeStep}. \tag{2.61}$$

Then, the *instantaneous ABR mass loading factor,* $LF_{ABR}(t)$, is modeled as

$$LF_{ABR}(t) = \frac{R_{UR}^{ABR}}{R_{DR}^{ABR}}, \tag{2.62}$$

and the *cumulative ABR mass loading factor,* $LF_{CUM}^{ABR}(t)$, is modeled as

$$\frac{dLF_{CUM}^{ABR}(t)}{dt} = LF_{ABR}(t). \tag{2.63}$$

The *number of ABR starting commercial operation per year,* $F_N^{ABR}(t)$, is modeled as

$$\frac{dF_N^{ABR}(t)}{dt} = R_{FO}^{ABR}(t) - O_{ABR}(t),\ F_{N\ 0}^{ABR}, \tag{2.64}$$

where $F_{N\ 0}^{ABR} = F_N^{ABR}(t=0)$, and $O_{ABR}(t)$ is a one year fixed delay applied to the fulfilled order rate. Last, the *FFF TRU discharged from ABR per year,* $TRU_{ABR}^{SF}(t)$, is modeled as

$$TRU_{ABR}^{SF}(t) = F_{ABR}(t) \cdot \overline{TRU}_{ABR}^{SF} \tag{2.65}$$

where $\overline{TRU}_{ABR}^{SF}$ is the *FFF TRU discharged per ABR per year.*

2.4.2.3 Construction of FFF reprocessing plants structure-policy diagram

The system-input of the FFF reprocessing plants structure-policy is the amount of TRU discharged from the ABR fleet, and TRU from Old and Young CONFU batches discharged from LWRs, as showed in Figure 2-7. The system-output is the number of FFF reprocessing plants under commercial operation. Next, the model of the FFF reprocessing plants structure-policy diagram is detailed.

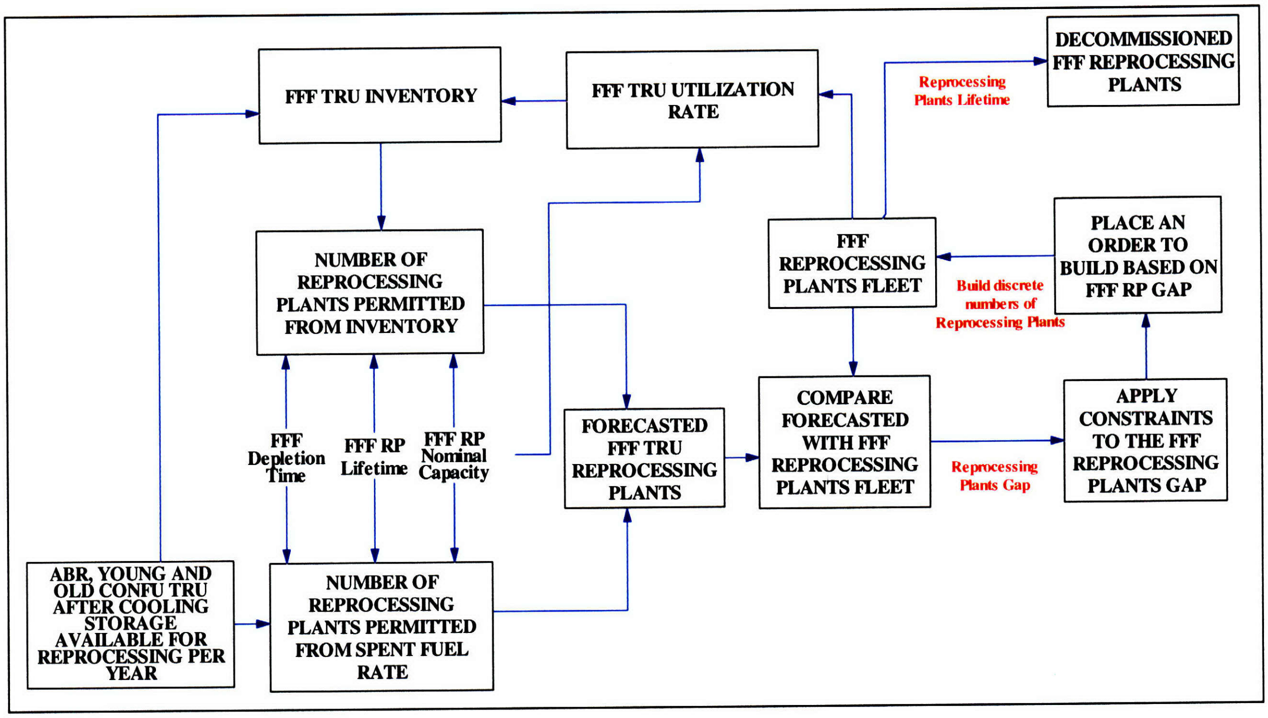

Figure 2-7 – Construction of FFF TRU reprocessing plants of the system

First, the amount of *FFF TRU available for reprocessing per year,* $TRU_{FFF}^{SF}(t)$, is modeled as

$$TRU_{FFF}^{SF}(t) = TRU_{ABR}^{SF}(t) + TRU_{Old}^{SF}(t) + TRU_{Young}^{SF}(t) \tag{2.66}$$

where $TRU_{ABR}^{SF}(t)$ is the *ABR FFF TRU discharged from ABR per year* after cooling storage, $TRU_{Young}^{SF}(t)$ is the *young CONFU FFF TRU discharged from LWR per year* after cooling storage, and $TRU_{Old}^{SF}(t)$ is the *old CONFU FFF TRU discharged from LWR per year*, also after cooling storage. Next, the *FFF TRU available for reprocessing,* $S_{FFF}(t)$, is modeled as

$$\frac{dS_{FFF}(t)}{dt} = R_{IR}^{FFF}(t) - R_{UR}^{FFF}(t),\ S_{FFF_0} \tag{2.67}$$

where $S_{FFF_0} = S_{FFF}(t=0)$. The *FFF TRU utilization rate,* $R_{UR}^{FFF}(t)$, is detailed in equation 2.85. The *FFF TRU inflow rate,* $R_{IR}^{FFF}(t)$, is modeled as

$$R_{IR}^{FFF}(t) = TRU_{FFF}^{SF}(t) \tag{2.68}$$

The *forecasted fleet of FFF reprocessing plants,* $F_{EST}^{FFF}(t)$, is assumed as

If *time* $t < D_{FFF}$: $$F_{EST}^{FFF}(t)=0, \text{ or} \tag{2.69}$$

If *time* $t > D_{FFF}$: $$F_{EST}^{FFF}(t)=F_{INV}^{FFF}(t)+F_{SUS}^{FFF}(t), \tag{2.70}$$

where the *number of FFF reprocessing plants permitted from inventory,* $F_{INV}^{FFF}(t)$, *and the number of FFF reprocessing plants permitted from FFF TRU rate* , $F_{SUS}^{FFF}(t)$, are modeled as

$$F_{INV}^{FFF}(t)=\frac{S_{FFF}(t)}{DT_{FFF}}\cdot\frac{1}{NC_{FFF}}, \text{ or} \tag{2.71}$$

$$F_{SUS}^{FFF}(t)=\frac{TRU_{FFF}^{SF}(t)}{NC_{FFF}}\cdot\frac{LT_{FFF}}{DT_{FFF}}, \tag{2.72}$$

where NC_{FFF} is the *FFF reprocessing plant nominal capacity,* LT_{FFF} is the *FFF reprocessing plants lifetime,* and DT_{FFF} is the *instantaneous FFF reprocessing plant target depletion time* which has the same definition that DT_{SP}. The *introduction date for FFF reprocessing plant,* D_{FFF}, is modeled as the minimum between D_{ABR} and D_{CONFU}

$$D_{FFF}=Minimum(D_{ABR},D_{CONFU}). \tag{2.73}$$

Next, the *forecasted FFF reprocessing fleet,* $F_{EST}^{FFF}(t)$, is compared to the *total fleet of FFF reprocessing plant,* $F_{FFF}(t)$. The *adjustment for the fleet of FFF reprocessing plants,* $ADJ_{FFF}(t)$, is modeled as:

$$ADJ_{FFF}(t)=\frac{F_{EST}^{FFF}(t)-F_{FFF}(t)}{\tau_{FFF}}, \tag{2.74}$$

where τ_{FFF} is the *FFF reprocessing plant adjustment time,* which has the same definition that the *LWR fleet adjustment time.* In addition, the *fractional FFF RP construction order rate,* $R_{CO}^{FFF}(t)$, is defined as the maximum between zero and the minimum between the *adjustment for* *the fleet of FFF RP* and the *maximum construction starting rate for FFF RP plants,* $R_{MAX}^{FFF}(t)$, at each time step

$$R_{CO}^{FFF}(t) = Maximum[0, Minimum[ADJ_{FFF}(t), R_{MAX}^{FFF}(t)]]. \quad (2.75)$$

Next, the *fractional number of FFF RP ordered* is modeled as

$$\frac{dF_{FRAC}^{FFF}(t)}{dt} = R_{CO}^{FFF}(t) - R_{FO}^{FFF}(t), F_{FRC_0}^{FFF}, \quad (2.76)$$

where $R_{FO}^{FFF}(t)$ is the *FFF RP fulfilled order rate*, and $F_{FRAC_0}^{FFF} = F_{FRAC}^{FFF}(t=0)$. The $R_{FO}^{FFF}(t)$ is defined as

$$R_{FO}^{FFF}(t) = \frac{I_{FFF}(t)}{TimeStep}, \quad (2.77)$$

where $I_{FFF}(t)$ is the *integer number of separation plants ready to start commercial operation*

$$I_{FFF}(t) = Integer[F_{FRAC}^{FFF}(t)]. \quad (2.78)$$

$R_{MAX}^{FFF}(t)$ is modeled to be the ratio between the *FFF RP nominal capacity,* NC_{FFF}, and the *FFF RP industrial capacity,* $IC_{FFF}(t)$

$$R_{MAX}^{FFF} = \frac{IC_{FFF}}{NC_{FFF}(t)}. \quad (2.79)$$

In addition, $IC_{FFF}(t)$ is modeled as

If *time* $t < D_D^{FFF}$: $\quad IC_{FFF}(t) = IC_i^{FFF}$, or (2.80)

If *time* $t > D_D^{FFF}$: $\quad IC_{FFF}(t) = IC_f^{FFF}$, (2.81)

where IC_i^{FFF} is the *initial FFF RP industrial capacity,* IC_f^{FFF} is the *final FFF RP industrial capacity*, and D_D^{FFF} is the date when the industrial capacity changes.

The fleet of FFF reprocessing plants, $F_{FFF}(t)$, increases by the *FFF RP construction rate,* $R_{CR}^{FFF}(t)$, and decreases by the *FFF RP decommissioning rate,* $R_{DR}^{FFF}(t)$. The assumptions for the $F_{SP}(t)$ are considered for the *fleet of FFF reprocessing plants*, which is modeled as

$$\frac{dF_{FFF}(t)}{dt} = R_{CR}^{FFF}(t) - R_{DR}^{FFF}(t),\ F_0^{FFF}, \tag{2.82}$$

$$R_{DR}^{FFF}(t) = Delay[R_{CR}^{FFF}(t), LT_{FFF}]. \tag{2.83}$$

$$R_{CR}^{FFF}(t) = R_{FO}^{FFF}(t), \tag{2.84}$$

where $F_0^{FFF} = F_{FFF}(t=0)$. Next, the *FFF TRU utilization rate,* $R_{UR}^{FFF}(t)$, is calculated as the minimum between the *maximum FFF TRU utilization rate due to inventory,* $R_{PR}^{FFF}(t)$, and the *desired FFF TRU utilization rate,* $R_{DU}^{FFF}(t)$

$$R_{UR}^{FFF} = MIN(R_{PR}^{FFF}, R_{DU}^{FFF}). \tag{2.85}$$

Then, $R_{DU}^{FFF}(t)$ is modeled as

$$R_{DU}^{FFF} = NC_{FFF} \cdot F_{FFF}(t), \tag{2.86}$$

and the *maximum FFF TRU utilization rate due to inventory* is the ratio between the $S_{FFF}(t)$ and the simulation time step:

$$R_{PR}^{FFF} = \frac{S_{FFF}(t)}{TimeStep}. \tag{2.87}$$

Then, the *instantaneous FFF RP mass loading factor,* $LF_{FFF}(t)$, is modeled as

$$LF_{FFF}(t) = \frac{R_{UR}^{FFF}}{R_{DR}^{FFF}}, \tag{2.88}$$

and the *cumulative FFF RP mass loading factor,* $LF_{CUM}^{FFF}(t)$, is modeled as

$$\frac{dLF_{CUM}^{FFF}(t)}{dt} = LF_{FFF}(t). \tag{2.89}$$

Then, the *number of FFF RP starting commercial operation per year,* $F_N^{FFF}(t)$, is modeled as

$$\frac{dF_N^{FFF}(t)}{dt} = R_{FO}^{FFF}(t) - O_{FFF}(t),\ F_{N\ 0}^{FFF}, \tag{2.90}$$

where $F_{N\ 0}^{FFF} = F_N^{FFF}(t=0)$, and $O_{FFF}(t)$ is a one year fixed delay applied to the fulfilled order rate. Finally, the amount of *reprocessed FFF TRU per year,* $TRU_{FFF}^{FUEL}(t)$, is modeled as

$$TRU_{FFF}^{FUEL} = (1 - L_{FFF}) \cdot NC_{FFF} \cdot F_{FFF}(t), \tag{2.91}$$

where L_{FFF} designates *FFF reprocessing losses.*

2.4.2.4 Construction of GFRs structure-policy diagram

The system-input for the construction of GFRs structure-policy is the total *TRU available for fuel fabrication per year,* $TRU_{FUEL}(t)$, mixed with recycled U, discharged from separation plants, as presented in Figure 2-8. The system-output is the number of GFRs under commercial operation. Next, the model of this subsystem is detailed.

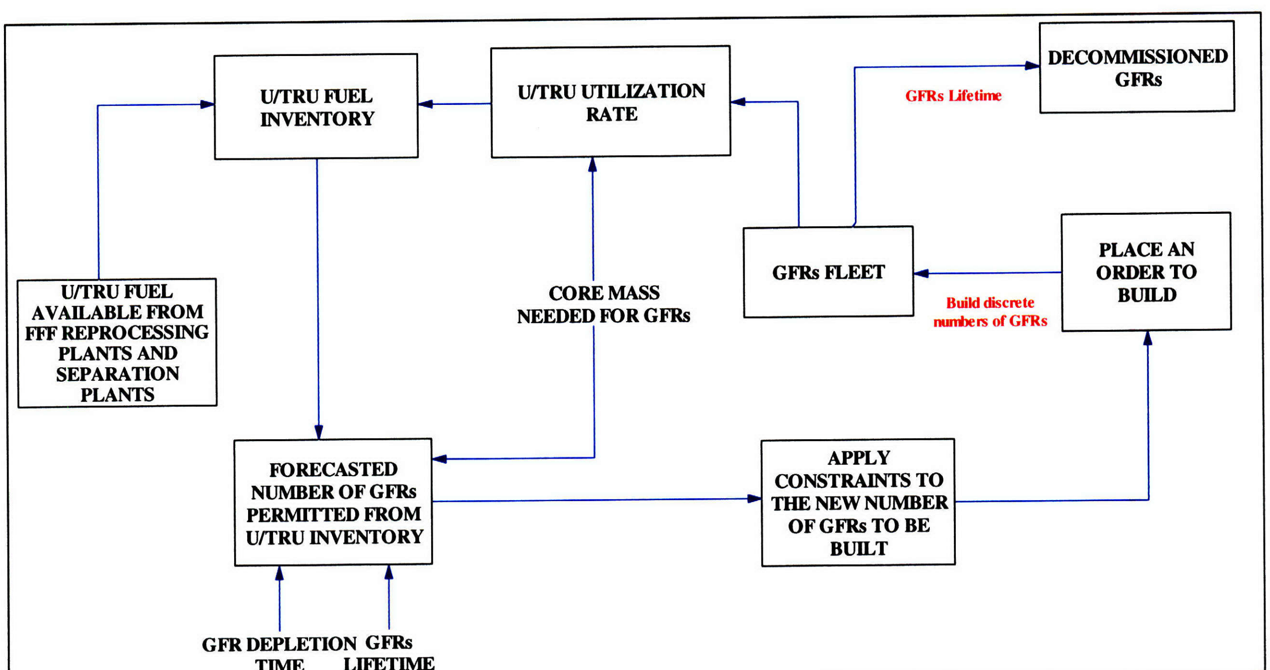

Figure 2-8 – Construction of GFRs structure-policy diagrams

Initially, the amount of *TRU available for new GFR fuel fabrication per year,* $TRU_{GFR}^{FUEL}(t)$, is modeled as

$$TRU_{GFR}^{FUEL}(t) = P_{GFR}^{TRU}(t) \cdot TRU_{FUEL}(t). \tag{2.92}$$

The *percentage of TRU available for new GFR fuel fabrication,* $P_{GFR}^{TRU}(t)$, which is an user input that defines the ratio of reprocessed or separated TRU for fuel fabrication for each technology, is modeled as

$$\text{If } time\ t < D_{GFR}: \qquad P_{GFR}^{TRU}(t) = 0, \quad \text{or} \tag{2.93}$$

$$\text{If } time\ t > D_{GFR}: \qquad P_{GFR}^{TRU}(t) = \overline{P}_{GFR}^{TRU}, \tag{2.94}$$

where $\overline{P}_{GFR}^{TRU}$ is the *percentage of TRU for new GFR fuel after introduction of technology.* The *U/TRU available for new GFR fuel fabrication per year,* $GFR_{FUEL}(t)$, is evaluated as

$$GFR_{FUEL}(t) = \frac{TRU_{GFR}^{FUEL}(t)}{(1 - \overline{P}_{U}^{TRU})}, \tag{2.95}$$

where $\overline{P}_{U}^{TRU}$ is the *percentage of recycled U to be mixed with separated TRU for GFR fuel fabrication.* In addition, the *total U mixed with TRU for GFR fuel fabrication,* $U_{TRU}^{GFR}(t)$, and *the remaining recycled U per year after mixing with TRU for GFR fuel fabrication,* $U_{REM}^{SP}(t)$ is evaluated

$$U_{TRU}^{GFR}(t) = \overline{P}_{U}^{TRU} \cdot GFR_{FUEL}(t), \tag{2.96}$$

$$U_{REM}^{SP}(t) = U_{SP}(t) - U_{TRU}^{GFR}(t) - U_{U/TRU}^{GFR}(t), \tag{2.97}$$

where $U_{U/TRU}^{GFR}(t)$ is the *total U mixed with reprocessed U/TRU for GFR fuel fabrication.* The *GFR U/TRU Fuel inventory* is then modeled as the following stock

$$\frac{dS_{GRF}(t)}{dt} = R_{IR}^{GRF}(t) - R_{UR}^{GRF}(t), \ S_{GRF_0}, \tag{2.98}$$

where $S_{GRF_0} = S_{GRF}(t=0)$, and the *GFR U/TRU inflow rate,* $R_{IR}^{GRF}(t)$, is modeled as

$$R_{IR}^{GRF}(t) = (1 - L_{GFR}) \cdot GFR_{FUEL}(t), \tag{2.99}$$

and L_{GFR} defines *fuel fabrication losses for new GFRs*. Next, the *forecasted fleet of new GFRs that could be fully loaded,* $F_{EST}^{GRF}(t)$, is modeled as

$$\text{If } time\ t < D_{GFR}: \quad F_{EST}^{GFR}(t) = 0, \text{ or} \tag{2.100}$$

$$\text{If } time\ t > D_{GFR}: \quad F_{EST}^{GFR}(t) = \left(\frac{S_{GFR}(t)}{CM_{GFR}}\right) \cdot \frac{LT_{GFR}}{DT_{GFR}}, \tag{2.101}$$

where LT_{GFR} is *GFR lifetime,* CM_{GFR} is the *GFR mass needed for new core,* and DT_{GFR} is the *GFR instantaneous depletion time* which has the same definition that DT_{SP}. Next, the *fractional GFR construction order rate,* $R_{CO}^{GFR}(t)$, is defined as

$$R_{CO}^{GFR}(t) = Maximum[0, F_{EST}^{GFR}(t)]. \tag{2.102}$$

Next, the *fractional number of GFR ordered,* $F_{FRAC}^{GFR}(t)$, is modeled as

$$\frac{dF_{FRAC}^{GFR}(t)}{dt} = R_{CO}^{GFR}(t) - R_{FO}^{GFR}(t), F_{FRC_0}^{GFR}, \tag{2.103}$$

where $R_{FO}^{GFR}(t)$ is the *GFR fulfilled order rate*, and $F_{FRAC_0}^{GFR} = F_{FRAC}^{GFR}(t=0)$. The $R_{FO}^{GFR}(t)$ is defined as

$$R_{FO}^{GFR}(t) = \frac{I_{GFR}(t)}{TimeStep}, \tag{2.104}$$

where $I_{GFR}(t)$ is the *integer number of reactors ready to start commercial operation*

$$I_{GFR}(t) = Integer[F_{FRAC}^{GFR}(t)]. \tag{2.105}$$

The fleet of GFRs, $F_{GFR}(t)$, increases by the GFR construction rate and decreases by the GFR decommissioning rate

$$\frac{dF_{GFR}(t)}{dt} = R_{CR}^{GFR}(t) - R_{DR}^{GFR}(t),\ F_0^{GFR}, \tag{2.106}$$

where $F_0^{GFR} = F_{GFR}(t=0)$. The *GFR construction rate,* $R_{CR}^{GFR}(t)$, and the *GFR decommissioning rate,* $R_{DR}^{GFR}(t)$, are modeled as

$$R_{CR}^{GFR}(t) = R_{FO}^{GFR}(t), \tag{2.107}$$

$$R_{DR}^{GFR}(t) = Delay\left(R_{CR}^{GFR}(t), LT_{GFR}\right). \tag{2.108}$$

Next, the *U/TRU utilization rate,* $R_{UR}^{GFR}(t)$, is modeled as

$$R_{UR}^{GFR} = R_{DU}^{GFR}, \tag{2.109}$$

Where the *U/TRU desired utilization rate,* $R_{DU}^{GFR}(t)$, is the fuel mass that must be loaded to start new GFRs cores, and it is modeled as

$$R_{DU}^{GFR} = CM_{GFR} \cdot F_N^{GFR}(t) \tag{2.110}$$

where the *number of GFR starting commercial operation per year,* $F_N^{GFR}(t)$, is modeled as

$$\frac{dF_N^{GFR}(t)}{dt} = R_{FO}^{GFR}(t) - O_{GFR}(t),\ F_{N0}^{GFR}, \tag{2.111}$$

where $F_{N0}^{GFR} = F_N^{GFR}(t=0)$, and $O_{GFR}(t)$ is a one year fixed delay applied to the fulfilled order rate. Finally, the *U/TRU discharged from the GFR fleet,* $GFR_{SF}(t)$, is modeled as

$$GFR_{SF}(t) = F_{GFR}(t) \cdot (GFR_{TRU}^{SF} + GFR_U^{SF}) \tag{2.112}$$

where GFR_{TRU}^{SF} is the amount of *TRU discharged per year per GFR* and GFR_U^{SF} is the *U discharged per year per GFR.* Moreover, a six year fixed delay is applied to $GFR_{SF}(t)$ to take into account the cooling time.

2.4.2.5 Construction of GFR reprocessing plants structure-policy diagram

The system-input of the GFR reprocessing plants structure-policy is the amount of U/TRU discharged from the GFR fleet after cooling storage, as presented in Figure 2-9. The system-output is the number of GFR U/TRU reprocessing plants under commercial operation. The reprocessed U/TRU fuel must be mixed with recycled U to be use as fuel in the self-sustaining *Gas-cooled Fast Reactors*. Next, the model for the construction of GFRs reprocessing plants structure-policy diagram is described.

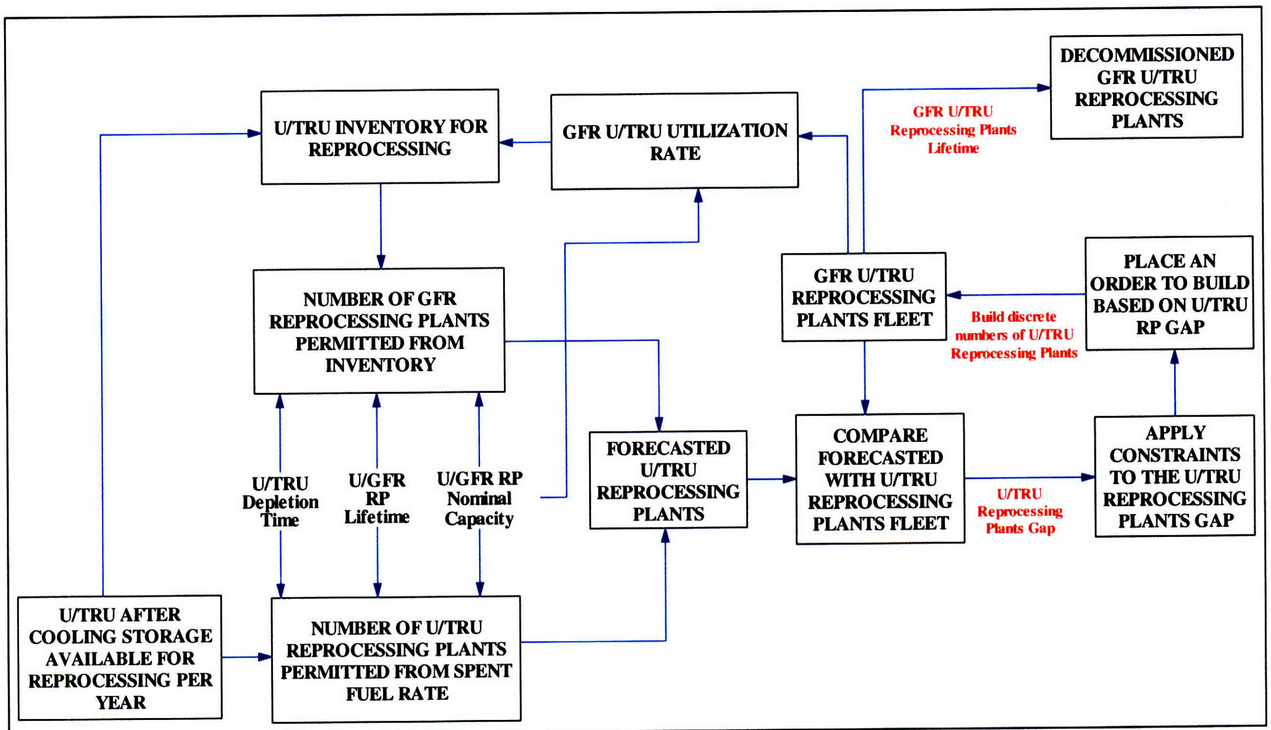

Figure 2-9 – Construction of GFR U/TRU reprocessing plants structure-policy of the system

First, the *GFR U/TRU stock for reprocessing*, $S_{RP}(t)$, is modeled as

$$\frac{dS_{RP}(t)}{dt} = R_{IR}^{RP}(t) - R_{UR}^{RP}(t), \; S_{RP_0} \tag{2.113}$$

where $S_{RP_0} = S_{RP}(t=0)$. The *GFR U/TRU inflow rate*, $R_{IR}^{RP}(t)$, is modeled as

$$R_{IR}^{RP}(t) = GFR_{SF}(t) \tag{2.114}$$

where $GFR_{SF}(t)$ is the *U/TRU discharged from the GFR fleet after cooling storage*. Then, the *forecasted fleet of GFR reprocessing plants*, $F_{EST}^{RP}(t)$, is assumed as

If *time* $t < D_{GFR}$: $$F_{EST}^{RP}(t)=0, \text{ or} \tag{2.115}$$

If *time* $t > D_{GFR}$: $$F_{EST}^{RP}(t)=F_{INV}^{RP}(t)+F_{SUS}^{RP}(t), \tag{2.116}$$

where the *number of GFR reprocessing plants permitted from inventory,* $F_{INV}^{RP}(t)$, and the *number of GFR reprocessing plants permited from spent GFR fuel rate,* $F_{SUS}^{RP}(t)$, are modeled as

$$F_{INV}^{RP}(t)=\frac{S_{RP}(t)}{DT_{RP}}\cdot\frac{1}{NC_{RP}}, \text{ or} \tag{2.117}$$

$$F_{SUS}^{RP}(t)=\frac{GRF_{SF}(t)}{NC_{RP}}\cdot\frac{LT_{RP}}{DT_{RP}}, \tag{2.118}$$

where NC_{RP} is the *GFR reprocessing plant nominal capacity,* LT_{RP} is the *GFR reprocessing plants lifetime,* and DT_{RP} is the *instantaneous GFR reprocessing plant target depletion time,* which has the same definition that DT_{SP}.

Next, the *forecasted GFR reprocessing fleet,* $F_{EST}^{RP}(t)$, is compared to the *total fleet of GFR reprocessing plant,* $F_{RP}(t)$, and the *adjustment for the fleet of FFF reprocessing plants,* $ADJ_{RP}(t)$, is modeled as

$$ADJ_{RP}(t)=\frac{F_{EST}^{RP}(t)-F_{RP}(t)}{\tau_{RP}} \tag{2.119}$$

where τ_{RP} is the *GFR reprocessing plant adjustment time,* which has the same definition that the *LWR fleet adjustment time*. The *fractional GFR RP construction order rate,* $R_{CO}^{RP}(t)$, is defined as the maximum between zero and the minimum between the *adjustment for the fleet of GFR RP* and the *maximum construction starting rate for GFR RP plants,* $R_{MAX}^{RP}(t)$, at each time step

$$R_{CO}^{RP}(t)=Maximum[0, Minimum[ADJ_{RP}(t), R_{MAX}^{RP}(t)]]. \tag{2.120}$$

Next, the *fractional number of GFR RP ordered* is modeled as

$$\frac{dF_{FRAC}^{RP}(t)}{dt} = R_{CO}^{RP}(t) - R_{FO}^{RP}(t), F_{FRC_0}^{RP}, \tag{2.121}$$

where $R_{FO}^{RP}(t)$ is the *GFR RP fulfilled order rate*, and $F_{FRAC_0}^{RP} = F_{FRAC}^{RP}(t=0)$. The $R_{FO}^{RP}(t)$ is defined as

$$R_{FO}^{RP}(t) = \frac{I_{RP}(t)}{TimeStep}, \tag{2.122}$$

where $I_{RP}(t)$ is the *integer number of separation plants ready to start commercial operation*

$$I_{RP}(t) = Integer[F_{FRAC}^{RP}(t)]. \tag{2.123}$$

$R_{MAX}^{RP}(t)$ is modeled to be the ratio between the *GFR RP nominal capacity*, NC_{RP}, and the *GFR RP industrial capacity*, $IC_{RP}(t)$

$$R_{MAX}^{RP} = \frac{IC_{RP}}{NC_{RP}(t)}. \tag{2.124}$$

In addition, $IC_{RP}(t)$ is modeled as

If *time* $t < D_D^{RP}$: $\quad IC_{RP}(t) = IC_i^{RP}$, or (2.125)

If *time* $t > D_D^{RP}$: $\quad IC_{RP}(t) = IC_f^{RP}$, (2.126)

where IC_i^{RP} is the *initial GFR RP industrial capacity*, IC_f^{RP} is the *final GFR RP industrial capacity*, and D_D^{GFR} is the date when the industrial capacity changes.

The fleet of GFR reprocessing plants, $F_{RP}(t)$, increases by the *GFR RP construction rate*, $R_{CR}^{RP}(t)$, and decreases by the *GFR RP decommissioning rate*, $R_{DR}^{RP}(t)$. The assumptions for the $F_{SP}(t)$ are considered for the fleet of GFRs reprocessing plants, which is modeled as

$$\frac{dF_{RP}(t)}{dt} = R_{CR}^{RP}(t) - R_{DR}^{RP}(t),\ F_0^{RP}, \tag{2.127}$$

$$R_{DR}^{RP}(t) = Delay[R_{CR}^{RP}(t), LT_{RP}], \tag{2.128}$$

$$R_{CR}^{RP}(t) = R_{FO}^{RP}(t), \tag{2.129}$$

where $F_0^{RP} = F_{RP}(t=0)$. Next, the *GFR U/TRU utilization rate,* $R_{UR}^{RP}(t)$, is calculated as the minimum between the *maximum GFR U/TRU utilization rate due to inventory,* $R_{PR}^{RP}(t)$, and the *desired GFR U/TRU utilization rate,* $R_{DU}^{RP}(t)$

$$R_{UR}^{RP} = MIN(R_{PR}^{RP}, R_{DU}^{RP}). \tag{2.130}$$

Then $R_{DU}^{RP}(t)$ is modeled as

$$R_{DU}^{RP} = NC_{RP} \cdot F_{RP}(t), \tag{2.131}$$

and the *maximum GFR TRU utilization rate due to inventory* is the ratio between the $S_{RP}(t)$ and the simulation time step:

$$R_{PR}^{RP} = \frac{S_{RP}(t)}{TimeStep}. \tag{2.132}$$

Then, the *instantaneous GFR RP mass loading factor,* $LF_{RP}(t)$, is modeled as

$$LF_{RP}(t) = \frac{R_{UR}^{RP}}{R_{DR}^{RP}}, \tag{2.133}$$

and the *cumulative GFR RP mass loading factor,* $LF_{CUM}^{RP}(t)$, is modeled as

$$\frac{dLF_{CUM}^{RP}(t)}{dt} = LF_{RP}(t). \tag{2.134}$$

The *number of GFR RP starting commercial operation per year,* $F_N^{RP}(t)$, is modeled as

$$\frac{dF_N^{RP}(t)}{dt} = R_{FO}^{RP}(t) - O_{RP}(t),\ F_{N\,0}^{RP}, \tag{2.135}$$

where $F_{N\ 0}^{RP} = F_N^{RP}(t=0)$, and $O_{RP}(t)$ is a one year fixed delay applied to the fulfilled order rate. Finally, the amount of *reprocessed GFR U/TRU per year*, $GFR_{RP}^{FUEL}(t)$, is modeled as

$$GFR_{RP}^{FUEL} = (1-L_{RP}) \cdot NC_{RP} \cdot F_{RP}(t), \qquad (2.136)$$

where L_{RP} designs *GFR reprocessing losses.*

2.4.3. Front-end structure-policy diagram

Figure 2-10 presents the block diagram of the front-end structure-policy diagram.

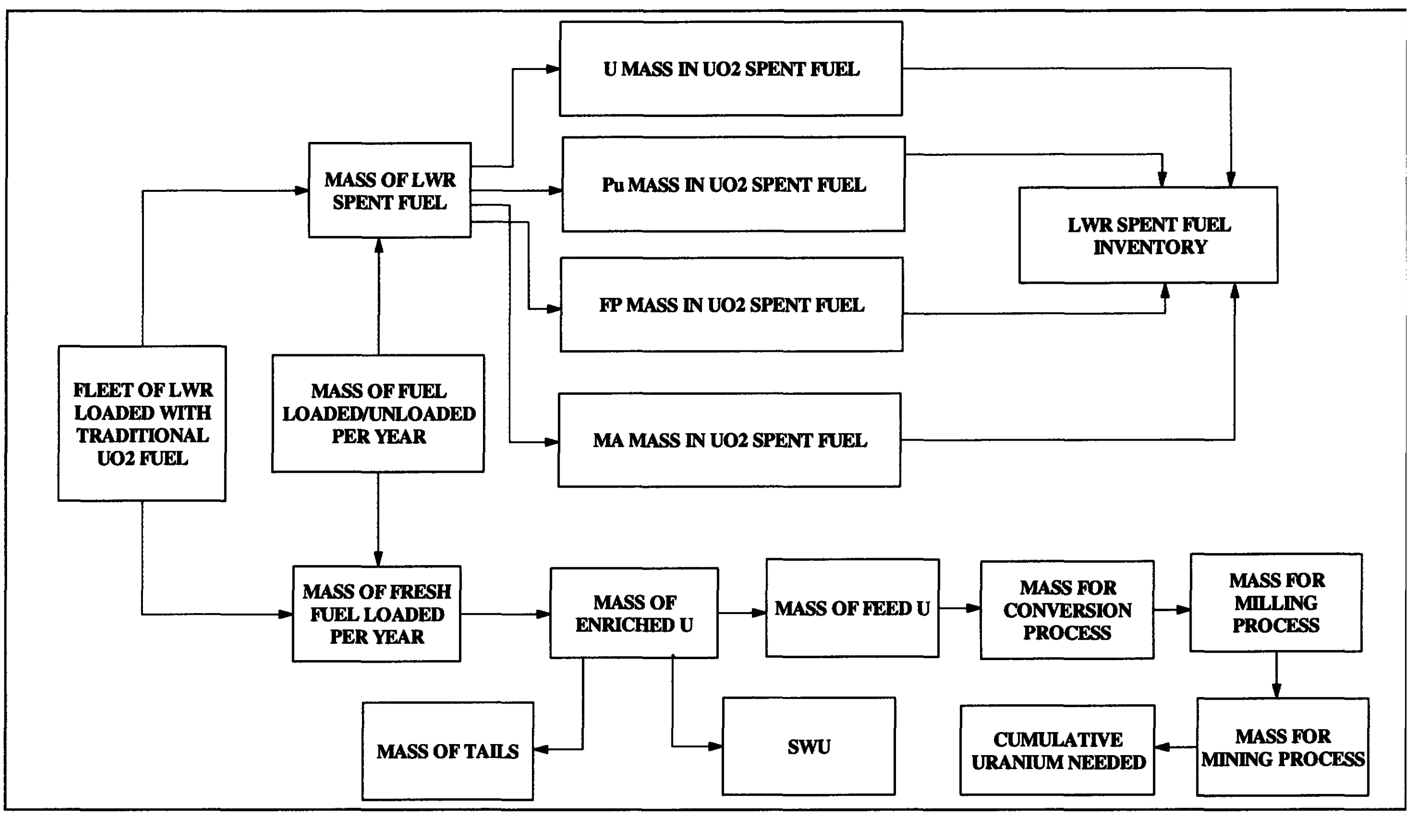

Figure 2-10 – Front-end structure-policy diagram of the system

The system-input is the number of LWR loaded with traditional UO_2 fuel. The mass transferred through the front-end steps of fabrication, enrichment, conversion, milling and mining, is calculated based on the fuel loaded in the LWRs fleet per year. The sytem-output is the amount of spent fuel discharged per year. Nevertheless, the cumulative UO_2 spent fuel, the cumulative natural uranium consumption, and the SWU requirements can be accessed anytime.

The CONFU technology structure-policy diagram is detailed in Section 2.4.4. Next, the model for this diagram is detailed.

First, the total *U mass loaded per year for LWR loaded with* UO_2 *fuel,* $M_{LWR}(t)$, is modeled as

$$M_{LWR}(t)=\left(F_{LWR}(t)-F_{Young}^{LWR}(t)-F_{Old}^{LWR}(t)\right)\cdot\overline{M}_{LWR}, \tag{2.137}$$

where $F_{Young}^{LWR}(t)$ is the *number of LWR loaded with young CONFU fuel,* $F_{Old}^{LWR}(t)$ is the *number of LWR loaded with old CONFU fuel,* and $\overline{M}_{LWR}$ is the U mass loaded per LWR per year. Next, the *mass of enriched uranium for* UO_2 *per year,* $P_{UO_2}(t)$, is modeled as

$$P_{UO_2}(t)=\frac{M_{LWR}(t)}{(1-L_F)}, \tag{2.138}$$

where L_F defines *losses due to the* UO_2 *fuel fabrication process.* The *mass of natural uranium feeding the enrichment process per year,* $F_U(t)$, is calculated as

$$F_U(t)=P_{UO_2}(t)\cdot\left(\frac{x_P^{LWR}-x_T^{LWR}}{x_F^{LWR}-x_T^{LWR}}\right), \tag{2.139}$$

where $x_P^{LWR}(t)$ is the *enrichment of the product for* UO_2, $x_T^{LWR}(t)$ is the *enrichment of the tails for* UO_2, and $x_F^{LWR}(t)$ is the *enrichment of the feed for* UO_2. The *mass of the* UO_2 *tails,* $T_{UO_2}(t)$, is modeled as

$$T_{UO_2}(t)=P_{UO_2}(t)\cdot\left(\frac{x_P^{LWR}-x_F^{LWR}}{x_F^{LWR}-x_T^{LWR}}\right), \tag{2.140}$$

The *Separative Work Unit for traditional fuel,* $SWU_{LWR}(t)$, requirements is evaluated as

$$SWU_{LWR}(t)=P_{UO_2}(t)\cdot V\left(x_P^{LWR}\right)+T_{UO_2}(t)\cdot V(x_T^{LWR})-F_U(T)\cdot V(x_F^{LWR}), \tag{2.141}$$

where $F_U(t)$ is the *mass rate of natural uranium feed enrichment for traditional fuel per year,* and $V(x)$ is the following value function

$$V(x) = (2 \cdot x - 1) \cdot \ln\left(\frac{x}{1-x}\right). \tag{2.142}$$

The *U mass feeding the conversion process per year,* $M_{CON}(t)$, and the *U mass feeding the milling process per year,* $M_{MIL}(t)$, are evaluated as

$$M_{CON}(t) = \frac{F_U(t)}{(1-L_C)}, \tag{2.143}$$

$$M_{MIL}(t) = \frac{M_{CON}(t)}{(1-L_M)}, \tag{2.144}$$

where L_M is the Uranium milling process losses, and L_C is the Uranium conversion process losses. In addition, the *mining mass rate,* $M_{MIN}(t)$, is considered as equal to $M_{MIL}(t)$.

The *cumulative demand for natural Uranium* is represented by one stock, $S_D^U(t)$. The inflow for this stock is the sum of the *mining mass rate for traditional fuel, mining mass rate for young,* and *mining mass rate for old CONFU* fuel fabrication, $M_{MIN}(t) + M_{MIN}^{Young}(t) + M_{MIN}^{Old}(t)$. $S_{D_0}^U$ is the initial demand at time $t = 0$

$$\frac{dS_D^U(t)}{dt} = M_{MIN}(t) + M_{MIN}^{Young}(t) + M_{MIN}^{Old}(t),\ S_{D_0}^U. \tag{2.145}$$

The stock $S_R^U(t)$ represents the amount of *natural Uranium resources available*. The outflow for this stock is also the sum of the mining mass rate for traditional fuel, young and old CONFU fuel fabrication. $S_{R_0}^U$ is the amount of resources available at time $t = 0$

$$\frac{dS_R^U(t)}{dt} = -(M_{MIN}(t) + M_{MIN}^{Young}(t) + M_{MIN}^{Old}(t)),\ S_{R_0}^U. \tag{2.146}$$

Then, from mass conservation, the total *mass unloaded per year,* $M_{SF}(t)$, is modeled as

$$M_{SF}(t) = \left(F_{LWR}(t) - F_{Young}^{LWR}(t) - F_{Old}^{LWR}(t)\right) \cdot \overline{M}_{LWR}. \tag{2.147}$$

The amount of *Miner Actinides (S_{MA}), Uranium (S_U), Plutonium (S_{Pu}),* and *Fissions Products (S_{FP}),* are modeled as the following stocks:

$$\frac{dS_{MA}(t)}{dt} = P_{MA}^{UO_2} \cdot M_{SF}(t),\ S_{MA_0}, \tag{2.148}$$

$$\frac{dS_U(t)}{dt} = P_U^{UO_2} \cdot M_{SF}(t),\ S_{U_0}, \tag{2.149}$$

$$\frac{dS_{Pu}(t)}{dt} = P_{Pu}^{UO_2} \cdot M_{SF}(t),\ S_{Pu_0}, \tag{2.150}$$

$$\frac{dS_{FP}(t)}{dt} = P_{FP}^{UO_2} \cdot M_{SF}(t),\ S_{FP_0}, \tag{2.151}$$

where $S_{U_0} = S_U(t=0)$, $P_U^{UO_2}$ is the *fraction of U in the UO2 spent fuel,* $S_{Pu_0} = S_{Pu}(t=0)$, $P_{Pu}^{UO_2}$ is the *fraction of Pu in the UO2 spent fuel,* $S_{FP_0} = S_{FP}(t=0)$, $P_{FP}^{UO_2}$ is the *fraction of FP in the UO2 spent fuel,* $S_{MA_0} = S_{MA}(t=0)$, and $P_{MA}^{UO_2}$ is the *fraction of MA in the UO2 spent fuel.* The amount of UO_2 Spent Fuel $SF_{UO_2}(t)$ available for separation is modeled as the mass of *fuel unloaded from LWR per year,* $M_{SF}(t)$, after cooling storage

$$SF_{UO_2}(t) = M_{SF}(t). \tag{2.152}$$

Last, the total *Separative Work Unit requirements,* $SWU(t)$, is modeled as

$$SWU(t) = SWU_{LWR}(t) + SWU_{Young}(t) + SWU_{Old}(t) \tag{2.153}$$

where $SWU_{LWR}(t)$ is the *Separative Work Unit requirement for traditional fuel,* $SWU_{Young}(t)$ is the *Separative Work Unit requirements for young CONFU fuel,* and $SWU_{Old}(t)$ is the *Separative Work Unit requirements for old CONFU fuel.*

2.4.4. CONFU technology structure-policy diagram

The system-input for this subsystem is the sum of the *separated TRU,* $TRU_{SP}^{FUEL}(t)$, from separation plants, and the *reprocessed TRU,* $TRU_{FFF}^{FUEL}(t)$, from FFF reprocessing plants. Separated TRU is used for the fabrication of young CONFU fuel, and reprocessed TRU is used for the fabrication of old CONFU fuel, as presented in Figure 2-11. Also, for the fabrication of CONFU fuel, UO_2 fuel with different enrichment must be added for fabrication of old and young CONFU batches. The output for this system is the number of LWRs loaded with CONFU batches. Next, the model is described considering the precedence order to deplete CONFU TRU fuel is first young CONFU fuel and then old CONFU fuel.

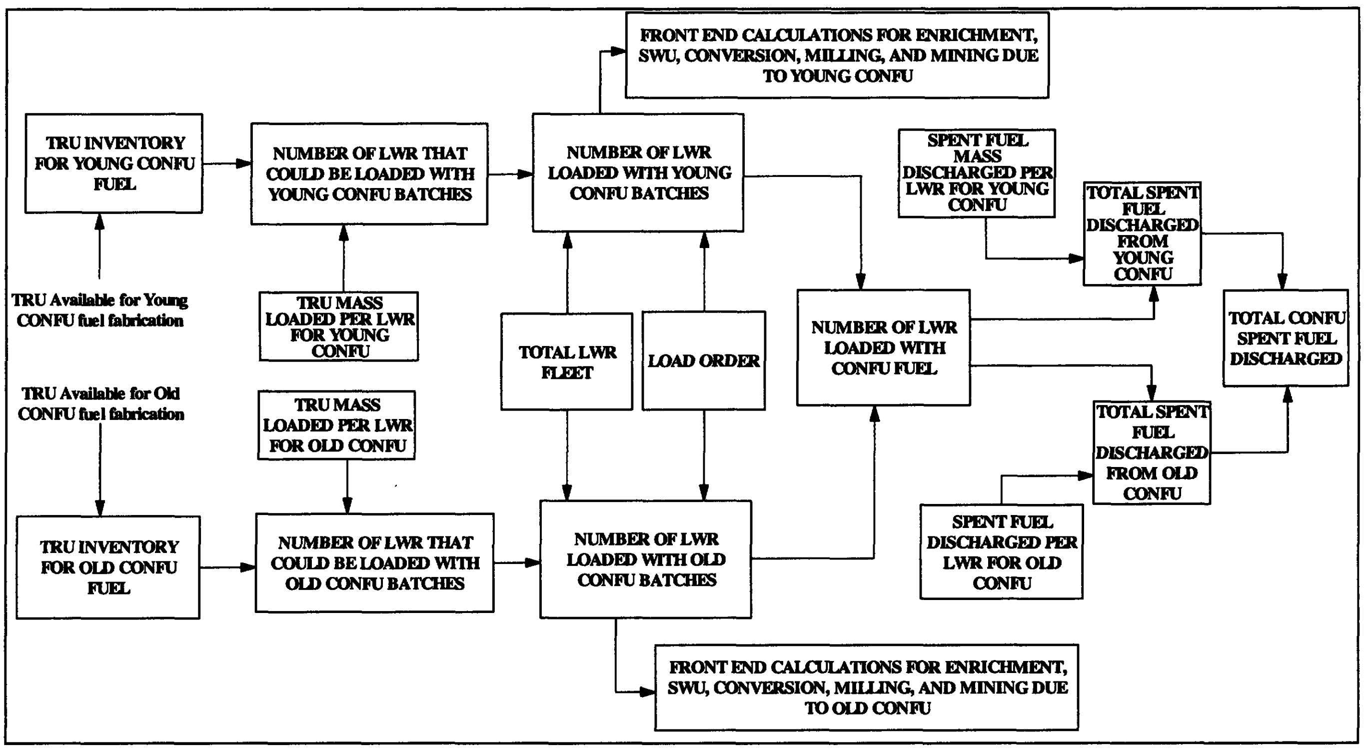

Figure 2-11 – CONFU technology structure-policy diagram of the system

2.4.4.1 Young CONFU model

The *mass of TRU available for young CONFU fuel fabrication,* $TRU_{Young}^{FUEL}(t)$, is modeled as

$$TRU_{Young}^{FUEL}(t) = P_{CONFU}^{TRU}(t) \cdot TRU_{SP}^{FUEL} \quad (2.154)$$

where the *fraction of TRU available for CONFU fabrication* , $P_{CONFU}^{TRU}(t)$, is modeled as

$$\text{If } time\ t < D_{CONFU}\text{:} \quad P_{CONFU}^{TRU}(t) = 0\text{, or} \tag{2.155}$$

$$\text{If } time\ t > D_{CONFU}\text{:} \quad P_{CONFU}^{TRU}(t) = 1 - P_{ABR}^{TRU}(t) - P_{GFR}^{TRU}(t). \tag{2.156}$$

Next, the *TRU inventory for young CONFU fuel,* $S_{Young}^{TRU}(t)$, is modeled as

$$\frac{dS_{Young}^{CONFU}(t)}{dt} = R_{IR}^{Young}(t) - R_{OR}^{Young}(t),\ S_{Young\ 0}^{CONFU}, \tag{2.157}$$

where $S_{Young\ 0}^{CONFU} = S_{Young}^{CONFU}(t=0)$, $R_{IR}^{Young}(t)$ is the *young CONFU inflow rate,* and $R_{OR}^{Young}(t)$ is the *young CONFU outflow rate.* $R_{IR}^{Young}(t)$ is modeled as

$$R_{IR}^{Young}(t) = TRU_{Young}^{FUEL}(t) \tag{2.158}$$

Next, the *maximum number of LWRs loaded with young CONFU batches,* $F_{MAX}^{Young}(t)$, is modeled as

$$F_{MAX}^{Young}(t) = \frac{TRU_{Young}^{FUEL}(t)}{\overline{M}_{Young}^{TRU}}, \tag{2.159}$$

where $\overline{M}_{Young}^{TRU}$ is the *mass of TRU loaded per year for young CONFU per LWR.* The *number of LWR loaded with young CONFU fuel,* $F_{Young}^{LWR}(t)$, is modeled as

$$F_{Young}^{LWR}(t) = MIN(F_{MAX}^{Young}(t), F_{LWR}(t) - F_{Old}^{LWR}(t)), \tag{2.160}$$

where $F_{Old}^{LWR}(t)$ is the *number of LWR loaded with old CONFU fuel.* The *mass of UO_2 spent fuel discharged per year from young CONFU,* $M_{Young}^{SF}(t)$ is modeled as

$$M_{Young}^{SF}(t) = F_{Young}^{LWR}(t) \cdot \overline{M}_{Young}^{SF}, \tag{2.161}$$

where $\overline{M}^{SF}_{Young}$ is the *mass of UO2 spent fuel discharged from young CONFU per LWR per year.* A fixed delay, CT_{Young}, is the *young CONFU fuel cooling time,* and it is applied to $M^{SF}_{Young}(t)$ due to cooling storage

$$SF_{Young}(t) = Delay[M^{SF}_{Young}(t), CT_{Young}], \tag{2.162}$$

where $SF_{Young}(t)$ is the *young CONFU UO2 spent fuel discharged per year* after cooling storage. The *mass of TRU discharged per year from young CONFU,* $M^{TRU}_{Young}(t)$ is modeled as

$$M^{TRU}_{Young}(t) = F^{LWR}_{Young}(t) \cdot \overline{M}^{SF}_{Young}, \tag{2.163}$$

where $\overline{M}^{TRU}_{Young}$ is the *mass of TRU discharged from young CONFU per LWR per year.* A fixed delay, CT_{Young}, is also applied to $M^{TRU}_{Young}(t)$

$$TRU^{SF}_{Young}(t) = Delay[M^{TRU}_{Young}(t), CT_{Young}], \tag{2.164}$$

where $TRU^{SF}_{Young}(t)$ is the *young CONFU FFF TRU discharged from LWR per year* after cooling storage.

Next, the *total U mass loaded into young CONFU per year,* $M^{LWR}_{Young}(t)$, is modeled as

$$M^{LWR}_{Young}(t) = F^{Young}_{LWR}(t) \cdot \overline{M}^{LWR}_{Young}, \tag{2.165}$$

where $\overline{M}^{LWR}_{Young}$ is the *U mass loaded for young CONFU per reactor per year.* Next, front-end steps calculations for mining, milling, conversion, fabrication and enrichment are applied. The SWU requirements for young CONFU is also calculated. The *mass product of the enrichment process for young CONFU fuel per year,* $P_{Young}(t)$, is modeled as

$$P_{Young}(t) = \frac{M^{LWR}_{Young}(t)}{(1 - L_F)}. \tag{2.166}$$

The *mass of natural uranium feeding enrichment process for young CONFU per year,* $F_{Young}(t)$, is evaluated as

$$F_{Young}(t) = P_{Young}(t) \cdot \left(\frac{x_P^{Young} - x_T^{Young}}{x_F^{Young} - x_T^{Young}} \right), \qquad (2.167)$$

where $x_P^{Young}(t)$ is the *enrichment of the product for young CONFU,* $x_T^{young}(t)$ is the *enrichment of tails for young CONFU,* and $x_F^{Young}(t)$ is the *enrichment of the feed for young CONFU.* Similarly, the *mass of the young CONFU per year* , $T_{Young}(t)$, is modeled as

$$T_{Young}(t) = P_{Young}(t) \cdot \left(\frac{x_P^{Young} - x_F^{Young}}{x_F^{Young} - x_T^{Young}} \right). \qquad (2.168)$$

The *Separative Work Unit requirement for young CONFU fuel,* $SWU_{Young}(t)$, is modeled as

$$SWU_{Young}(t) = P_{Young}(t) \cdot V\left(x_P^{Young}\right) + T_{Young}(t) \cdot V(x_T^{Young}) - F_{Young}(T) \cdot V(x_F^{Young}), \qquad (2.169)$$

where $V(x)$ is the same value function defined in Equation 2.142.

The total *U mass feeding the young CONFU conversion process per year,* $M_{CON}^{Young}(t)$, and the total *U mass for the young CONFU milling process per year,* $M_{MIL}^{Young}(t)$, are modeled as

$$M_{CON}^{Young}(t) = \frac{F_{Young}(t)}{(1 - L_C)}, \qquad (2.170)$$

$$M_{MIL}^{Young}(t) = \frac{M_{CON}^{Young}(t)}{(1 - L_M)}. \qquad (2.171)$$

Last, the *mining mass rate for young CONFU fuel,* $M_{MIN}^{Young}(t)$, is considered equal to $M_{MIL}^{Young}(t)$

$$M_{MIN}^{Young}(t) = M_{MIL}^{Young}. \qquad (2.172)$$

2.4.4.2 Old CONFU model

The *mass of TRU available for old CONFU fuel fabrication,* $TRU_{Old}^{FUEL}(t)$ *(see Chapter 3 for details),* is modeled as

$$TRU_{Old}^{FUEL}(t) = P_{CONFU}^{TRU}(t) \cdot TRU_{FFF}^{FUEL}. \tag{2.173}$$

Next, the *TRU inventory for old CONFU fuel,* $S_{Old}^{CONFU}(t)$, is modeled as

$$\frac{dS_{Old}^{CONFU}(t)}{dt} = R_{IR}^{Old}(t) - R_{OR}^{Old}(t),\ S_{Old\ \ 0}^{CONFU}, \tag{2.174}$$

where $S_{Old\ \ 0}^{CONFU} = S_{Old}^{CONFU}(t=0)$, $R_{IR}^{Old}(t)$ is the *old CONFU inflow rate,* and $R_{OR}^{Old}(t)$ is the *old CONFU outflow rate.* $R_{IR}^{Old}(t)$ is modeled as

$$R_{IR}^{Old}(t) = TRU_{Old}^{FUEL}(t) \tag{2.175}$$

Next, the *maximum number of LWRs loaded with old CONFU batches,* $F_{MAX}^{Old}(t)$, is modeled as

$$F_{MAX}^{Old}(t) = \frac{TRU_{Old}^{FUEL}(t)}{\overline{M}_{Old}^{TRU}}, \tag{2.176}$$

where $\overline{M}_{Old}^{TRU}$ is the *mass of TRU loaded per year for old CONFU per LWR.* The *number of LWR loaded with old CONFU fuel,* $F_{Old}^{LWR}(t)$, is modeled as

$$F_{Old}^{LWR}(t) = MIN(F_{MAX}^{Old}(t), F_{LWR}(t) - F_{Young}^{LWR}(t)), \tag{2.177}$$

where $F_{Young}^{LWR}(t)$ is the *number of LWR loaded with young CONFU fuel.* The *mass of* UO_2 *spent fuel discharged per year from old CONFU,* $M_{Old}^{SF}(t)$ is modeled as

$$M_{Old}^{SF}(t) = F_{Old}^{LWR}(t) \cdot \overline{M}_{Old}^{SF}, \tag{2.178}$$

where $\overline{M}_{Old}^{SF}$ is the *mass of UO_2 spent fuel discharged from old CONFU per LWR per year.* A fixed delay, CT_{Old} is the *old CONFU fuel cooling time,* is applied to $M_{Old}^{SF}(t)$ due to cooling storage

$$SF_{Old}(t) = Delay[M_{Old}^{SF}(t), CT_{Old}], \tag{2.179}$$

where $SF_{Old}(t)$ is the *old CONFU UO_2 spent fuel discharged per year* after cooling storage. The *mass of TRU discharged per year from old CONFU,* $M_{Old}^{TRU}(t)$ is modeled as

$$M_{Old}^{TRU}(t) = F_{Old}^{LWR}(t) \cdot \overline{M}_{Old}^{SF}, \tag{2.180}$$

where $\overline{M}_{Old}^{TRU}$ is the *mass of TRU discharged from old CONFU per LWR per year.* A fixed delay, CT_{Old}, is also applied to $M_{Old}^{TRU}(t)$

$$TRU_{Old}^{SF}(t) = Delay[M_{Old}^{TRU}(t), CT_{Old}], \tag{2.181}$$

where $TRU_{Old}^{SF}(t)$ is the *old CONFU FFF TRU discharged from LWR per year* after cooling storage.

Next, the *total U mass loaded for old CONFU per year,* $M_{Old}^{LWR}(t)$, is modeled as

$$M_{Old}^{LWR}(t) = F_{LWR}^{Old}(t) \cdot \overline{M}_{Old}^{LWR}, \tag{2.182}$$

where $\overline{M}_{Old}^{LWR}$ is the *U mass loaded for old CONFU per reactor per year.* Next, front-end steps calculations for mining, milling, conversion, fabrication and enrichment are applied. The SWU requirements for old CONFU are also calculated. The *mass product of the enrichment process for old CONFU fuel per year,* $P_{Old}(t)$, is modeled as

$$P_{Old}(t) = \frac{M_{Old}^{LWR}(t)}{(1 - L_F)}. \tag{2.183}$$

The *mass of natural uranium feeding enrichment process for old CONFU per year,* $F_{Old}(t)$, is evaluate as

$$F_{Old}(t) = P_{Old}(t) \cdot \left(\frac{x_P^{Old} - x_T^{Old}}{x_F^{Old} - x_T^{Old}} \right), \tag{2.184}$$

where $x_P^{Old}(t)$ is the *enrichment of the product for old CONFU*, $x_T^{Old}(t)$ is the *enrichment of tails for old CONFU,* and $x_F^{Old}(t)$ is the *enrichment of the feed for old CONFU.* Similarly, the *mass of the old CONFU per year,* $T_{Old}(t)$, is modeled as

$$T_{Old}(t) = P_{Old}(t) \cdot \left(\frac{x_P^{Old} - x_F^{Old}}{x_F^{Old} - x_T^{Old}} \right). \tag{2.185}$$

The *Separative Work Unit requirement for Old CONFU fuel,* $SWU_{Old}(t)$, is modeled as

$$SWU_{Old}(t) = P_{Old}(t) \cdot V\left(x_P^{Old}\right) + T_{Old}(t) \cdot V(x_T^{Old}) - F_{Old}(T) \cdot V(x_F^{Old}), \tag{2.186}$$

where $V(x)$ is the same value function defined in Equation 2.142.

The total *U mass feeding the old CONFU conversion process per year,* $M_{CON}^{Old}(t)$, and the total *U mass for the old CONFU milling process per year,* $M_{MIL}^{Old}(t)$, are modeled as

$$M_{CON}^{Old}(t) = \frac{F_{Old}(t)}{(1 - L_C)}, \tag{2.187}$$

$$M_{MIL}^{Old}(t) = \frac{M_{CON}^{Old}(t)}{(1 - L_M)}. \tag{2.188}$$

Last, the *mining mass rate for old CONFU fuel,* $M_{MIN}^{Old}(t)$, is considered equal to $M_{MIL}^{Old}(t)$

$$M_{MIN}^{Old}(t) = M_{MIL}^{Old}. \tag{2.189}$$

2.5. Summary

This chapter described the modeling strategy adopted for the nuclear fuel cycle simulation. The model of the nuclear fuel cycle was presented as a ***high level structure diagram,*** and details of the system were presented as *structure-policy diagrams*. The *high level structure diagram* provides an overview of the model, highlighting interconnections among blocks of the system, without showing all the details for the computer simulation. The high level structure diagram represents the nuclear fuel cycle; the fleet of thermal and fast reactors; the separation and reprocessing plants; the waste repository; the spent fuel storage; and the path for the mass transfers. The *structure-policy diagram* reproduces the structure of the system, and the decision rules applied. Each structure-policy diagram is a single-input single-output (SISO) system that consists of two subsystems: system-structure and policy-structure. The first subsystem described the structure, and the second one defined decision rules.

The following structure-policy diagrams are detailed in this chapter:

- *LWRs structure-policy diagram* for construction and decommissioning of LWRs. The system-input for this diagram is the nuclear annual growth rate, and the system-output is the number of LWRs under commercial operation.

- *Back-end structure-policy diagram* for construction and decommissioning of FR, separation and reprocessing plants. The system-input is the nuclear fuel available for fast reactors, or the mass available for partitioning. The system-output is the number of fast reactors under commercial operation, or the number of facilities to treat spent fuel. The following systems are modeled as back-end structure-policy diagrams: construction of UO_2 separation plants (SP), construction of FFF reprocessing plants, construction of ABRs, construction of GFR reprocessing plants, and construction of GFRs.

- *Front-end structure-policy diagram.* The system-input is the number of LWRs loaded with UO_2 fuel. The mass transferred through the front-end steps of fabrication, enrichment, conversion, milling and mining, is calculated based on the fuel loaded into the LWR fleet per year. The system-output is the amount of spent fuel discharged per year.

- *CONFU technology structure-policy diagram.* The system-input for this diagram is the TRU available for fuel fabrication, i.e. the separated TRU from separation plants, and reprocessed TRU from FFF reprocessing plants. The system-output for this system is the number of LWRs loaded with CONFU batches.

3 Recycling Options and Strategies

3.1. Introduction

The advanced fuel cycle strategies explored in this study are TRU recycling in Light Water Reactors (LWRs) using combined non-fertile and UO_2 fuel (CONFU), TRU recycling in fertile free fuel in fast cores of Actinide Burners Reactors (ABRs), and TRU recycling with UO_2 in self-sustaining Gas-cooled Fast Reactors (GFRs). Here, recycling means the partitioning of the spent fuel, the fabrication of the fuel, and the irradiation in thermal or fast reactors. Partitioning is defined as the process of separation of TRU from U in the UO_2 spent fuel, or the process of reprocessing TRU from spent fertile free fuels, or the reprocessing of TRU plus U, after extraction of the fission products, from GFRs spent fuel, as can be seen in Figure 3-1. In all cases plutonium and higher actinides are kept together.

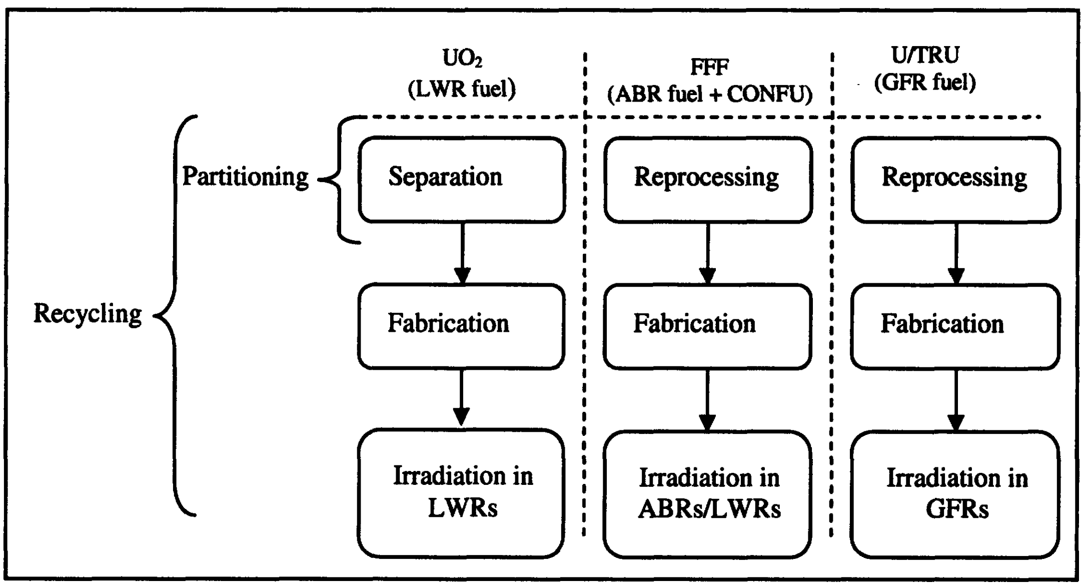

Figure 3-1 – Recycling of spent fuel

In this chapter, the equilibrium properties of the reload fuel and spent fuel of standard LWR, of the standard ABR, and of the standard GFR, used in this study, are presented. In addition, a summary of the equilibrium properties of the young and old CONFU fuel used for the simulation is provided. A detailed description of the three technologies can be found in reference [2].

Moreover, the parameters for separative work requirements calculations, and the default values for the size of the separation and reprocessing facilities, are presented here.

3.2. Equilibrium properties of traditional Light Water Reactors

The main properties of the Light Water Reactors (LWRs) loaded with traditional UO_2 fuel are presented in Table 3-1. In addition, LWRs can be loaded with CONFU batches. The reactor lifetime is taken to be sixty years, the net electric output is presumed to be 1 GWe, with a thermal power conversion efficiency of 0.33, and having equilibrium fuel is irradiated of a 50 MWd/kg burn up.

Table 3-1– Equilibrium properties for LWR

Property	Value
Net thermal output	3 GWth
Thermal efficiency	0.33
Net electrical output	1 GWe
Capacity factor	0.9
Core mass of heavy metal	77.2 MT HM
Equivalent HM mass loaded (at 4.2% U^{235} enriched)	17.153 MT/GWe/Year
Equivalent U mass discharged (at 0.83% enriched)	15.873 MT/GWe/Year (92.54% of the discharged fuel)
Equivalent TRU mass discharged	0.280 MT/GWe/Year (1.63% of the discharged fuel)
Equivalent Pu mass discharged	0.226 MT/GWe/Year (1.32% of the discharged fuel)
Equivalent FP mass discharged	1.00 MT/GWe/Year (5.83% of the discharged fuel)
Equivalent MA mass discharged	0.054 MT/GWe/Year (0.31% of the discharged fuel)
U net consumption	1.280 MT/GWe/Year
TRU net production	0.28 MT/GWe/Year
Number of batches	3
Cycle length	1.5 years
Cooling time	6 years

Furthermore, traditional LWRs can be loaded with CONFU fuel. The CONFU fuel is a combination of traditional UO_2 pins and fertile-free fuel (FFF) containing recycled transuranics. Two sources of TRU for CONFU fuel fabrication are considered. One is the separated TRU from UO_2 spent fuel irradiated only one time in a traditional LWRs core, which is used for the fabrication of young CONFU fuel. The other is the reprocessed TRU, from FFF reprocessing plants, irradiated more than one time in FFF pins, which is used for the fabrication of old CONFU fuel. In addition, equilibrium conditions are assumed for the CONFU fuel. Note that the thermal recycling of TRU in CONFU fuel allows for net TRU destruction rate, as transuranics in FFF pins are burned at least as fast as transuranics are produced in UO_2 pins. The main properties of the CONFU assembly for Light Water Reactors are presented Table 3-2 and Table 3-3. Note that old CONFU assemblies have higher enrichment to compensate for the less reactive composition of burned TRU.

Table 3-2 - Equilibrium properties for Young CONFU Fuel

Property	Value
Equivalent mass loaded from fresh/recycled U and TRU from separation plants	14 MT U/GWe/Year (4.2% enriched)
	0.653 MT TRU/GWe/Year
Equivalent TRU and U mass discharged	13 MT U/GWe/Year (0.83% enriched -- 88.72% of the UO_2 discharged fuel)
	0.193 MT TRU/GWe/Year (1.38% of the UO_2 discharged fuel)
	0.433 MT TRU/GWe/Year (from FFF discharged fuel)
Cooling time	6 years
TRU consumption (in FFF fuel)	0.22 MT TRU/GWe/Year
Net TRU consumption in CONFU fuel	0.027 MT/GWe/Year

Table 3-3 - Equilibrium properties for Old CONFU Fuel

Property	Value
Equivalent mass loaded from fresh/recycled U and TRU from ABR/CONFU reprocessing plants	14 MT U/GWe/Year (5% enriched)
	0.653 TRU MT/GWe/Year
Equivalent TRU and U mass Discharged per Year	13 MT U/GWe/Year (0.83% enriched -- 88.72% of the UO_2 discharged fuel)
	0.193 MT TRU/GWe/Year (1.38% of the UO_2 discharged fuel)
	0.433 MT TRU/GWe/Year (from FFF discharged fuel)
Cooling time	18 years
TRU consumption (in FFF fuel)	0.22 MT TRU/GWe/Yr
Net TRU consumption in CONFU fuel	0.027 MT/GWe/Year

3.3. Equilibrium properties of Actinide Burners Reactors

Actinide Burners Reactors are lead-cooled fast reactors fed with a non-fertile metal fuel, i.e. fertile-free fuels (FFF). The TRU for ABR fuel fabrication comes from separated TRU from UO_2 spent fuel, or from reprocessed TRU from ABR, or CONFU (FFF) spent fuel. For the purpose of this study, the number of recycles does not change the quality of the TRU in ABRs spent fuel [3]. The main properties of the lead-cooled Actinide Burner Reactors modeled in the system are presented in Table 3-4.

Table 3-4 - Equilibrium properties for ABR

Property	Value
Net thermal output	0.7 GWth
Thermal efficiency	0.45
Net electrical output	0.315 GWe
Capacity factor	0.9
Core mass	3.2 MT HM
Equivalent TRU mass loaded	4.232 MT/GWe/Year
Equivalent TRU mass discharged	3.467 MT/GWe/Year
Equivalent TRU net consumption	0.758 MT/GWe/Year
Number of batches	2
Cycle length	1.2 years
Cooling time	6 years

3.4. Fast Recycling of TRU in self-sustaining GFRs

In this study, the self-sustaining gas-cooled reactor (GFR) is a fast reactor with a fissile conversion ratio near one, and suitable for power generation or hydrogen production. As self-sustaining fast reactor, the mass of TRU in the fresh fuel is the same as that in the spent fuel. GFRs are initially fed with recycled uranium plus TRU from LWR U separation plants, and after that with reprocessed U/TRU, from GFR reprocessing plants, plus recycled uranium, from ore or depleted uranium. Reprocessed U/TRU is obtained from the GFR spent fuel without fission products. The main properties of the self-sustaining gas-cooled reactor modeled in the system are presented in Table 3-5.

Table 3-5 - Equilibrium properties for GFR

Property	Value
Net thermal output	2.4 GWth
Thermal efficiency	0.47
Net electrical output	1.128 GWe
Capacity factor	0.9
Core mass	59.3 MT HM
Equivalent mass loaded from fresh/recycled U plus TRU from UO_2 separation plants	1.297 MT TRU/GWe/Year (TRU from separation plants: 18.51 %)
	5.713 MT U/GWe/Year (Natural or recycled U: 81.49 %)
Equivalent mass loaded from fresh/recycled U plus U/TRU from GFR reprocessing plants	6.308 MT "U/TRU"/GWe/Year (U/TRU: 89.98%)
	0.702 MT U/GWe/Year (Natural U or recycled U: 10.02%)
Equivalent U/TRU mass discharged	5.011 MT U/GWe/Year
	1.298 MT TRU/GWe/Year
TRU Net consumption	0 MT/GWe/Year
Conversion ratio	1
Number of batches	3
Cycle length	2.5 years
Cooling time	6 years

3.5. Main parameters of the simulation

The simulation considers a period of 100 years. The annual nuclear power demand growth is assumed to be 2.4% for the U.S. However, the Brazilian annual nuclear power demand growth is assumed to be 7.3% per year for the first fifty years, and 4.1% for the last half of the century (see Chapter 6.4 for details). The separation and recycling facilities can be built in different throughput capacities. For the U.S., the nominal capacity of a fuel cycle plant is taken 1,000 MT/Year for a UO_2 separation facility and 50 MT/Year for TRU/inert fuel reprocessing facility. The current industrial capacity to build these facilities is taken to be 500 MT/Year/Year and 50 MT/Year/Year for the separation and recycling plants respectively -- which means it takes two years to build a nominal separation plan but only one year to build a nominal reprocessing plant. The U.S. industrial capacity doubles forty years after the beginning of the simulation. Also, the Brazilian industrial capacity doubles 75 years after the beginning of the simulation (see Chapter 6.4 for details). The default nominal and industrial capacities for the advanced fuel facilities are presented in Table 3-6 and Table 3-7.

Table 3-6 – Default nominal and industrial capacities for the U.S.

Nominal Capacity	Separation Plants	1,000 [MT/Year]
	ABR/CONFU Reprocessing Plants	50 [MT/Year]
	GFR Reprocessing Plants	1,000 [MT/Year]
Construction Capacity in the initial 40 years	Separation Plants	500 [MT/Year/Year]
	ABR/CONFU Reprocessing Plants	50 [MT/Year]
	GFR Reprocessing Plants	500 [MT/Year/Year]
Construction Capacity after 40 years	Separation Plants	1,000 [MT/Year/Year]
	ABR/CONFU Reprocessing Plants	100 [MT/Year]
	GFR Reprocessing Plants	1,000 [MT/Year/Year]

Table 3-7 - Default nominal and industrial capacities for Brazil

Nominal Capacity	Separation Plants	500 [MT/Year]
	ABR/CONFU Reprocessing Plants	50 [MT/ Year]
	GFR Reprocessing Plants	500 [MT/Year]
Construction Capacity in the initial 75 years	Separation Plants	250 [MT/Year/Year]
	ABR/CONFU Reprocessing Plants	12.5 [MT/Year]
	GFR Reprocessing Plants	250 [MT/Year/Year]
Construction Capacity after 75 years	Separation Plants	500 [MT/Year/Year]
	ABR/CONFU Reprocessing Plants	50 [MT/Year]
	GFR Reprocessing Plants	500 [MT/Year/Year]

The uranium, plutonium, fission products and minor actinides percentages in the UO_2 spent fuel for 50 MWd/kg burn up, and the TRU percentage composition in the spent fuel are presented in Table 3-8.

Table 3-8 – UO_2 spent fuel and TRU composition

UO_2 spent fuel composition		**TRU percentage composition**	
P_U	92.54%	TRU in UO_2 spent fuel	1.63%
P_{FP}	5.83%	TRU in young CONFU fuel	1.38%
P_{Pu}	1.32%	TRU in young CONFU fuel	1.38%
P_{MA}	0.31%		

The values of the enrichment of the product of the enrichment process, the enrichment of the mass tails, and the enrichment of the mass feeding, as well as the losses due to conversion, fabrication and mining processes are showed in Table 3-9.

Table 3-9 – Parameters for the front-end process

	UO_2 fuel	Young CONFU fuel	Old CONFU fuel
Enrichment of the product	4.51%	4.51%	5%
Enrichment of the fresh fuel	0.71%	0.71%	0.71%
Enrichment of the tails	0.25%	0.25%	0.25%
Conversion losses	0.5%	0.5%	0.5%
Mining losses	1%	1%	1%
Fabrication losses	0.5%	0.5%	0.5%

3.6. Summary

The main parameters for the technologies chosen in the simulation are presented, and the equilibrium properties of the Light Water Reactors, Actinide Burners Reactors, and Gas-cooled Fast Reactors used for the simulation are also reviewed. The LWR fleet is loaded with traditional UO_2 and CONFU batches. CONFU fuel is a combination of traditional UO_2 pins and fertile-free fuel (FFF) containing recycled transuranics. Two sources of TRU for CONFU fuel fabrication are considered: the separated TRU from UO_2 spent fuel, and the reprocessed TRU from FFF. The lead-cooled ABR fleet is fed with TRU in fertile-free fuels (FFF). The TRU for ABR fuel fabrication comes from separated TRU from UO_2 spent fuel, or from reprocessed TRU from its FFF spent fuel. The self-sustaining (fissile conversion ratio near one) GFR fleet is fed with U plus TRU after the extraction of fission products -- as self-sustaining fast reactor, the mass of TRU in the fresh fuel is the same as that in the spent fuel The simulation considers a period of 100 years, and different annual nuclear power demand growth are assumed for the U.S. and for Brazil.

4 Economic Model Analysis and Assumptions

4.1. Introduction

The economic model analysis and assumptions adopted for this study are presented in this chapter. The purpose of the economic model is to provide useful insights by comparing different simulations under the same assumptions. Furthermore, the economic model for the nuclear fuel cycle is based on the forecasted mass flow, and on the number of reactors and advanced facilities in the system. The *cost of electricity* (COE) is evaluated as the *total cost* divided by the *total produced electricity of the nuclear enterprise* at each time step. Moreover, the *cost of electricity* is the sum of the cost of construction and decommissioning of plants, i.e. *capital-related costs* (CC), the *operating and maintenance costs* (O&M), and the *fuel cycle costs* (FCC). Here, all money values are considered in 2007 dollars, and the construction of reactors and facilities is privately financed. This model and applied data are derived from references [2] and [3].

4.2. Cost of Electricity

The cost of electricity is the sum of the capital-related costs, and the production cost [13]. Capital-related costs are the sum of the overnight construction cost of the plant, the return on equity and debt to finance the project, and the decommissioning costs which are paid in advance at a risk-free interest rate. Capital costs don't depend on the level of the output of the plants, and they are related to the investments on land, plant, equipment, and inventory. Production cost is the sum of operating and maintenance costs plus fuel cost. O&M costs are fixed costs applied to the plant lifetime. The FCC is the fuel cycle cost of each step evaluated as the cost times the mass is transferred at each time step, adjusted for the expenditure and the point where the money is supposed to be collected. The annual *total cost of electricity,* $COE_{total}(t)$, is modeled as

$$COE_{total}(t) = \left(\frac{1}{CF_{\Delta t} \cdot \Delta t} \cdot \frac{Y_{const}(t) + Y_{decom}(t)}{K} \right) + \left(\frac{1}{CF_{\Delta t} \cdot \Delta t} \cdot \frac{O\&M(t)}{K} + FCC(t) \right), \qquad (4.1)$$

where Y_{decom} is the *decommissioning constant annuity,* Y_{const} is the *construction constant annuity,* K is the *plant nominal capacity,* Δt is the *time step,* $CF_{\Delta t}$ is the *average capacity factor at time* *step*, $O\&M(t)$ is the *operating and maintenance costs*, $FCC(t)$ is the *fuel cycle cost*. Therefore, the *cost of electricity* per *total electricity produce*d is then defined as:

$$COE(t) = \frac{COE_{total}(t)}{P_{IC}(t)}, \tag{4.2}$$

where the *installed nuclear capacity*, $P_{IC}(t)$, is modeled as

$$P_{IC}(t) = F_{LWR} \cdot P_{PWR}(t) + F_{ABR}(t) \cdot P_{ABR}(t) + F_{ABR}(t) \cdot P_{GFR}(t). \tag{4.3}$$

In the following, each component of the cost of electricity is discussed:

4.2.1. Fuel Cycle Cost

The total fuel cycle cost, $FCC_{total}(t)$, is the sum of all mass transferred times the cost per unit mass. $FCC_{total}(t)$ is modeled as

$$FCC_{total}(t) = \sum_i M_i(t) \cdot p_i(t) \cdot \left(\frac{(1-\tau) \cdot f_d \cdot e^{r_d \cdot SLT} + f_e \cdot \left(e^{r_e \cdot SLT} - 1\right)}{1-\tau} \right)_i, \tag{4.4}$$

where M_i is the heavy metal mass transferred to or from each facility, reactor or repository, p_i is the fuel cycle prices, and SLT is the fuel service lead time which are input to the system. The financial parameters for the simulation are presented in Table 4-1.

Table 4-1 – Financial parameters

Parameter	Definition	Value
r_f	Risk-free interest rate	2%
r_d	Expected rate of return on debt	5%
f_d	Fraction of debt in the capital structure	50%
r_e	Expected rate of return on equity	12%
$f_e = (1 - f_d)$	Fraction of equity in the project financing	50%
τ	Marginal Tax Rate	38%
$r = (1-\tau) \cdot r_d \cdot f_d + r_e \cdot f_e$	Discount rate for private financed	7.55%

The *fuel cycle cost* $FCC(t)$ is modeled as

$$FCC(t) = \frac{FCC_{total}(t)}{P_{IC}(t)}. \tag{4.5}$$

The mass transferred among facilities, reactors and repository is taken from the simulation at each time step. The *lead time*, the time between the investment and the midpoint of irradiation of the fuel, the point where the money is assumed to be collected from the electricity sale, and *ahead time*, the time interval between the time of investment and the fuel loading at the front- or back-end process, are both presented in Table 4-2. For the calculations of the lead times, is assumed to be the time in which the fuel remains in the core of the reactor (i.e. 4.5 years for LWRs, 2.4 years for ABRs, and 7.5 years for GFRs) and the time when the services are paid (front- and back-end process pay just before loading the fuel) and the interim storage service is paid one year before finishing the cooling time. In addition, it's assumed that uranium ore will be always available for LWRs, and lead times for uranium purchase for ABRs and GFRs are the same as that for LWRs.

Table 4-2 - Data lead times

Activity	Ahead Time [Years]	Lead Time [Years]
U ore purchase	2	4.25
Conversion process	2	4.25
Enrichment process	1	3.25
LWR: UO_2 fuel fabrication	0.5	2.75
LWR: UO_2 spent fuel separation	2.5	4.75
LWR: UO_2 spent fuel interim storage	-5	-7.25
CONFU FFF fuel fabrication	1.5	3.75
CONFU FFF spent fuel reprocessing	3	5.25
Young CONFU spent fuel interim storage	-5	-7.25
Old CONFU spent fuel interim storage	-17	-19.25
ABR FFF spent fuel reprocessing	3	4.2
ABR fuel fabrication	1.5	2.7
ABR spent fuel interim storage	-5	-6.2
GFR fuel fabrication	1.5	5.25
GFR spent fuel reprocessing	2.5	6.75
GFR spent fuel interim storage	-5	-7.5

The fuel cycle services prices assumed for the economic analysis are presented in Table 4-3, Table 4-4, and Table 4-5. They are derived from reference [2]. The price of the separation and reprocessing service is a function of the capital costs and the O&M costs. Uranium ore purchase is the price of natural ore, not the yellowcake, sold on the market as U_3O_8 (powder-form material consisting of natural uranium). The price of the conversion process is the price to convert milled uranium oxide, U_3O_8, to uranium hexafluoride (not enriched), UF_6, which is the form required by most commercial uranium enrichment facilities currently in use. UO_2 fuel fabrication includes the prices of fabrication for traditional UO_2 pins. The price for spent fuel interim storage includes the storage for traditional and advanced spent fuel.

Table 4-3 - Fuel cycle prices for the front- and back-end services

Service	Value
Ore Purchase [$/kg]	120
Conversion Process [$/kg]	12
Enrichment Process [$/kg]	130
UO_2 Fuel Fabrication [$/kg]	250
FFF Fuel Fabrication [$/kg]	11,000
GFR Fuel Fabrication [$/kg]	1,500
Spent Fuel interim storage [$/kg]	200
Young CONFU interim storage [$/kg]	200
Old CONFU interim storage [$/kg]	200

Table 4-4 - Fuel cycle prices for UO_2 separation and GFR reprocessing services

Nominal Capacity [MT/Year]	UO_2 separation [1,000 $/kg]	GFR reprocessing [1,000 $/kg]
100	4.7	9.4
500	1.6	3.2
1,000	1.3	2.6
2,000	1.03	2.06
7,000	0.920	1.84

Table 4-5 - Fuel cycle prices for FFF reprocessing

Nominal Capacity [MT/Year]	Service Price [1,000 $/kg]
50	11.5
100	7.5
200	5.5

4.2.2. Capital-Related Costs

The capital cost is evaluated from an *overnight construction cost*, i.e. considering a hypothetical instantaneous construction [13], $C_{overnight}^{const}$, and from an *overnight decommissioning cost*, i.e. the instantaneous cost of decommissioning the plant, $C_{overnight}^{dcom}$. The *overnight construction cost* must be paid during the amortization period of the plant thorough an annual payment of Y_{const}, given an effective discount rate, *r*, and tax rate an equity, τ

$$Y_{const} = C_{overnight}^{const} \cdot \left(\frac{e^{r \cdot T_{const}} - 1}{r \cdot T_{const}} \right) \cdot \frac{1}{(1-\tau)} \cdot \left(\frac{e^{r \cdot L_e} \cdot (e^r - 1)}{e^{r \cdot L_e} - 1} - \frac{\tau}{L_e} \right), \tag{4.6}$$

where L_e is the *amortization period,* T_{const} is the *plant construction time.* Similarly, the *overnight decommissioning cost* must be paid in advance during the plant lifetime thorough the annual payment of Y_{decom}

$$Y_{decom} = C_{overnight}^{decom} \cdot \left(\frac{e^{r_f \cdot T_{decom}} - 1}{r_f \cdot T_{decom}} \right) \cdot \left(\frac{e^{r_f \cdot L} \cdot (e^{r_f} - 1)}{e^{r_f \cdot L} - 1} \right). \tag{4.7}$$

where and L is the *plant lifetime*, and T_{decom} is the *plant decommissioning time*, and r_f is the interest rate earned in the collected funds. Table 4-6 presents time parameters for all reactors. The values for the overnight costs for reactors are presented in Table 4-7. Capital costs for separation and reprocessing plants are aggregated in the price of the separation and reprocessing service, and are not considered in the calculation of capital-related costs. Table 4-8 and Table 4-9 present the overnight costs for FFF reprocessing plants, UO_2 separation, and GFR reprocessing.

Table 4-6 – Time parameters for all reactors

Reactor	T_{const} **[Years]**	T_{decom} **[Years]**	L_e **[Years]**	L **[Years]**
LWR	4	1	20	60
GFR	4	1	20	60
ABR	4	1	20	60

Table 4-7 – Overnight costs for thermal and fast reactors

Reactor	$C_{overnight}^{const}$ **costs [$/kWe]**	$C_{overnight}^{decom}$ **costs [$/kWe]**
LWR	1,700	350
GFR	2,500	350
ABR	2,500	350

Table 4-8 - Overnight costs for FFF reprocessing

Nominal Capacity [MT/Year]	$C_{overnight}^{const}$ **costs [Billion $]**
50	4
100	4
200	4

Table 4-9 - Overnight costs for UO_2 separation and GFR reprocessing plants

Nominal Capacity [MT/Year]	LWR $C_{overnight}^{const}$ costs [Billion $]	GFR $C_{overnight}^{const}$ costs [Billion $]
100	4	8
500	4.5	9
1,000	6	12
2,000	6.6	13.2
7,000	14	28

4.2.3. O&M Costs

Operating and maintenance costs are fixed costs paid during the entire lifetime of the facility, and partially variable cost depending on production. For simplicity, they will be assumed as fixed. O&M costs include expenses due to operation, maintenance, administration, supervision, preservation and security of the building, and other fixed expenses which exist if the plant is fully operating. The O&M costs for thermal and fast reactors are presented in Table 4-10, and they are considered for cost of electricity calculation. They are adopted from reference [2]. The O&M cost for UO_2 separation, GFR reprocessing, and FFF reprocessing plants are presented in Table 4-10, Table 4-11, and Table 4-12. O&M for separation and reprocessing plants are aggregated in the price of the separation and reprocessing service.

Table 4-10 – O&M costs for thermal and fast reactors

Reactor	O&M costs [$/kWe]
LWR	70
GFR	70
ABR	70

Table 4-11 – O&M costs for UO_2 separation and GFR reprocessing plants

Nominal Capacity [MT/Year]	UO_2 separation [$/kg]	GFR reprocessing [$/kg]
100	700	1,400
500	700	1,400
1,000	700	1,400
2,000	700	1,400
7,000	700	1,400

Table 4-12 – O&M costs for FFF reprocessing

Nominal Capacity [MT/Year]	FFF reprocessing [$/kg]
50	11,500
100	7,500
200	5,500

4.3. Summary

The purpose of the economic model is to provide useful insights by comparing results from different cases under the same assumptions. The cost of electricity is calculated based on pre used parameters, and the price must be at least equal to the calculated cost. The cost does not reflect market prices that depend on externalities. The economics model is based on the forecasted mass flow, and on the number of reactors and advanced facilities in the system. The *cost of electricity* (COE) at each time step, it is the sum of the cost of construction and decommissioning plants, i.e. *capital-related costs* (CC), and the production cost, i.e. the *operating and maintenance costs* (O&M) plus the *fuel cycle costs* (FCC). Moreover, the capital and O&M costs for separation and reprocessing plants are aggregated in the price of the separation and reprocessing service.

5 Assessment of the U.S. Nuclear Market

5.1. Introduction

Uranium is primarily used for electricity generation, and nuclear power plants are responsible for 6% of the world's total energy production, as presented in Figure 5-1. Nevertheless, nuclear power plants provide about 20% of total net electricity generation in the U.S., as showed in Figure 5-2, although no new nuclear units have been constructed in the last decade [14].

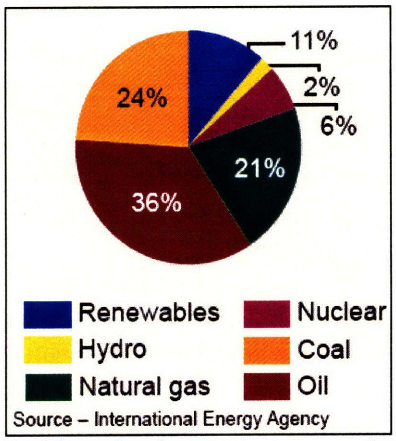

Figure 5-1 – World total primary energy supply (source: IEA)

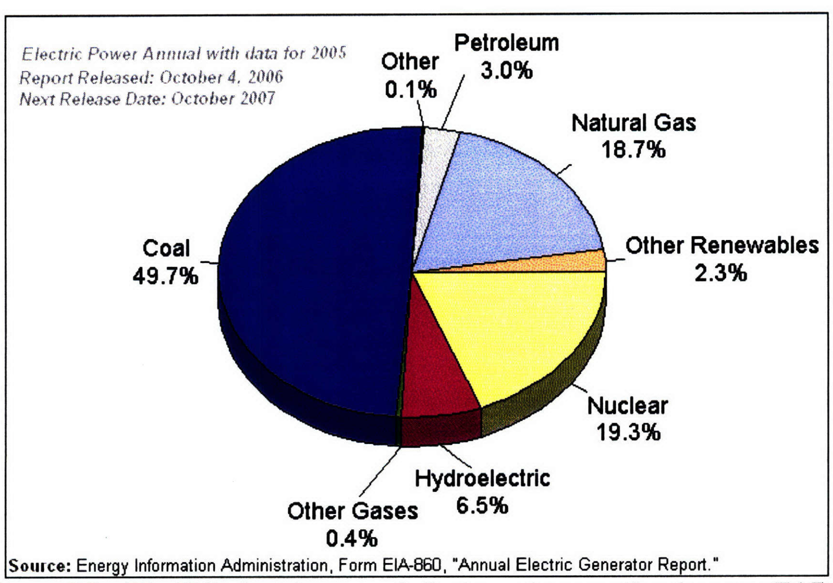

Figure 5-2 – The U.S. electric power industry net generation (source: EAI)

In the last four decades, uranium has become one of the world's most significant energy minerals, and its demand has been increasing [15]. As presented in Figure 5-3, the annual uranium production exceeded the requirements from the mid-1950s to 1990 [16]. On the other hand, after 1990 the annual uranium requirement surpassed production -- uranium mines now supply only 55% of the requirements of power utilities Indeed, due to the renaissance of the nuclear field, the demand for uranium should increase even more. This is partly due to the use of highly enriched uranium previously produced in the former USSR, which was released for civilian use.

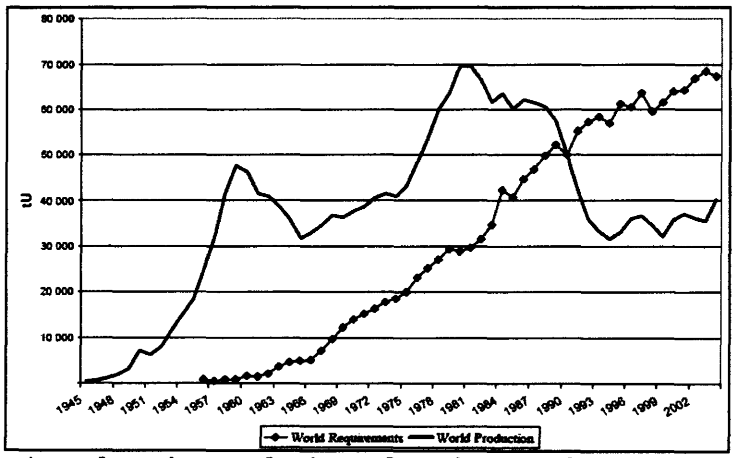

Figure 5-3 – Annual uranium production and requirement 1945-2004 (source: OECD)

However, the stock of military uranium available for use by nuclear power plants will be eventually exhausted, and uncertainties in the availability of uranium from other sources, i.e. highly-enriched uranium, recycled uranium from spent fuel, and uranium produced by re-enrichment of depleted tails, should have significant influence on the uranium market in the next decade. Nevertheless, the uranium mining industry has been responding to market development, and production capability is expected to increase in the next few years, therefore the primary production from mines should meet the world demand by 2010, if all projected mines open and operate at full capacity [16].

The over-production of uranium until the early-1990s plus the availability from other sources made the price of the mineral reach its lowest level in about 1995, as plotted in Figure 5-4 [16]. After 2001, the price of uranium has been increasing due to demand, and there is no indication that this behavior has ended. The sustainability of the uranium market depends on the strength of the uranium industry that should be developed to meet the growth in demand. Figure

5-5 and Figure 5-6 provide long-term values for U_3O_8, for conversion process, and for SWU requirements, as project by *TradeTech, LLC* [17].

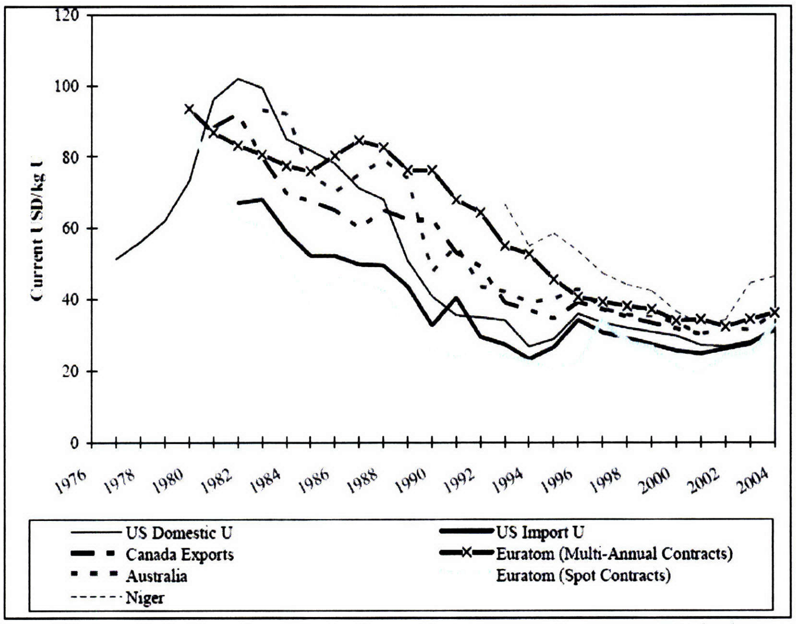

Figure 5-4- Development of uranium prices (source: OECD)

As revealed by Figure 5-5, the U_3O_8 long-term values present a sharp rise since 2004. In addition, the long-term value for SWU requirements increases up to 40% during the same period.

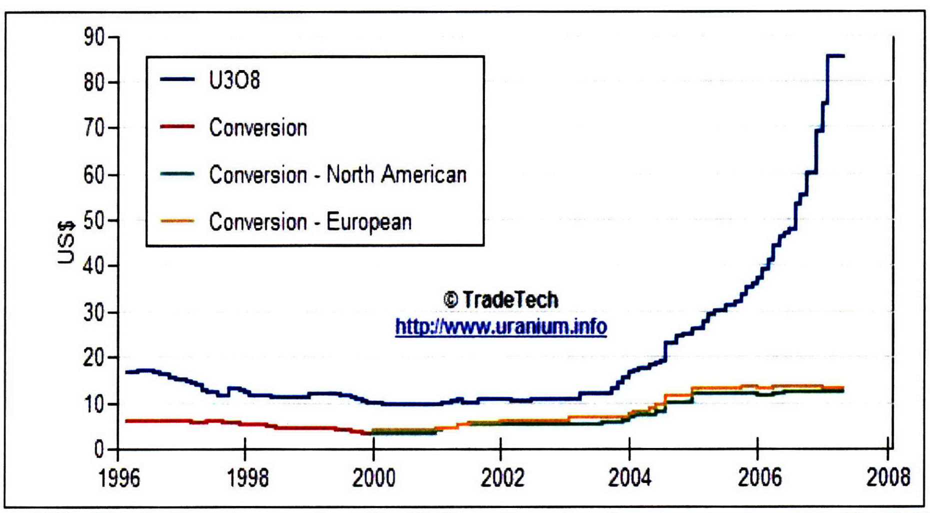

Figure 5-5 – Trade long-term values for U_3O_8 and conversion process (source: TradeTech)

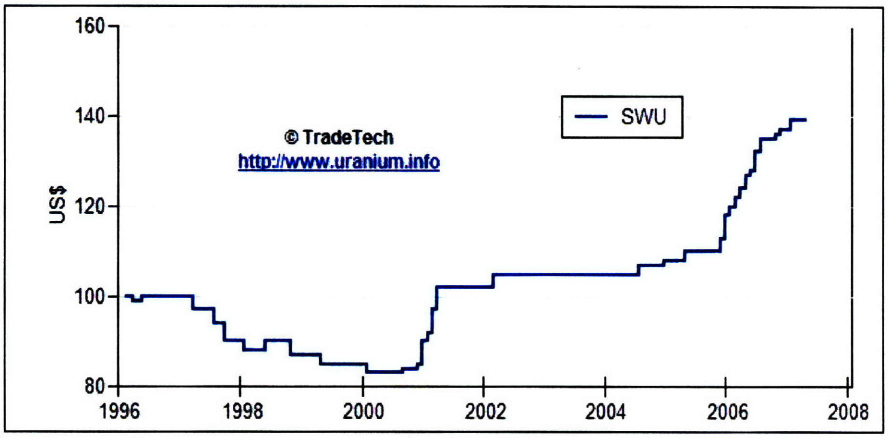

Figure 5-6 – Trade long-term values for SWU requirements (source: TradeTech)

In this chapter, the impacts of advanced technologies on uranium resources and SWU requirements are evaluated. Moreover, a sensitivity analysis for the uranium prices in the U.S. market is performed. In addition, the results of an economic analysis of different rates of TRU consumption are presented. The simulation is based on the U.S. nuclear market of about 100 LWRs today, with combined installed capacity of 100 GWe, and that requires up to 18,000 MT of uranium from mines each year. The demand is assumed to grow at 2.4% per year.

5.2. The impact of recycling on uranium resources

The introduction date of advanced technologies has an impact on the TRU inventory, on the availability of uranium resources, and on the SWU requirements. The increasing uranium demand, the long-term impact of radioactive spent fuel, and the fact that the nuclear industry must take full responsibility for minimization of the burden of its waste, justify the introduction of advanced fuel recycling technologies. For example, the U.S. decided for an open-cycle approach, leaving the spent fuel where it is, and the nuclear waste is currently stored at 131 sites around the country, as a result of nuclear power generation and national defense programs [18], the plan is to send this waste to an underground disposal facility, i.e. a geological repository, at Yucca Mountain. The legal geological repository capacity, which was limited by Congress, is 70,000 metric tons of heavy metal. Scientific analysis demonstrates that the Yucca Mountain site is physically capable of holding much more used fuel [19]. However, under the current spent fuel generating rate of almost 2,000 MT/Year, it should reach its maximum capacity in some twenty years, and uranium recycling could delay investments on a new repository.

The introduction of the *Global Nuclear Energy Partnership* (*GNEP*) program by the U.S. for the deployment of advanced nuclear technologies, for both TRU fuel and fast reactors, initiated much discussion about the size needed recycling capabilities for the country. The amount of spent fuel in the U.S. is about 50,000 MT [2] in 2005. Maximization of fuel resources utilization, reduction of the waste radio-toxicity, reduction of the thermal load on the repositories, high geological repository costs, and non-proliferation resistance issues, have all been motivating changes in the nuclear energy policy from an *open-cycle country* status to a *closed-cycle country* status. Furthermore, the increasing demand for ore, and the rising price of uranium fuel services for storing spent fuel, should also justify the investment on advanced recycling fuel facilities.

The impact of the introduction date of advanced technologies on the TRU inventory, on the availability of uranium resources, and on the SWU requirements are evaluated through five case studies, as briefly discussed in Table 5-1. The nuclear annual growth rate is taken as 2.4% [7]. The introduction date of the technology is chosen based on the date when the technology should be industrially accessible in the U.S., i.e. that the thermal recycling strategy and advanced fuel facilities can be deployed in 20 years, and that fast reactors can be deployed in 40 years.

Table 5-1 – Case study for assessment of uranium resources in the U.S.

Case study	Introduction date of the technology
Once-Through Cycle (OTC)	---
CONFU Technology	2027
Nominal introduction of ABR	2047
Late introduction of ABR	2067
Nominal introduction of GFR	2047
Late introduction of GFR	2067

Table 5-2 presents the amount of natural uranium ore from identified resources, i.e. from *Reasonably Assured Resources* (RAR), and from *Inferred Resources* (IR) as identified by the *International Atomic Energy Agency* (IAEA) [16]. However, other sources of uranium are likely to be identified at higher prices. In addition, stock holdings of natural uranium and low enriched uranium (LEU), re-enriched uranium from depleted uranium, and uranium blended down from high enriched uranium (HEU) should also be considered if the simulation refers to depletion of primary and secondary uranium resources. Thus, it is estimated that the world reserves can be four to five times the resources identified in Table 5-2. Therefore, the U.S. can expect to draw on these sources by itself.

Table 5-2 – Natural uranium resources OECD Red book in 2005 [16]

Resources	Cost Range		
	≤ 40 $/kgU	≤ 80 $/kgU	≤ 130 $/kgU
RAR [MT U]	1,947,383	2,643,343	3,296,689
IR [MT U]	798,997	1,161,038	1,446,164
TOTAL	2,746,380	3,804,381	4,742,853

As can be seen in Figure 5-7, Figure 5-8, and Figure 5-9, for a 2.4% annual growth on demand, which represents an U.S. nuclear installed capacity of 1,100 GWe after 100 years (see Figure 5-19, Figure 5-20, and Figure 5-21), the nominal introduction of the GFR recycling schemes provides the most significant reduction of the uranium ore mining rate, the uranium resources demand, and on delaying the depletion date of uranium ore from identified resources. Furthermore, the demand for ore and the SWU requirements remains steady for more than 30 years while GFRs are built to fulfill the nuclear power demand. However, after 2080, the demand for uranium increases again due to the limitation of TRU inventory available for the GFRs.

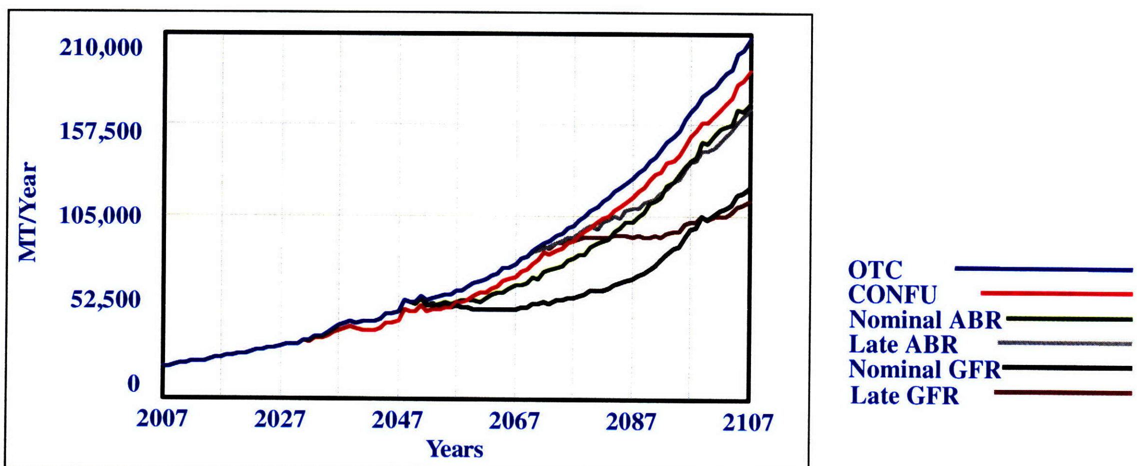

Figure 5-7 – Required natural uranium mining rate

It is not surprising that for a 2.4% annual nuclear growth rate, the more favorable scenario, the early introduction of the GFR technology, delays depletion of the uranium resources to 2102, at a nuclear installed capacity of 938 GWe. Under the assessed demand, the resources of uranium are enough for almost 80 years, considering only the U.S. nuclear energy growth†. On the other hand, the complete depletion of ore from identified resources for the once-through cycle occurs in 2088, fourteen years before the depletion date for nominal GFR, at the installed capacity of 667 GWe, 71.1% of the assessed installed capacity in 2102.

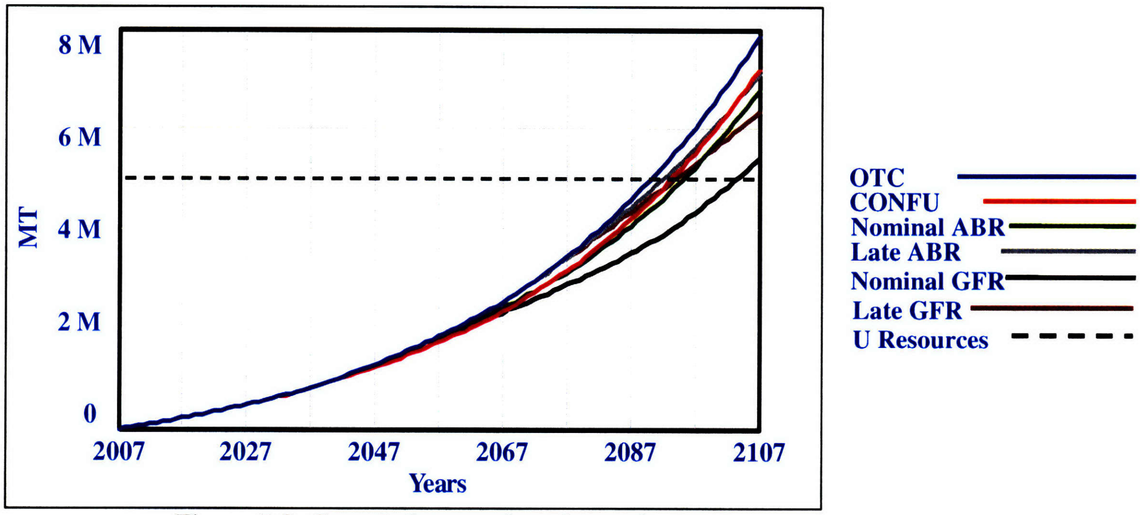

Figure 5-8 -Cumulative uranium demand

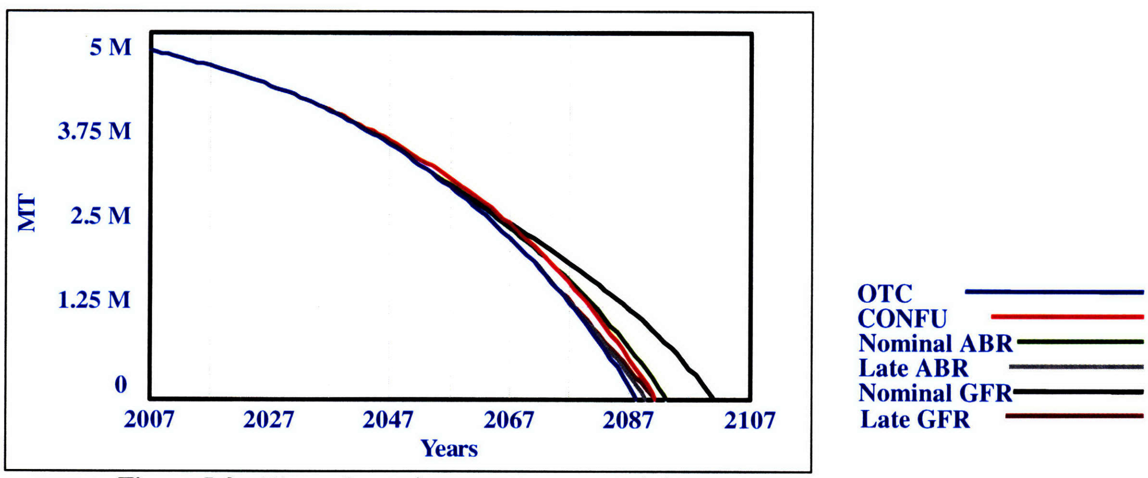

Figure 5-9 – Natural uranium resources remaining

Nevertheless, uranium ore is a mineral found in the ground and seawater, and the known resources depend on the exploration effort. The current amount of identified resources is very conservative [15]. The mining industry of uranium will expand with sustained high prices. For example, from 2003 to 2005, the overall increase in identified resources recoverable at less than 130 US$/kg was due to the result of reported re-evaluation of resources by Australia and Brazil [16] motivated by the increase of uranium ore prices.

† The world's current usage is about 66,500 MT U/Year. Therefore, the world's present measured resources of uranium under no nuclear growth in demand, and used only in conventional reactors, are enough to last for some 70 years [15].

As revealed by Figure 5-10, the SWU requirements for the U.S. should reach 145 million MT SWU/Year by 2107 if no recycling strategy is adopted. Nominal introduction of the GFR scheme reduces the SWU requirements to an estimated to be 85 million MT SWU/Year by 2107, 58.62% of the total separative work units required for the once-thorough cycle. However, the U.S. should expect a significant investment in enrichment facilities, since the current U.S. uranium enrichment capacity is 11,300 MT SWU/Year [20].

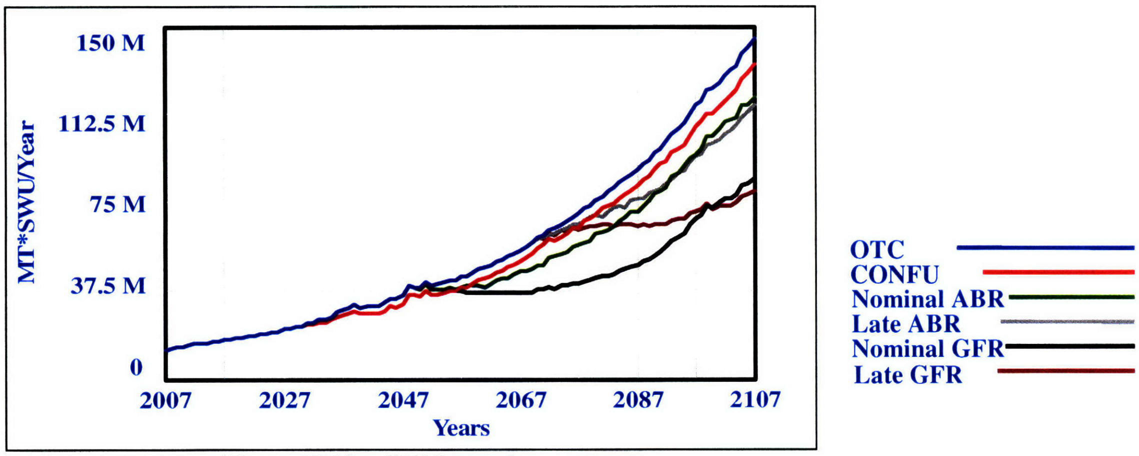

Figure 5-10 – SWU requirements

As shown in Figure 5-11, all three technologies are able to deplete the TRU inventory in interim storage. However, the deployment of the CONFU recycling scheme keeps the inventory below a lower level, and guarantees recycling equilibrium between the generation and consumption of TRU without further investments in construction of fast reactors. Also, the CONFU strategy is the most flexible technology since its batches can be mixed with traditional UO_2 batches in the current LWR fleet. However, the results shows that the CONFU technology has no significant impact on the amount of uranium resources needed neither on the SWU requirements. This is the case for any TRU burner, whether of thermal or fast spectrum.

Figure 5-12 shows the fleet of separation plants to deplete the TRU inventory at interim storage, and Figure 5-13 presents the instantaneous mass loading factor for all separation facilities. It is seem that the number of separation plants needed is the lowest with the nominal GFRs since the reactor is designed to require limited recycling. There is a chance for reduced capacity factors in the post-depletion of interim waste. Figure 5-14 gives the number of FFF reprocessing plants to be build to reprocess FFF spent fuel from CONFU and ABR technology, and Figure 5-15 plots the instantaneous FFF mass loading factor.

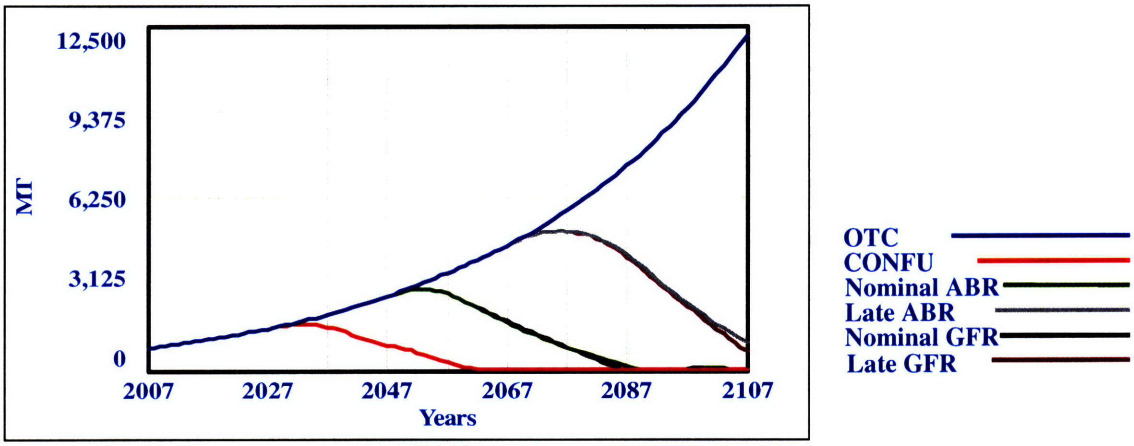

Figure 5-11 – TRU inventory

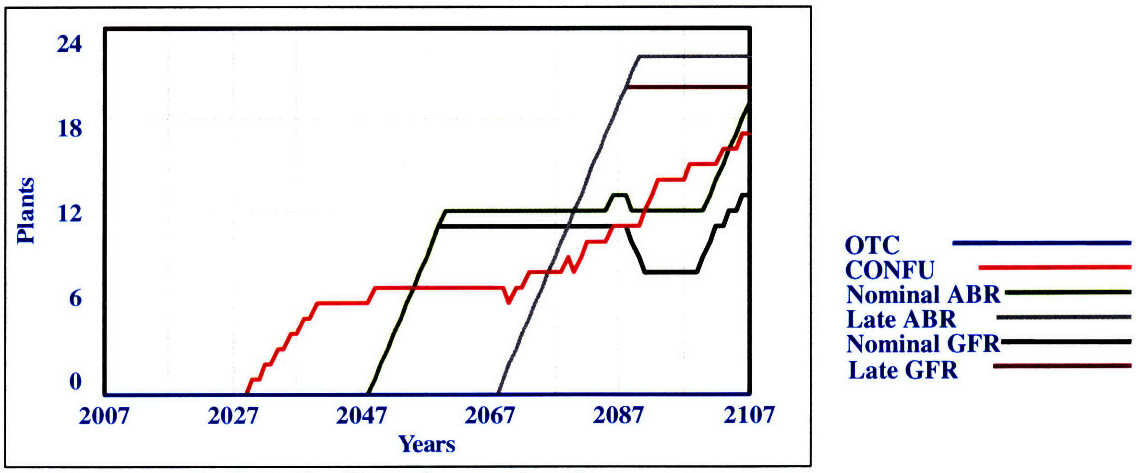

Figure 5-12 – Fleet of separation plants

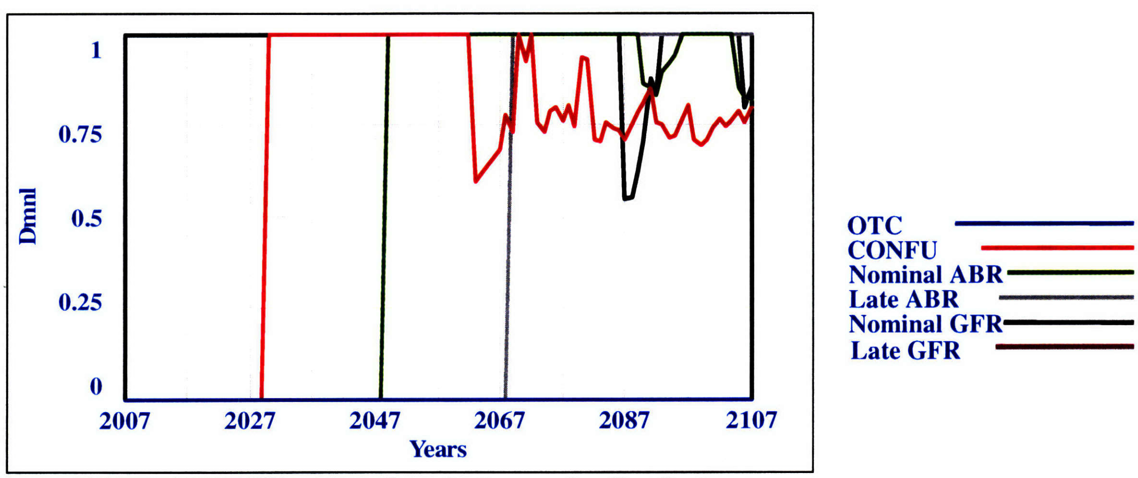

Figure 5-13 – UO_2 separation plants mass loading factor

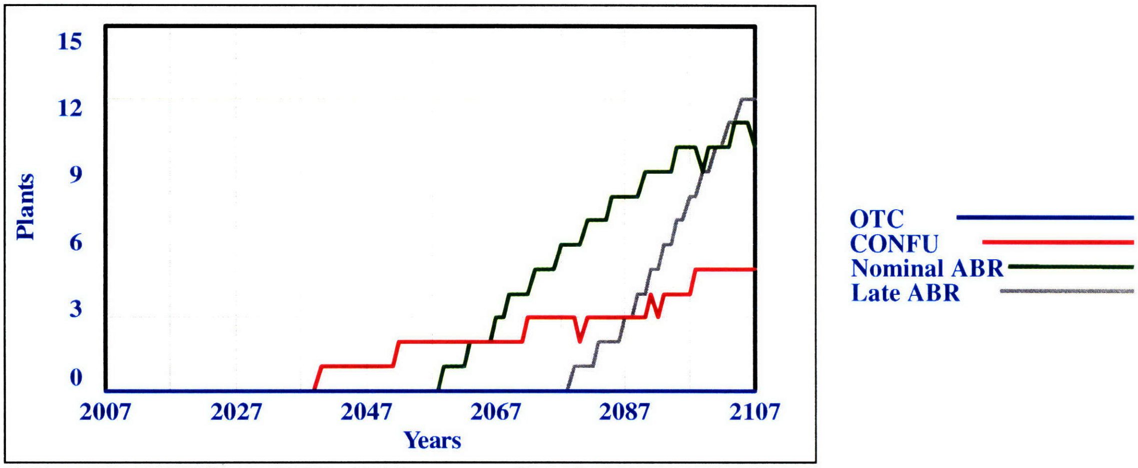

Figure 5-14 – FFF reprocessing plants

As shown in Figure 5-14, the construction rate of fuel advanced facilities must be large enough to guarantee that the late introduction of the technology will keep the TRU inventory under reasonable levels. The number of GFR reprocessing plants, and their instantaneous mass loading factor, are presented in Figure 5-16 and Figure 5-17.

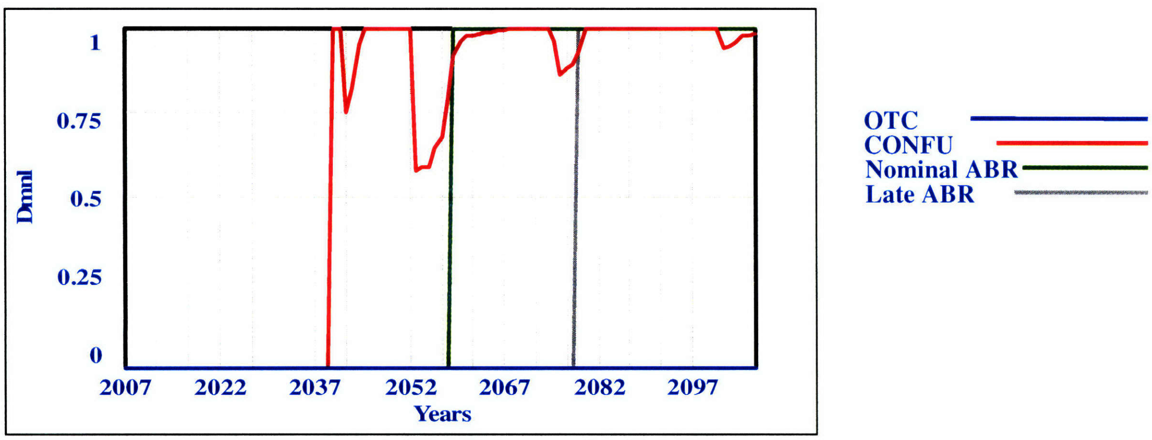

Figure 5-15 – FFF reprocessing plants mass loading factor

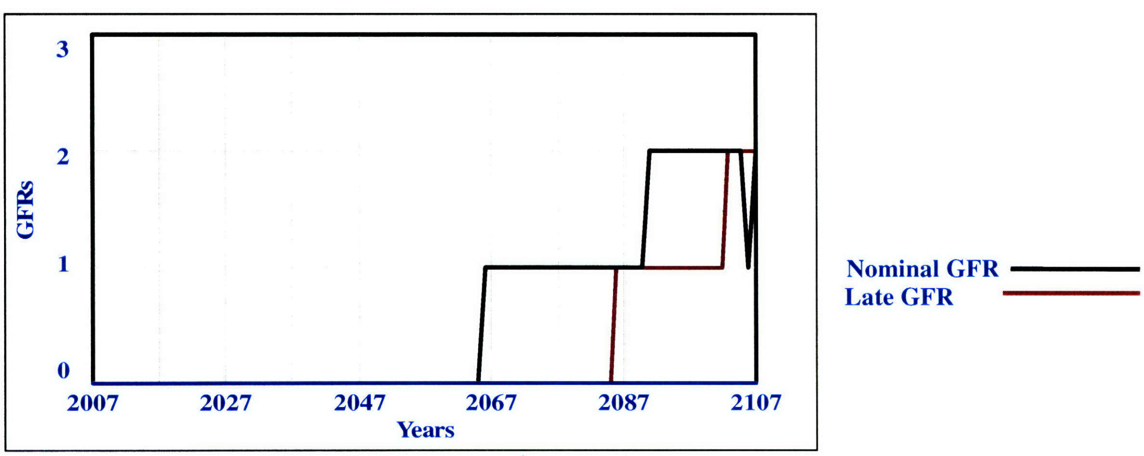

Figure 5-16 – GFR reprocessing plants

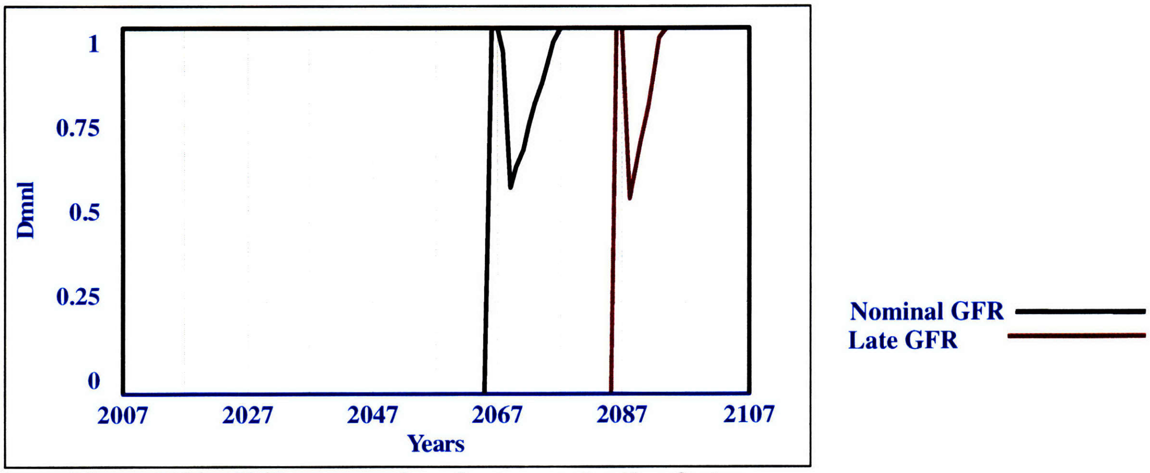

Figure 5-17 – GFR reprocessing plants mass loading factor

Last, the installed nuclear capacity and the ratio of fast to thermal reactors are presented in Figure 5-18, Figure 5-19, Figure 5-20, and Figure 5-21.

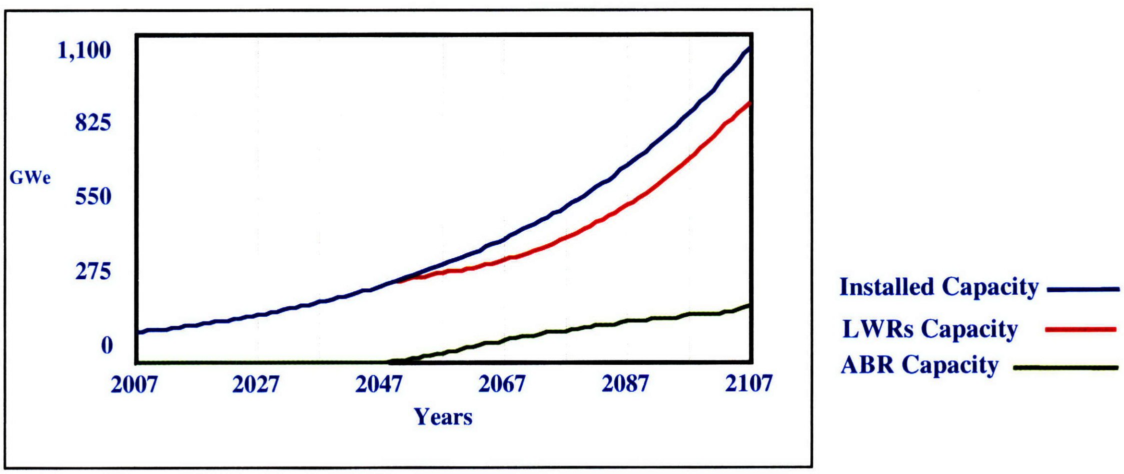

Figure 5-18 – Early ABR - Installed nuclear capacity

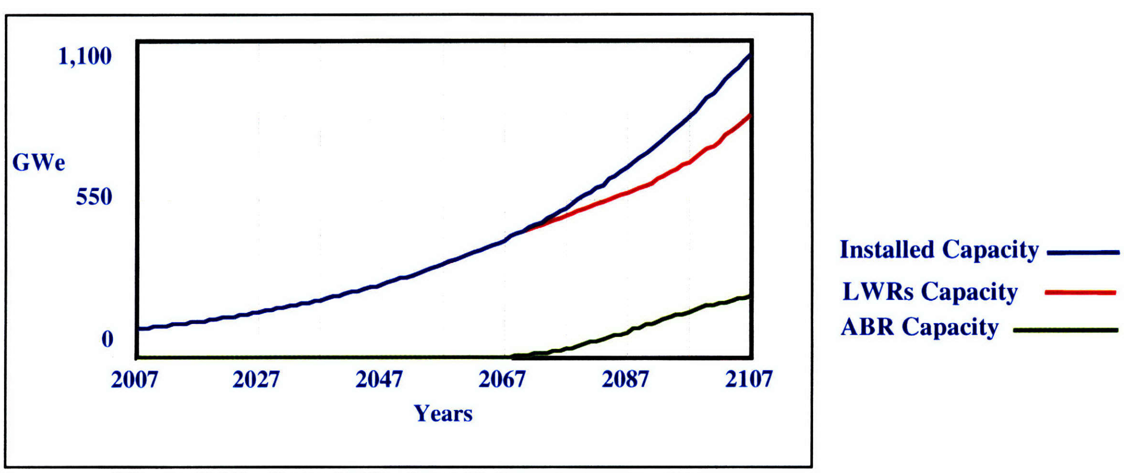

Figure 5-19 – Late ABR - Installed nuclear capacity

As explained before, Figure 5-20 plots the increase in the installed capacity due to LWRs in 2080. At that moment, GFRs can not be built due to the depletion of TRU inventory. Therefore, the demand for uranium increases again. This lack of TRU suggests that advanced fast reactors with conversion ratio greater than one should be built about the 2080 year.

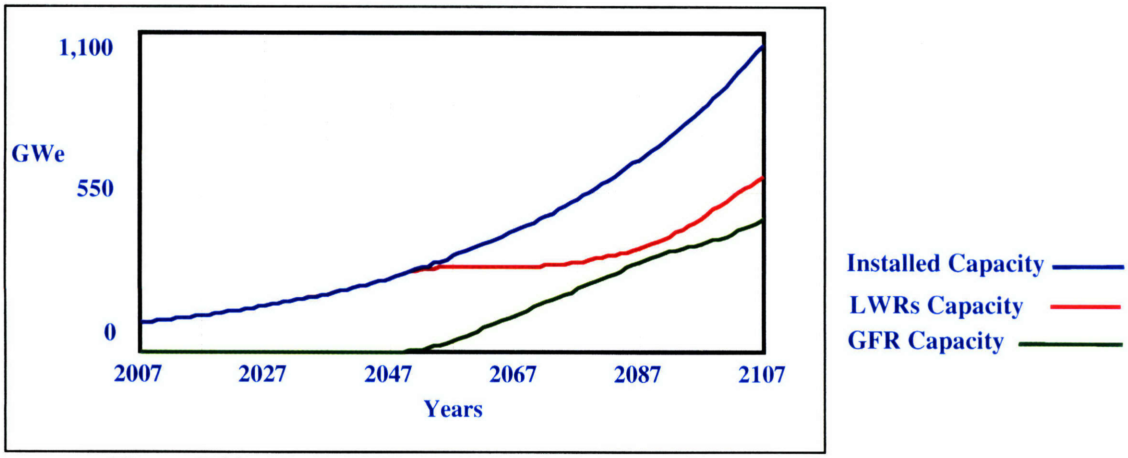

Figure 5-20 – Early GFR - Installed nuclear capacity

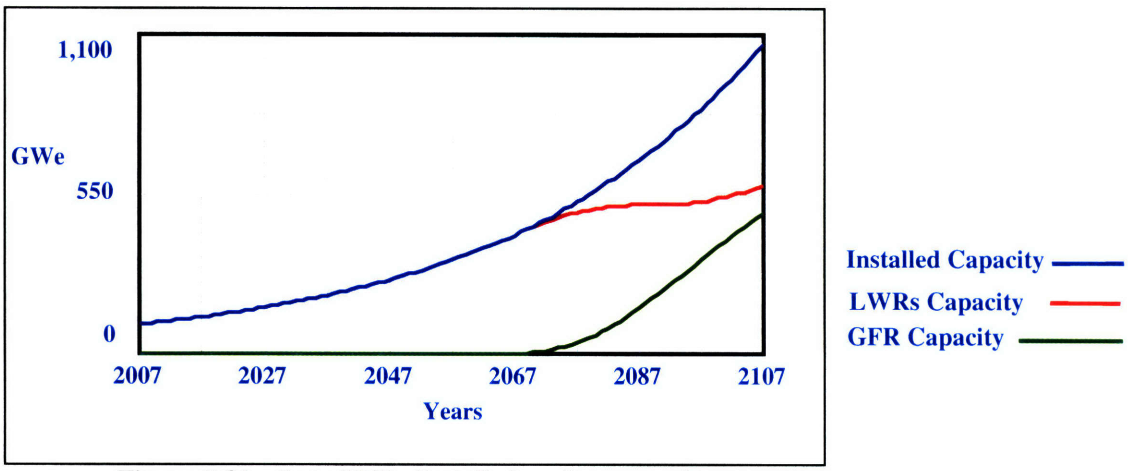

Figure 5-21 – Late GFR - Installed nuclear capacity

5.3. Fuel cycle cost and sensitivity to uranium prices

The electricity generated from current nuclear power reactors is cost competitive with other forms of energy generation [21]. Furthermore, it has the advantage of being carbon-free, and does not contribute to global warming. However, the capital cost for the nuclear plants is higher than the capital cost for other plants. Although the fuel cycle cost is small compared to all generation costs, the front-end steps of the nuclear fuel cycle are complex and are not available for all countries. Besides, an economic analysis must consider the aggregate costs of waste disposal and decommissioning. Here, the impact of uranium price on the fuel cycle cost, and on the total cost of the electricity, is evaluated through the case studies summarized in Table 5-3.

Table 5-3 – Case study for sensitivity analysis of uranium prices

Case study	Introduction date of the technology	Uranium prices [US$/kg]		
Once-Through Cycle (OTC)	---	60	120	180
CONFU Technology	2027	60	120	180
Nominal introduction of ABR	2047	60	120	180
Nominal introduction of GFR	2047	60	120	180

The introduction of the CONFU technology occurs in 2027, and the introduction of the GFR and the ABR technology occurs in 2047. The price of uranium is taken as 60, 120 and 180 US$/kg for all schemes including the once-through cycle. The simulation results for the mass flow, SWU requirements, advanced fuel facilities, and reactors are the same presented in Section 5.2 since the simulation parameters are identical. Therefore, only the economics results are discussed here.

Figure 5-22 shows the LWRs aging distribution [2] considered for the calculation of the initial nuclear installed capacity for the simulation. The LWRs lifetime is taken as 60 years. Since the overnight construction cost must be paid during the amortization period, which is taken as twenty years, the capital cost is expected to steeply fall at the beginning of the simulation as the number of LWRs which are close to 20 years old (amortization period) inverses, as revealed by Figure 5-23. The rate of construction of new LWRs is lower than the number of reactors going behind the 20 years age.

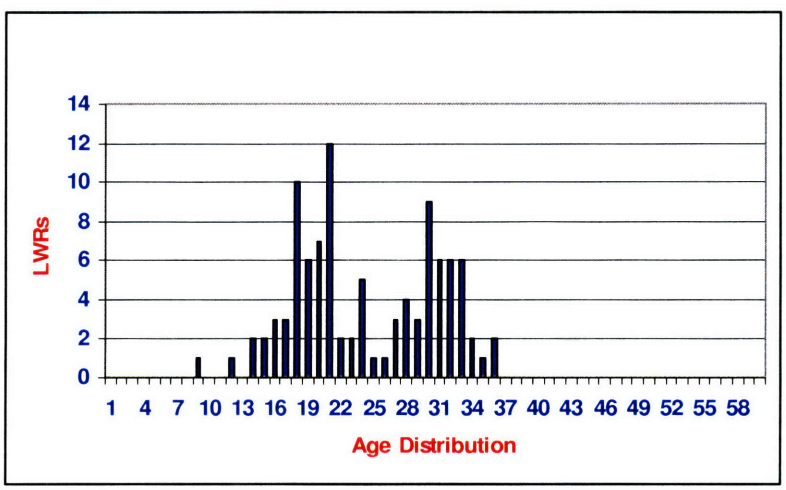

Figure 5-22 – LWRs aging distribution

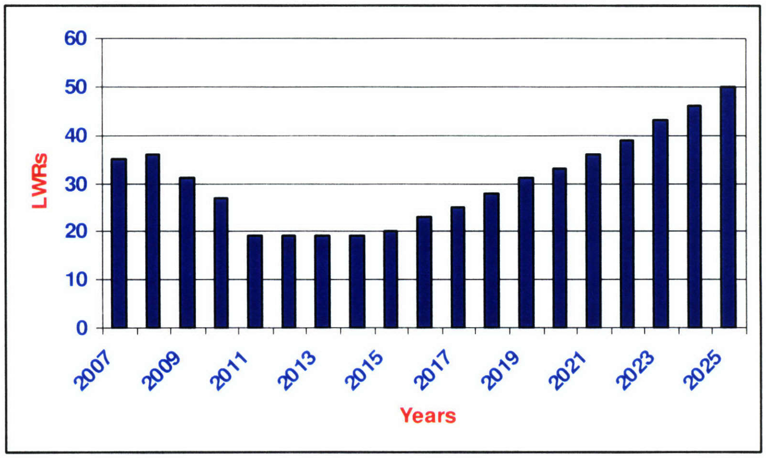

Figure 5-23 – Number of LWRs younger than 20 years old from 2020 to 2025

Figure 5-24 shows the capital cost for all uranium prices of 60, 120 and 180 US$/kg. As expected, the capital cost does not change with changes on the price of uranium. The simulation indicates that first the capital cost falls off, as explained before, and then it assumes an upward trend as the first fleet of LWRs is decommissioned, replaced by new reactors are built to fulfill the growing power demand. The capital cost for the GFR technology is higher because of the GFR nuclear installed capacity is higher than that for the ABR, as plotted in Figure 5-18 and Figure 5-20.

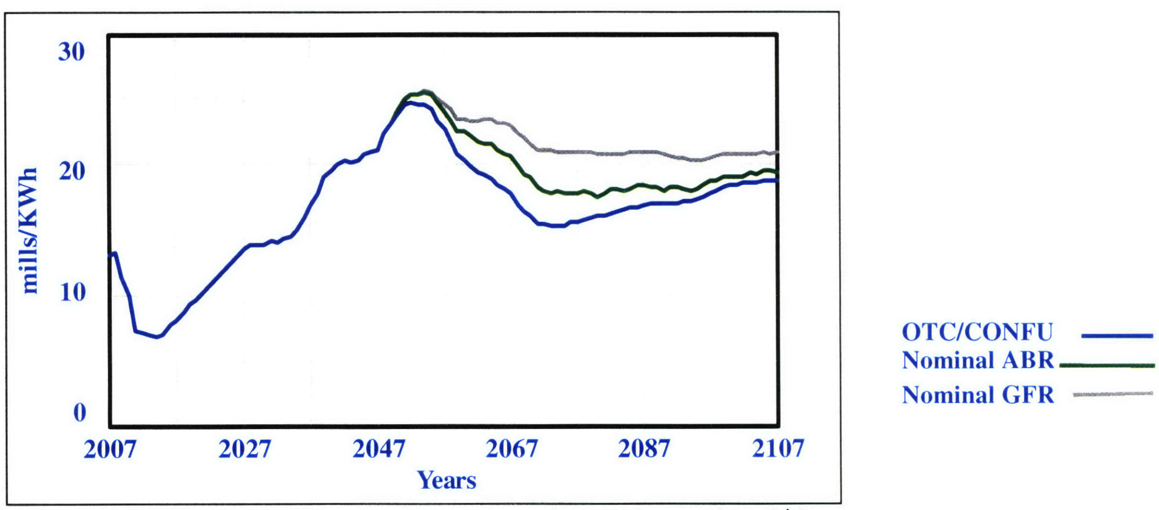

Figure 5-24–Capital cost for uranium prices of 60, 120 and 180 US$/kg

Figure 5-25 gives the O&M cost (for uranium prices of 60, 120 and 180 US$/kg). As expected, the operating and maintenance cost has the same value, 9 mills/kWh, for all technologies.

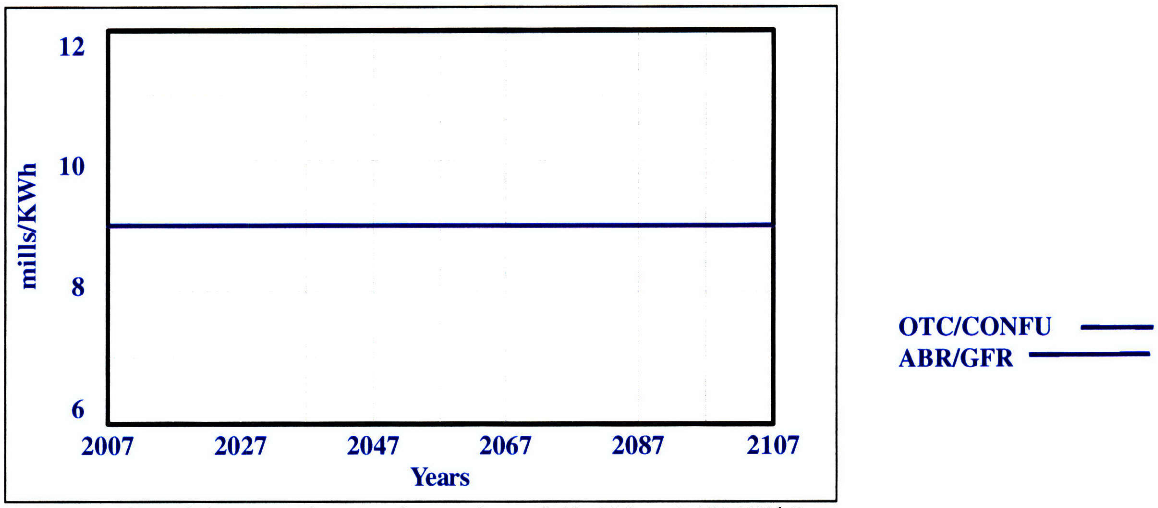

Figure 5-25 – O&M cost for uranium prices of 60, 120 and 180 US$/kg

As demonstrated in Figure 5-26, early introduction of GFRs for uranium prices of 60 US$/kg becomes economically interesting, from the fuel cycle point of view, after 2085. In addition, the delay in the introduction of both fast technologies, compared to the thermal technology, also postpones the fast reactors investment. The fuel cycle cost for the once-through cycle remains steady at 5 mills/kWh with peaks due to the commissioning of new LWRs.

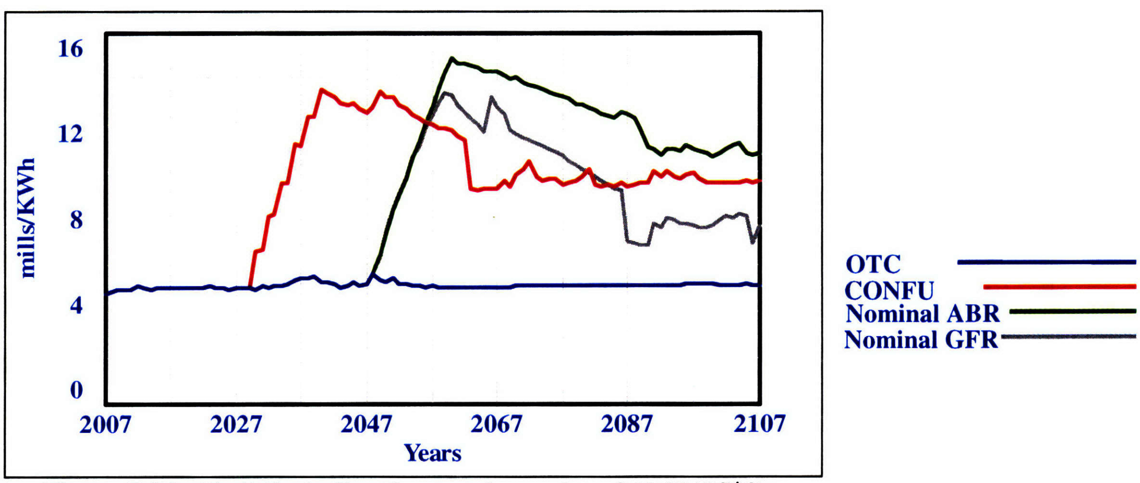

Figure 5-26 – Fuel Cycle Cost for uranium price of 60.00 US$/kg

Figure 5-27 and Figure 5-28 give the fuel cycle cost for uranium prices of 120 and 180 US$/kg respectively.

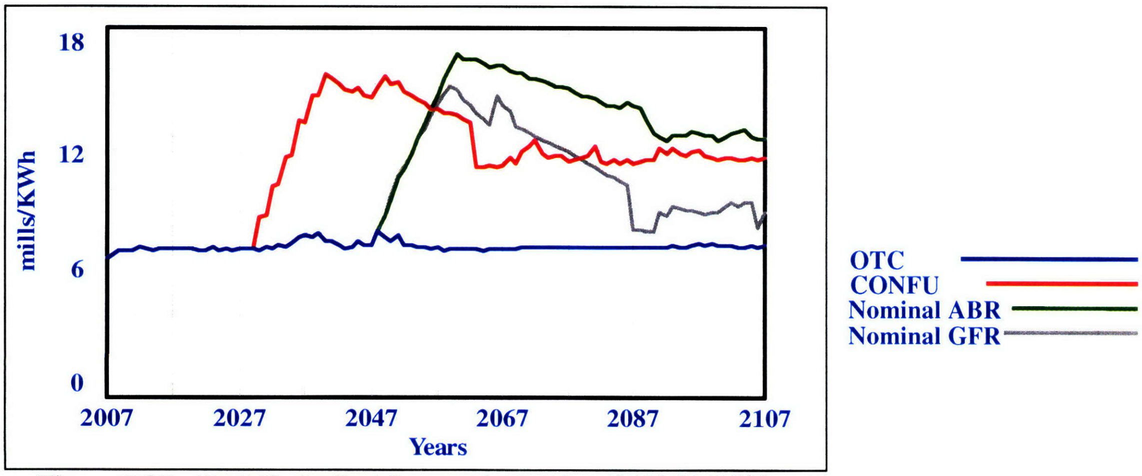

Figure 5-27 – Fuel Cycle Cost for uranium price of 120.00 US$/kg

As can be seen, the fuel cycle cost for the once-through cycle increases 2 mills/kWh when the uranium price doubles from 60 to 120 US$/kg, and more than 2 mills/kWh when it goes from 120 to 180 US$/kg. Moreover, the increase in the price of uranium makes the economics of the GFR strategy more attractive for two reasons. First, the fuel cycle costs for *early GFR* gets close to the OTC fuel cycle cost at equilibrium. Second, the cross over point when the early GFR is more attractive gets close to the introduction date of the technology. As shown in Figure 5-27, the cross over point is 2077 for uranium prices of 120 US$/kg. As plotted in Figure 5-28, the cross over point is 2070 for uranium prices of 180 US$/kg. For uranium prices of 60 US$/kg, the cross over point is 2085.

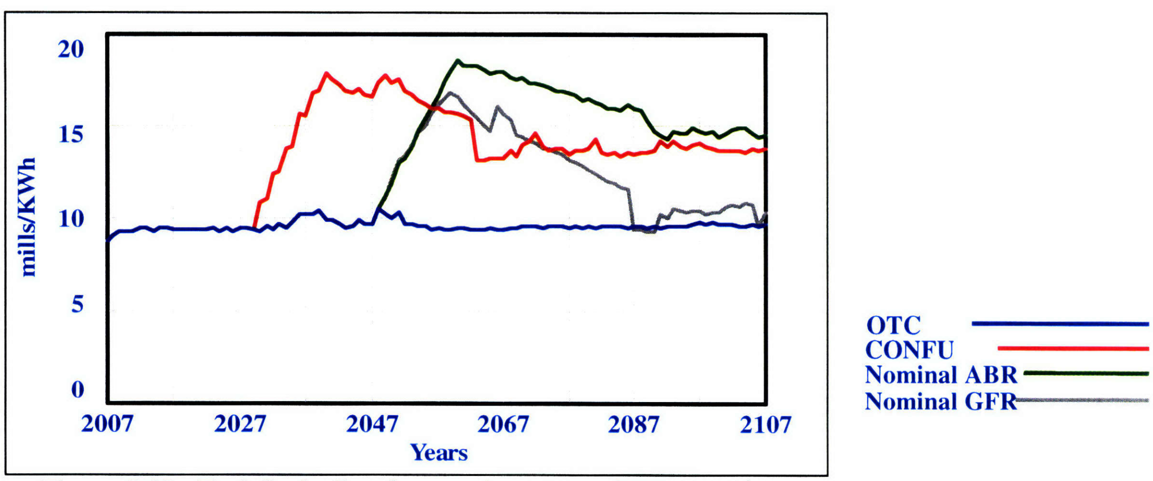

Figure 5-28 - Fuel Cycle Cost for uranium price of 180.00 US$/kg

The increase in the uranium prices makes the economics of recycling of TRU in GRFs more attractive than recycling in ABRs, as presented in total electricity prices in Figure 5-29, Figure 5-30, and Figure 5-31.

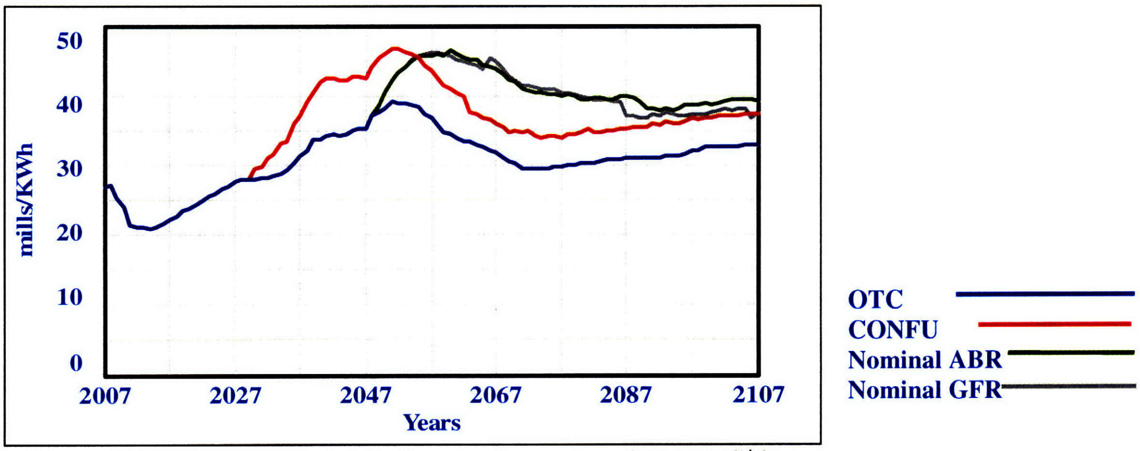

Figure 5-29 – Cost of Electricity for uranium price of 60.00 US$/kg

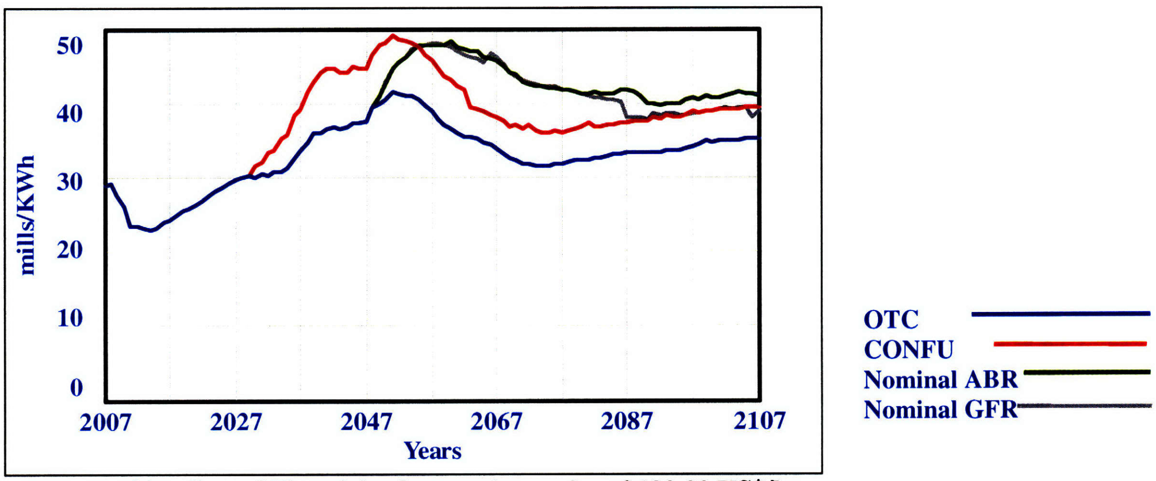

Figure 5-30 – Cost of Electricity for uranium price of 120.00 US$/kg

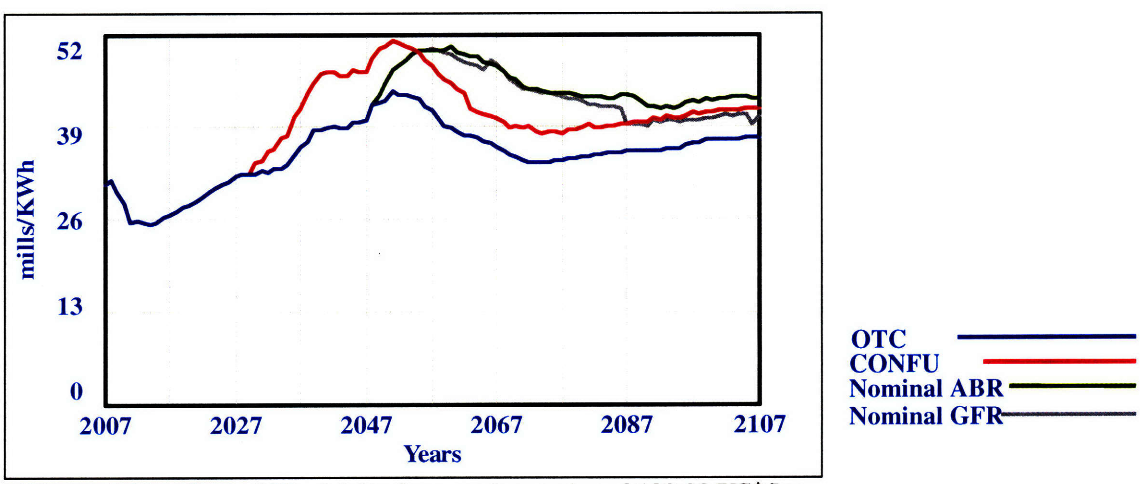

Figure 5-31 – Cost of Electricity for uranium price of 180.00 US$/kg

The fast recycling of TRU by the GFR technology may also present economic advantage compared to thermal recycling because the advantages due to fuel cycle cost surpass the disadvantages due to capital-related cost for fast reactors.

5.4. Economic analysis of the rate of TRU consumption

The TRU consumption rate should be considered a matter subject to economic analysis. The high fuel cycle and capital-related costs for the construction of fast reactors and advanced fuel facilities could not justify high consumption rate of TRU. However, the TRU consumption rate should be able to keep the TRU inventory below the current inventory level, and equilibrium is expected within 100 years.

In this Section, the economics of different rates of TRU consumption are considered. The uranium price is taken equal to 120 US$/kg, and the *instantaneous depletion time,* DT_{SP}, is adjusted to deplete the TRU inventory period the horizon of simulation. The economic analysis is performed through the case studies summarized in Table 5-4.

Table 5-4 - Case studies for different rates of TRU consumption

Case study	Introduction date of the technology	Short depletion time	Long depletion time
CONFU Technology	2027	30	40
Nominal introduction of ABR	2047	30	40
Nominal introduction of GFR	2047	30	40

The depletion time is the period to deplete the current mass inventory if there is no change in the net inflow, and if no constraints are applied to the shortfall. It is used for forecasting of the number of reactors and fuel facilities, as explained in Chapter 2. A short depletion time (SDT) is the same used in Section 5.2 and Section 5.3, therefore, the simulation results are identical. A long depletion time (LDT) is taken as the facilities lifetime, and is the natural choice for a more conservative approach. The simulation results for CONFU, ABR and GFR technology are descried in the following sections.

5.4.1. CONFU Technology

As can be seen in Figure 5-32, both the long and the short initial depletion times are able to reach the TRU inventory equilibrium within 100 years of simulation. However, the construction rate of separation and reprocessing plants for the SDT is higher than that for the long depletion time, as presented in Figure 5-33, and Figure 5-34. Therefore, the investment for the construction of advanced fuel facilities can be delayed with the LDT.

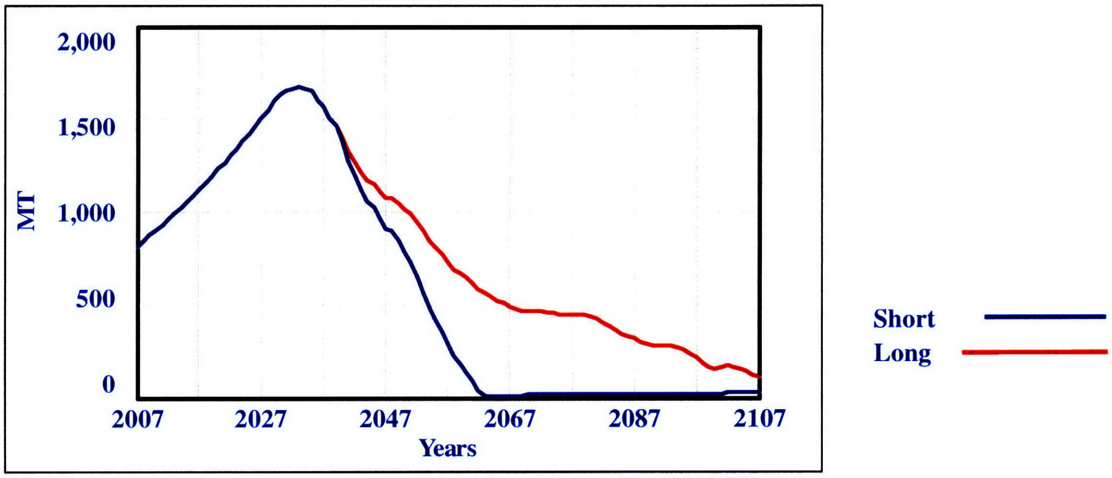

Figure 5-32 - TRU inventory at interim storage for CONFU

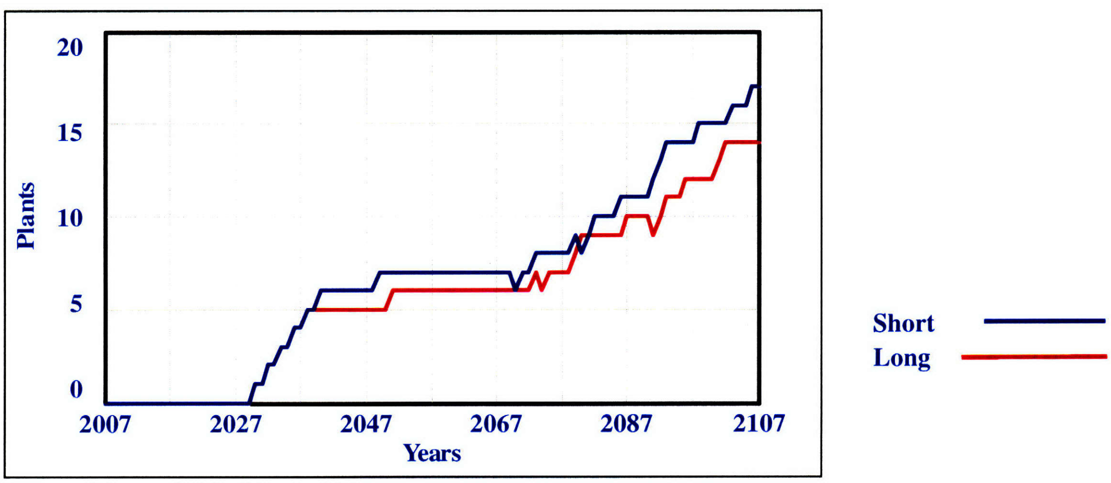

Figure 5-33 - Fleet of UO2 separation plants for CONFU

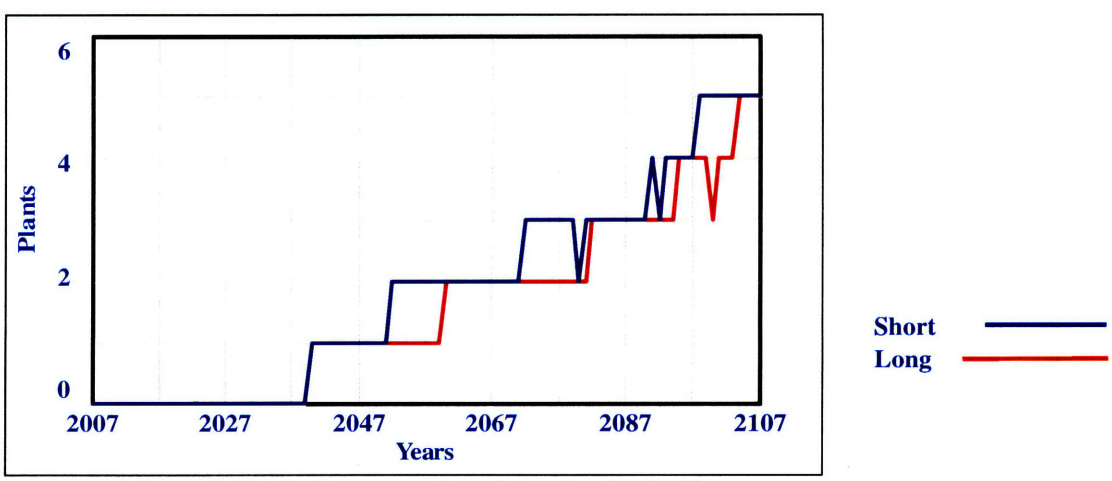

Figure 5-34 - FFF reprocessing plants for CONFU

Furthermore, the mass loading factor for separation plants is always equal one for the LDT as a result of the expansion in LWRs and the rate of treatment of UO_2 spent fuel, as can be seen in Figure 5-35.

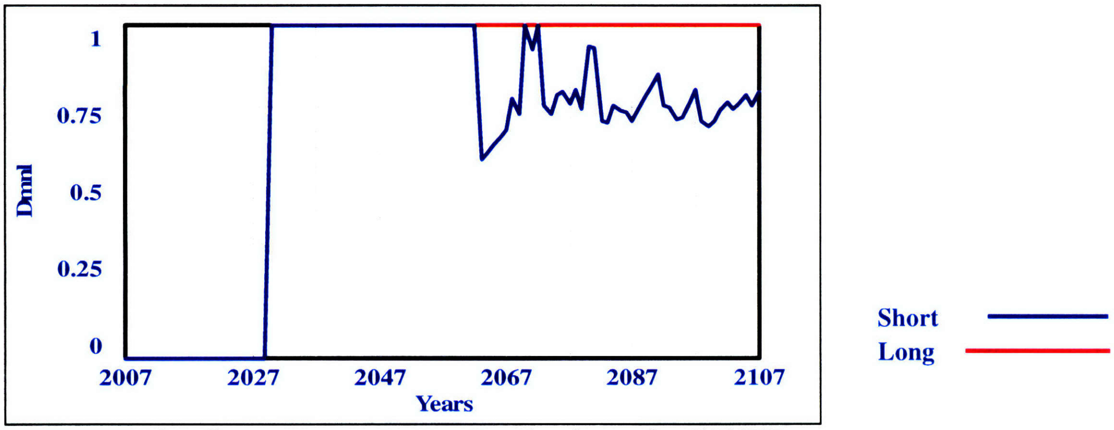

Figure 5-35 - Separation plants mass loading factor for CONFU

Figure 5-36 presents the capital costs for SDT and LDT. The capital-related costs are estimated based on the fleet of reactors, but the capital cost for advanced facilities is included in the price of the fuel service. The operating and maintenance cost has the same value, 9 mills/kWh, for the short and long depletion time.

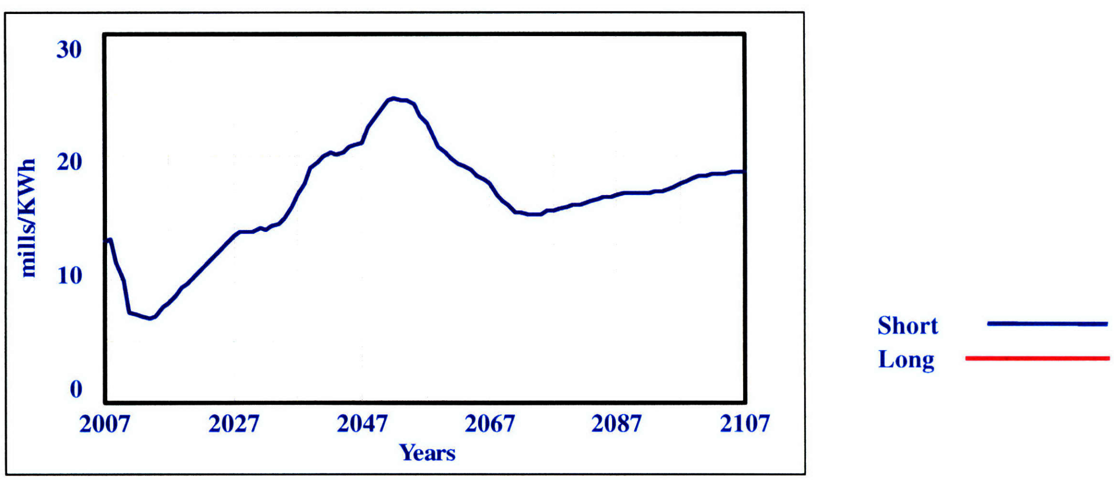

Figure 5-36 - Capital cost for CONFU

Figure 5-37 plots the fuel cycle cost for the short and long depletion time. The results validate the hypothesis that the investment in the construction of advanced facilities for partitioning of the fuel can be delayed, and that the price of fuel services, which contemplate the facilities capital and O&M costs, is lower for the LDT than for the SDT most of the time. The peak value in the cost of the fuel cycle is 14.23 mills/kWh for the LDT, and 15.68 mills/kWh for the SDT. Therefore, the peak value is 9.24% lower for the long depletion time, and the difference remains steady for up to twenty years. After equilibrium, however, the fuel cycle cost for both depletion times fluctuate around 12 mills/kWh.

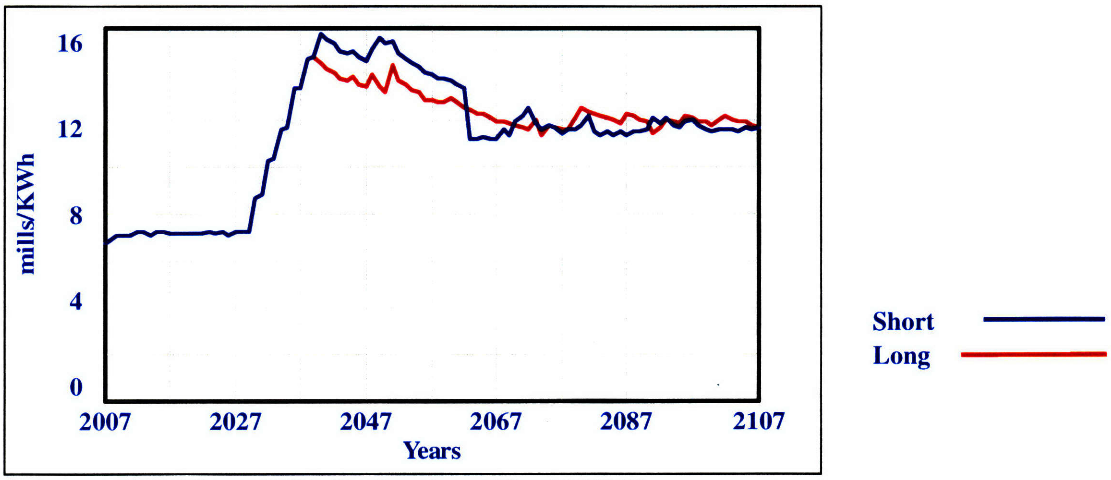

Figure 5-37 - Fuel cycle cost for CONFU

Figure 5-38 plots the cost of electricity for both depletion times. As shown, the cost of electricity for LDT is lower from the peak period for up to twenty years, and reaches a final value of 39.50 mills/kWh by the end of the simulation.

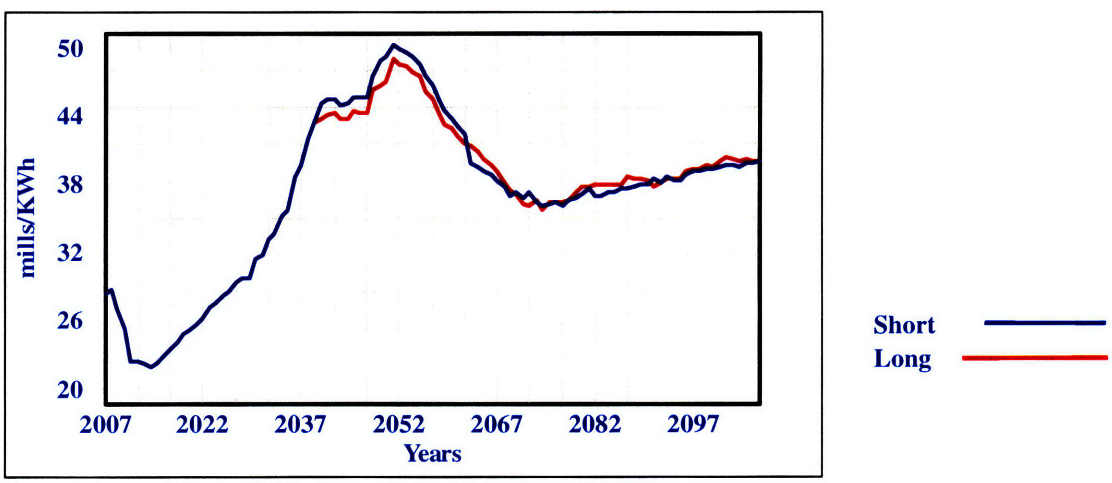

Figure 5-38 -Cost of electricity for CONFU

5.4.2. ABR technology

As can be seen in Figure 5-39, the short depletion time is able to deplete the TRU inventory within 100 years, and the long depletion time leads the TRU inventory down to 567 MT by the end of the simulation. Therefore, the remaining TRU inventory is justified by the number of separation plants built during the time horizon, as presented in Figure 5-40. From 2061 to 2101, there is one more separation plant for the SDT simulations. Hence, the mass loading factor for the separation plants is always equal to one for the long depletion time, as show in Figure 5-41.

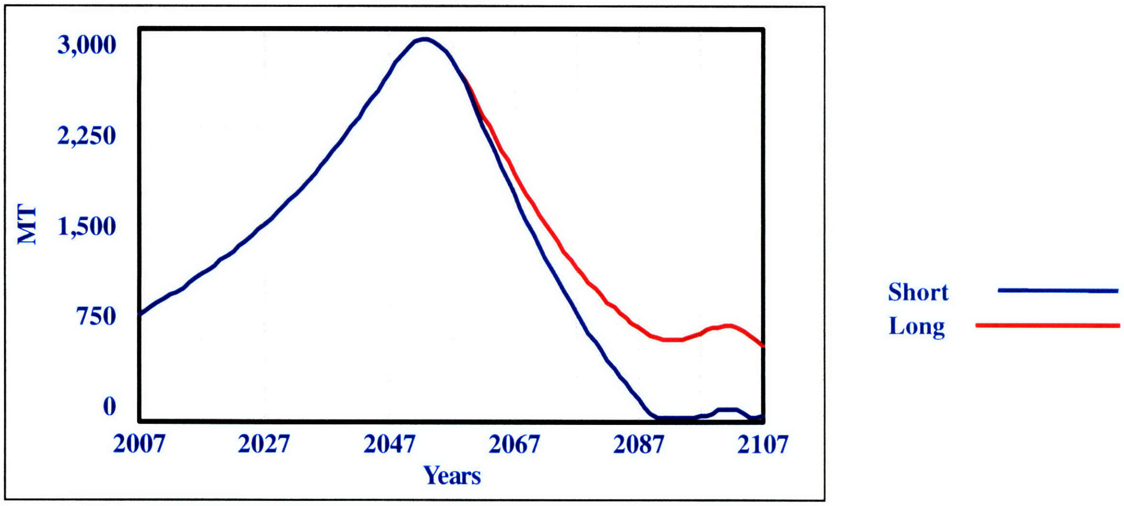

Figure 5-39 – TRU inventory at interim storage for ABRs

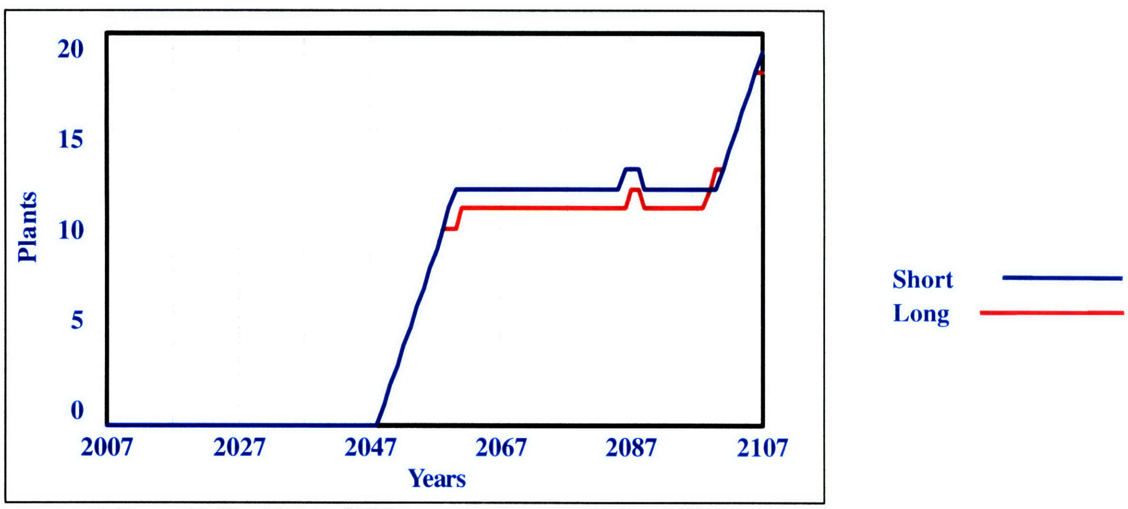

Figure 5-40 – Fleet of UO2 separation plants for ABRs

Figure 5-42 gives the fleet of FFF reprocessing plants for both depletion times. Figure 5-43 and Figure 5-44 present the total nuclear installed capacity, and the ratio of fast to thermal reactors installed capacity. For the SDP, the ABR fleet is responsible for 183.64 GWe of the total installed capacity, and for LDP is responsible for 173.56 GWe.

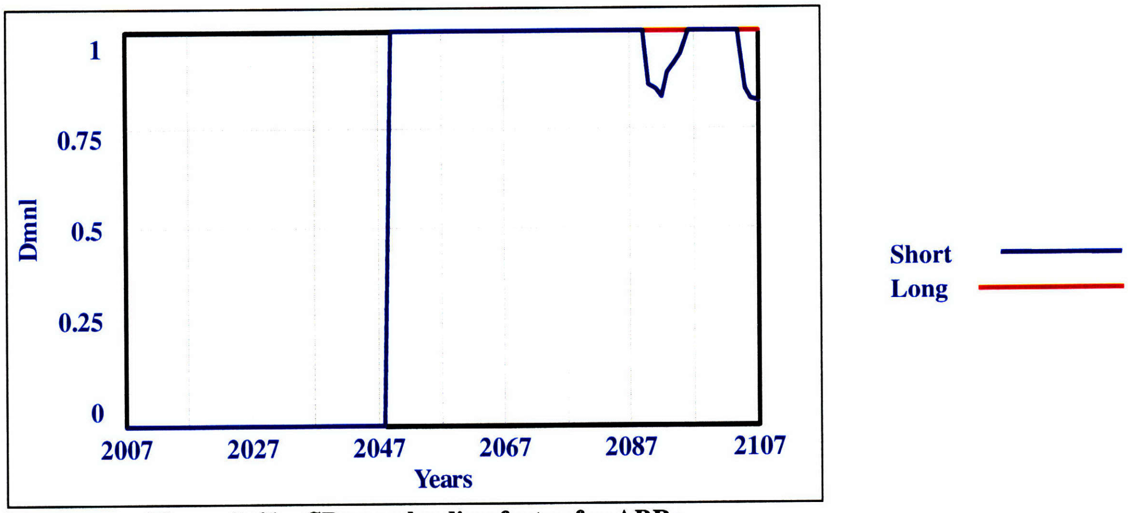

Figure 5-41 – SP mass loading factor for ABRs

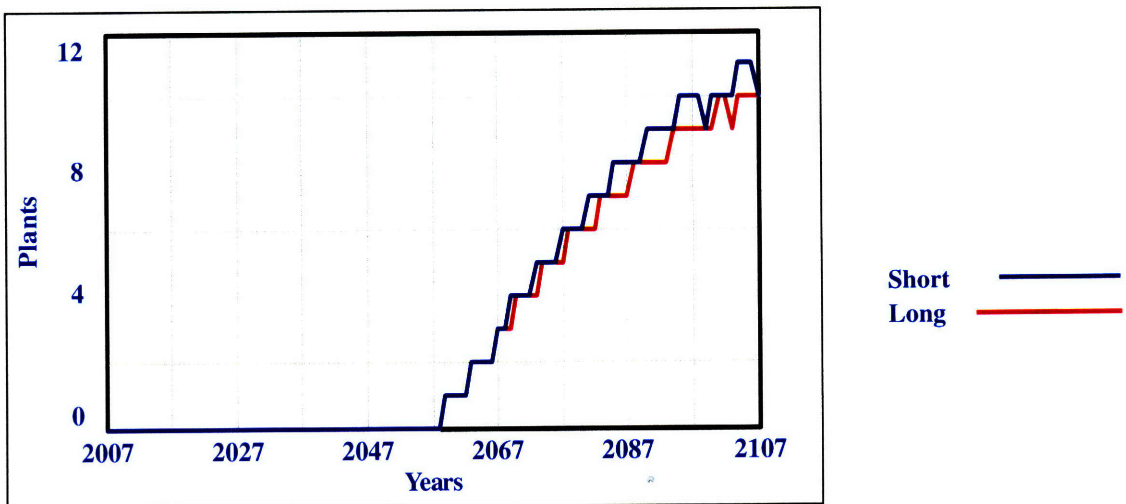

Figure 5-42 – Fleet of FFF reprocessing plants for ABRs

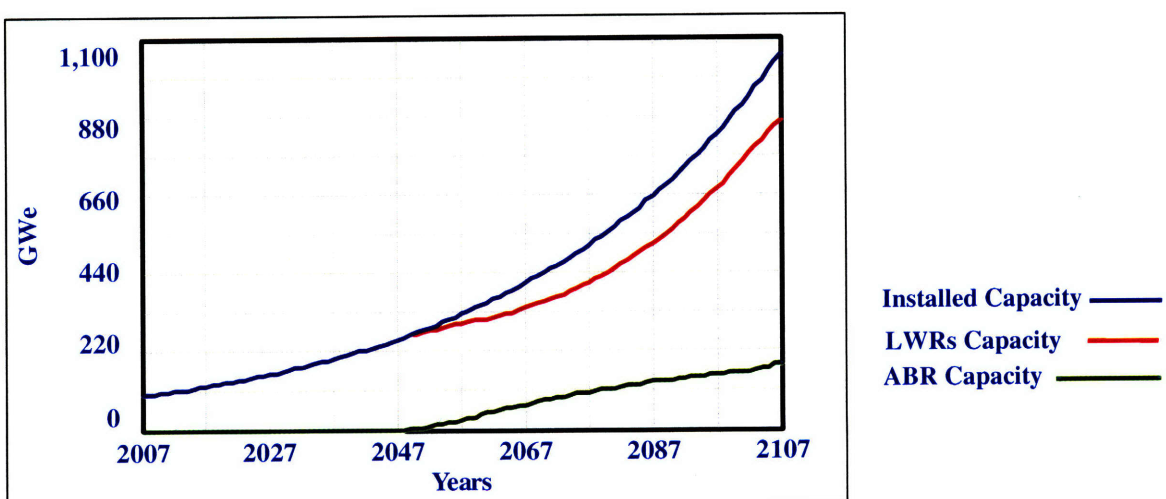

Figure 5-43 – Installed nuclear capacity for ABRs SDT

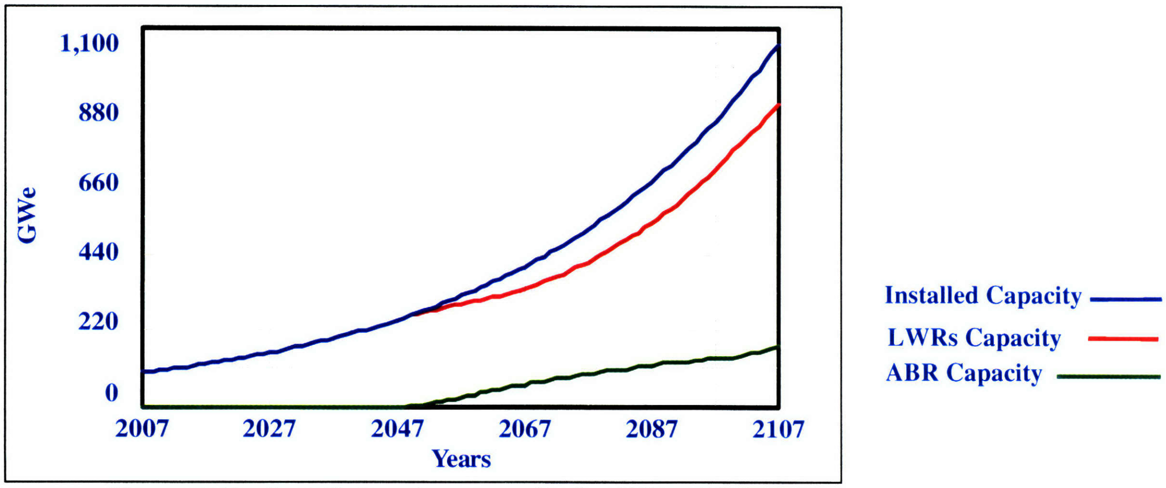

Figure 5-44 – Installed nuclear capacity for ABRs LDT

Figure 5-45, presents the capital costs for SDT and LDT. The capital costs are estimated based on the fleet of reactors, but the capital cost for advanced facilities are included in the price of the fuel service. The capital-related costs for the short depletion time are slightly higher than for the long depletion time, as a consequence of the higher ABR installed capacity for the SDT, but the difference is negligible. Moreover, the operating and maintenance cost has the same value, 9 mills/kWh, for the LDT and SDT.

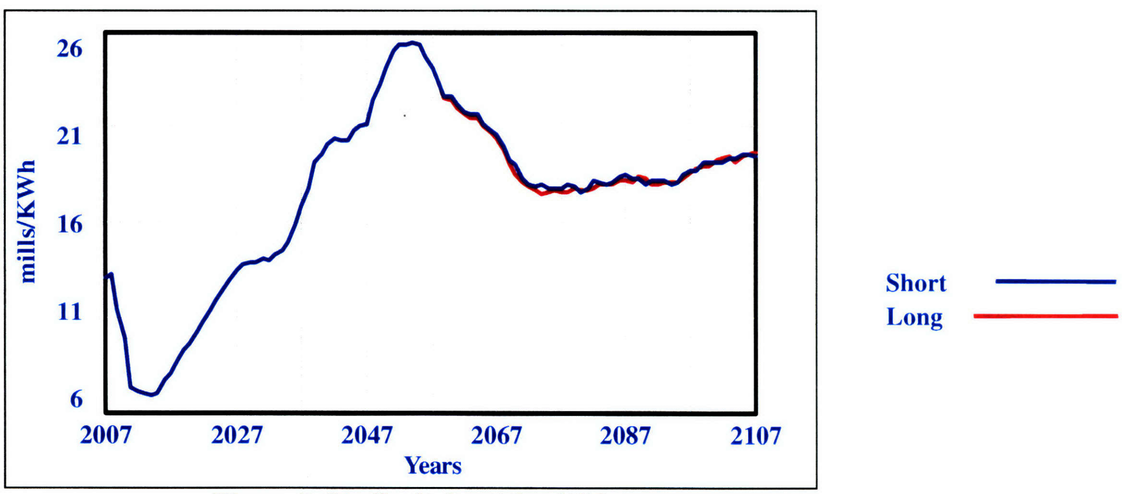

Figure 5-45 –Capital cost for ABRs

Figure 5-46 plots the fuel cycle cost for the short and long depletion time. The results validate the hypotheses that the price of fuel services, which contemplate the advanced fuel facilities capital and O&M costs, are lower for the LDT than for the SDT most of the time of the simulation. The peak value in the cost of fuel cycle is 15.75 mills/kWh for the LDT, and 16.44

mills/kWh for the SDT. Therefore, the peak value is only 4.2% lower for the long depletion time, even so, the difference remains steady for up to twenty five years.

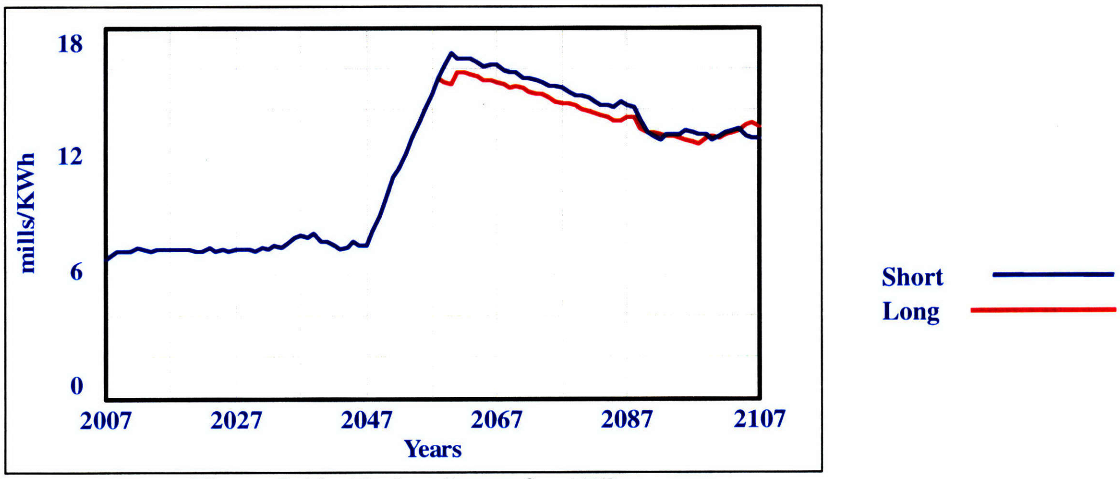

Figure 5-46 – Fuel cycle cost for ABRs

Figure 5-47 plots the cost of electricity for both depletion times. As can be seen, the cost of electricity for LDT is lower from 2059 for almost the end of the simulation.

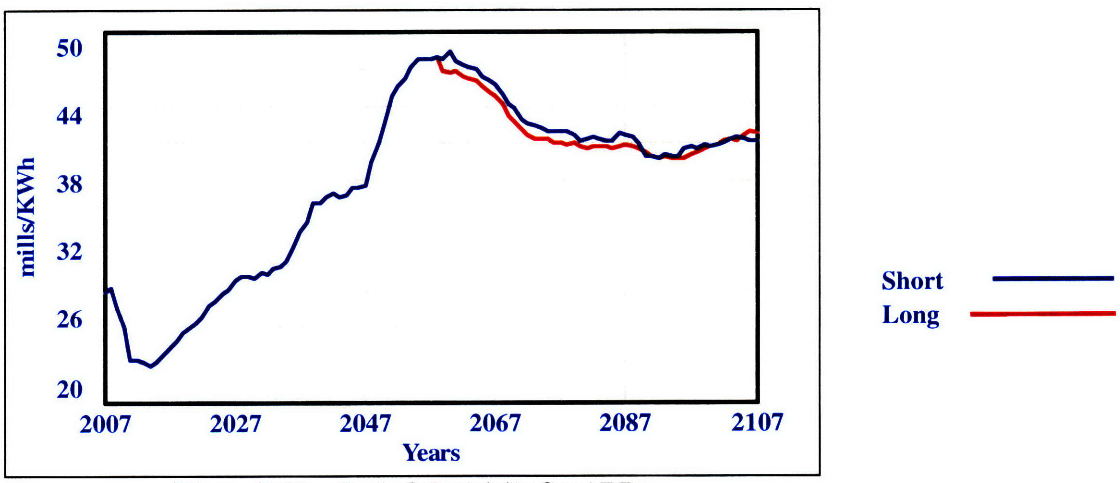

Figure 5-47 – Cost of electricity for ABRs

5.4.3. GFRs technology

As can be seen in Figure 5-48, the short depletion time is able to deplete the TRU inventory within 100 years, and the long depletion time leads the TRU inventory down to 351 MT by the end of the simulation. Therefore, the remaining TRU inventory is justified by the number of separation plants built during the time horizon, as presented in Figure 5-49. From 2058 to 2088, there are 11 separation plants for the SDT and 10 for the LDT. In 2098, due to accumulation of TRU, more separation plants are built. Hence, the mass loading factor for the separation plants is always equal to one for the long depletion time as a result of a more conservative approach in the rate of treatment of UO_2 spent fuel, as show in Figure 5-50. Figure 5-51 gives the fleet of GFR reprocessing plants for both depletion times.

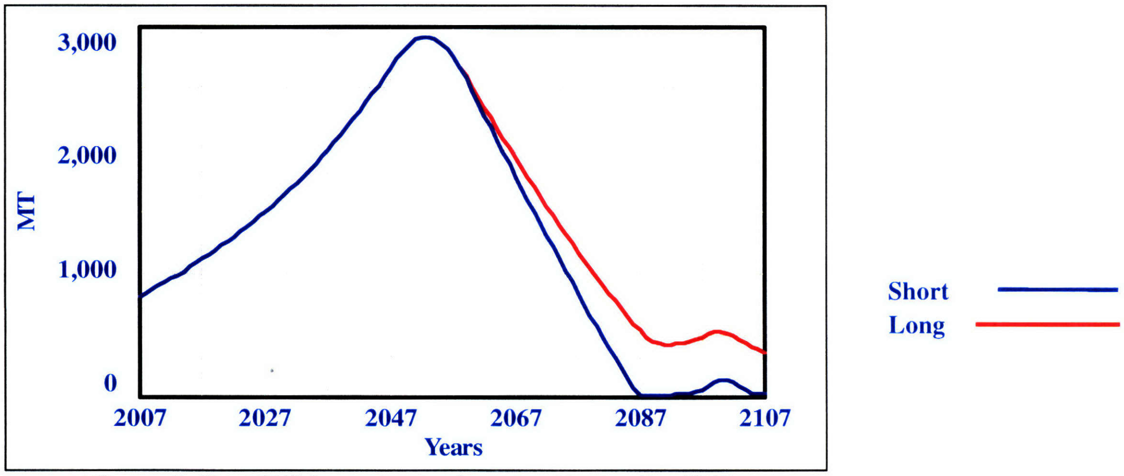

Figure 5-48 – TRU inventory at interim storage for GFRs

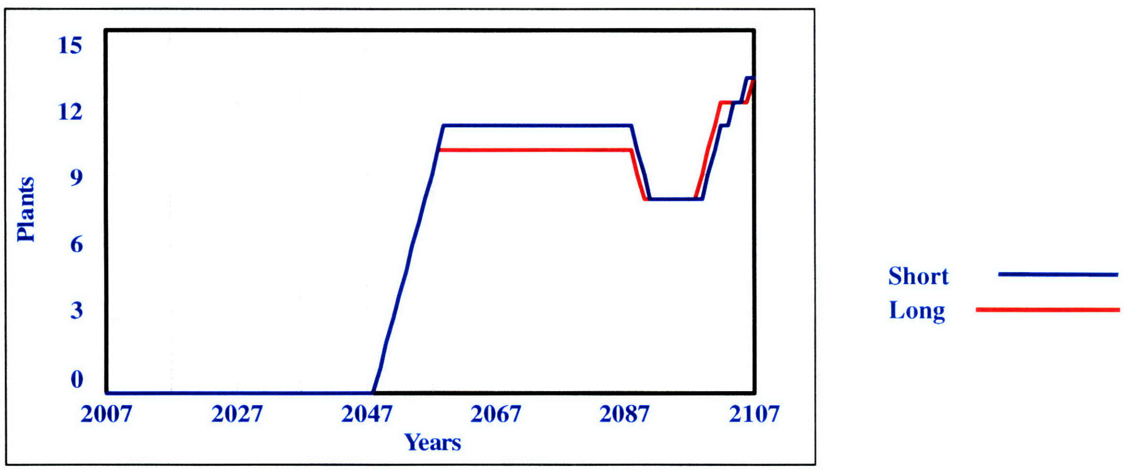

Figure 5-49 – Fleet of UO_2 separation plants for GFRs

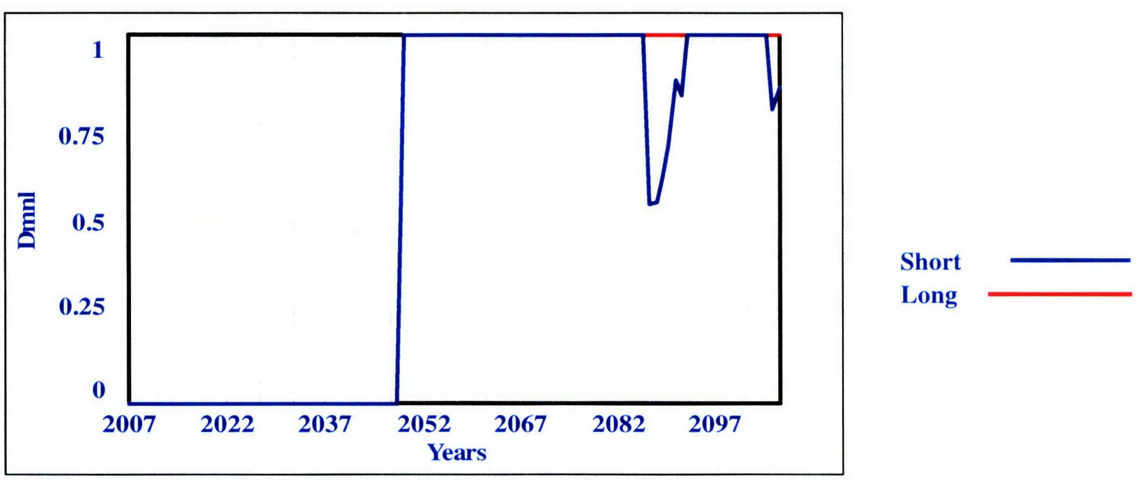

Figure 5-50– SP mass loading factor for GFRs

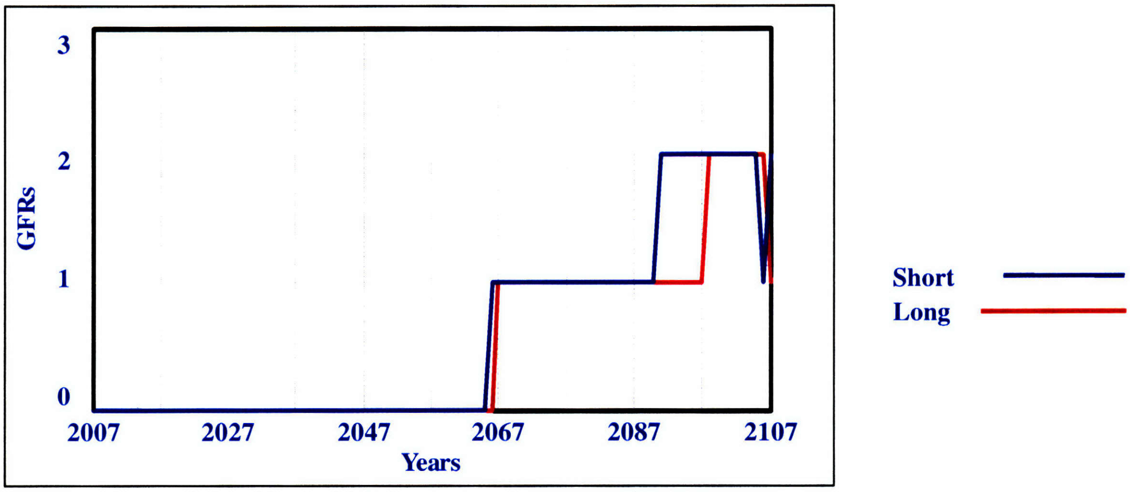

Figure 5-51– Fleet of FFF reprocessing plants for GFRs

Figure 5-52 and Figure 5-53 present the total nuclear installed capacity, and the ratio of fast to thermal reactors installed capacity. For the SDP, the GFR fleet is responsible for 455.71 GWe of the total installed capacity, and for LDP is responsible for 433.15 GWe.

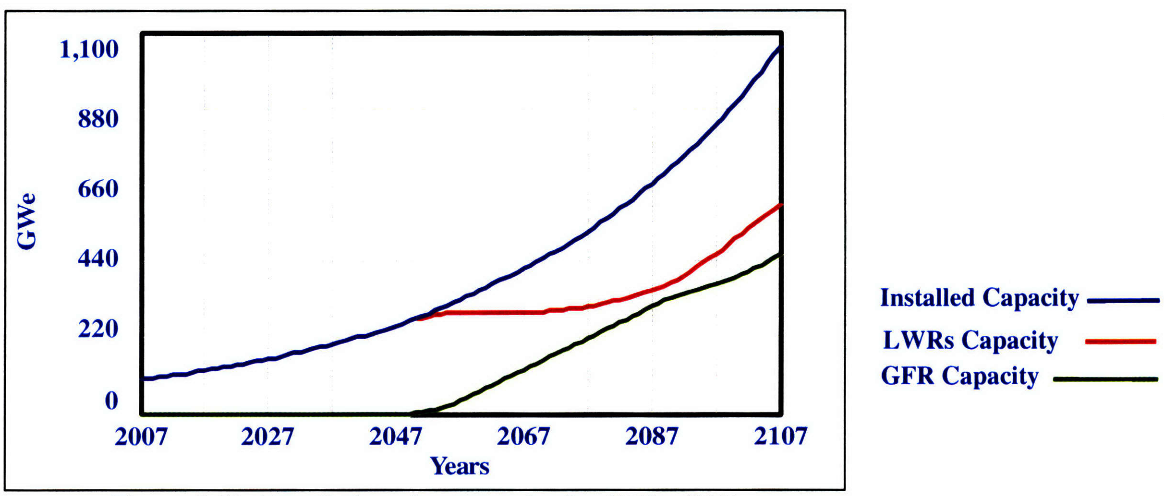

Figure 5-52– Installed nuclear capacity for GFRs SDT

Figure 5-54 presents the capital costs for SDT and LDT. The capital-related costs are nearly identical. After 2057, the capital costs for the short depletion time are slightly higher than for the long depletion time, as a consequence of the higher GFR installed capacity for the SDT. Figure 5-55 gives the identical operating and maintenance costs for short and long depletion time

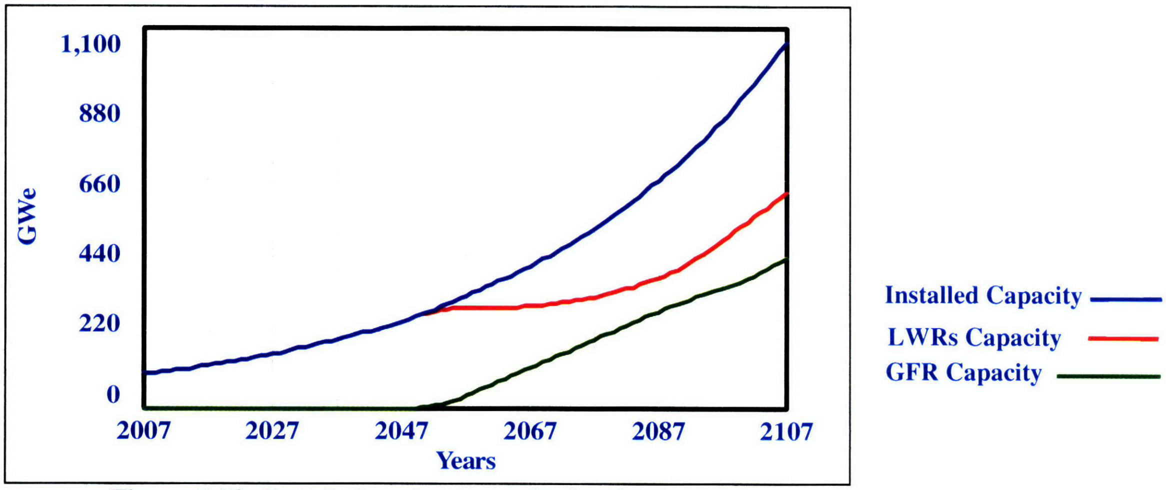

Figure 5-53– Installed nuclear capacity for GFRs LDT

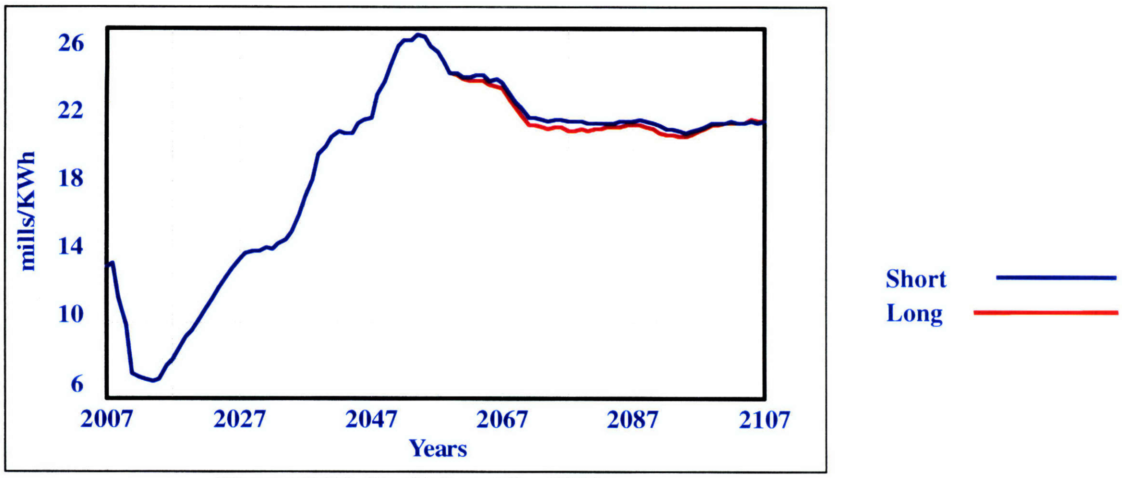

Figure 5-54–Capital cost for GFRs

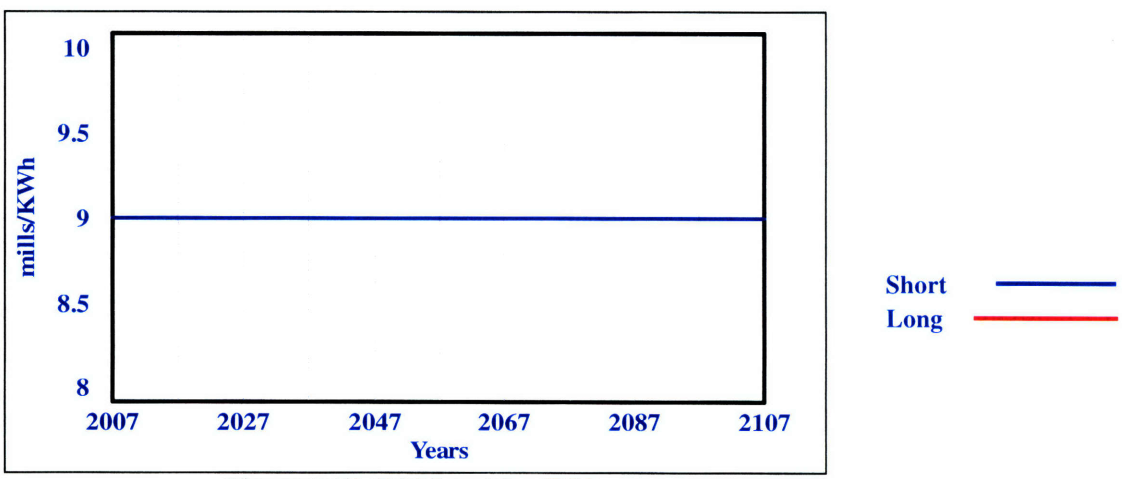

Figure 5-55–O&M cost for GFRs

Figure 5-56 plots the fuel cycle cost for the short and long depletion time. The results suggest that the accumulation of TRU after 2087 due to decommissioning of two separation plants for both depletion times makes the price of the service fluctuate around 9 mills/kWh. The peak value in the cost of fuel cycle is 14.71 mills/kWh for the LDT, and 15.10 mills/kWh for the SDT. Therefore, the peak value is only 2.6% lower for the long depletion time, even so, the difference remains steady for up to twenty five years.

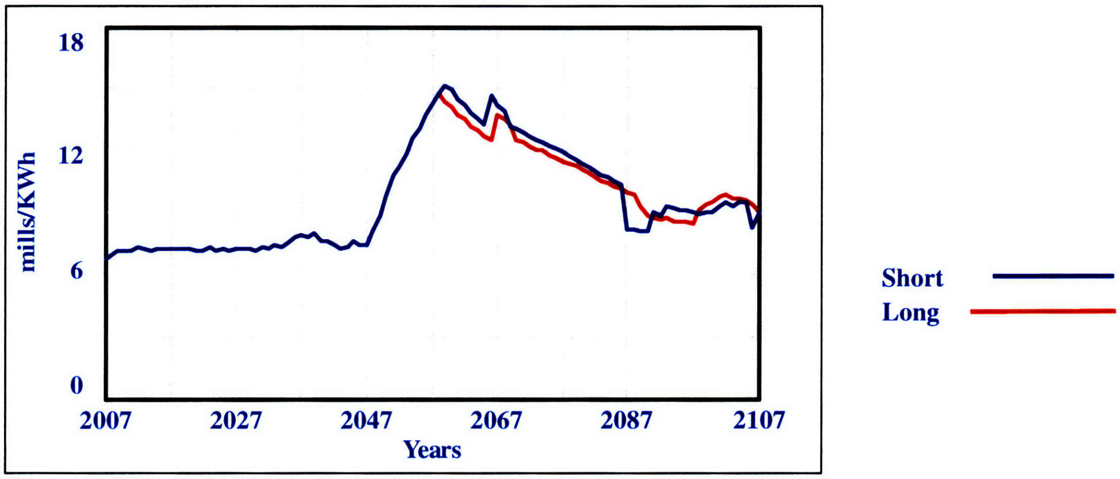

Figure 5-56 – Fuel cycle cost for GFRs

Figure 5-57 plots the cost of electricity for both depletion times. As can be seen, the cost of electricity for LDT is lower from 2057 for up to 35 years.

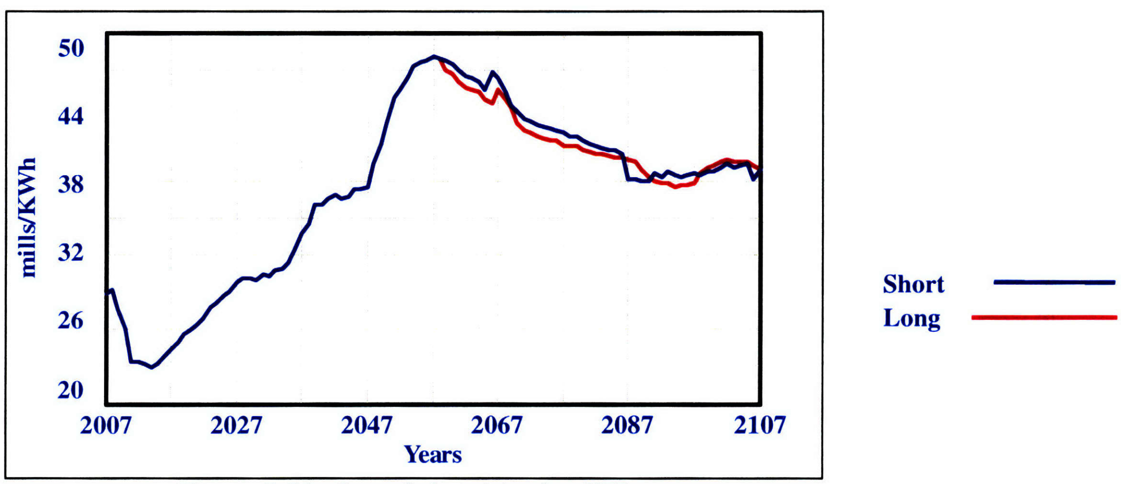

Figure 5-57– Cost of electricity for GFRs

5.5. Assessment of uranium resources and economics for early fast reactor recycling

The fast recycling schemes in the U.S. can be deployed before 2047 if the economics of fast reactors become more attractive. Furthermore, the nuclear power industry has some experience with fast reactor technology as more than 20 fast reactors have already been operating since 1950s [21]. Therefore, an optimistic scenario for the introduction of the technology in 2027 is evaluated in this section through the case studies summarized in Table 5-5 for a 2.4% nuclear annual growth rate, and for 120 US$/kg uranium price.

Table 5-5 - Case studies for early fast recycling

Case study	Introduction date of the technology	Uranium prices [US$/kg]
Once-Through Cycle (OTC)	---	120
CONFU Technology	2027	120
Early ABR	2027	120
Early GFR	2027	120

5.5.1. Assessment of uranium resources for early fast recycling

For a 2.4% annual growth on demand represents an installed capacity up to 1,100 GWe after 100 years, as can be seen in Figure 5-58, Figure 5-59, and Figure 5-60, the early introduction of the GFR recycling scheme has the most significant reduction of demand for uranium ore mining rate, on the cumulative demand for uranium, and on delaying, from 2088 (OTC) to 2106, the depletion date of the assumed uranium ore from identified resources. Furthermore, the curve for SWU requirements for early GFR does not have a sharp rise as for the OTC, as plotted in Figure 5-61. However, the demand for uranium increases again due to the inability to start GFRs due to limitation on TRU inventory, as plotted in Figure 5-62, and due to constant growth on demand after 2067. The nuclear installed capacity is 1,047 GWe when uranium resources are exhausted. On the other hand, the OTC installed capacity in 2088 is 667 GWe, 63.7% of the assessed installed capacity in 2106.

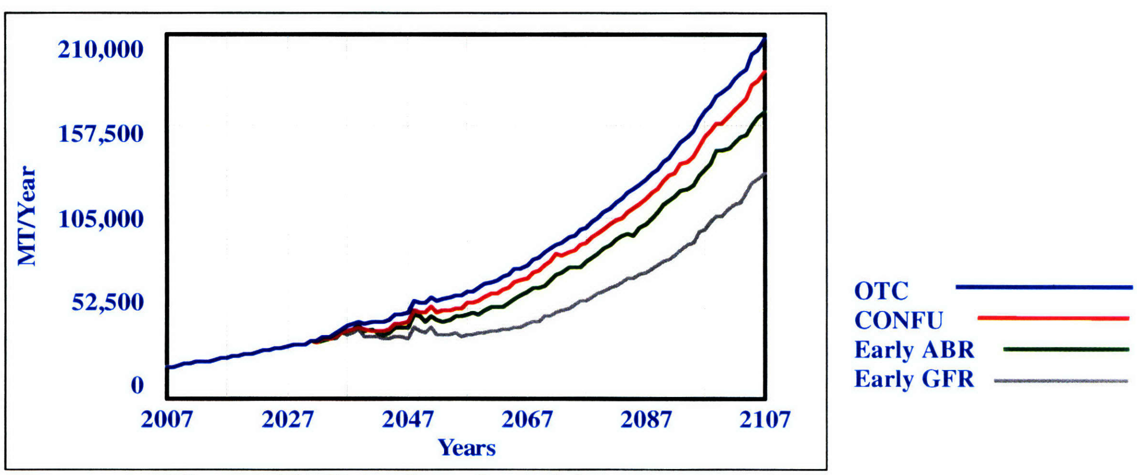

Figure 5-58 - Natural uranium mining rate

The SWU requirements for the U.S. would reach 145 million MT SWU/Year if no recycling strategy is adopted. For the case of early introduction of the GFR scheme, the SWU requirements is estimated as 90 million MT SWU/Year by the end of the simulation, 62.06% of the total separative work units required for the once-thorough cycle.

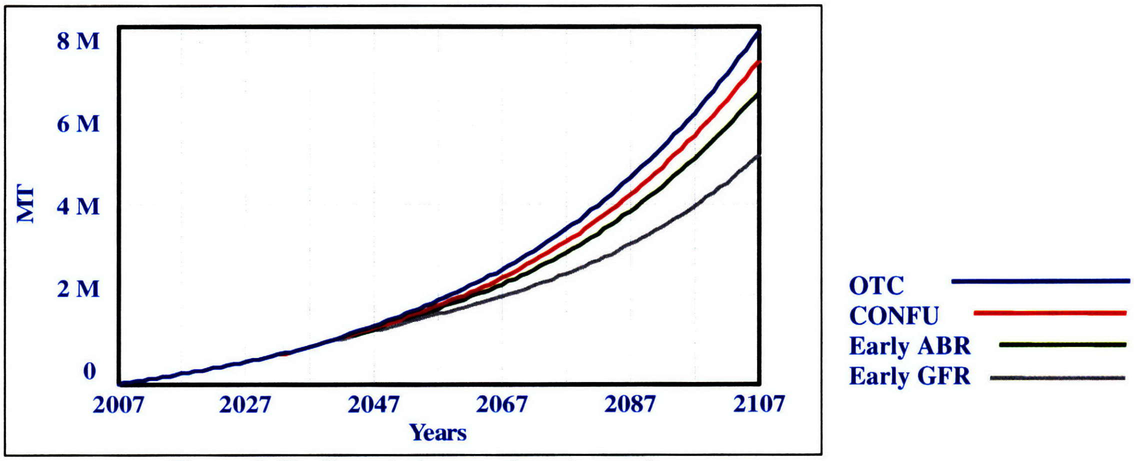

Figure 5-59 -Cumulative uranium demand

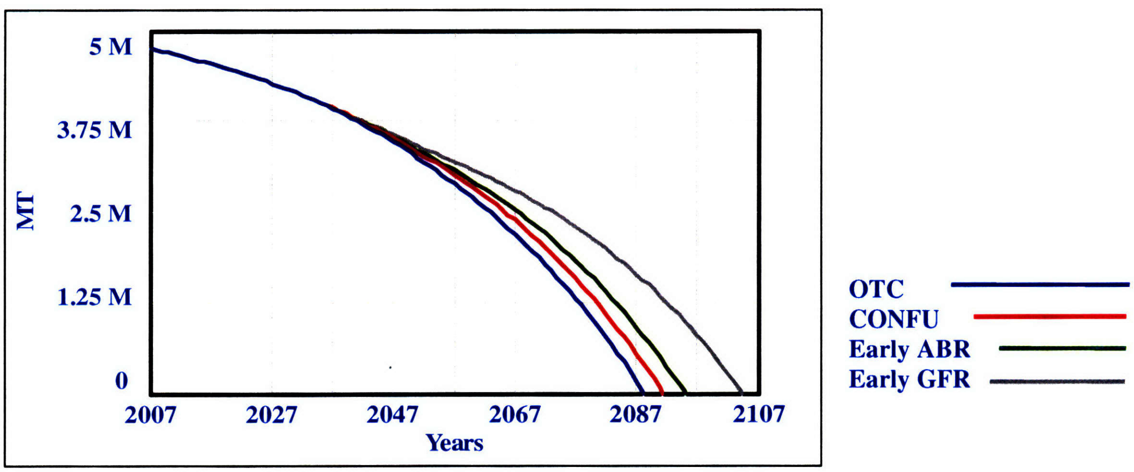

Figure 5-60 - Natural uranium resources

The results indicate that all three technologies are able to limit and eventually deplete the TRU inventory in interim storage. However, the CONFU strategy is the most flexible technology since its batches can be mixed with traditional UO2 batches in the current LWR fleet. Nevertheless, low conversion ratio reactors, like the CONFU technology, have no significant impact on the amount of uranium resources needed nor on the SWU requirements

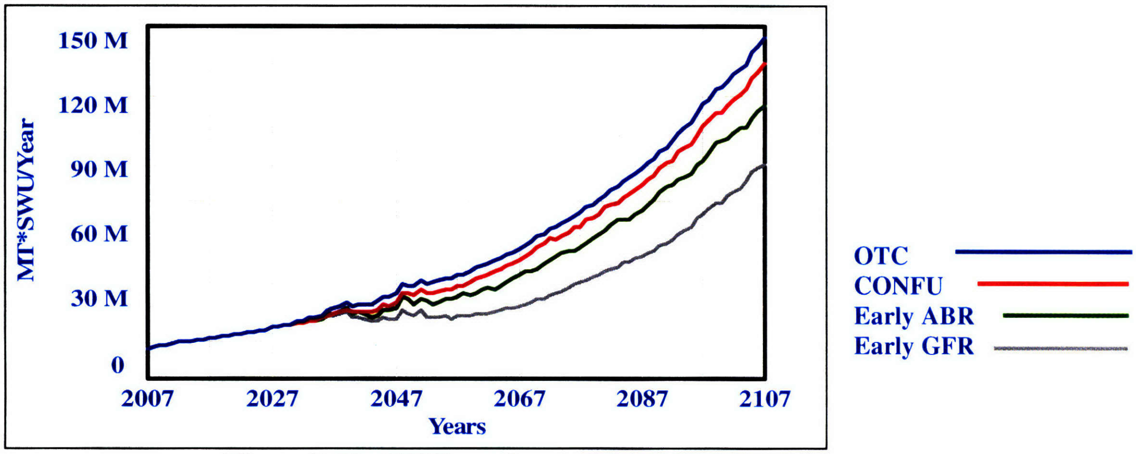

Figure 5-61 – SWU requirements

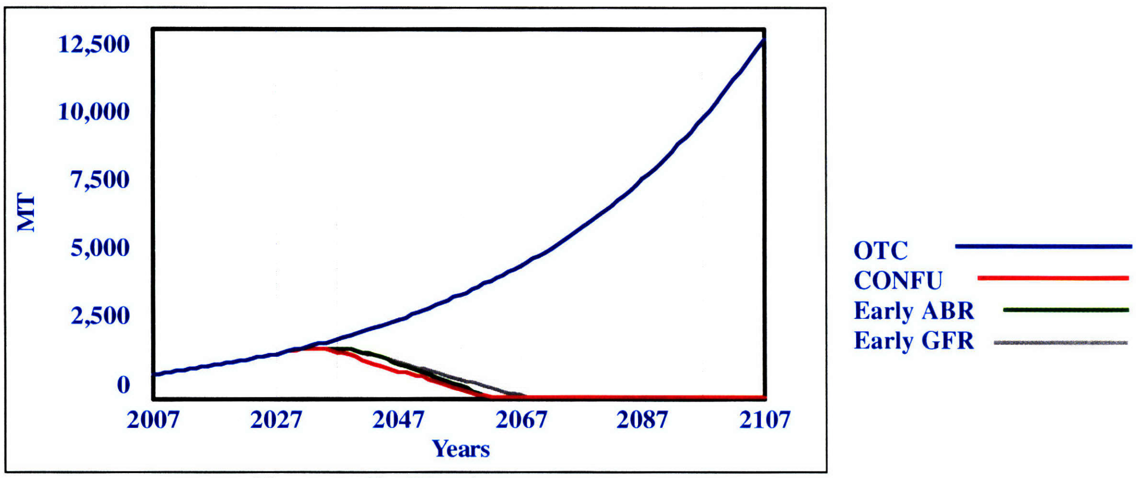

Figure 5-62 - TRU inventory

Figure 5-63 shows the fleet of separation plants to deplete the TRU inventory, Figure 5-64 gives the number of FFF reprocessing plants built to reprocess FFF spent fuel from CONFU and ABR technology, and Figure 5-65 shows the number of GFR reprocessing plants to treat U/TRU from the GFR fleet. As can be seen, the rate of construction of separation and FFF reprocessing plants for ABRs is higher than for the CONFU technology, for the same depletion TRU rate, and the construction of the GFR reprocessing plant is delayed until there is enough U/TRU spent fuel, after cooling storage, to operate. The cumulative mass loading factor for GFR reprocessing plant fleet is 0.8992 during the entire lifetime of the plants.

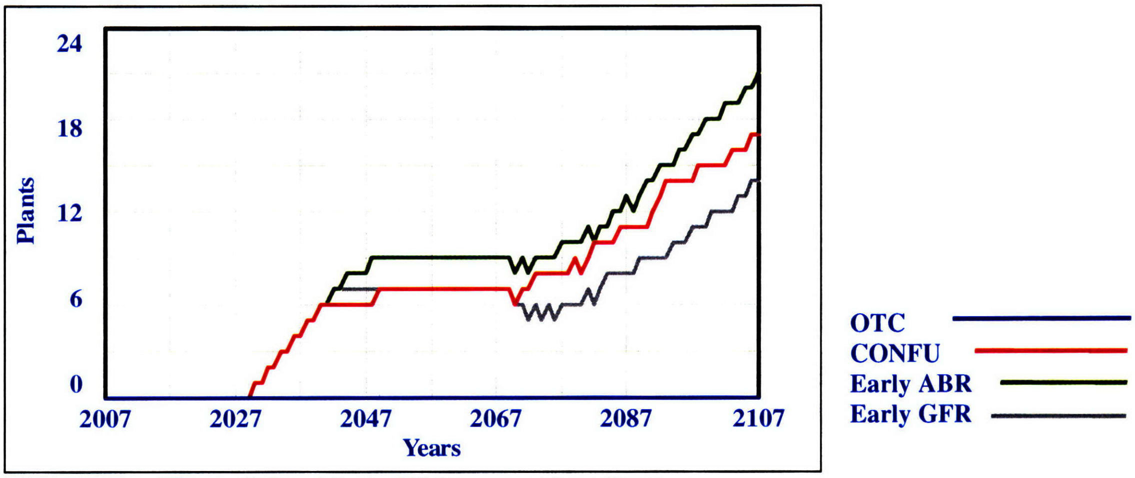

Figure 5-63 – Fleet of UO2 separation plants

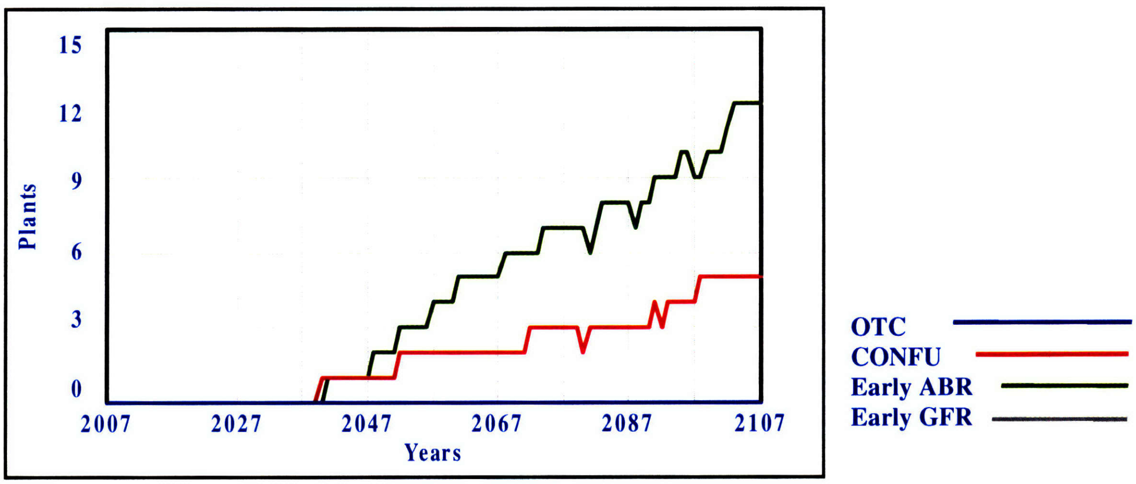

Figure 5-64 – Fleet FFF reprocessing plants

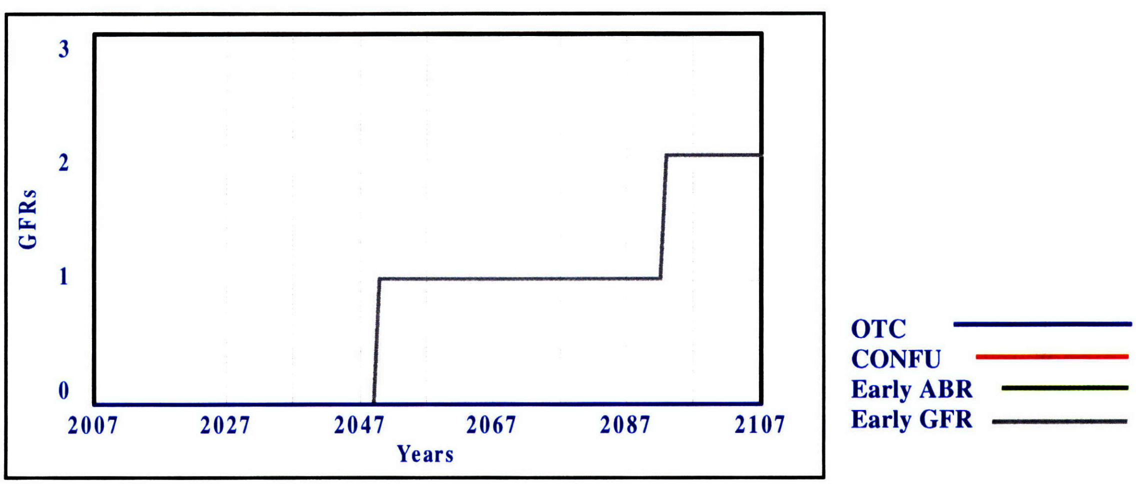

Figure 5-65 –GFR reprocessing plants

Next, the installed nuclear capacity and the ratio of fast to thermal reactors are presented in Figure 5-66, and Figure 5-67.

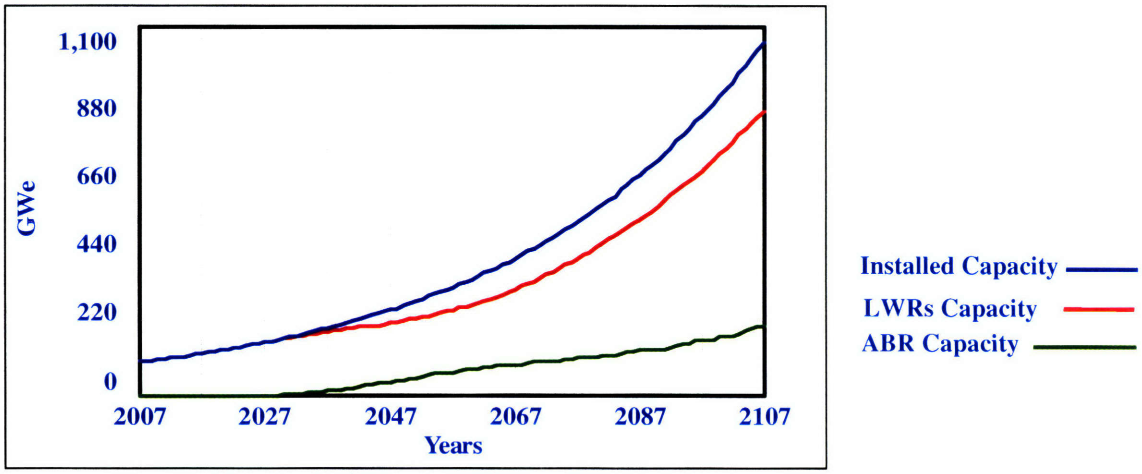

Figure 5-66 –Early ABR - Installed nuclear capacity

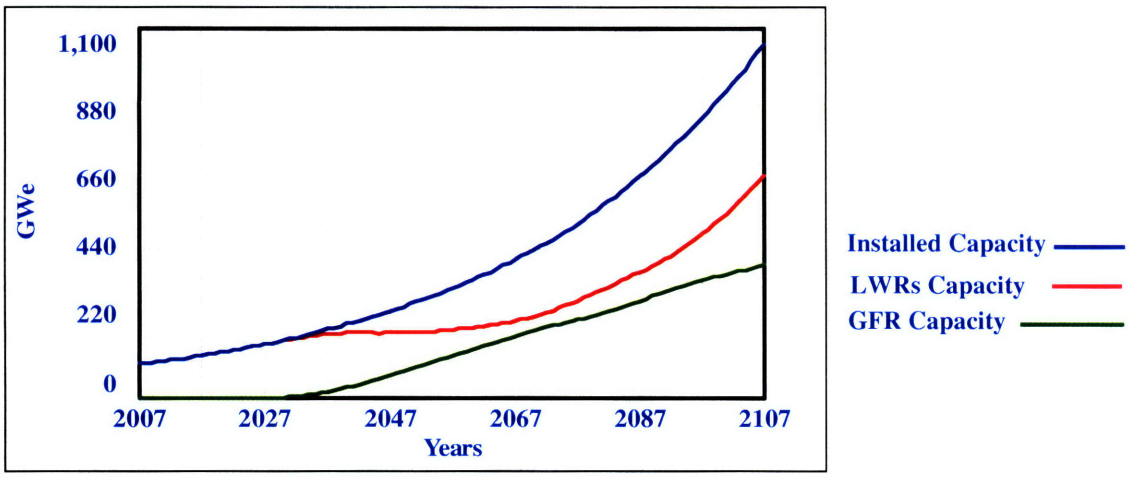

Figure 5-67 – Early GFR - Installed nuclear capacity

5.5.2. Economics analysis of early fast recycling

The economic analysis was evaluated considering the same case studies presented in Table 5-5. The results from the previous section suggest that the early introduction of GFR technology is the best option to deplete the TRU inventory, and to delay the depletion of identified uranium resources. However, uncertainties in uranium availability (further exploration and higher prices will yield further resources as the known ones are used), improvement in the reactors efficiency, and developments in the mineral exploration technology exist. Therefore, the early introductions of thermal and fast technologies are discussed here from an economics perspective.

First, Figure 5-68 shows the capital cost for all case studies. The simulation indicates that although at first the capital cost fall off, it later assumes an upward trend as the current fleet of LWRs is decommissioned, and new reactors are to be built to fulfill the power demand. In addition, after introduction of the fast reactor, the capital cost will rise at faster rate than the LWR schemes and more for the GFR technology than for the ABR. Even after the capital cost peaks in 2050, the cost remains higher for the GFR than ABR, and for both compared to the LWR. The O&M cost for early fast recycling, CONFU and OTC is 9 mills/kWh.

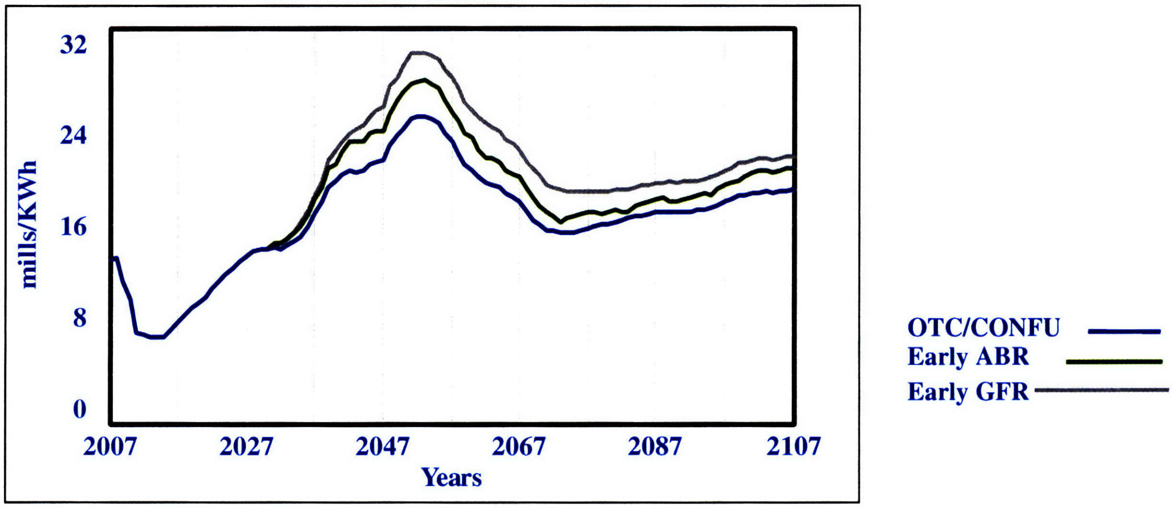

Figure 5-68–Capital cost for early fast recycling

As revealed by Figure 5-69 the early introduction of GFRs becomes economically interesting, from the fuel cycle point of view, just after the introduction of the technology. In addition, the equilibrium fuel cycle cost fluctuate around 9 mills/kWh, way below the 11.68 mills/kWh (CONFU) and 12.61 mills/kWh (ABR). The fuel cycle cost for the once-through cycle remained steady in 7.5 mills/kWh, with peaks due to the commissioning of new LWRs.

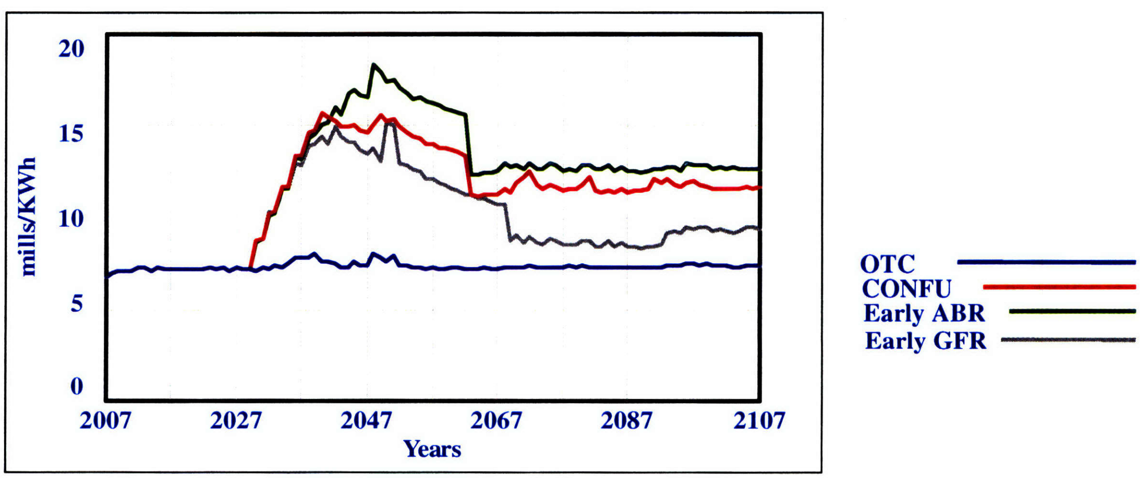

Figure 5-69 – Fuel Cycle Cost for early fast recycling

As can be seen in Figure 5-70, the cost of electricity for the CONFU technology is more attractive during the peak period from 2037 to 2067. However, after equilibrium, the cost of electricity for the CONFU and GFR technology both fluctuate around 39 mills/kWh. The equilibrium value for OTC is 35.18 mills/kWh and, for ABR is 42.11 mills/kWh.

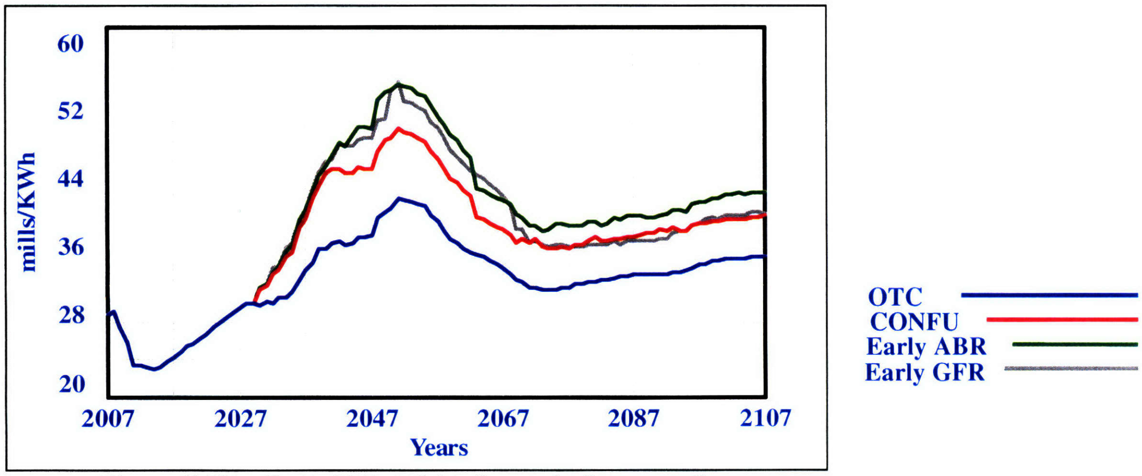

Figure 5-70 – Cost of Electricity for early fast recycling

5.6. Summary

The results indicate that all three technologies are able to limit and eventually deplete the TRU inventory in interim storage. However, the CONFU strategy is the most flexible technology since its batches can be mixed with traditional UO_2 batches in the current LWR fleet. Nevertheless, low conversion ratio reactors, like the CONFU technology, have no significant impact on the amount of uranium resources needed nor on the SWU requirements. The deployment of the CONFU recycling scheme keeps the inventory below reasonable level, and guarantee equilibrium between the generation and consumption of TRU without investments in construction of fast reactors.

The early introduction of fast recycling schemes is also able to keep the TRU inventory at interim storage at reasonable levels. Furthermore, the cost of the fuel cycle, and the cost of electricity, becomes more economically attractive. However, the late introduction of GFRs and ABRs postpones the high investment needed. Interesting enough is that for uranium price of 180 US$/kg, the advanced technology starts to be more economically attractive than OTC or the thermal recycling even for the late introduction of the strategy.

6 Simultaneous deployment of two recycling technologies

6.1. Introduction

In this chapter, the simultaneous deployment of two recycling technologies in the U.S. nuclear market is analyzed. The cumulative uranium consumption, incinerated TRU, TRU inventory at interim storage, fuel cycle costs and costs of electricity are evaluated considering three cases of allocation of fractions of separated TRU for fast recycling equal to 25, 50 and 75%. The introduction of technologies occurs early, i.e. in 2027, as presented in Table 6-1. Next, the impact of an evolving fraction of separated TRU for the two recycling schemes is evaluated through the cases presented in Table 6-2. The ratio of separated TRU changes with time as we prolong the use of LWRs, and GFRs are introduced to conserve fuel resources. The introduction of the CONFU scheme occurs in 2027. GFRs are introduced in 2047 at TRU ratio of 25% for ten years, then 50% for the next then years, and 75% for more than ten years. After that, all TRU is available for GFRs. In addition, the introduction of ABRs instead of CONFU, to reduce the TRU in the system, then switching gradually to GFRs, is analyzed. The introduction of ABRs occurs early in 2027. GFRs are introduced in 2047 at a separated TRU ratio of 25% for ten years, then 50% for the next ten years, and 75% for more ten years. After that, all TRU is available for GFRs.

Table 6-1 – Case studies for simultaneous deployment of two recycling technologies

Case study	Introduction date of the technology	Uranium prices [US$/kg]	TRU percentage for fast technology		
CONFU/ABR Technology	2027	120	25%	50%	75%
CONFU/GFR Technology	2027	120	25%	50%	75%

Table 6-2– Case studies for sliding fractions of separated TRU

Case study	Introduction date of the technology	Uranium prices [US$/kg]	TRU percentage for GFR technology
CONFU/GFR Technology	CONFU: 2027 GFR: 2047	120	25% (2047-2057)
			50% (2057-2067)
			75% (2067-2077)
			100% (2077-2107)
ABR/GFR Technology	ABR: 2027 GFR: 2047	120	25% (2047-2057)
			50% (2057-2067)
			75% (2067-2077)
			100% (2077-2107)

6.2. Deployment of two recycling technologies with an allocation of a fixed ratio of separated TRU for each

6.2.1. CONFU/ABR recycling schemes

The ABR is restricted to a rate that limits the recycling facilities to an instantaneous mass loading factor of 0.5, and a cumulative mass loading factor of 0.8. Among the various choices within this group of technologies, the ABR technology has the most significant reduction of the uranium ore mining rate, the cumulative demand for uranium, and delays the depletion date of uranium ore from identified resources, as presented in Figure 6-1 and Figure 6-2. The CONFU technology, which demands the same number of LWRs as OTC, requires more uranium resources. The introduction of the ABR/CONFU simultaneous recycling technologies, considering 25, 50 and 75% fraction of separated TRU for the fast scheme, maintains the uranium requirements between the needs of the CONFU and the ABR schemes.

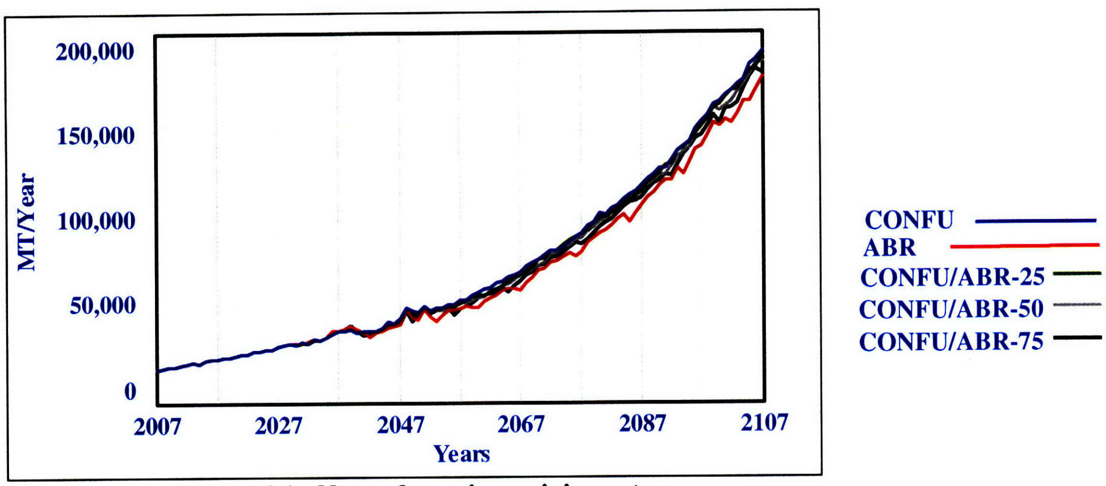

Figure 6-1 - Natural uranium mining rate

Furthermore, the consumption of uranium resources is delayed with the ABR technology. The higher the percentage of TRU dedicated for the fast recycling scheme, the more delayed is the date of depletion of uranium resources, as shown in Figure 6-3. The curve for SWU requirements shows that the higher the percentage of TRU for ABRs, the lower the SWU requirements. This behavior is expected due to results presented in Section 5.2, and the properties of CONFU and ABRs schemes presented in Chapter 3.

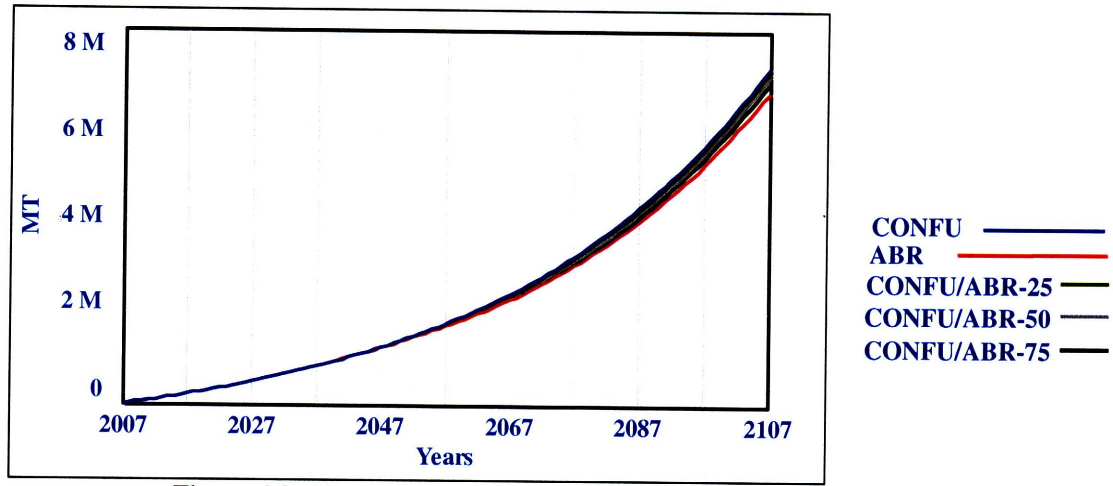

Figure 6-2 – Cumulative uranium demand

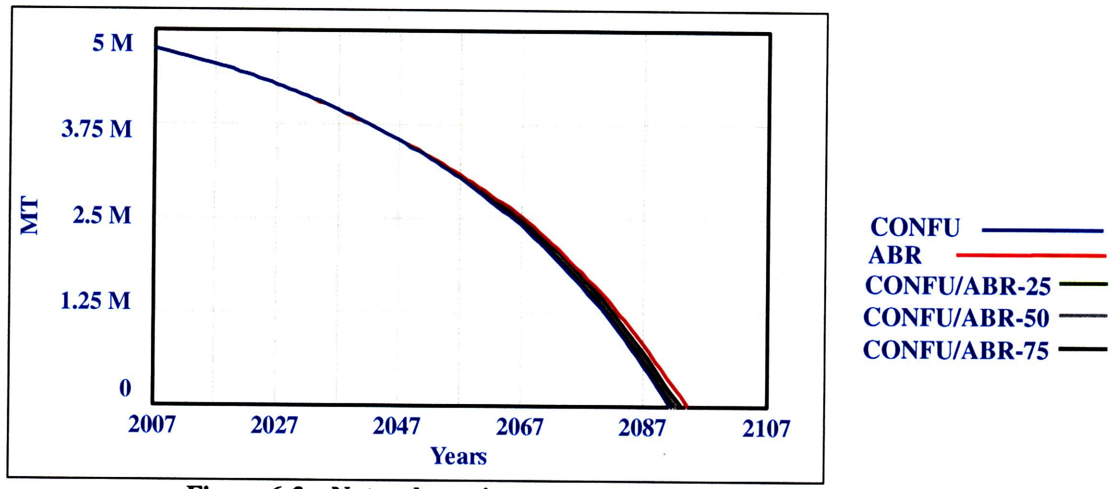

Figure 6-3 – Natural uranium resources

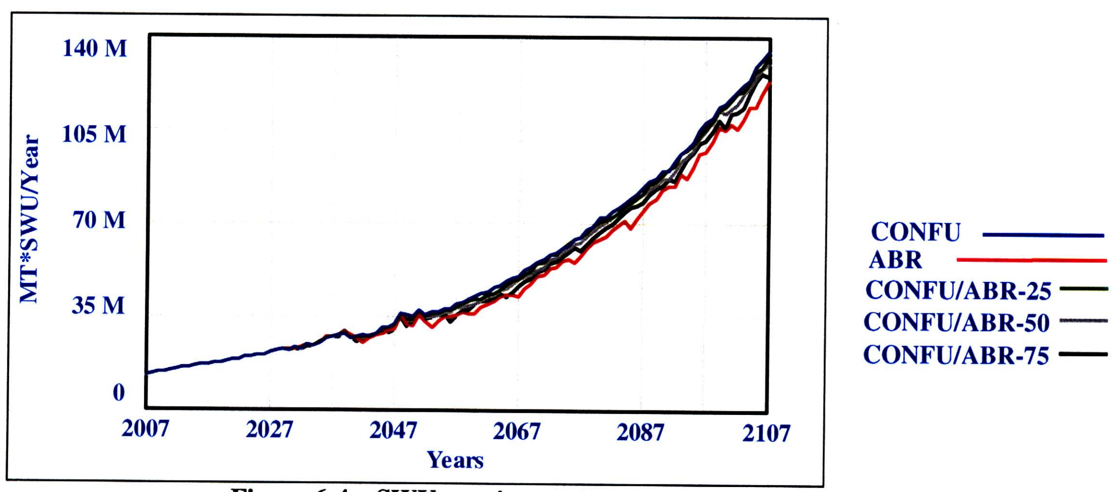

Figure 6-4 – SWU requirements

The simulation results indicate that all cases are able to deplete the TRU inventory at interim storage, and that the peak occurs at the same time at the value of 1,578 MT. However, the CONFU/ABR 25% strategy is able to deplete the TRU inventory earlier, as can be seen in Figure 6-5. Nevertheless, the results demonstrate that all strategies have a small impact on the amount of uranium resources needed nor on the SWU requirements.

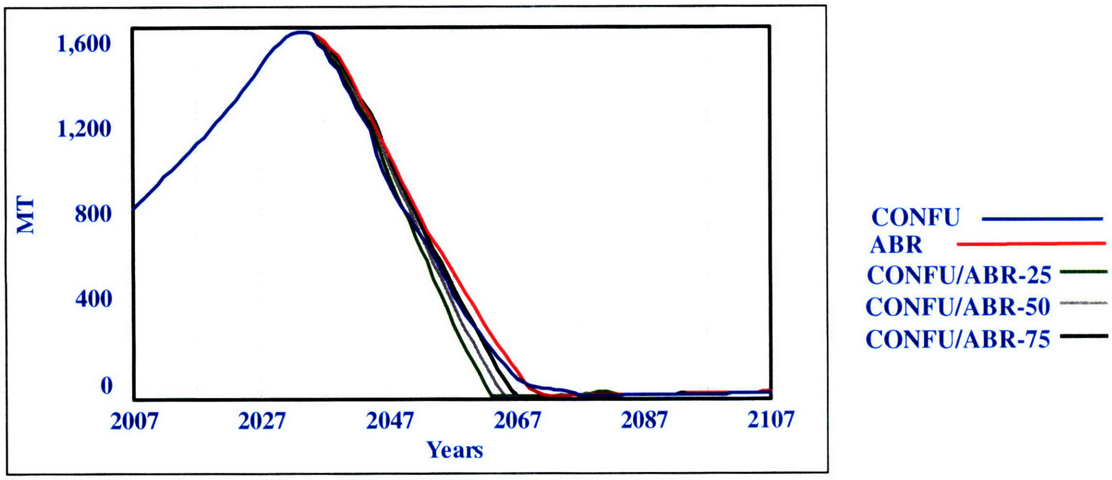

Figure 6-5 – TRU inventory

Figure 6-6 shows the fleet of separation plants to deplete the TRU inventory, and Figure 6-7 presents the number of plants to reprocess FFF spent fuel from CONFU and ABR schemes. As can be seen, the number of separation and FFF reprocessing plants for the ABR scheme is higher than that for the CONFU technology. The number of separation plants fluctuated around the expected number of plants for the ABR and CONFU schemes alone in the second half of the century.

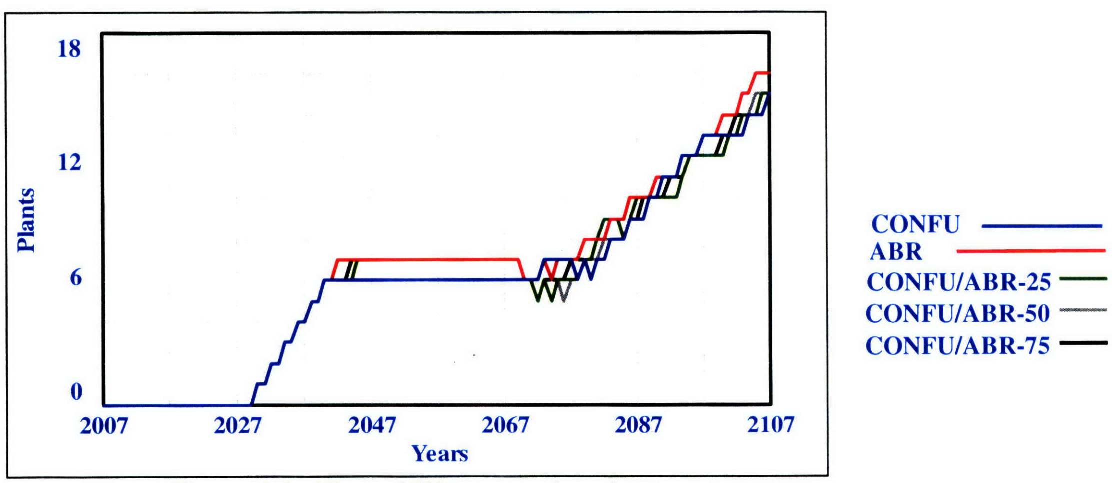

Figure 6-6 – Fleet of UO2 separation plants

Figure 6-7 presents the number of FFF reprocessing plants for simultaneous recycling schemes. As plotted, the higher the percentage of TRU for ABR, the higher is the number of plants needed. This trend is explained due to the higher CONFU TRU incineration rate. Following, the installed nuclear capacity and the ratio of fast to thermal reactors are presented in

Figure 6-8, Figure 6-9, and Figure 6-10. As can be seen, the ratio of installed fast capacity to total installed capacity increases as the ratio of separated TRU for fast recycling increases.

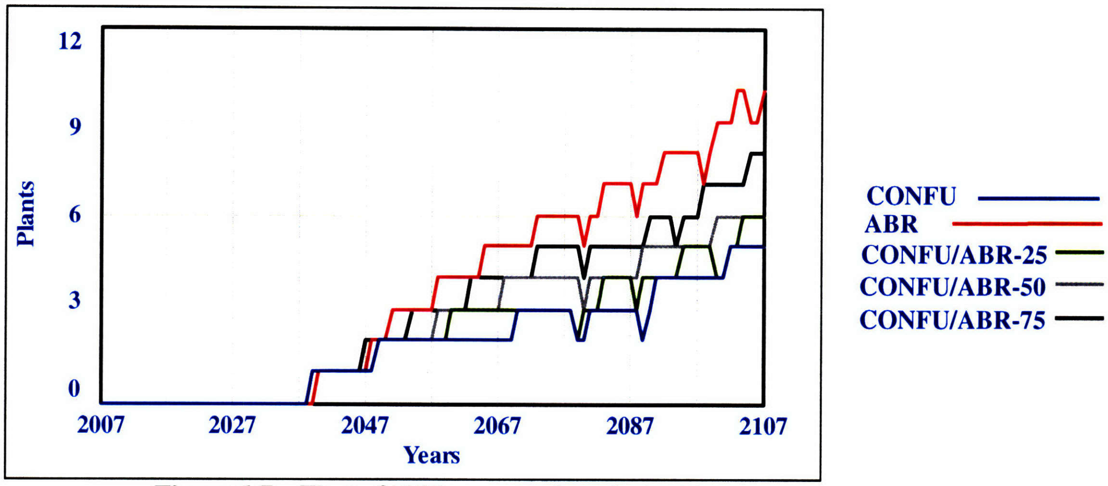

Figure 6-7 – Fleet of FFF reprocessing plants

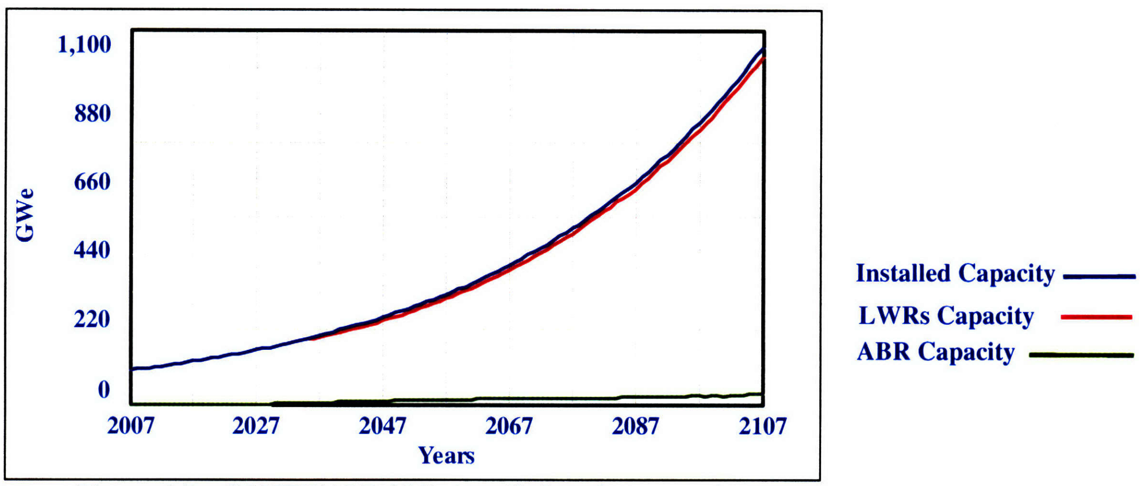

Figure 6-8 – CONFU/ABR 25% installed nuclear capacity

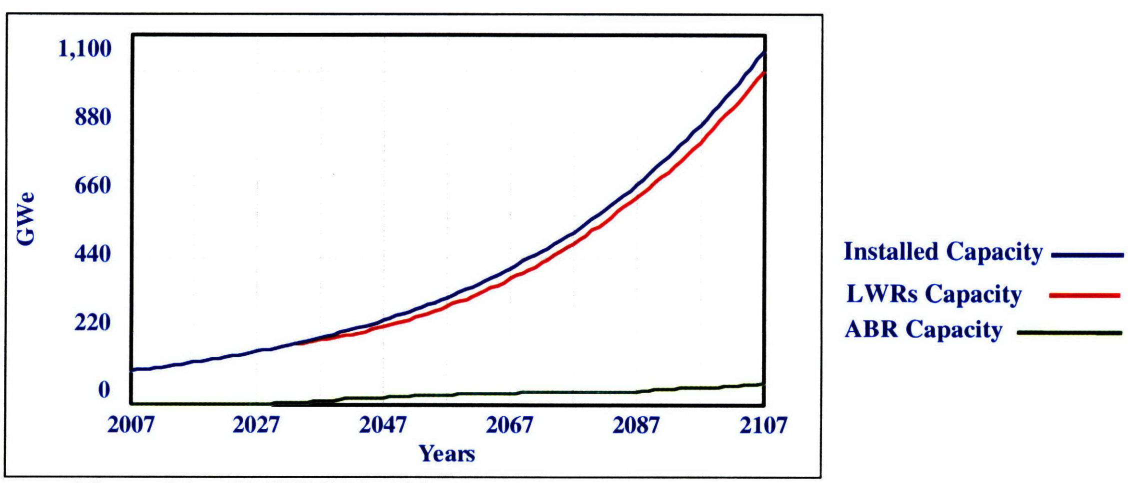

Figure 6-9 – CONFU/ABR 50% installed nuclear capacity

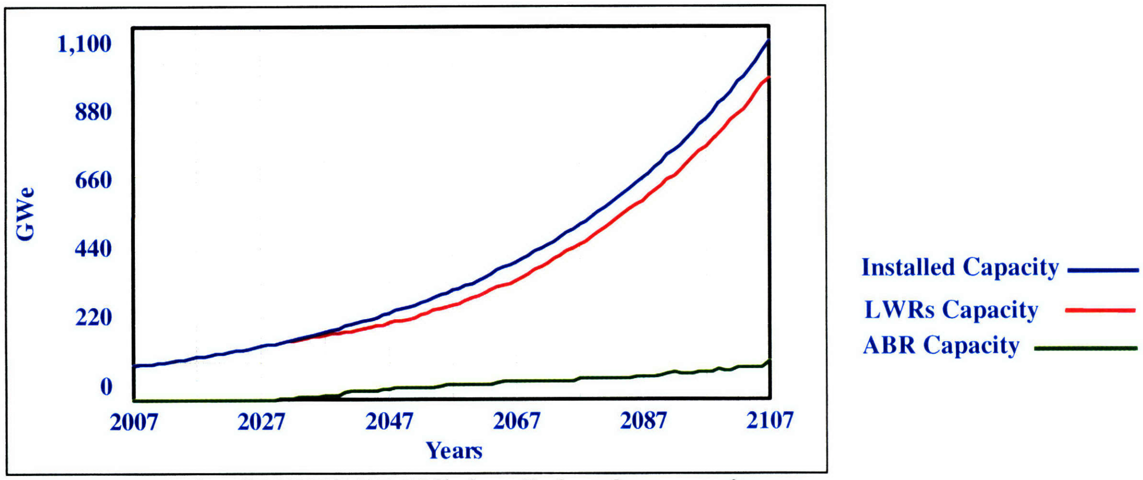

Figure 6-10 – CONFU/ABR 75% installed nuclear capacity

6.2.2. CONFU/GFR simultaneous recycling strategy

For a lower limit of an instantaneous mass loading factor of 0.5, and a lower limit cumulative mass loading factor of 0.8, the GFR technology most significantly reduces the uranium ore mining rate and the cumulative demand for uranium. The introduction of the GFR delays the depletion date of uranium ore resources by more than 10 years compared to the CONFU scheme. The introduction of the CONFU/GFR simultaneous recycling technologies considering 25, 50 and 75% fraction of separated TRU for the fast scheme, maintains the uranium requirements between the needs of the CONFU and the GFR schemes, as can be seen in Figure 6-11, Figure 6-12, and Figure 6-13. Furthermore, there is a significant impact on the cumulative uranium consumption.

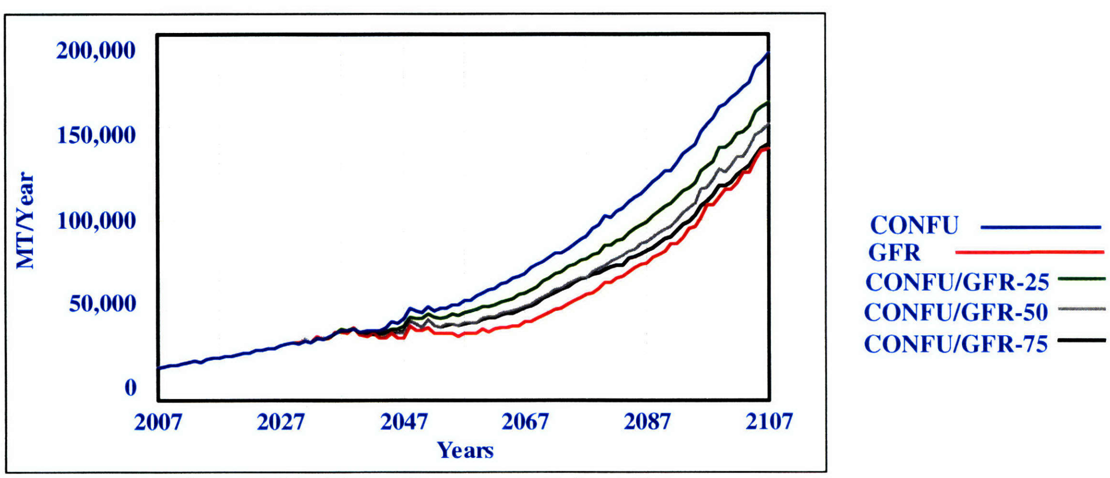

Figure 6-11 - Natural uranium mining rate

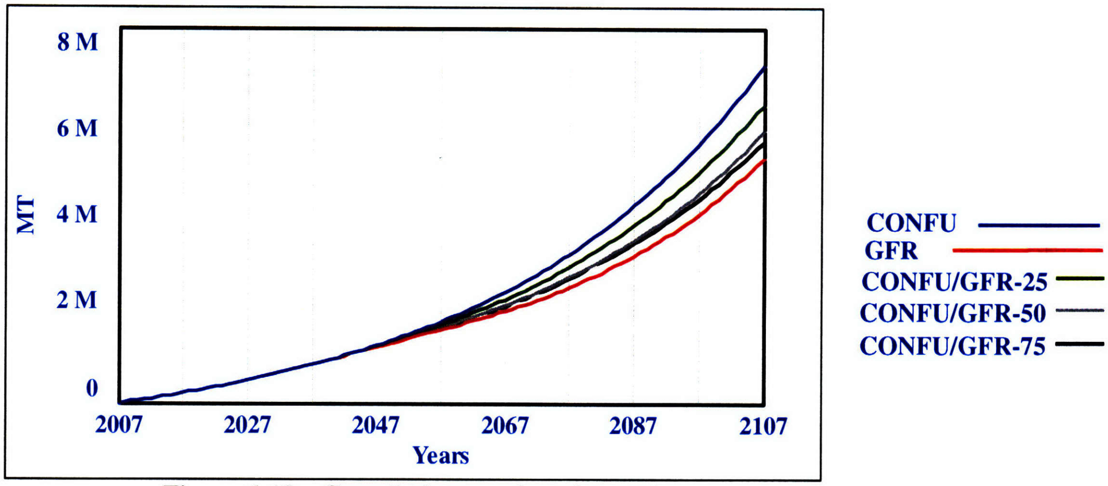

Figure 6-12 – Cumulative uranium demand

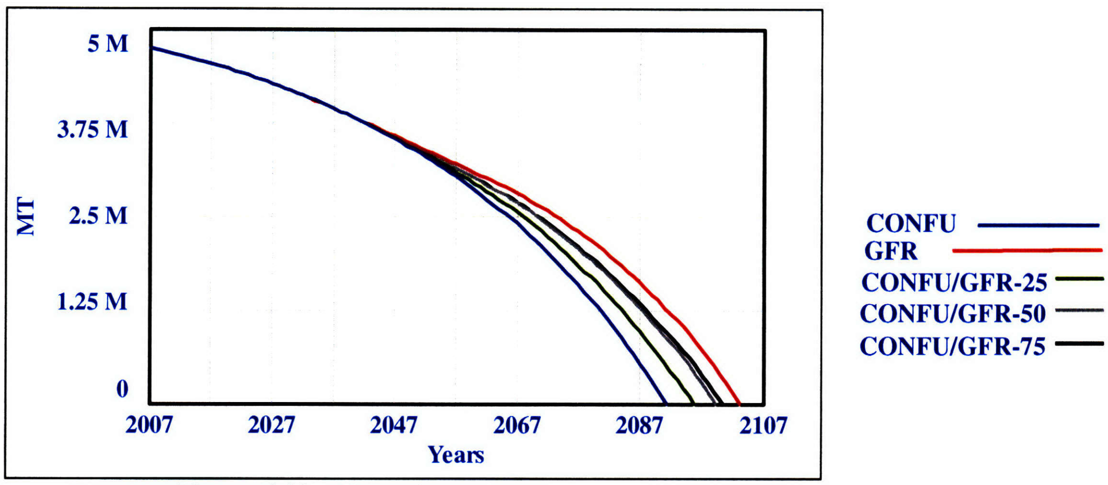

Figure 6-13 – Natural uranium resources

Figure 6-14 shows that the higher the percentage of TRU for GFRs, the lower are the SWU requirements.

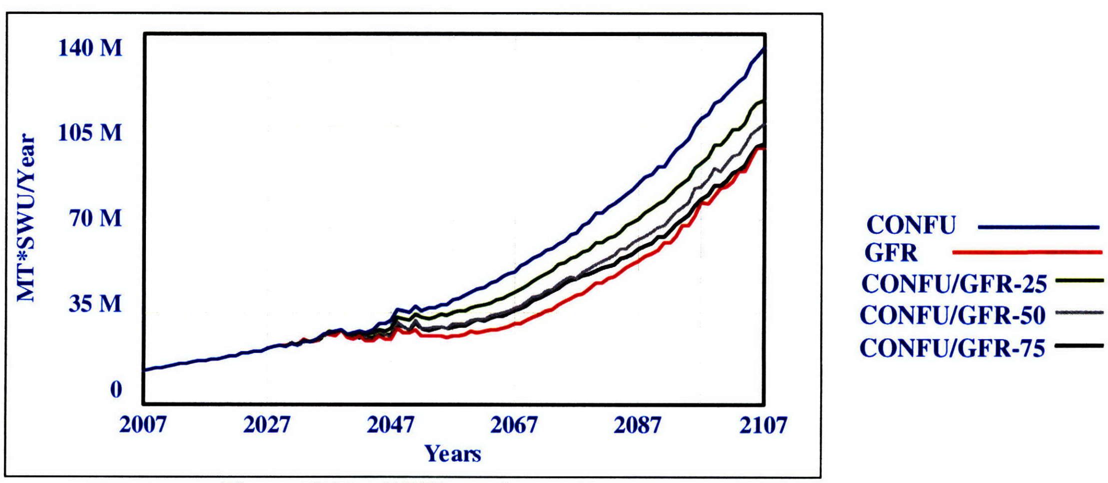

Figure 6-14 – SWU requirements

The simulation results indicate that all cases are able to deplete the TRU inventory at interim storage, and that the peak occurs at the same time at the value of 1,578 MT. However, the CONFU/GFR 25% strategy is able to deplete the TRU inventory somewhat earlier, as can be seen in Figure 6-15. Nevertheless, the results demonstrate that CONFU/GFR schemes with higher ratio of self-sustaining reactors to thermal reactors have more significant impact on the amount of uranium resources needed and on the SWU requirements.

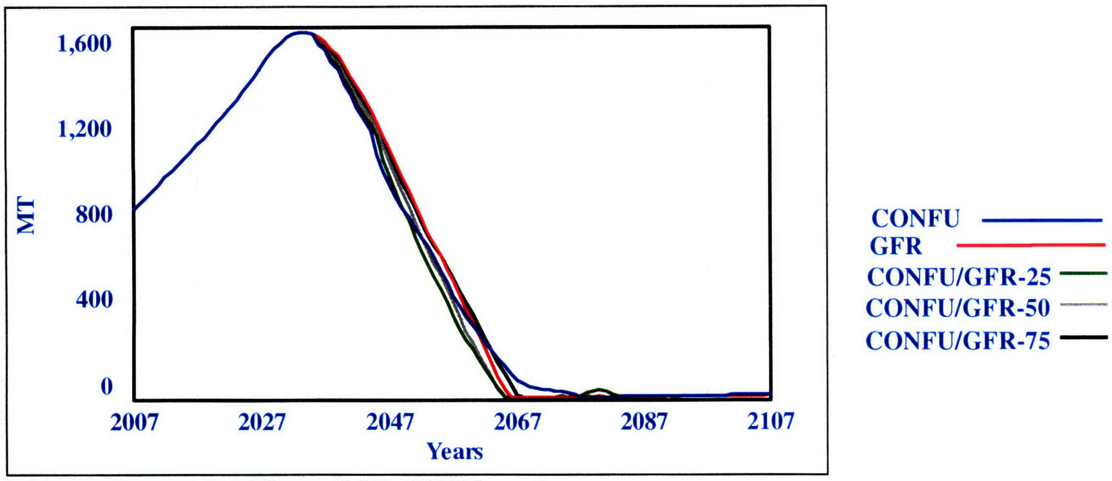

Figure 6-15 – TRU inventory

Figure 6-16 shows the fleet of separation plants to deplete the TRU inventory, and Figure 6-17 presents the number of plants to reprocess FFF spent fuel from CONFU. As can be seen, the number of separation and FFF reprocessing plants for the CONFU/GFR scheme is lower than for the CONFU technology. Figure 6-18 presents the number of GFR U/TRU reprocessing plants for all cases. As can be seen, the lower fraction of TRU for CONFU/GFR delays the construction of U/TRU reprocessing plants.

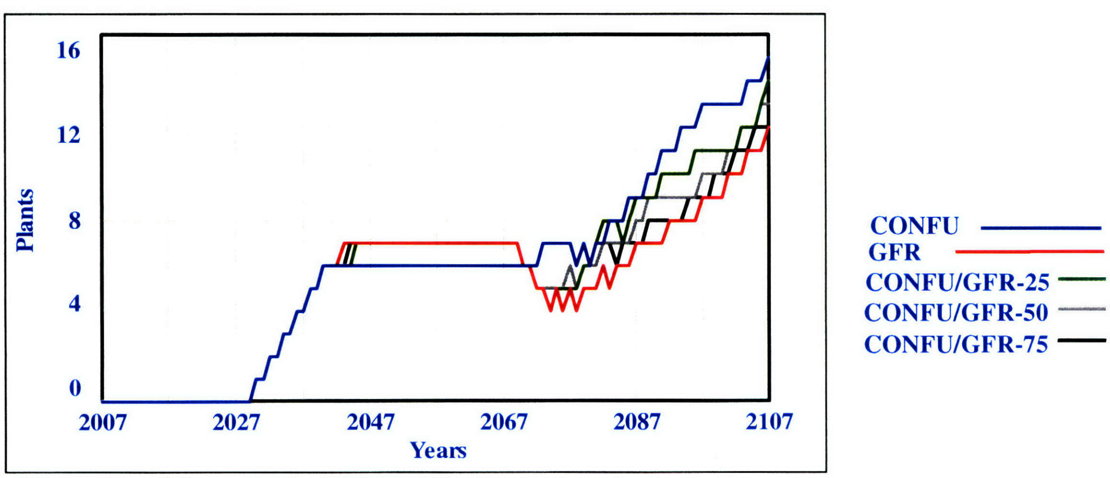

Figure 6-16 – Fleet of UO2 separation plants

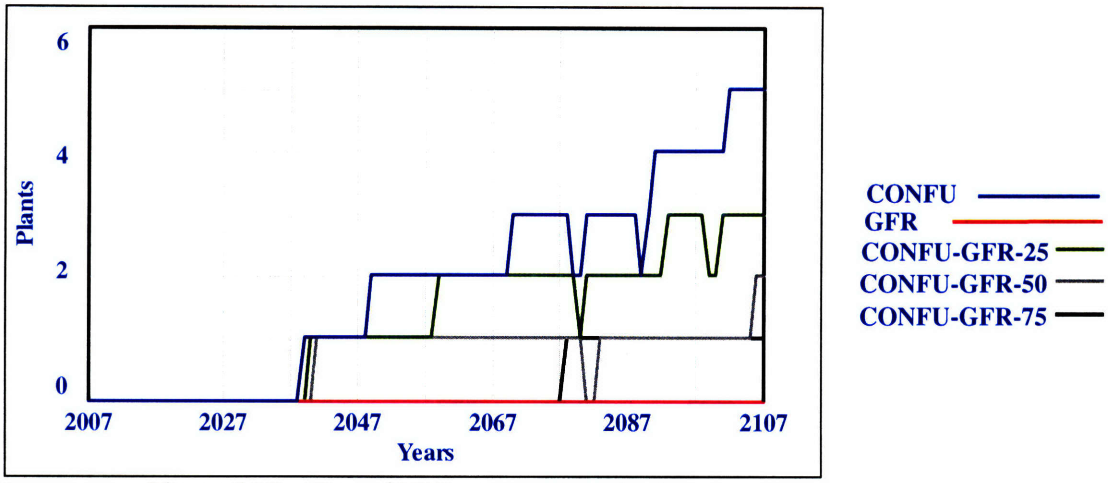

Figure 6-17 – Fleet of FFF reprocessing plants

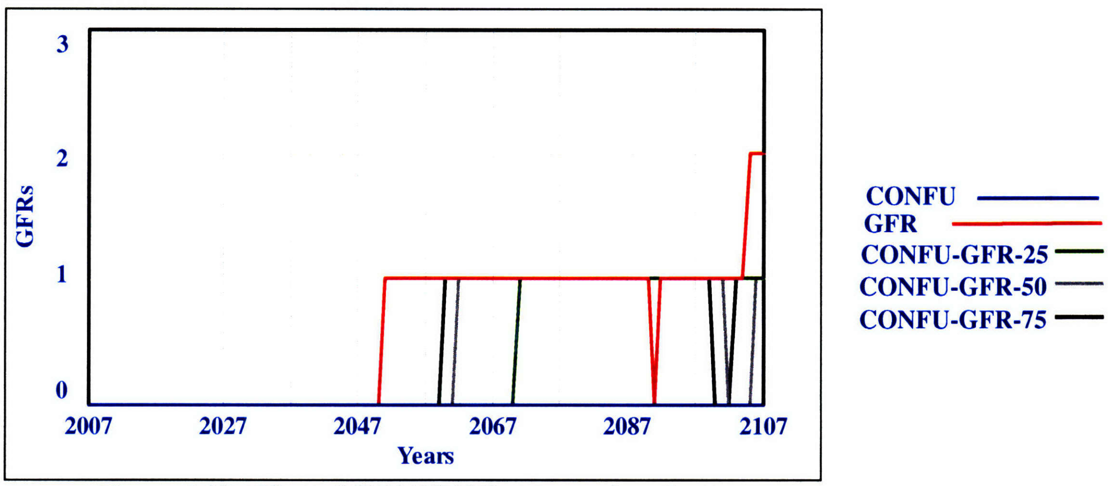

Figure 6-18 – Fleet of GFR U/TRU reprocessing plants

The installed nuclear capacity and the ratio of fast to thermal reactors are presented in Figure 6-19, Figure 6-20, and Figure 6-21.

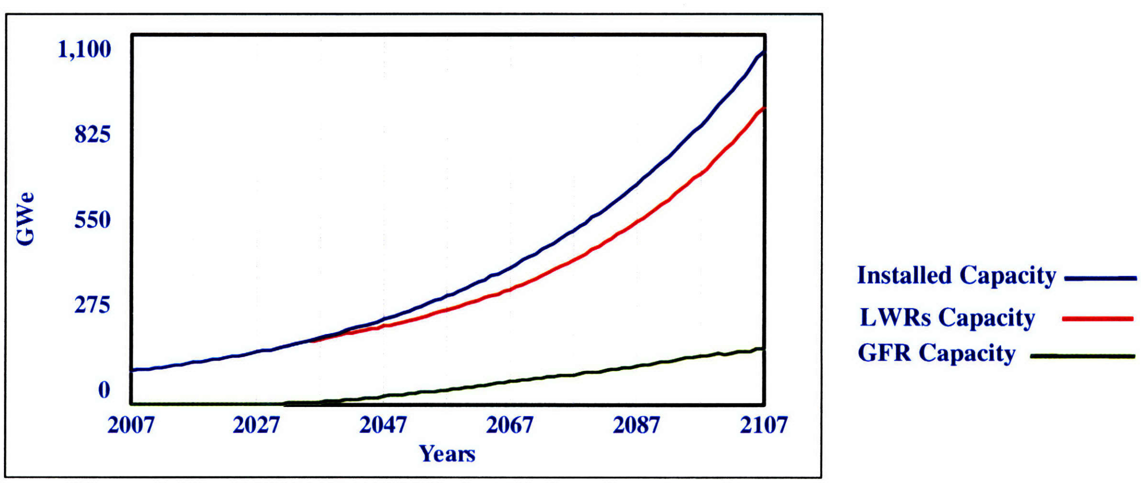

Figure 6-19 – CONFU/GFR 25% installed nuclear capacity

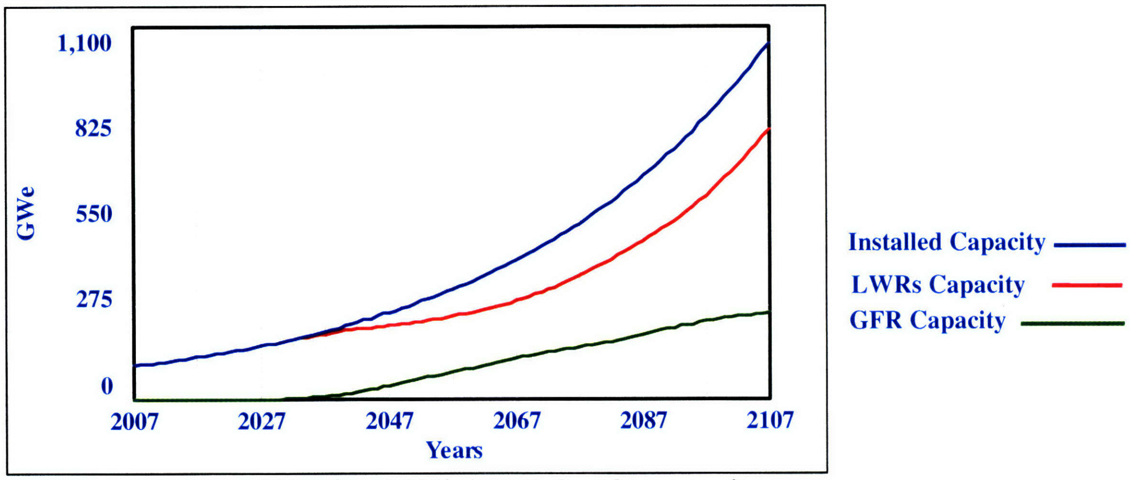

Figure 6-20 – CONFU/GFR 50% installed nuclear capacity

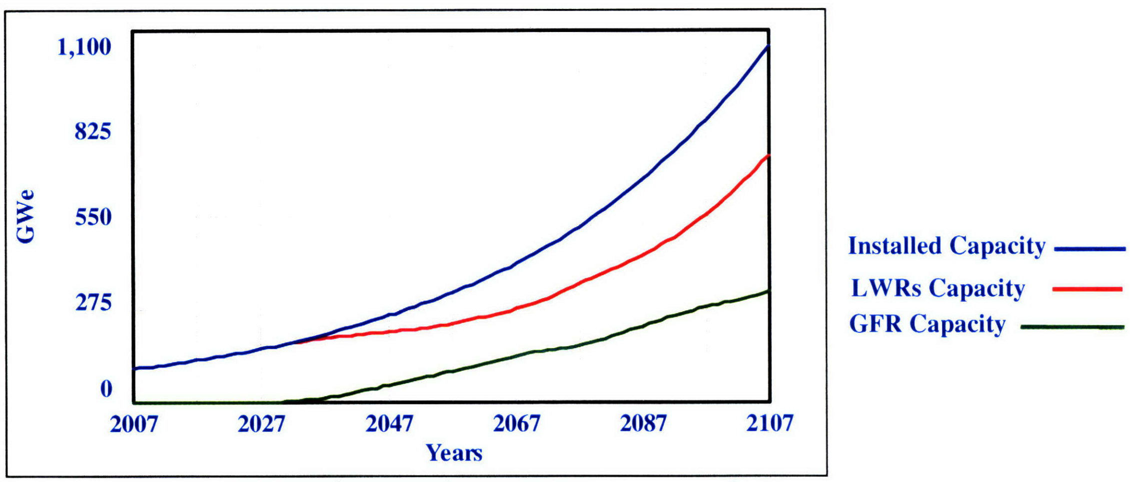

Figure 6-21 – CONFU/GFR 75% installed nuclear capacity

As can be seen, the ratio of installed fast capacity to total installed capacity increases as the percentage of separated TRU for fast recycling increases.

6.2.3. TRU mass balance of simultaneous recycling strategy

In this section, the impact on incinerated TRU, and on TRU in storage in the system for the simultaneous recycling strategies presented in Table 6-1 is evaluated. The TRU in storage is the sum of TRU in the interim storage, TRU in cooling storage, and TRU for fuel fabrication. As can be seen in Figure 6-22, Figure 6-23, and Figure 6-24, the CONFU scheme is the best option to incinerate TRU. By 2107, the ABR scheme incinerates 78.20% of the TRU incinerated by the

CONFU technology. As expected, the GFR technology does not incinerate‡ TRU. As the fraction of TRU available for fuel fabrication increases from 25 to 50 and then 75%, the amount of TRU inventory incinerated decreases and gets closer to the stand-alone deployment of the advanced technology.

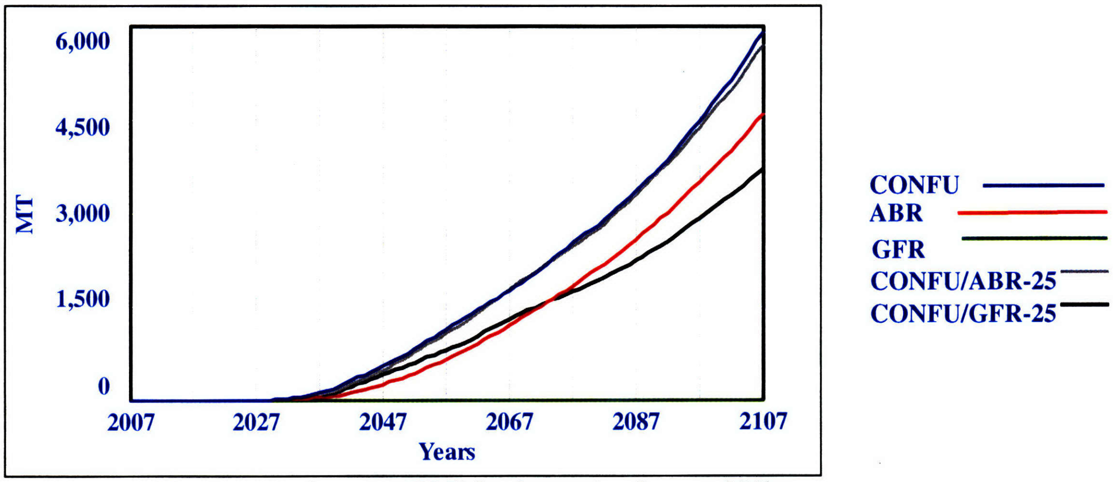

Figure 6-22 – Total incinerated TRU for fast technology at 25%

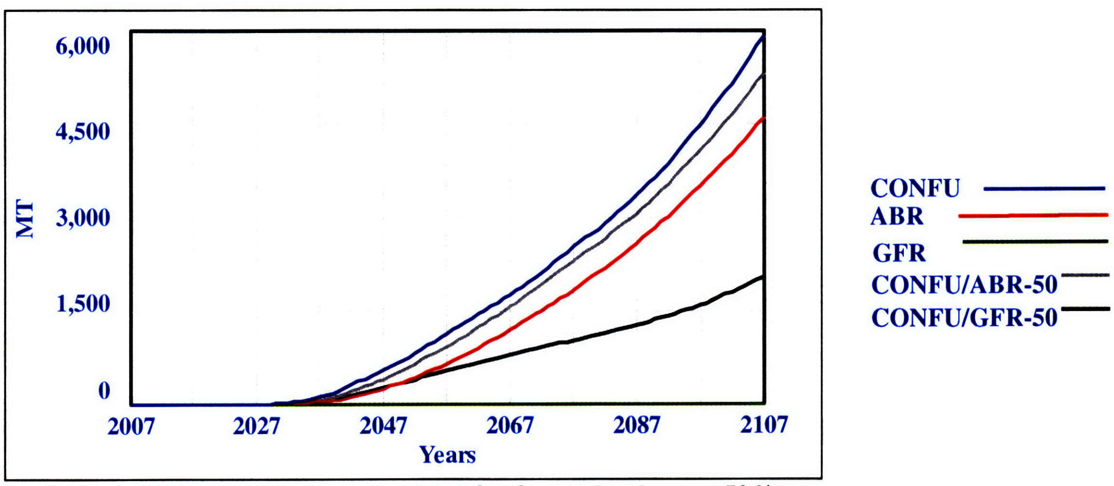

Figure 6-23 – Total incinerated TRU for fast technology at 50%

‡ Incinerated TRU means TRU destroyed in the FFF fuel. Thus, even though the net TRU balance in CONFU is zero since the transuranics created in UO_2 pins equal the TRU consumed in CONFU FFF pins, the plots show TRUs destroyed in FFF pins. On the other hand, GFRs, which also have zero net TRU balance, generate and incinerate TRUs in the same fuel pin, hence zero is shown for TRU incinerated (no FFF pins).

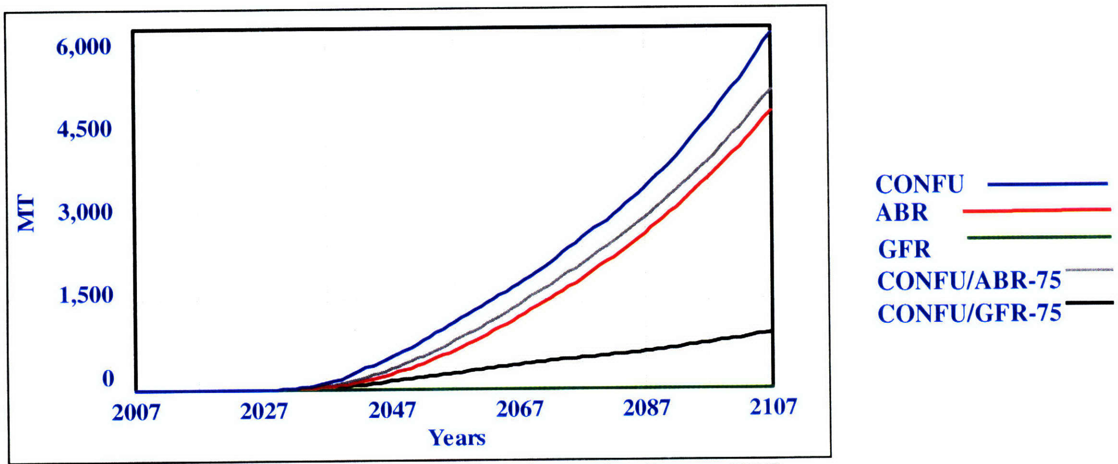

Figure 6-24 – Total incinerated TRU for fast technology at 75%

As can be seen in Figure 6-25, Figure 6-26, and Figure 6-27 the ABR and CONFU schemes maintain approximately the same amount of TRU in storage.

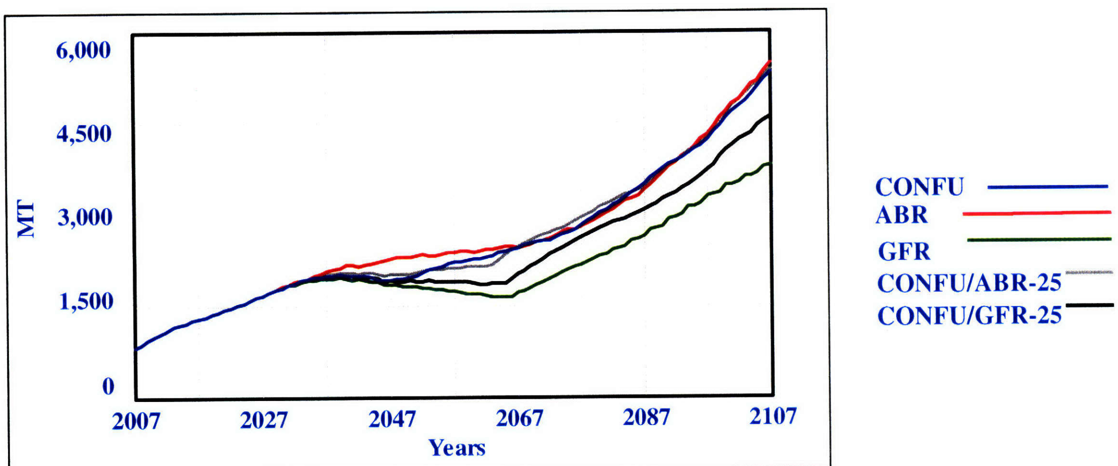

Figure 6-25 – Total TRU in storage for fast technology at 25%

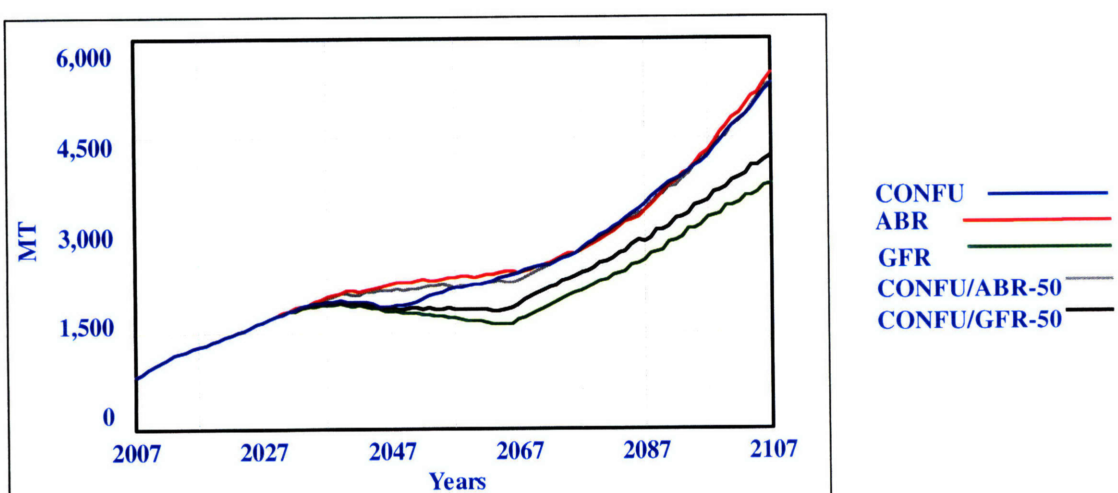

Figure 6-26 – Total TRU in storage for fast technology at 50%

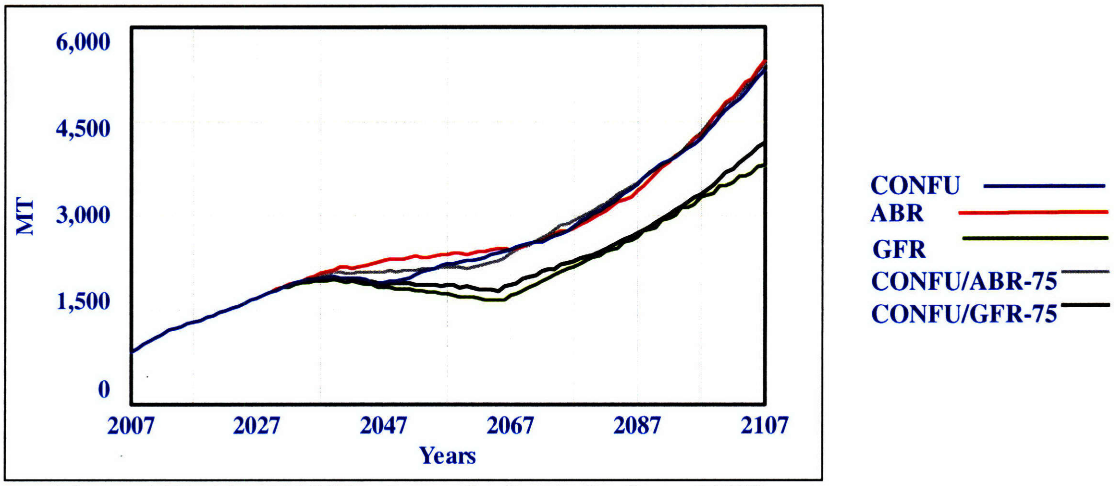

Figure 6-27 – Total TRU in storage for fast technology at 75%

The simultaneous introduction of both those technologies in any ratio does not have a significant impact on TRU in storage. Moreover, as the fraction of TRU to GFR fuel fabrication increases, the amount of TRU in interim storage decreases.

6.2.4. Economic analysis of simultaneous recycling technologies

Uncertainties of uranium availability, reactors efficiency improvement, and the fuel technology development should prevent policy decisions to be made only based on the depletion of uranium resources, or based on the incinerated rate of TRU. Therefore, the thermal and fast simultaneous recycling strategies are discussed here based on economics.

Figure 6-28 and Figure 6-29 show the capital costs for all case studies. The capital costs first fall off, and then assume an upward trend as the current fleet of LWRs is decommissioned and new reactors are built. The capital costs for simultaneous recycling schemes are between the thermal and fast technologies alone. Figure 6-30 and Figure 6-31 present the fuel cycle costs for all cases. The simultaneous introduction of thermal and fast technology makes the fuel cycle costs fall off around 2065, which makes the simultaneous introduction of the technology more economically attractive from the fuel cycle point of view. The fall off in the fuel cycle cost occurs because of the decreasing in the amount of mass treated in the separation plants. The equilibrium fuel cycle cost fluctuates around 11.50 mills/kWh for the CONFU/ABR scheme, and between 8.2 mills/kWh (GFR) and 11.68 mills/kWh (CONFU) for the CONFU/GFR. The fuel cycle cost for the CONFU/GFR-75% sometimes goes below the cost of the GFR technology alone.

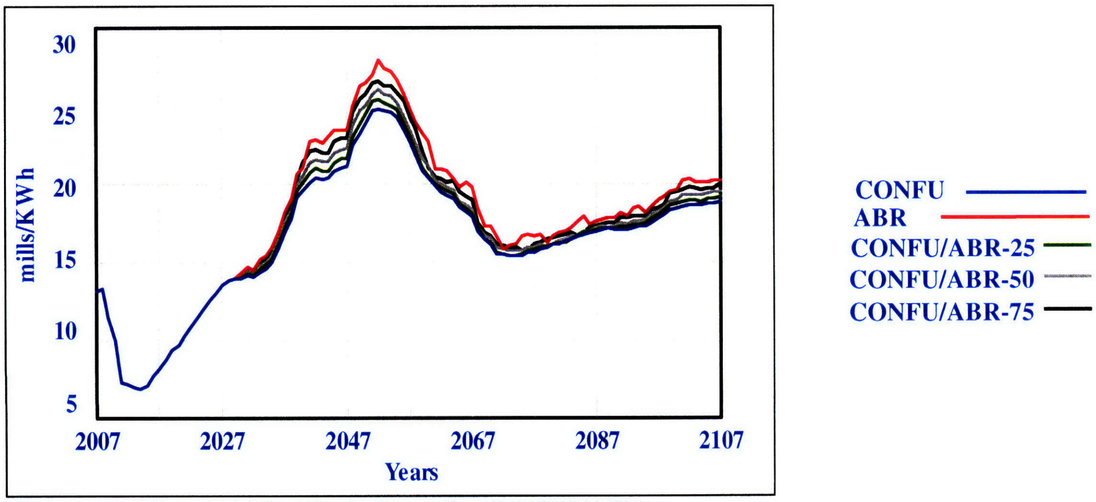

Figure 6-28 – Capital cost for CONFU/ABR

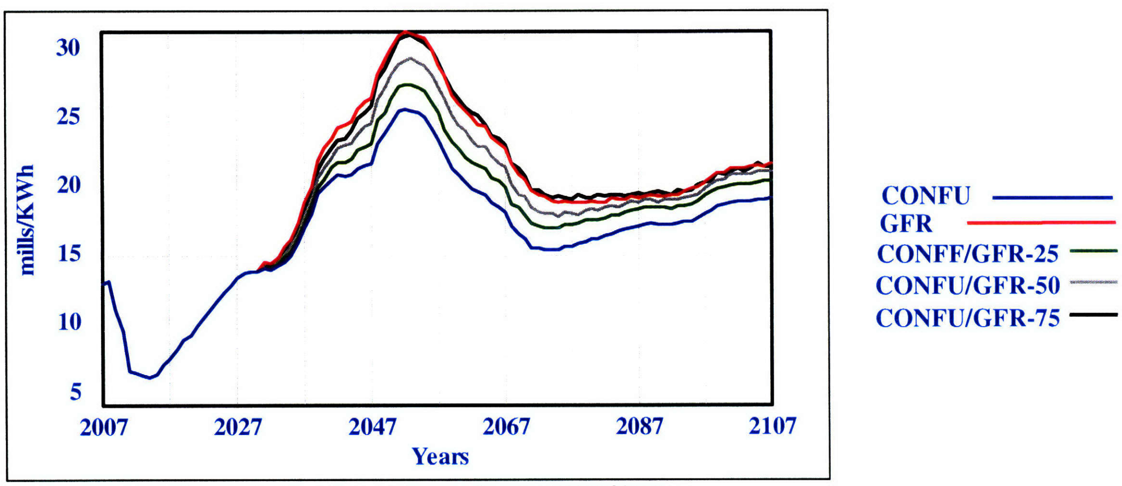

Figure 6-29 – Capital cost for CONFU/GFR

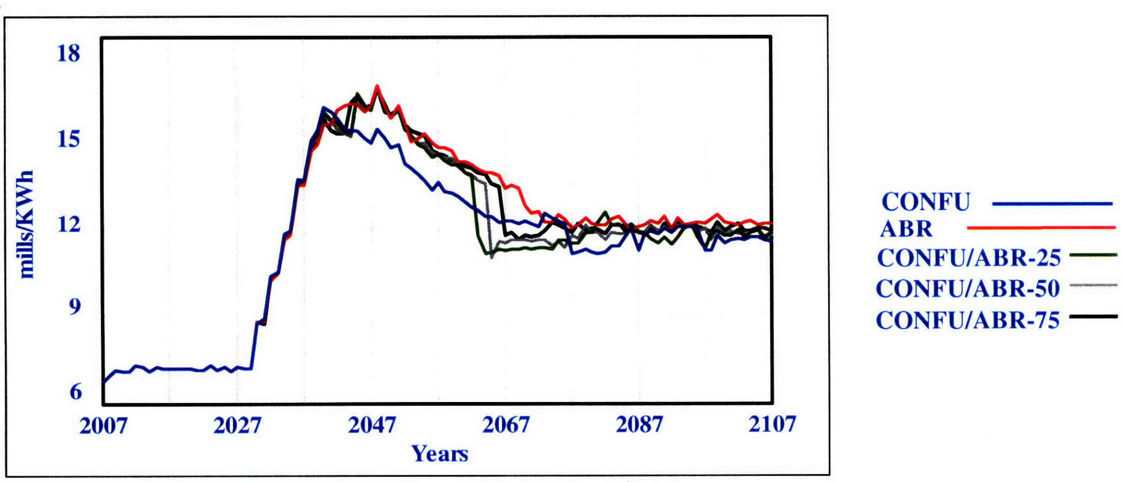

Figure 6-30 – Fuel cycle cost for CONFU/ABR

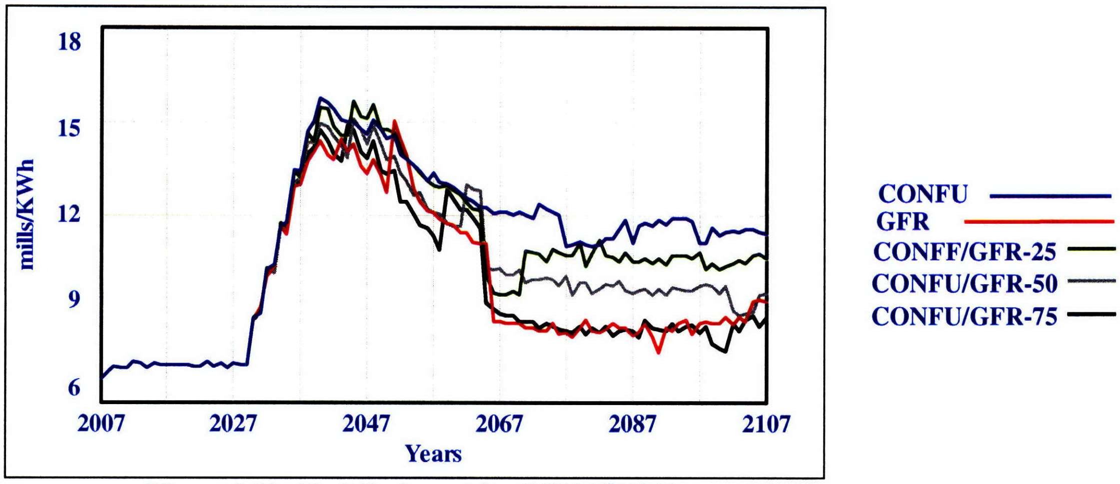

Figure 6-31 –Fuel Cycle cost for CONFU/GFR

As can be seen in Figure 6-32 and Figure 6-33, the costs of electricity for simultaneous recycling schemes are between the thermal and fast technologies alone.

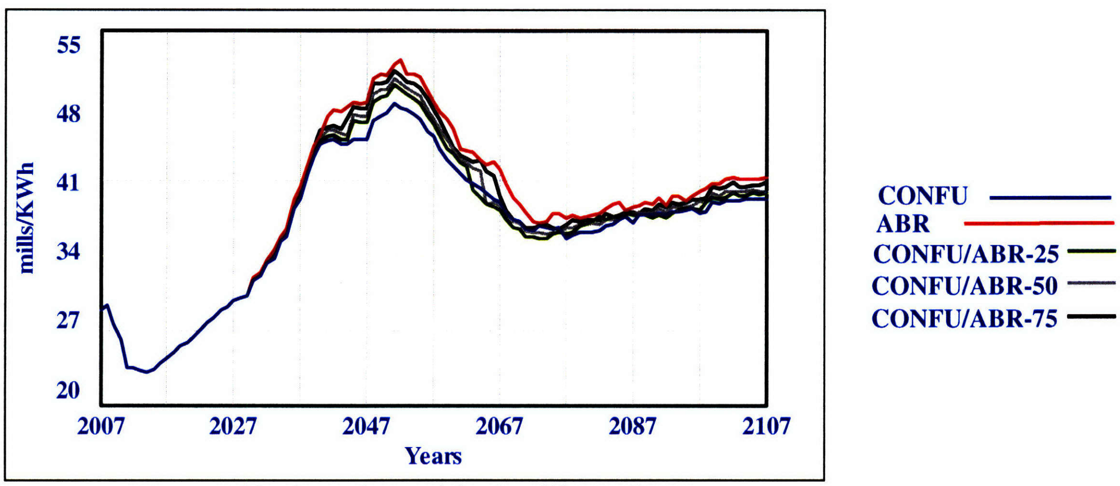

Figure 6-32 –Cost of electricity for CONFU/ABR

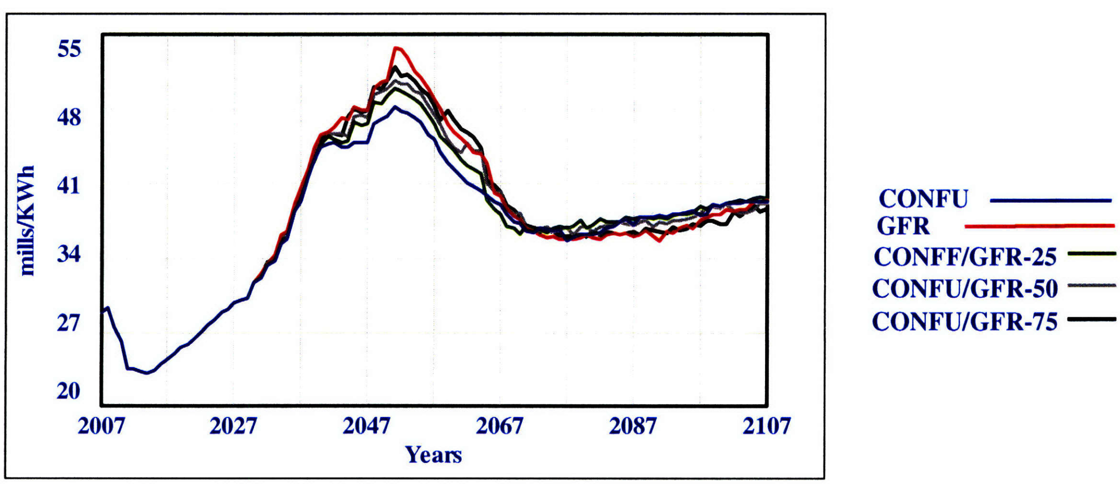

Figure 6-33 – Cost of electricity for CONFU/GFR

6.3. Deployment of two recycling technologies with a sliding ratio of separated TRU

6.3.1. Assessment of uranium resources of simultaneous recycling strategy

For a limit instantaneous mass loading factor of 0.5, and a limit cumulative mass loading factor of 0.8, first the GFR technology has the most significant reduction of the uranium ore mining rate during seventy years, then the ABR/GFR schemes becomes more attractive, as can be seen in Figure 6-34. The stand-alone GFR scheme requires lowers cumulative uranium demand, and delays the depletion date of uranium ore resources, as presented in Figure 6-35. However, the introduction of the ABR/GFR simultaneous recycling technologies takes the cumulative uranium requirements closer to the GFR scheme by 2107.

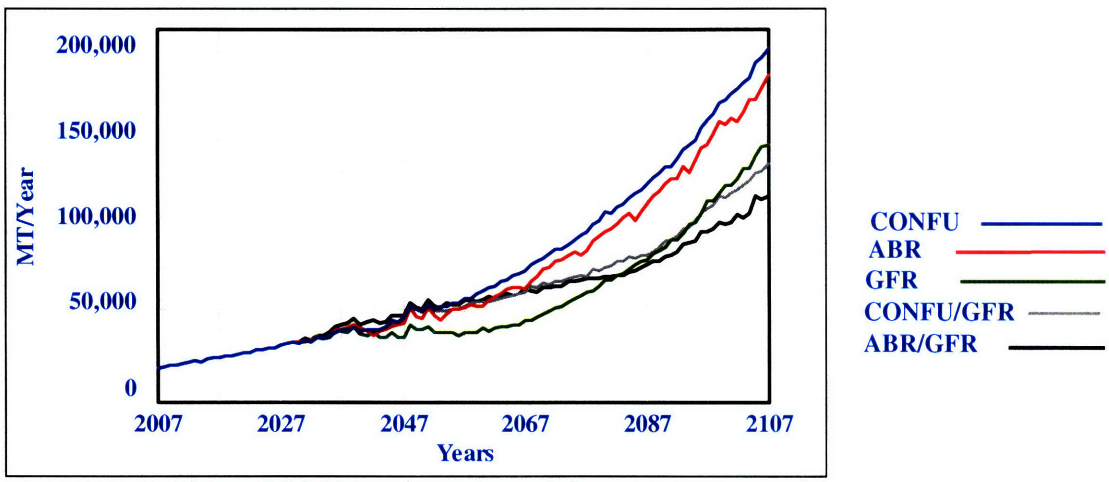

Figure 6-34- Natural uranium mining rate

Furthermore, the consumption of uranium resources is delayed for the simultaneous deployment of recycling technologies compared with the CONFU and ABR schemes, as shown in Figure 6-36. The curve for SWU requirements, Figure 6-37, shows that the ABR/GFR scheme reduces SWU requirements. The simulation results indicate that all cases are able to deplete the TRU inventory at interim storage, and that the peak occurs at the same time at the value of 1,578 MT. However, the CONFU/GFR strategy is able to deplete the TRU inventory earlier, as can be seen in Figure 6-38.

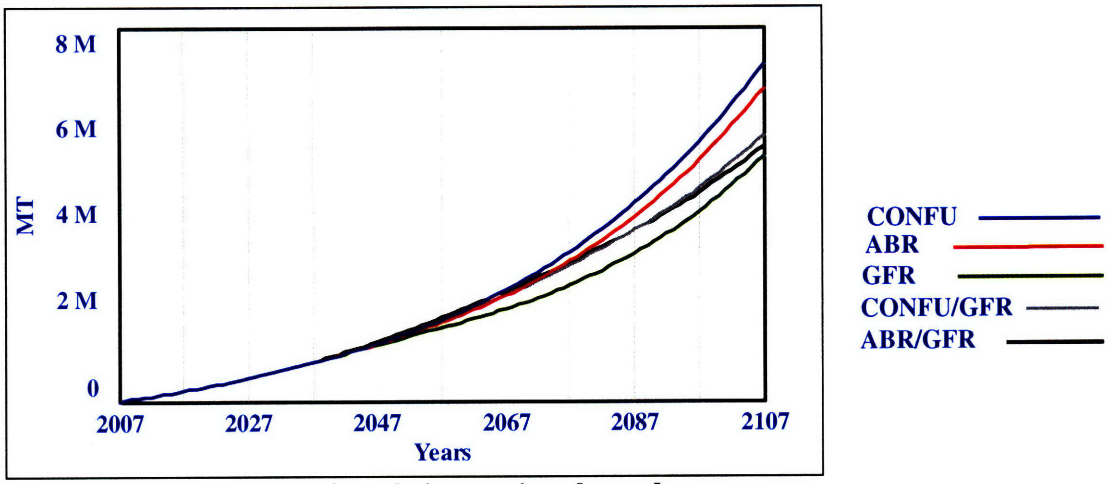

Figure 6-35 – Cumulative uranium demand

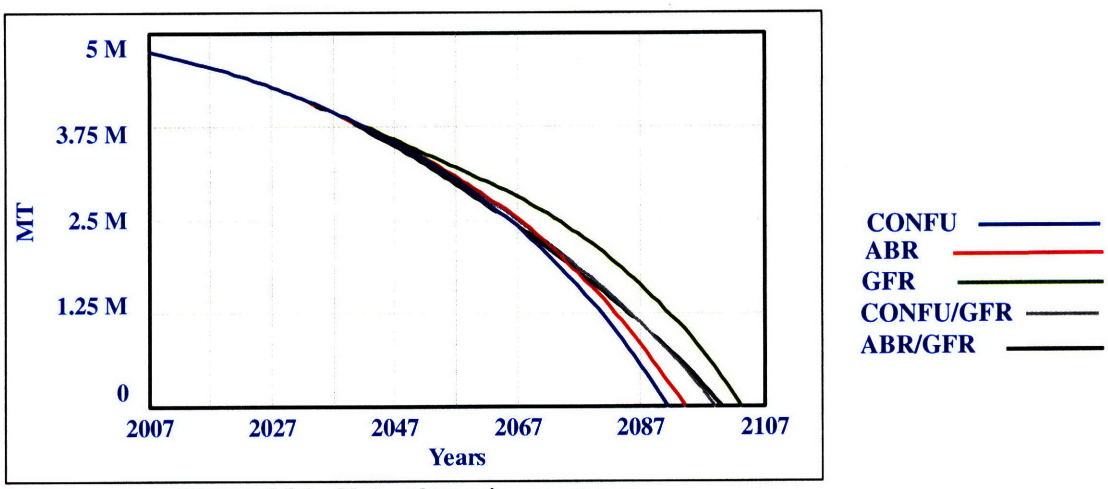

Figure 6-36 – Natural uranium resources

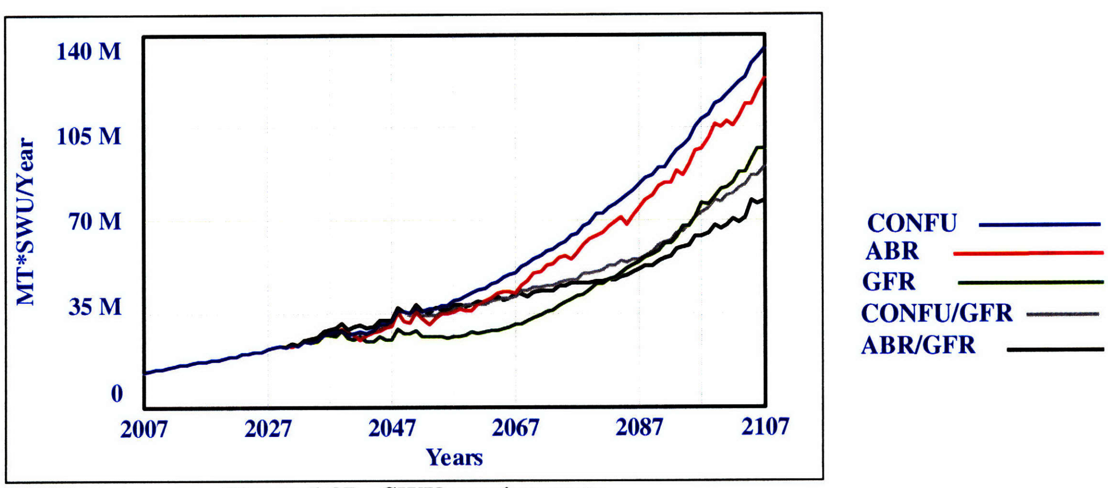

Figure 6-37 – SWU requirements

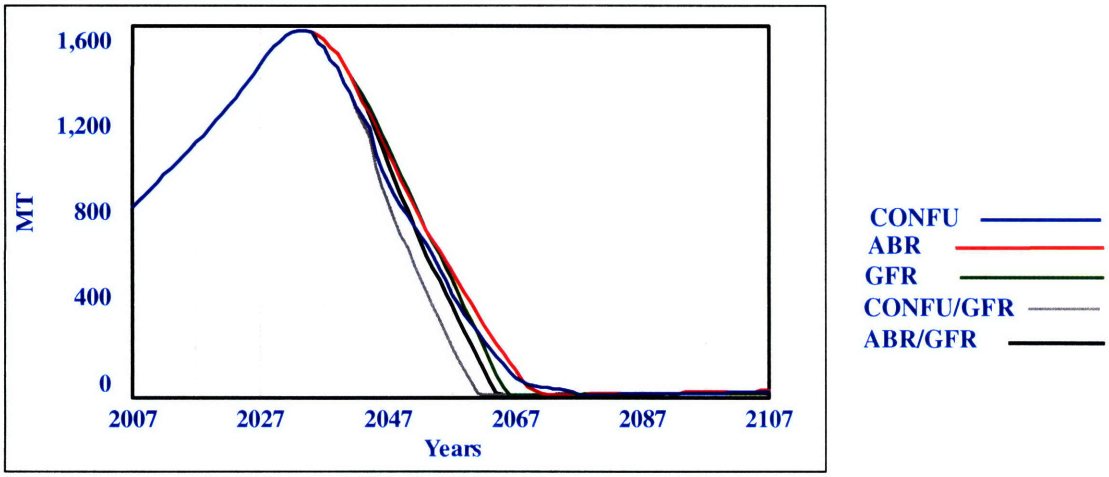

Figure 6-38 – TRU inventory

Figure 6-39 shows the fleet of separation plants required to deplete the TRU inventory. As can be seen, the initial number of separation plants for the ABR/GFR schemes is the highest, but after 2070 it decreases and gets closer to the number of plants for the GFR scheme alone. Figure 6-40 presents the number of FFF reprocessing plants to treat spent fuel from CONFU and ABR schemes. As expected, the introduction of the GFR strategy simultaneously with the CONFU and ABR schemes reduces the number of FFF reprocessing plants in the second half of the century.

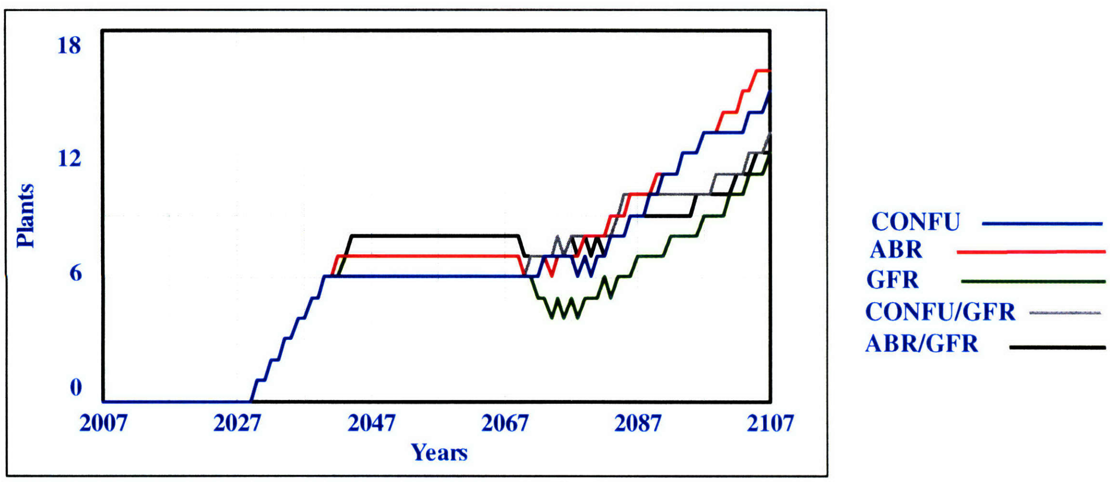

Figure 6-39 – Fleet of UO_2 separation plants

Figure 6-41 presents the number of GFR U/TRU reprocessing plants for simultaneous recycling schemes. As plotted, the simultaneous deployment of the recycling technologies delays the construction of the first GFR U/TRU reprocessing plant. The installed nuclear capacity and the ratio of fast to thermal reactors are presented in Figure 6-42 and Figure 6-43. As can be seen, the ratio of installed GFR capacity to total installed capacity increases by the end of the century for the simultaneous deployment of ABR and GFRs schemes.

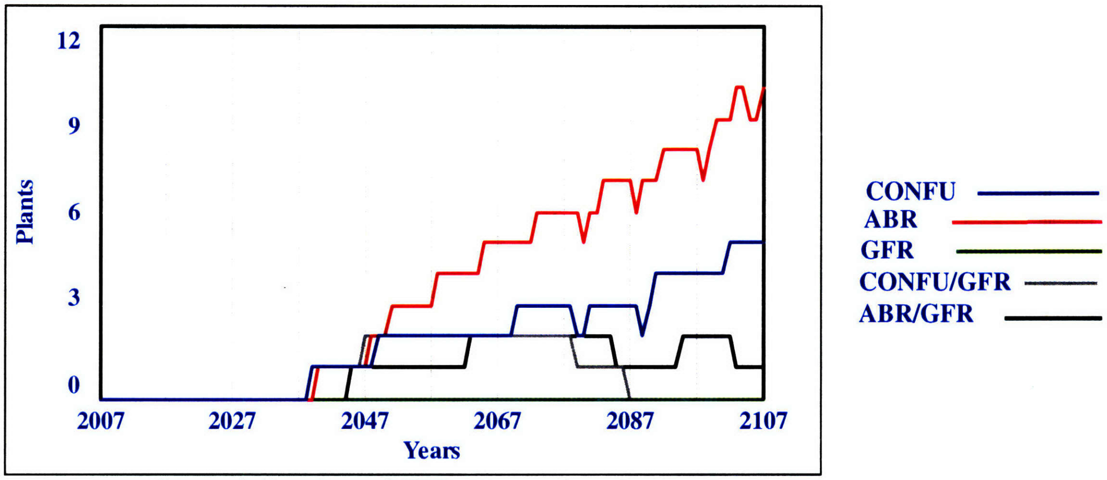

Figure 6-40 – Fleet of FFF reprocessing plants

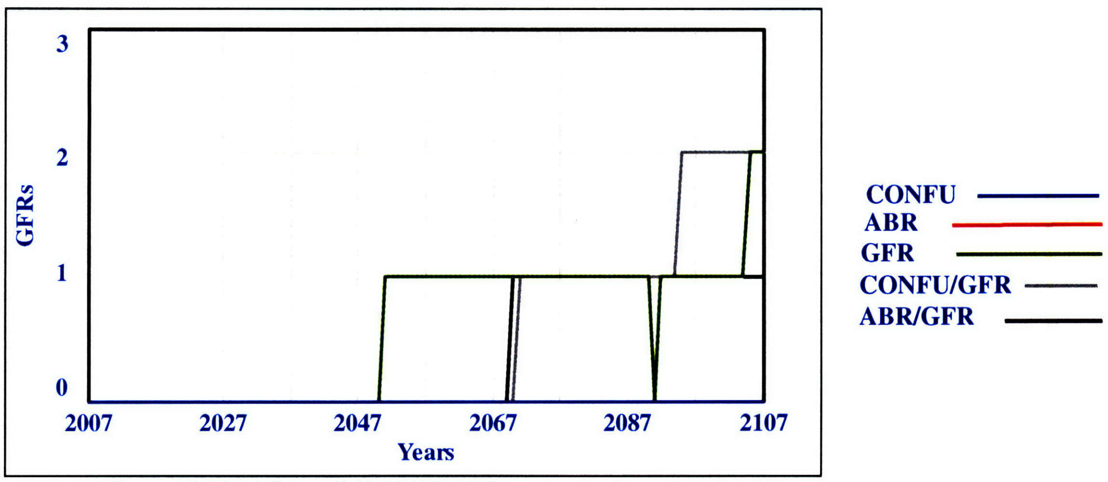

Figure 6-41 – Fleet of GFR U/TRU reprocessing plants

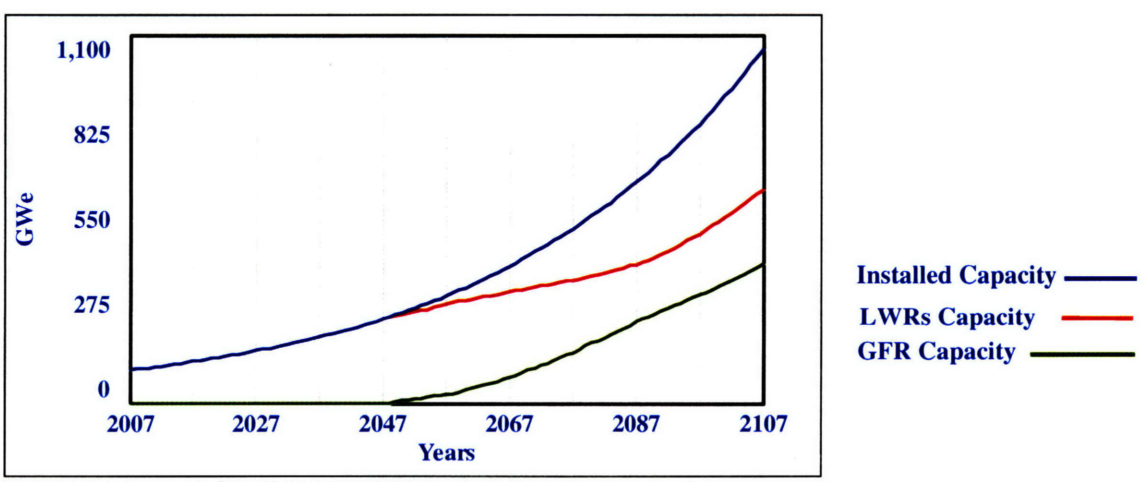

Figure 6-42 –CONFU/GFR installed nuclear capacity

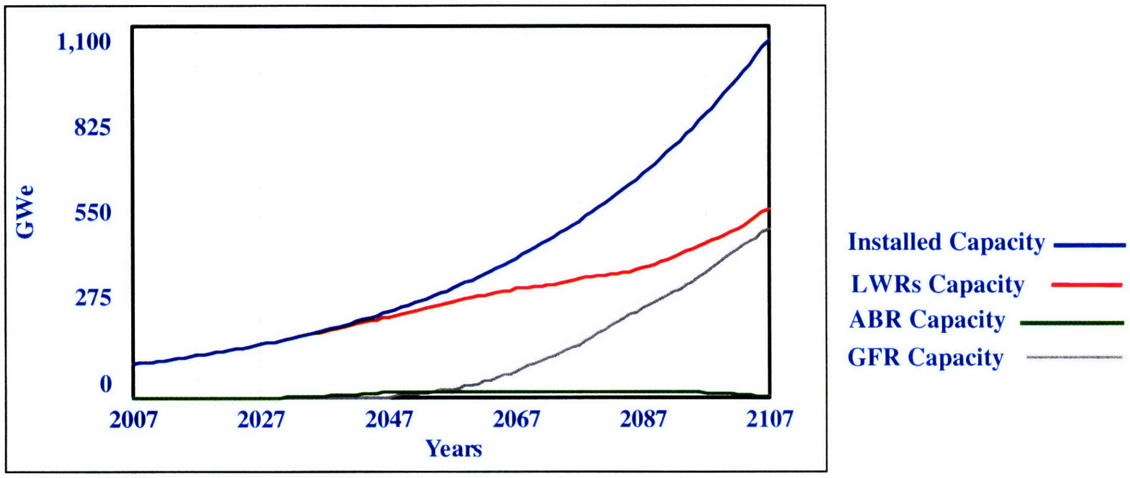

Figure 6-43 – ABR/GFR installed nuclear capacity

6.3.2. TRU mass balance of simultaneous recycling strategy

Figure 6-44 shows the total incinerated TRU in the system. As can be seen, the CONFU/GFR scheme incinerates more TRU than the ABR/GFR. As the GFR technology does not incinerate TRU, the higher ratio of GFR installed nuclear capacity to total installed capacity for the ABR/GFR scheme justifies this trend. However, note that the highest incineration amount belongs to the CONFU, then the ABR.

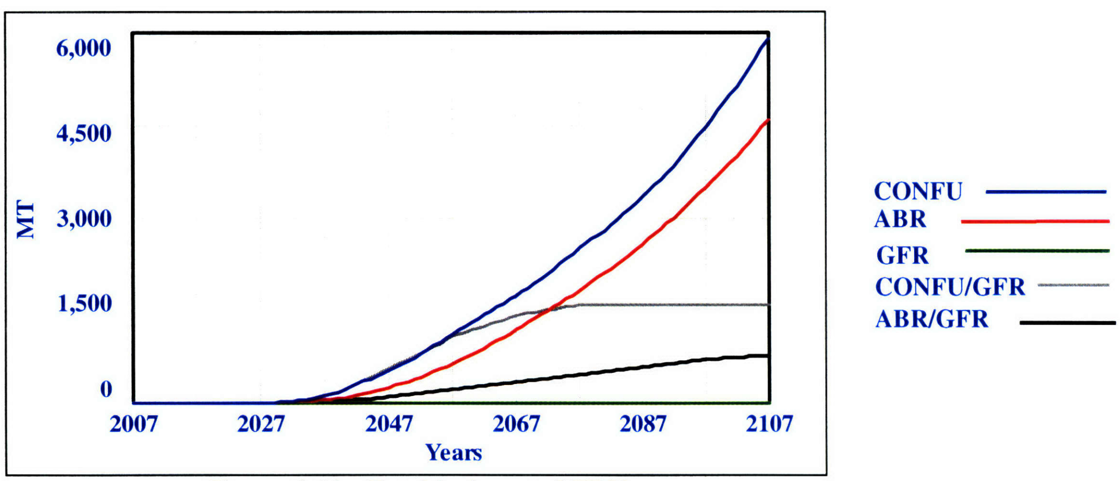

Figure 6-44 – Total incinerated TRU

As can be seen in Figure 6-45, the CONFU/GFR scheme maintains less TRU in total system storage than the ABR/GFR scheme which leads to the highest amount of TRU in storage in the system.

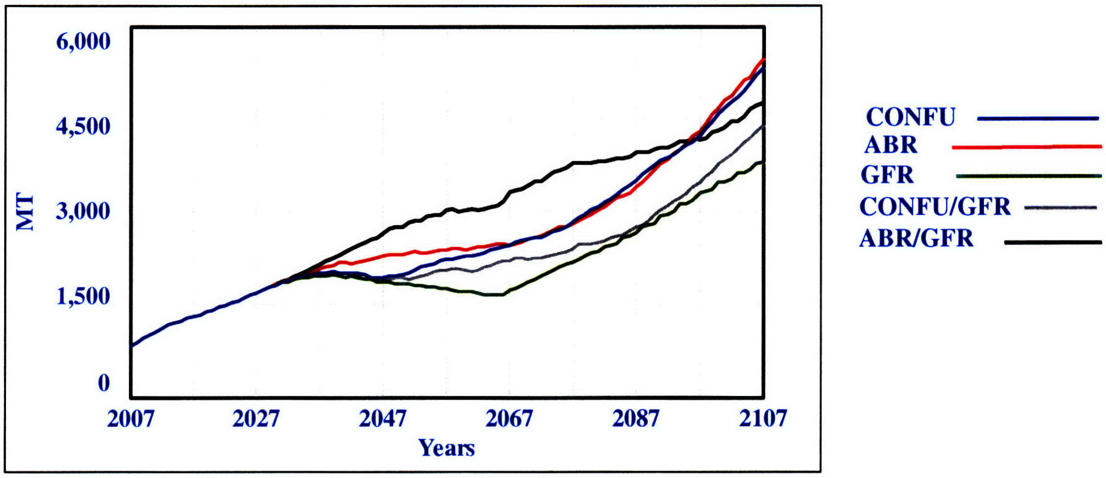

Figure 6-45 – Total TRU in storage

6.3.3. Economic analysis of simultaneous recycling technologies

Figure 6-46 shows the capital costs for all case studies. The capital costs for simultaneous recycling schemes are between the thermal and ABR technologies alone during the peak, but their capital costs at equilibrium are higher than all stand-alone schemes. This is because more TRU available at later time allows construction of more GFRs than in the GFR-only case. Figure 6-47 shows that after 2071, the number of GFRs having age < 20 years used for capital cost depreciation exceeds the number of GFRs under depreciation in the GFR-alone case. This result in a higher capital cost (see Figure 5-68 showing that GFR capital cost in GFR stand-alone scenario is higher than for ABR or CONFU only technologies for early fast recycling). Figure 6-48 presents the fuel cycle costs for all cases. The simultaneous introduction of two technologies makes the fuel cycle costs more expensive at the peak, and the costs fall off around 2065 due to decreasing amount of spent fuel treated at separation plants. By 2097, the ABR/GFR scheme is more economically attractive from the fuel cycle cost point of view.

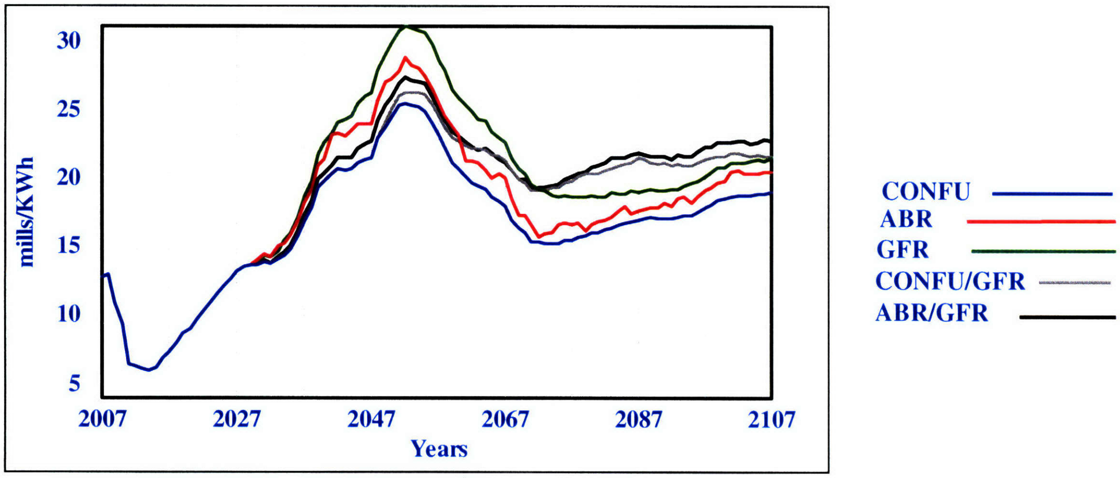

Figure 6-46 – Capital cost of alternative schemes

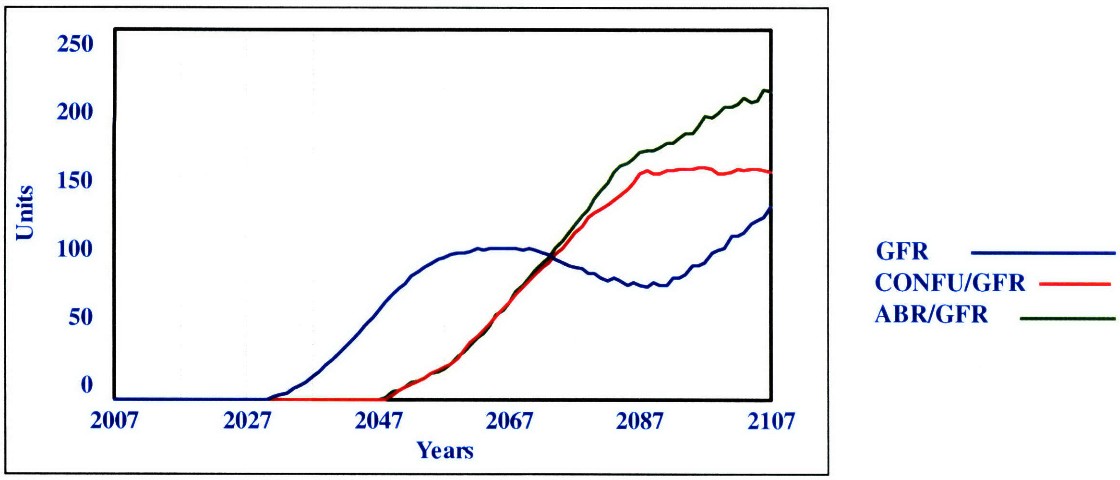

Figure 6-47 – GFRs younger than 20 years old

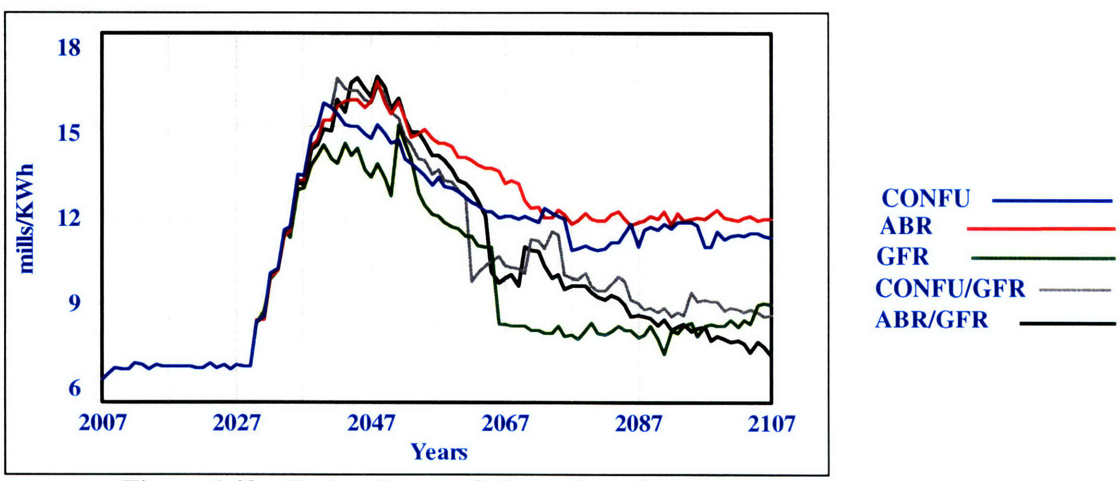

Figure 6-48 – Fuel cycle cost of alternative schemes

As can be seen in Figure 6-49, the cost of electricity for the CONFU/GFR scheme is lower than that for the ABR/GFR during the peak. At equilibrium, both electricity costs are approximately the same, and they are higher than that for stand-alone deployment of the CONFU and GFR schemes.

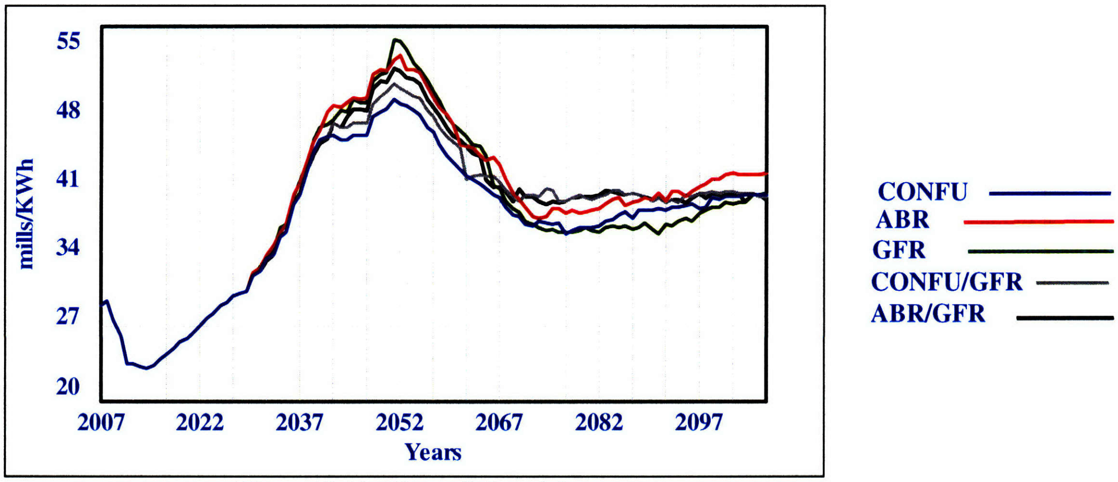

Figure 6-49 –Cost of electricity

6.4. Sensitivity analysis of nuclear growth demand of two simultaneous recycling technologies with a sliding ratio of separated TRU

For an instantaneous mass loading factor limit of 0.5, and a cumulative mass loading factor limit of 0.8, the cases presented in Table 6-3 were investigated. The uranium mining rate and the SWU requirements for a nuclear growth demand of 1.4% remain almost constant for the second half of the century for the CONFU/GFR case, as can be seen in Figure 6-50 and Figure 6-52. For a 3.4% nuclear growth rate, i.e. for an installed capacity of 2,831 GWe by the end of the century, the uranium and SWU requirements are significantly higher. Figure 6-51 and Figure 6-53 show the uranium and SWU requirements for the ABR/GFR technology. In this case, for 1.4% nuclear growth, the uranium and SWU requirements slightly decrease in the second half of the century. This is because there is more TRU available for GFR fuel fabrication. Therefore, there is no need for LWRs to fulfill the power demand. Moreover, the introduction of the GFR recycling technology reduces the demand for uranium and for SWU for the lower nuclear growth rate.

Table 6-3 - Case studies for sliding fractions of separated TRU

Case study	Introduction date of the technology	Nuclear Growth Rate	TRU percentage for GFR technology
CONFU/GFR Technology	CONFU: 2027 GFR: 2047	1.4 % 2.4 % 3.4 %	25% (2047-2057)
			50% (2057-2067)
			75% (2067-2077)
			100% (2077-2107)
ABR/GFR Technology	ABR: 2027 GFR: 2047	1.4 % 2.4 % 3.4 %	25% (2047-2057)
			50% (2057-2067)
			75% (2067-2077)
			100% (2077-2107)

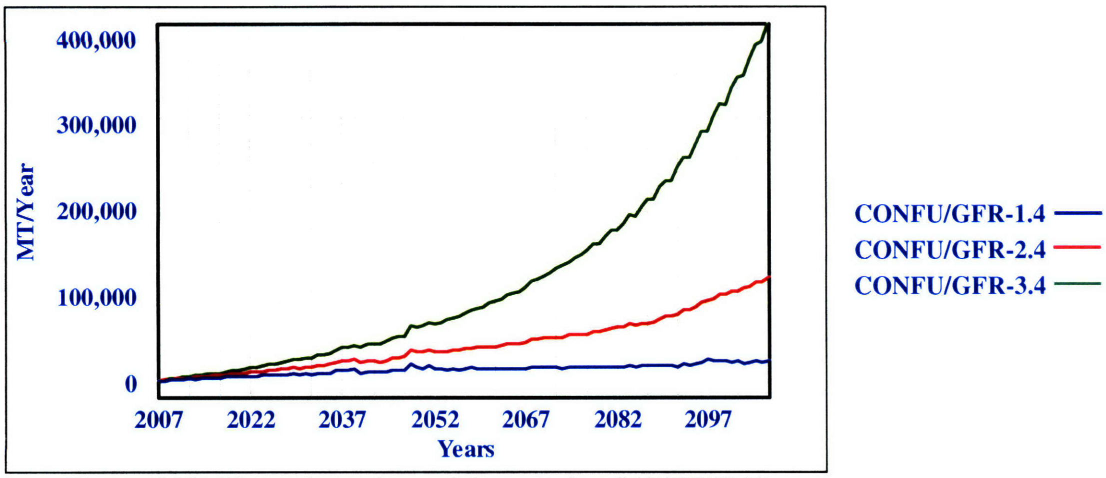

Figure 6-50 - Natural uranium mining rate for CONFU/GFR

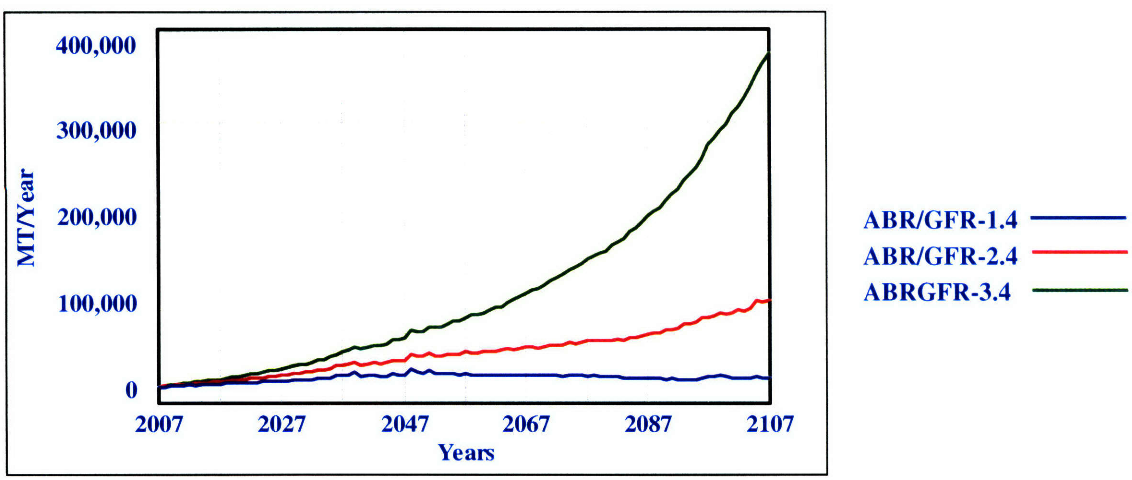

Figure 6-51 - Natural uranium mining rate for ABR/GFR

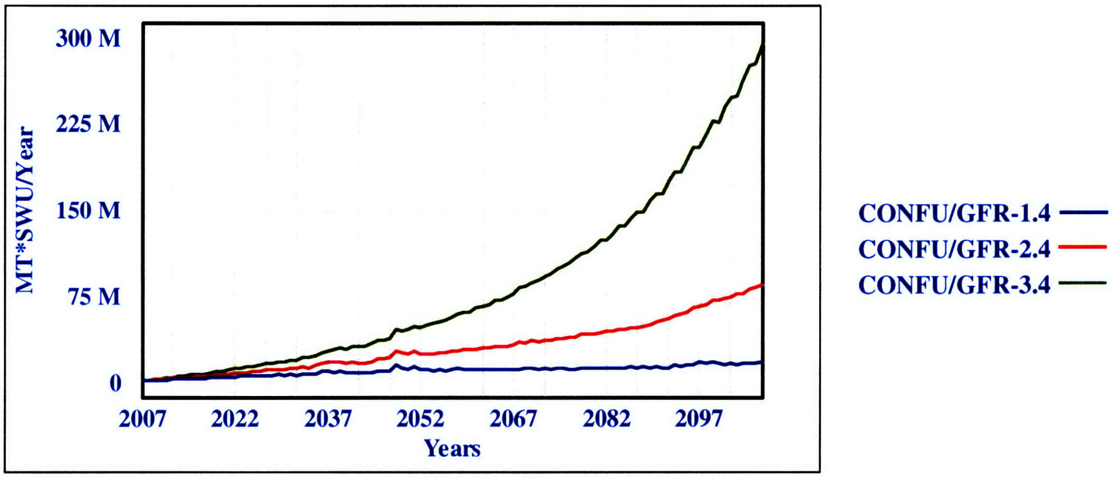

Figure 6-52 - SWU requirements for CONFU/GFR

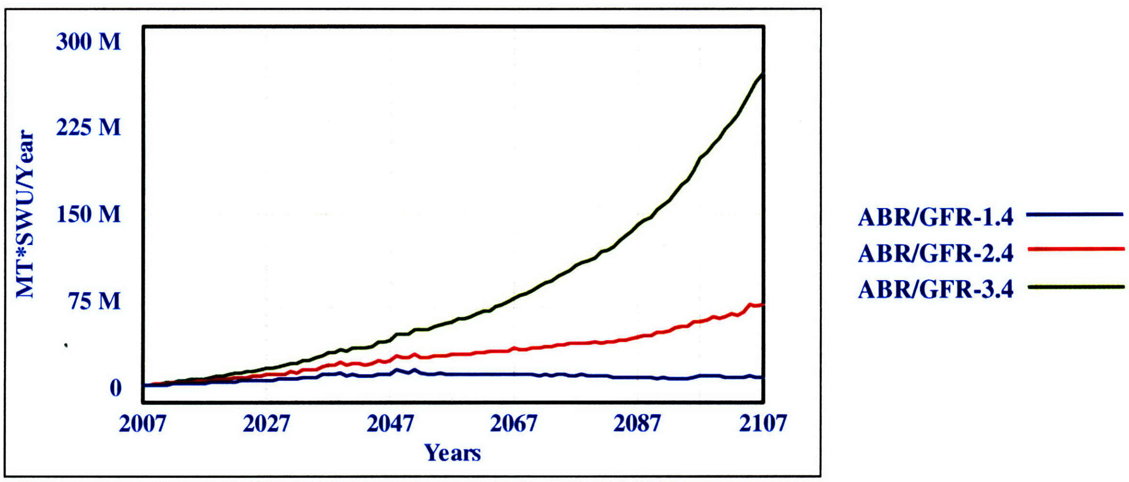

Figure 6-53 - SWU requirements for ABR/GFR

Furthermore, the cumulative uranium demand for the ABR/GFR is lower than that for the CONFU/GFR for each nuclear growth rate, as presented in Figure 6-54 and Figure 6-55. The consumption of uranium resources occurs earlier for a 3.4% growth rate even with the deployment of GFRs to save resources, as can be seen in Figure 6-56 and Figure 6-57. This occurs due to the lack of TRU to start new GFRs core. Therefore, LWRs need to be built.

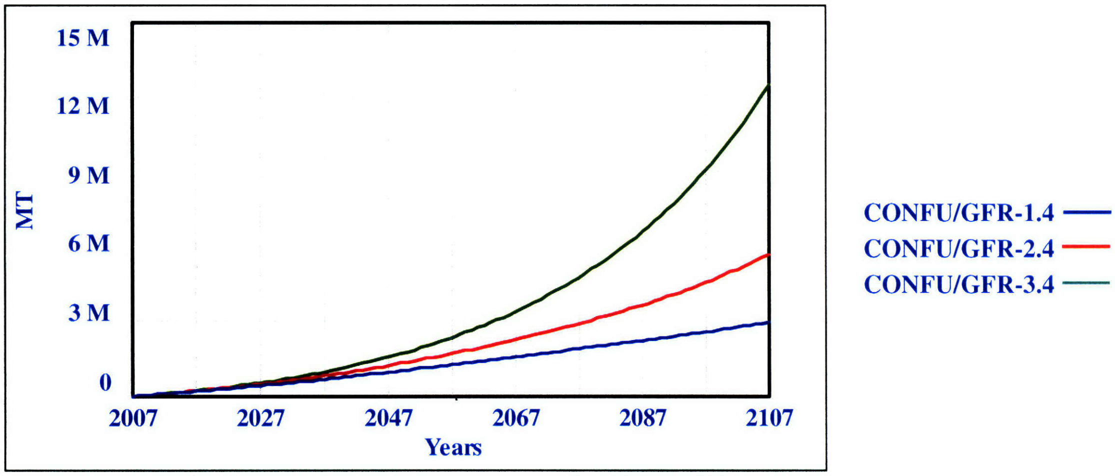

Figure 6-54 - Cumulative uranium demand for CONFU/GFR

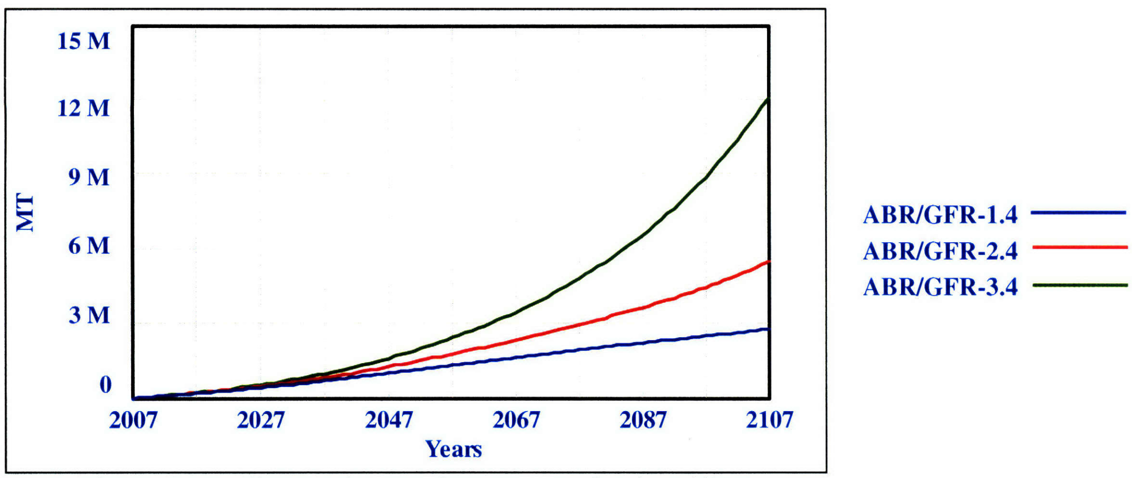

Figure 6-55 – Cumulative uranium demand for ABR/GFR

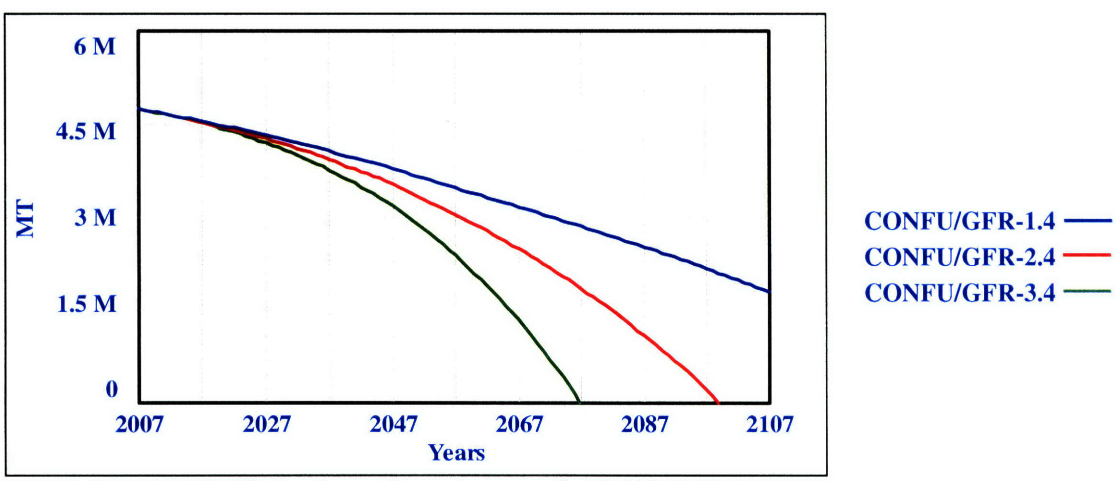

Figure 6-56 – Natural uranium resources for CONFU/GFR

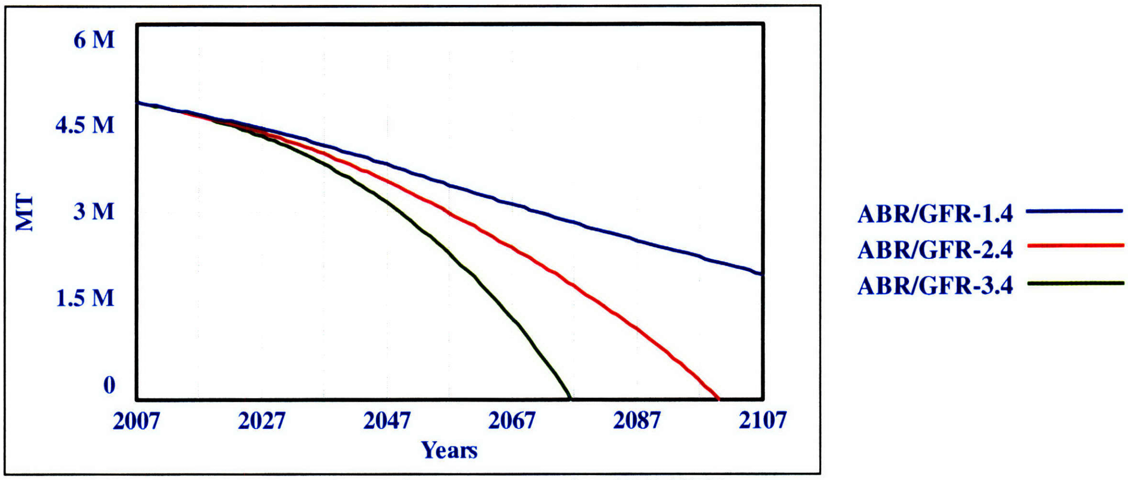

Figure 6-57 – Natural uranium resources for ABR/GFR

Figure 6-58 and Figure 6-61 show the fleet of separation plants required to deplete the TRU inventory. As can be seen, the number of separation plants for the both cases remain constant by the last 20 years of simulation for a 1.4% nuclear growth rate. This is because there is no need for the construction of new LWRs to fulfill power demand. Figure 6-59 and Figure 6-62 show the mass loading factor for the separation plants fleet, and Figure 6-60 and Figure 6-63 present the cumulative mass loading factor. As expected, the number of separation plants is significantly higher for a 3.4% nuclear growth rate in the second half of the century for the CONFU/GFR and ABR/GFR cases.

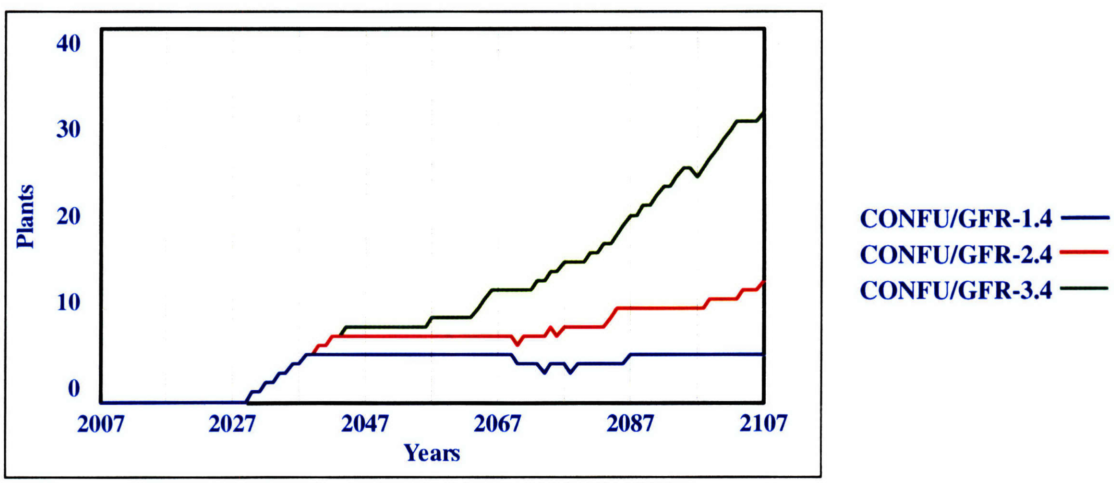

Figure 6-58 – Fleet of UO_2 SP for CONFU/GFR

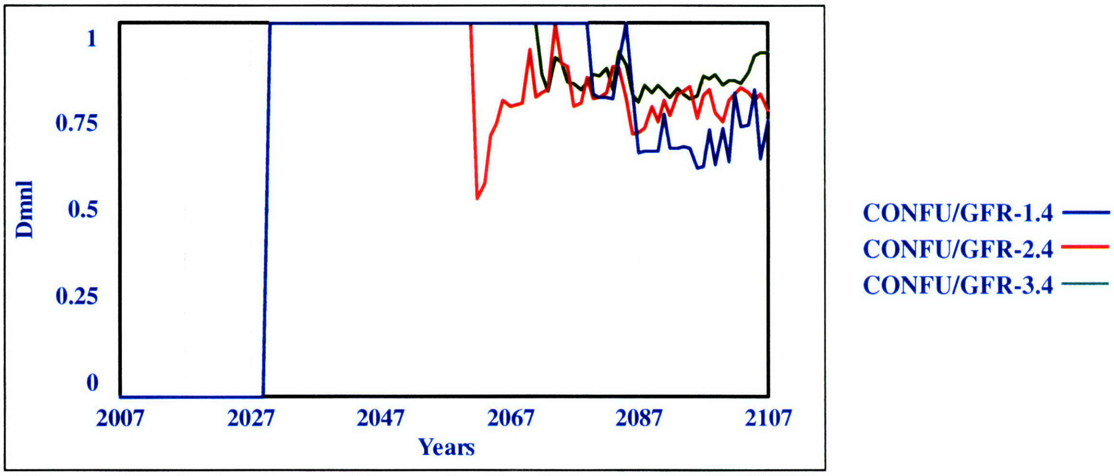

Figure 6-59 – Instantaneous SP mass loading factor for CONFU/GFR

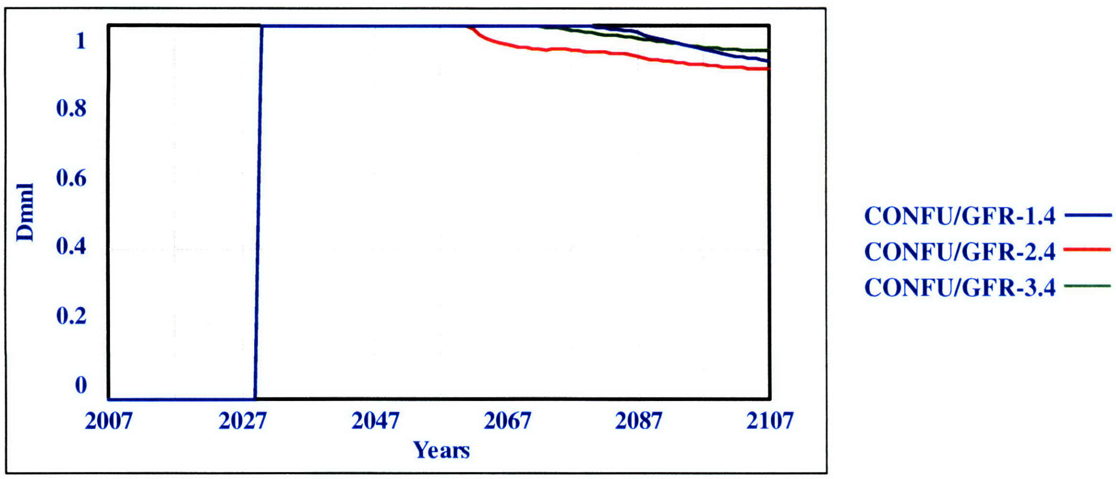

Figure 6-60 – Cumulative SP mass loading factor

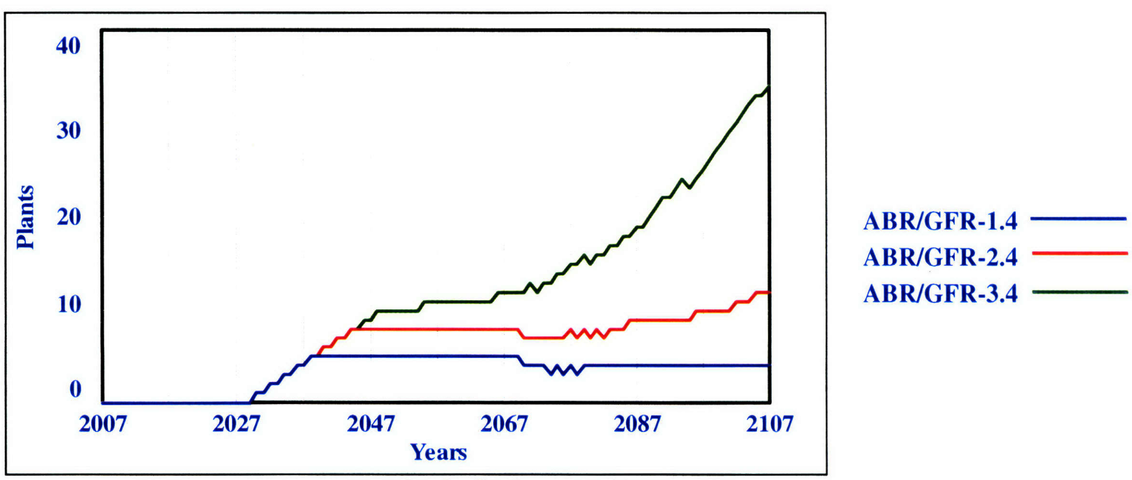

Figure 6-61 – Fleet of UO_2 SP for ABR/GFR

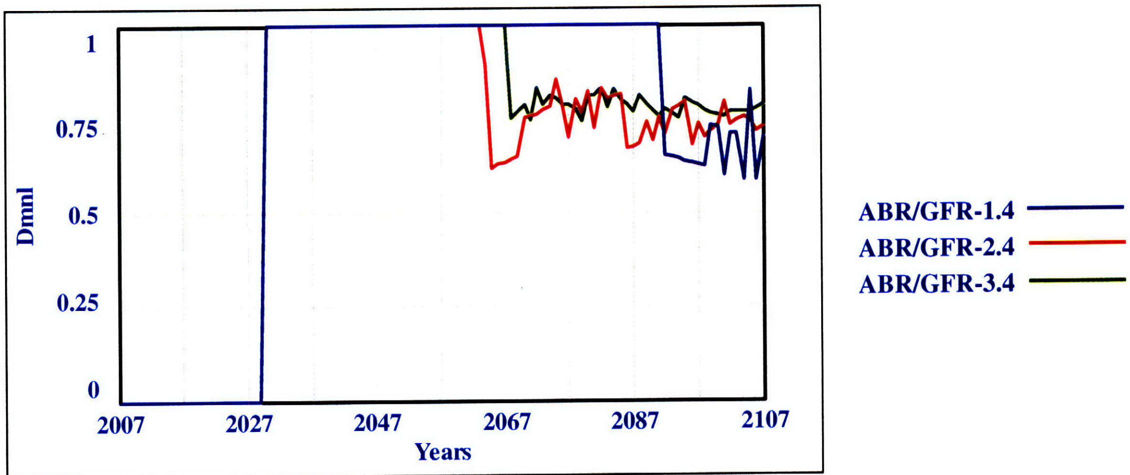

Figure 6-62 – Instantaneous SP mass loading factor for ABR/GFR

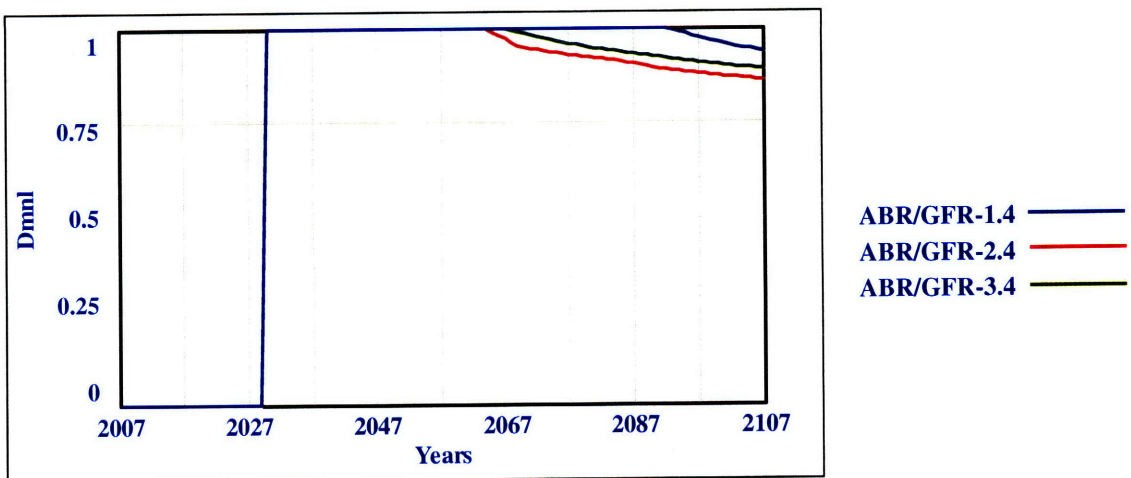

Figure 6-63 – Cumulative SP mass loading factor

The simulation results indicate that TRU in interim storage is depleted, and reaches equilibrium, for the three nuclear growth rates, as presented in Figure 6-64 and Figure 6-65. For the CONFU/GFR case, and 2.4% growth rate, the equilibrium is reached earlier, which is due to sufficient spent fuel to build one more separation plant in 2042 without having a mass loading factor lower than 0.5 in 2061 (see Figure 6-59). For the ABR/GFR case, and 1.4% growth rate, the equilibrium is reached later, which reflects on a mass loading factor of 1 and a total number of separation plant of 4 (CONFU/GFR) instead of 5 (ABR/GFR).

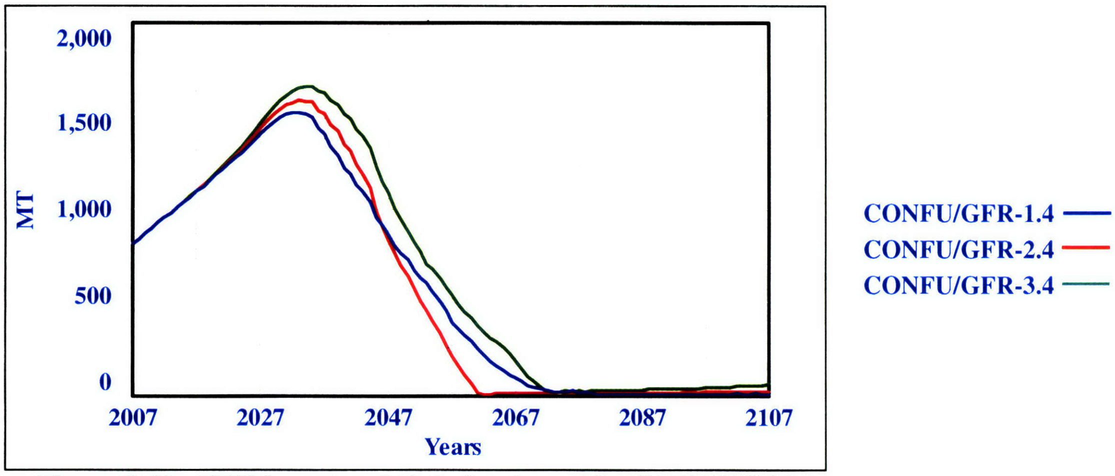

Figure 6-64 – TRU inventory in interim storage for CONFU/GFR

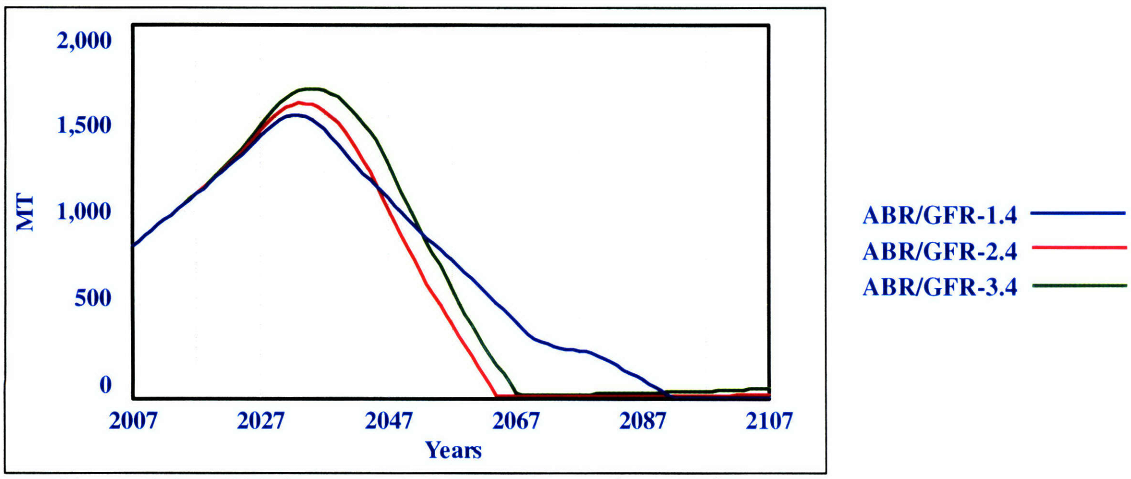

Figure 6-65 – TRU inventory in interim storage for ABR/GFR

Figure 6-66 and Figure 6-67 show the number of FFF reprocessing plants to treat FFF spent fuel from CONFU and ABRs for the three growth rate. As plotted, the number of separation plants after 2087 is zero for CONFU/GFR because there is no more CONFU fuel fabrication, and one plant stays online until 2087 to treat the FFF spent fuel after cooling storage for 2.4 and 3.4% growth rate. Figure 6-68 and Figure 6-69 present the number of GFR U/TRU reprocessing plants to be built. As can be seen, the number of GFR U/TRU reprocessing plants is higher for the CONFU/GFR case for 2.4 and 3.4% by the end of the simulation. This is because there is TRU fuel available for the ABR fleet until the end of its lifetime. For the 1.4% nuclear growth rate, the construction of the first GFR U/TRU reprocessing plant is delayed due to lack of GFR spent fuel to guarantee the minimal mass loading factor.

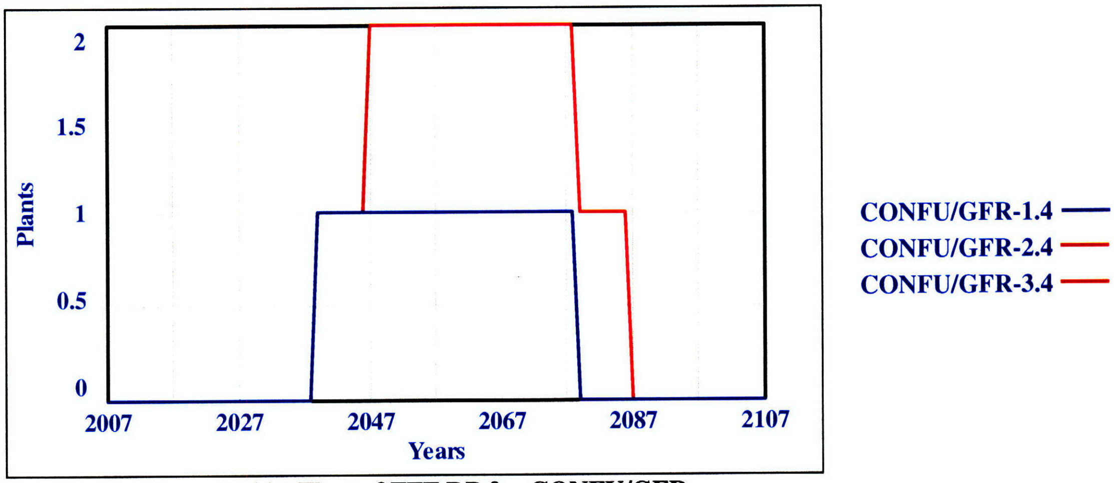

Figure 6-66 – Fleet of FFF RP for CONFU/GFR

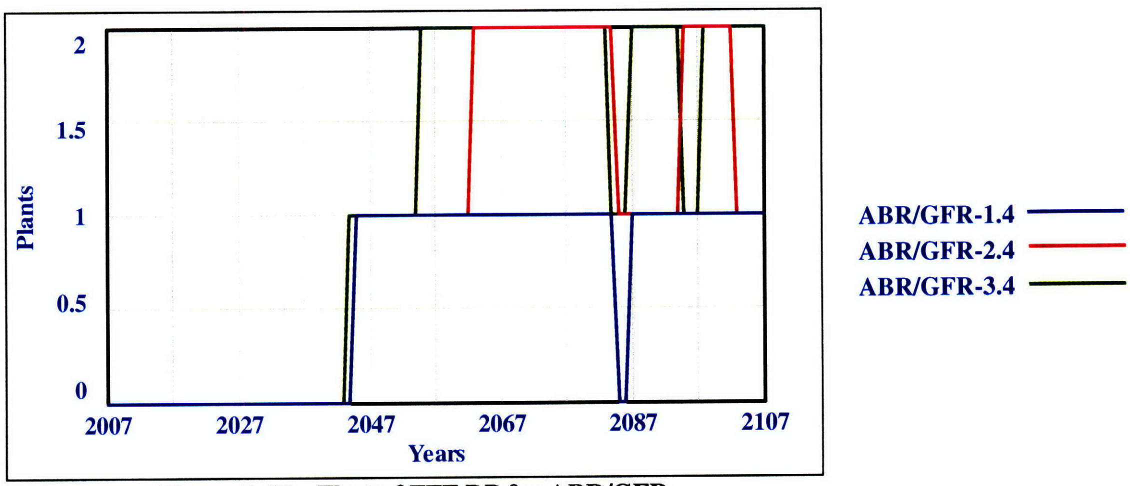

Figure 6-67 – Fleet of FFF RP for ABR/GFR

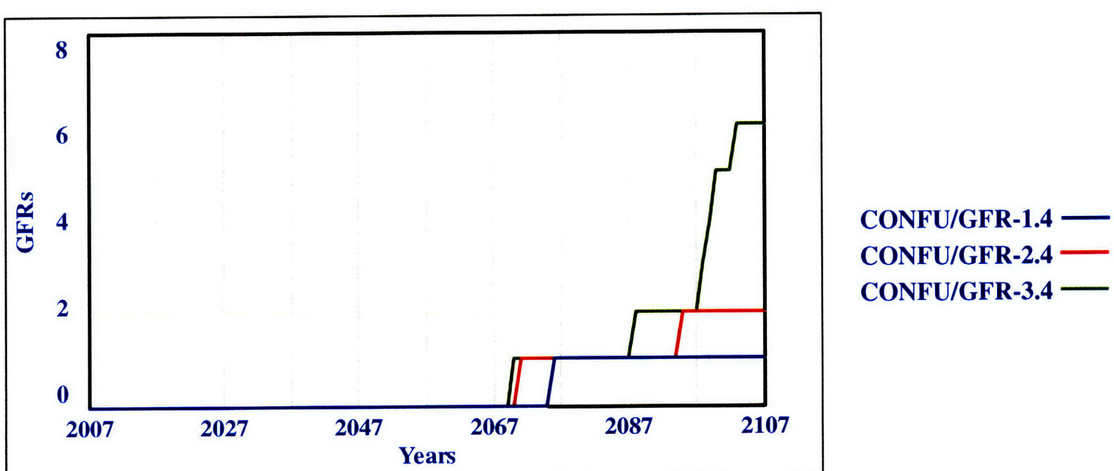

Figure 6-68 – Fleet of GFR RP for CONFU/GFR

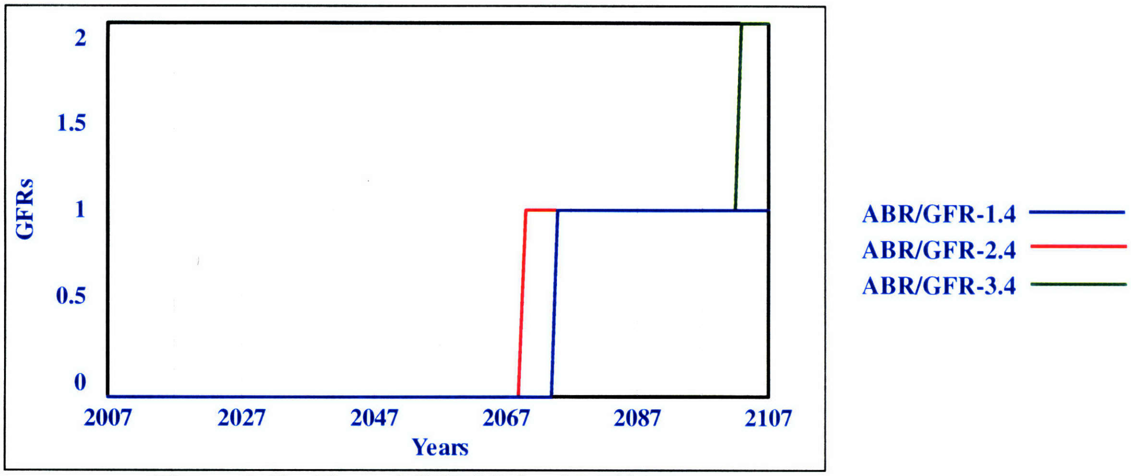

Figure 6-69 – Fleet of GFR RP for ABR/GFR

The installed nuclear capacity and the ratio of fast to thermal reactors are presented in Figure 6-70, Figure 6-71 and Figure 6-72 for the CONFU/GFR case, and in Figure 6-73, Figure 6-74, and Figure 6-75 for the CONFU/ABR case. As can be seen in Figure 6-70, for the 1.4 % nuclear growth, the GFR installed capacity surpasses the LWRs installed capacity by the end of the simulation. The LWRs installed capacity remains constant after the introduction of the GFR because there is enough TRU available for the construction of new GFRs to fulfill power demand. For the 2.4% nuclear growth, as seen in Figure 6-71, LWRs are built, particularly after 2087, due to lack of TRU to fabricate fuel for new GFRs.

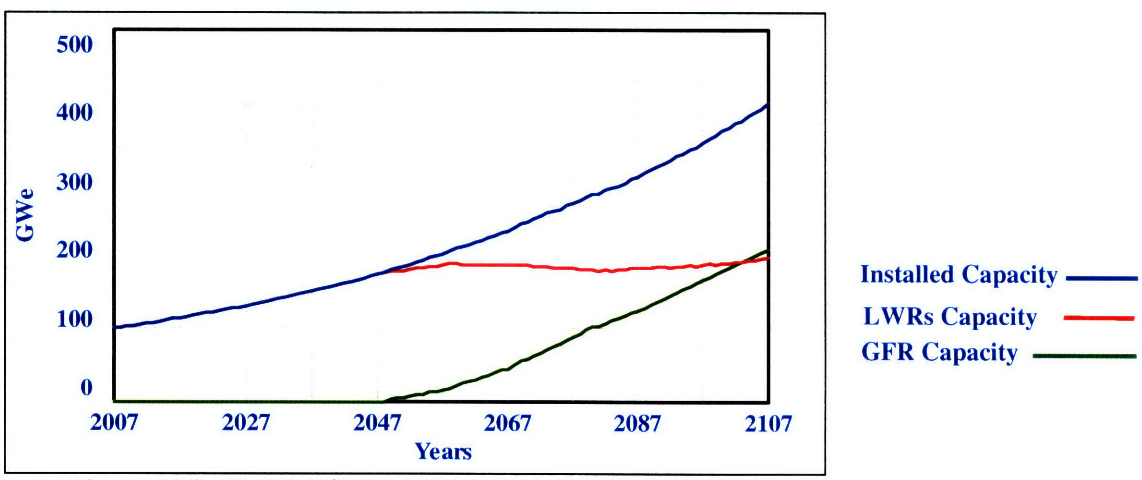

Figure 6-70 – CONFU/GFR-1.4% installed nuclear capacity

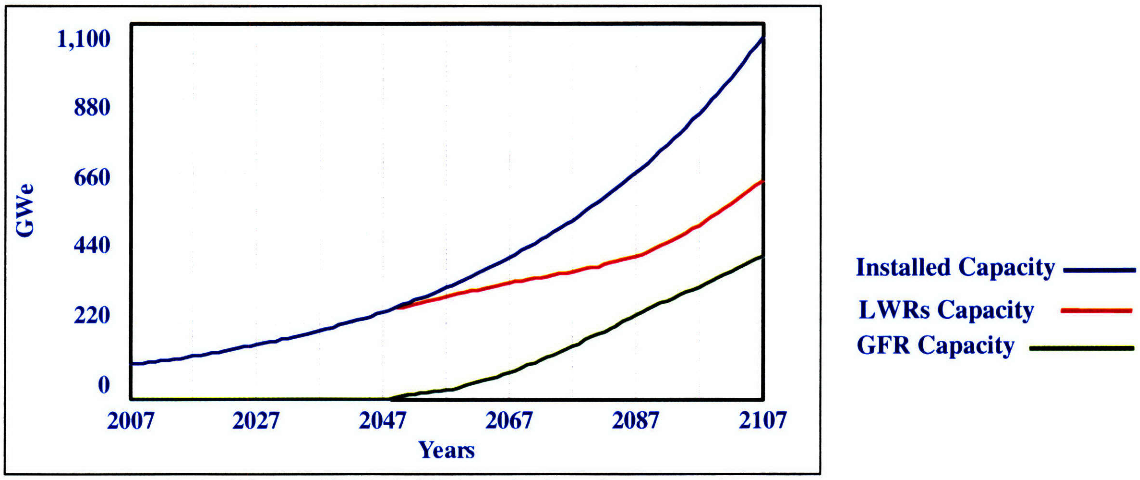

Figure 6-71- CONFU/GFR-2.4% installed nuclear capacity

For the 3.4% nuclear growth, as seen in Figure 6-72, both LWRs and GFRs are built at high rate due to higher electricity demand by the end of the simulation.

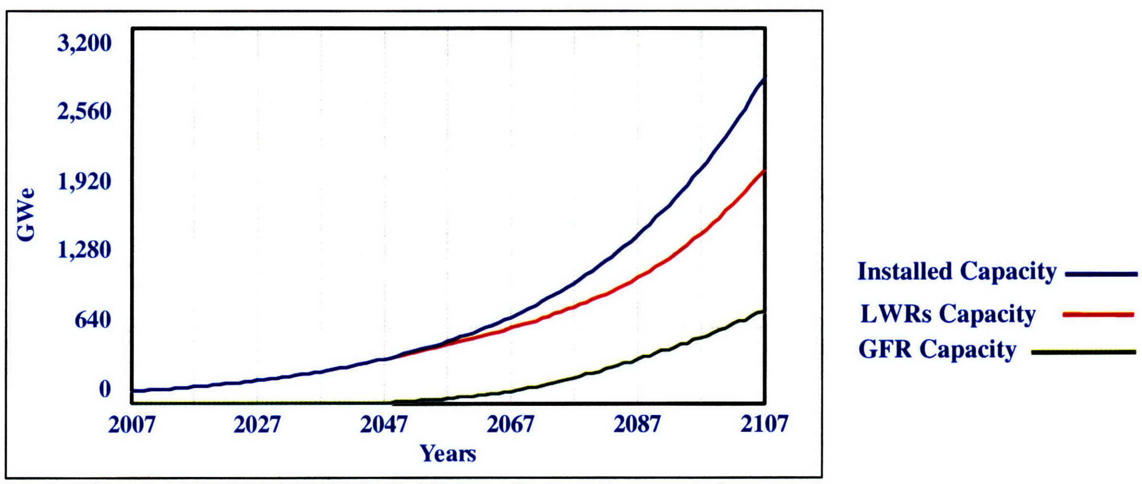

Figure 6-72- CONFU/GFR-3.4% installed nuclear capacity

As can be seen in Figure 6-73 for the 1.4 % nuclear growth, the GFR installed capacity surpasses the LWRs installed capacity after 2087, and the LWRs installed capacity decreases. In addition, very little ABR capacity is needed. The ABR installed capacity first stays constant and then decreases as ABRs are decommissioned and no more TRU is allocated to the construction of new Actinide Burner Reactors. For the 2.4% nuclear growth, as seen in Figure 6-74, the LWRs are built, particularly after 2087, due to lack of TRU to fabricate fuel for new GFRs. For the 3.4% nuclear growth, as seen in Figure 6-75, both LWRs and GFRs are built due to higher electricity demand by the end of the simulation. The LWRs continue to have the dominant share of power. It should be remembered that it is assumed that GFRs are only fueled with TRU. On reality, the GFR could be fueled with U-235, but that is not considered here.

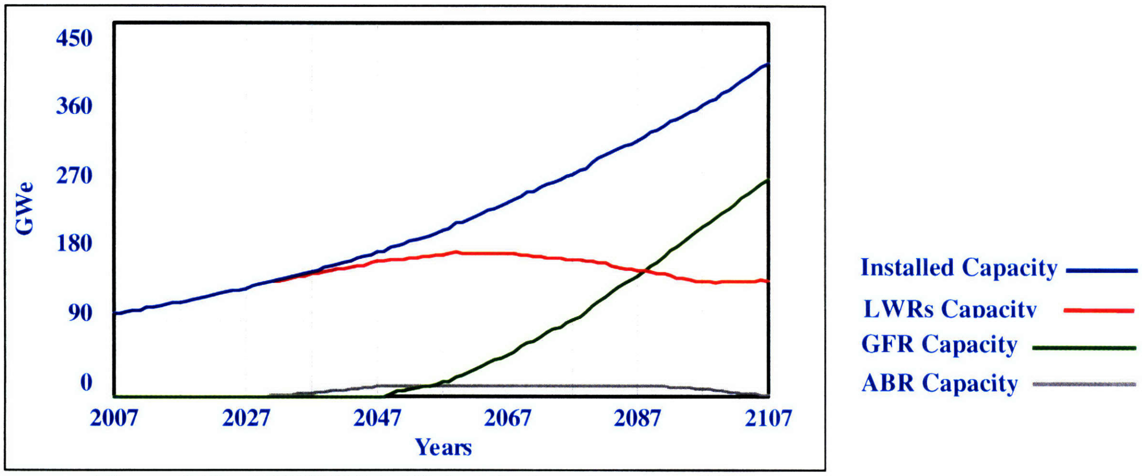

Figure 6-73- ABR/GFR-1.4% installed nuclear capacity

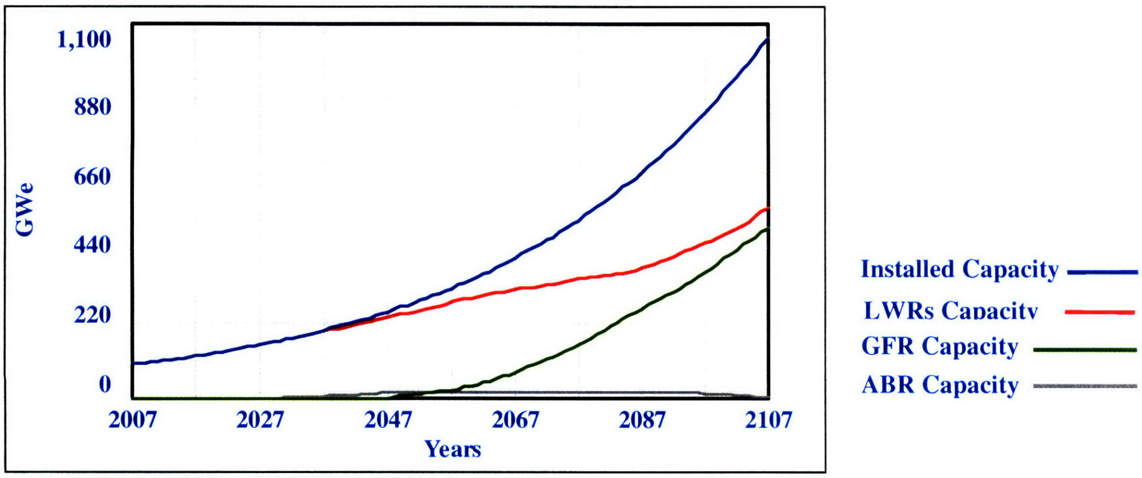

Figure 6-74 - ABR/GFR-2.4% installed nuclear capacity

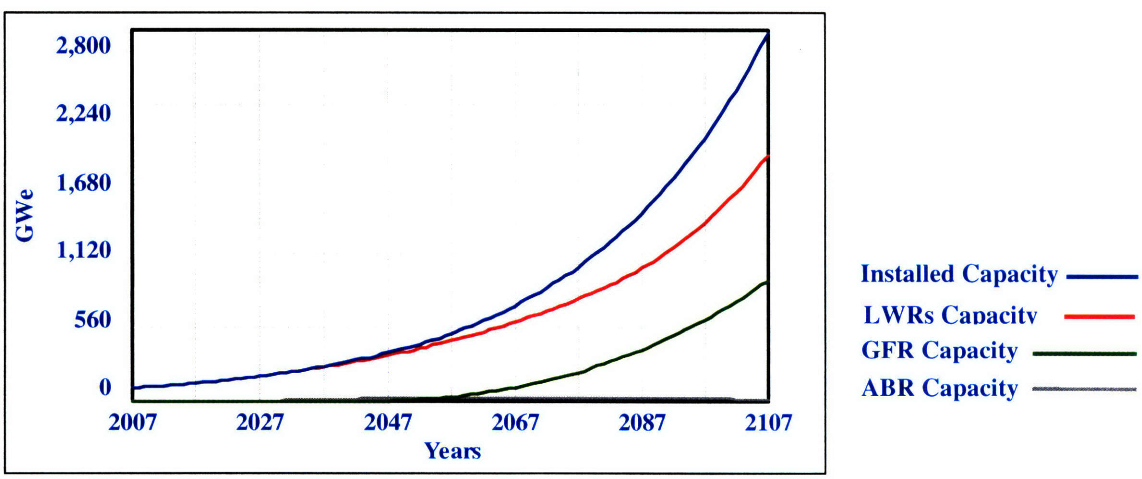

Figure 6-75 - ABR/GFR-3.4% installed nuclear capacity

Figure 6-76 and Figure 6-77 present the total incinerated[§] TRU for CONFU/GFR and ABR/GFR schemes respectively. The amount of incinerated TRU is higher in the CONFU/GFR case than in the ABR/GFR case. As can be seen, the incinerated TRU reaches a plateau after 2077 for the CONFU/GFR scheme (no more TRU for CONFU fuel fabrication after 2077 – see Table 6-3). For the ABR/GFR scheme, the amount of incinerated TRU decreases with time as ABRs are retired (there is fuel available for the ABR fleet until the end of its lifetime). It appears that a plateau would be reached beyond the period of simulation.

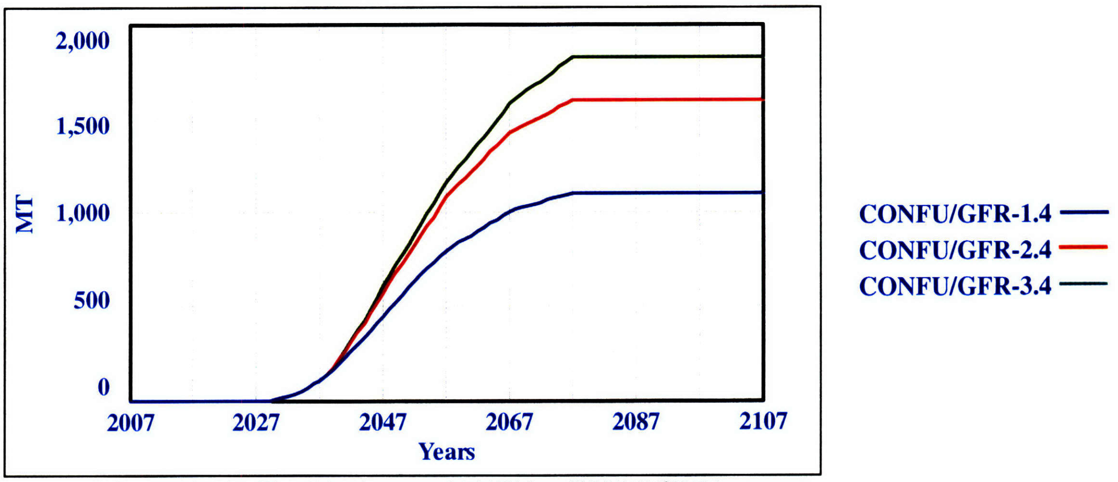

Figure 6-76 – Total incinerated TRU for CONFU/GFR

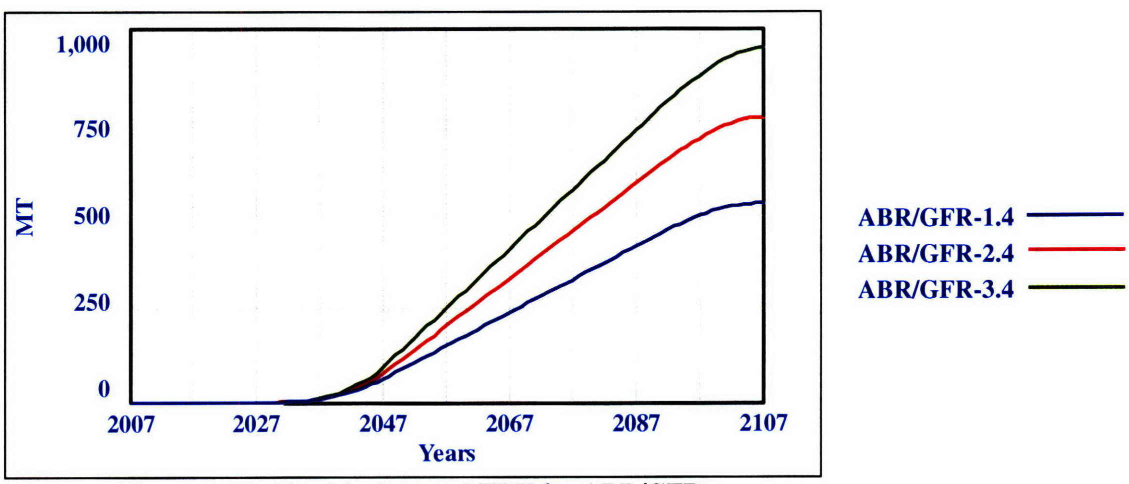

Figure 6-77 - Total incinerated TRU for ABR/GFR

[§] Incinerated TRU means TRU destroyed in the FFF fuel. Thus, even though the net TRU balance in CONFU is zero since the transuranics created in UO_2 pins equal the TRU consumed in CONFU FFF pins, the plots show TRUs destroyed in FFF pins. On the other hand, GFRs, which also have zero net TRU balance, generate and incinerate TRUs in the same fuel pin, hence zero is shown for TRU incinerated (no FFF pins).

Figure 6-78 and Figure 6-79 show the total TRU in storage[**] for both schemes. For the 1.4% nuclear growth, the total TRU in storage decreases slightly in the last 30 years of simulation for the ABR/GFR strategy. This is because of the higher ratio of GFRs to total installed capacity, as presented in Figure 6-73. However, for the 2.4% and 3.4% growth rates, there is a build up of TRU in storage. The higher the growth rate, the higher is the build up.

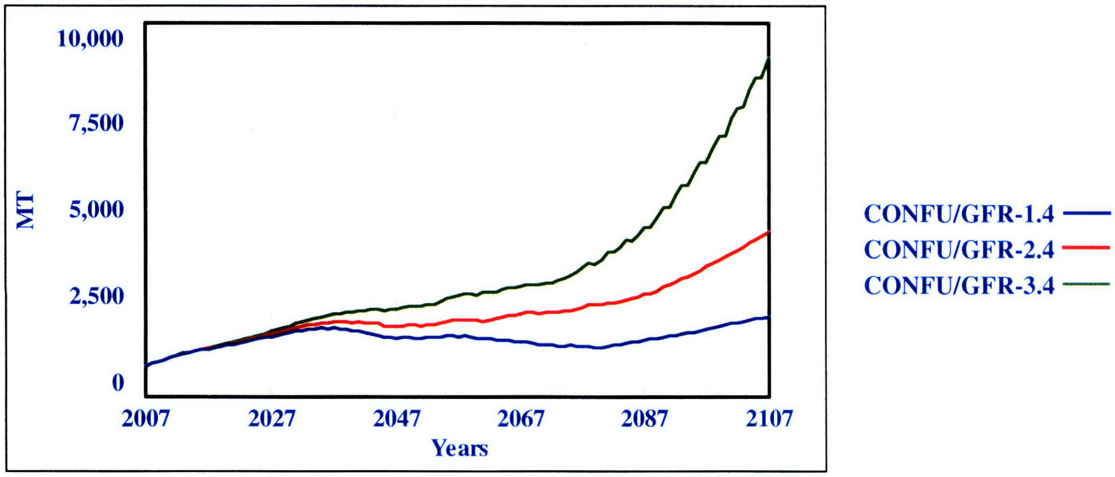

Figure 6-78 - Total TRU in storage for CONFU/GFR

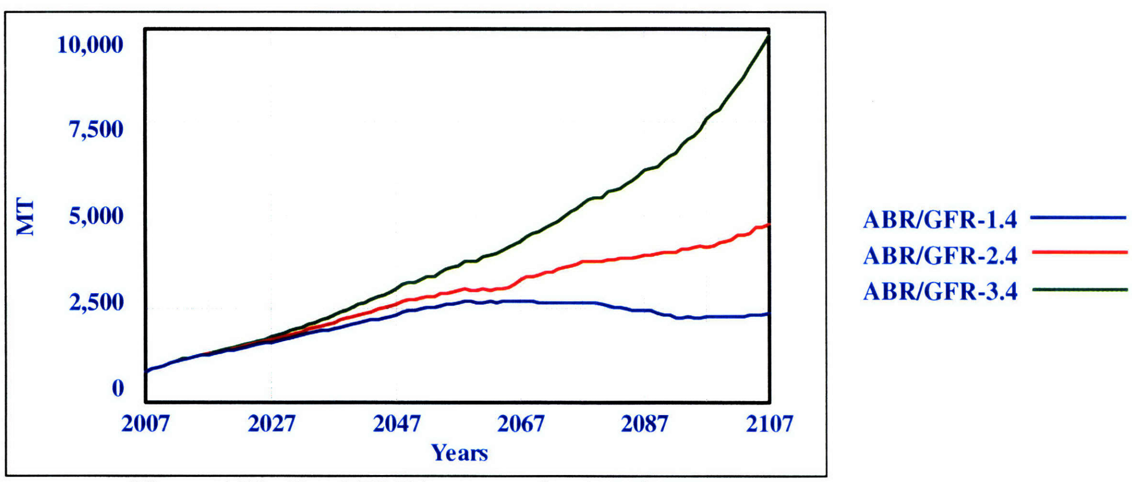

Figure 6-79 - Total TRU in storage for ABR/GFR

[**] TRU in storage is the sum of TRU in the interim storage, TRU in cooling storage, and TRU for fuel fabrication.

6.5. Summary

The simultaneous introduction of recycling technologies considering the increase in time of the fixed ratios of TRU dedicated for the fast reactors, maintains the uranium consumption, advanced fuel facilities, and SWU requirements between the needs of the CONFU scheme alone and the fast technology alone. Furthermore, the higher the percentage of TRU dedicated to the fast scheme, the more delayed is the date of depletion of known uranium resources. In addition, as the percentage of TRU available for fuel fabrication goes from 25 to 50 and then 75%, the amount of incinerated TRU decreases and gets closer to the stand-alone deployment of the advanced technology. Table 6-4 summarizes the main simulation results of the deployment of two recycling technologies with an allocation of a fixed ratio of separated TRU for each.

The simultaneous introduction of ABR/GFR recycling technologies considering a sliding fraction of separated TRU reduces the uranium consumption in the second half of the century, and demands less SWU requirements than the CONFU/GFR. However, the CONFU/GFR scheme is able to deplete the TRU inventory earlier. The initial number of UO_2 separation plants is highest for the ABR/GFR scheme, but the number of FFF reprocessing plants for two simultaneous recycling schemes is significantly lower by the second half of the century. In addition, the CONFU/GFR scheme incinerates more TRU than the ABR/GFR. As the GFR technology does not incinerate TRU, the higher ratio of GFR installed nuclear capacity to total installed capacity for the ABR/GFR scheme justifies this trend. At equilibrium, the electricity costs are approximately the same, and they are higher than those for stand-alone deployment of the CONFU and GFR schemes. Table 6-5 summarizes the main simulation results of the deployment of two recycling technologies with a sliding ratio of separated TRU.

The sensitivity analysis of nuclear growth demand of 1.4, 2.4 and 3.4% of two simultaneous recycling technologies with a sliding ratio of separated TRU indicates that the uranium mining rate and the SWU requirements for a nuclear growth demand of 1.4% remains almost constant for the second half of the century for the CONFU/GFR scheme, and they decrease after fifty years of simulation for the ABR/GFR strategy. The availability of TRU for GFR fuel fabrication and the lower growth demand justifies this trend. In addition, for a lower growth in demand, the number of separation plants remains almost constant by the end of the century. Therefore, the TRU in interim storage is depleted, and reaches equilibrium, for the three nuclear growth rates, for 1.4 % nuclear growth, the GFR installed capacity surpasses the LWRs installed capacity by the end of the simulation – the LWRs installed capacity remains constant because there is enough TRU available for the construction of new GFRs to fulfill power demand. For 2.4% nuclear growth, Figure 6-71, LWRs must be built after 2087 due to lack of TRU to fabricate fuel for new GFRs. Table 6-6 summarizes the main simulation results of the sensitivity analysis of nuclear growth demand of 1.4, 2.4 and 3.4% of two simultaneous recycling technologies.

Table 6-4 – Main simulation results for simultaneous deploying of two recycling technologies (fixed ratio)

		Cumulative U Resources [10^6 MT]	SWU Requirements [10^6 MT SWU]	TRU Inventory [MT]	UO_2 SP [Plants]	FFF RP [Plants]	TRU in Storage [10^3 MT]	Incinerated TRU [10^3 MT]
OTC	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.279	35.40	2,430	0	0	2.834	0
	2067	2.546	54.31	4,036	0	0	4.666	0
	2087	4.696	89.28	6,558	0	0	7.592	0
	2107	7.853	145.09	10,671	0	0	12.349	0
CONFU/ ABR 25%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.208	30.71	959.9	7	1	2.003	0.471
	2067	2.311	48.65	7.292	7	3	2.458	1.752
	2087	4.144	80.83	15.68	10	4	3.448	3.294
	2107	7.123	132.63	25.22	15	6	5.360	5.694
CONFU/ ABR 50%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.208	30.14	1,008	7	1	2.098	0.397
	2067	2.296	49.82	8.157	7	3	2.377	1.549
	2087	4.100	80.68	15.79	10	4	3.522	3.084
	2107	7.036	129.70	24.67	15	6	5.408	5.284
CONFU/ ABR 75%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.205	29.79	1,045	7	2	2.172	0.330
	2067	2.265	46.17	9.07	7	4	2.309	1.397
	2087	4.025	77.93	16.13	9	5	3.394	2.832
	2107	6.901	142.95	26.15	15	8	5.318	4.937
CONFU/ GFR 25%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.196	29.03	965.30	7	1	1.900	0.406
	2067	2.195	42.18	6.687	7	2	2.001	1.277
	2087	3.780	69.87	13.76	9	2	3.050	2.231
	2107	6.361	114.60	23.66	14	3	4.582	3.704
CONFU/ GFR 50%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.184	26.36	1,016	7	1	1.890	0.268
	2067	2.066	35.99	7.695	7	1	1.893	0.792
	2087	3.450	61.81	12.64	8	1	2.711	1.262
	2107	5.765	104.47	20.74	12	2	4.169	2.034
CONFU/ GFR 75%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.179	25.21	1,052	7	1	1.884	0.126
	2067	1.938	29.50	6.752	7	1	1.948	0.394
	2087	3.081	51.66	10.54	6	1	2.910	0.604
	2107	5.113	95.19	19.81	11	1	4.233	0.914

Table 6-5 – Main simulation results for simultaneous deployment of two recycling technologies (sliding ratio)

		Cumulative U Resources [10^6 MT]	SWU Requirements [10^6 MT SWU]	TRU Inventory [MT]	UO_2 SP [Plants]	FFF RP [Plants]	TRU in Storage [10^3MT]	Incinerated TRU [10^3MT]
OTC	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.279	35.40	2,430	0	0	2.834	0
	2067	2.546	54.31	4,036	0	0	4.666	0
	2087	4.696	89.28	6,558	0	0	7.592	0
	2107	7.853	145.09	10,671	0	0	12.349	0
CONFU/ GFR	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.205	31.19	834.5	7	2	1.868	0.570
	2067	2.247	41.27	10.23	7	2	2.196	1.417
	2087	3.634	55.37	14.22	10	0	2.733	1.592
	2107	5.682	89.97	20.17	13	0	4.384	1.592
ABR/ GFR	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.255	32.23	1005	8	1	2.632	0.077
	2067	2.331	42.12	10.34	8	2	3.304	0.330
	2087	3.638	51.89	12.42	9	1	3.954	0.583
	2107	5.454	77.27	17.81	12	1	4.757	0.756

Table 6-6 - Main simulation results for simultaneous deployment of two recycling technologies

		Cumulative U Resources [10^6 MT]	SWU Requirements [10^6 MT SWU]	TRU Inventory [MT]	UO_2 SP [Plants]	FFF RP [Plants]	TRU in Storage [10^3MT]	Incinerated TRU [10^3MT]
OTC 2.4%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.279	35.40	2,430	0	0	2.834	0
	2067	2.546	54.31	4,036	0	0	4.666	0
	2087	4.696	89.28	6,558	0	0	7.592	0
	2107	7.853	145.09	10,671	0	0	12.349	0
CONFU/ GFR 1.4%	2027	0.421	17.04	1,402	0	0	1.671	0
	2047	0.952	20.19	863.9	5	1	1.556	0.442
	2067	1.573	21.42	95.04	5	1	1.451	0.999
	2087	2.217	23.27	6.54	5	0	1.498	1.094
	2107	2.942	27.43	7.05	5	0	2.132	1.094
CONFU/ GFR 2.4%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.205	31.19	834.5	7	2	1.868	0.570
	2067	2.247	41.27	10.23	7	2	2.196	1.417
	2087	3.634	55.37	14.22	10	0	2.733	1.592
	2107	5.682	89.97	20.17	13	0	4.384	1.592
CONFU/ GFR 3.4%	2027	0.540	26.13	1,458	0	0	1.741	0
	2047	1.556	46.70	1,083	8	2	2.332	0.603
	2067	3.387	82.74	182.57	12	2	2.952	1.572
	2087	6.587	148.45	31.95	20	0	4.536	1.825
	2107	12.450	282.97	57.98	31	0	9.057	1.852
ABR/ GFR 1.4%	2027	0.421	17.04	1,402	0	0	1.671	0
	2047	0.993	21.90	1,067	5	1	1.609	0.061
	2067	1.630	21.40	0.408	5	1	2.714	0.237
	2087	2.216	19.35	0.100	4	1	2.476	0.441
	2107	2.764	18.60	0.574	4	1	2.381	0.530
ABR/ GFR 2.4%	2027	0.477	21.27	1,429	0	0	1.671	0
	2047	1.255	32.23	1005	8	1	2.632	0.077
	2067	2.331	42.12	10.34	8	2	3.304	0.330
	2087	3.638	51.89	12.42	9	1	3.954	0.583
	2107	5.454	77.27	17.81	12	1	4.757	0.756

		Cumulative U Resources [10^6 MT]	SWU Requirements [10^6 MT SWU]	TRU Inventory [MT]	UO_2 SP [Plants]	FFF RP [Plants]	TRU in Storage [10^3 MT]	Incinerated TRU [10^3 MT]
ABR/ GFR 3.4%	2027	0.540	26.13	1,458	0	0	1.741	0
	2047	1.605	48.90	1,253	9	1	3.047	0.092
	2067	3.456	82.38	28.55	12	2	4.325	0.407
	2087	6.543	141.24	29.68	19	2	6.199	0.723
	2107	12.06	262.32	54.66	34	2	9.806	0.946

7 Assessment of the Brazilian Nuclear Market

7.1. Introduction

Brazil has several R&D nuclear facilities, including few research reactors, and one nuclear power station with two commercial power reactors, *Angra 1* and *Angra 2*, with an installed capacity of 2 GWe. However, the planned scenario for nuclear growth in Brazil is for the constructions of one more LWR at the same site of *Angra 1* and *Angra 2:* the construction of the 1.3 GWe *Angra 3* was approved in July 2007, and it should start commercial operation in 2012. Moreover, at least eight new nuclear power reactors will be built in the next three decades [28]. Under this assumption, the calculated annual growth rate is 7.3% per year, close to the 7.8% found in the reference [8]. However, with electricity demand by 2030 expected, by the OECD's International Energy Agency, to double from that of 2004, there is plenty of potential for growth in nuclear capacity in the country. Furthermore, Brazil has been discussing the construction of new nuclear power reactors as regulator element in the installed electric capacity, which relies heavily on hydropower and is susceptible to effects of droughts.

The desire to acquire all fuel cycle steps for peaceful applications started just after the country bought the first power reactor, *Angra 1*, in the mid-70s. However, the public attitude concerns about nuclear, the large hydro potential of more than 260 GWe, and the use of alternative sources of energy, did not justify investments in nuclear power. Nevertheless, Brazil is the only country in South America with significant inferred uranium resources, as presented in Table 7-1. In addition, it has commercial uranium mining facilities, and small facilities for conversion and commercial enrichment, as presented in Table 7-2 and Table 7-3. Looking three decades ahead, the nuclear market in Brazil is expected to grow, and investments in R&D, in advanced nuclear fuel facilities, and reactors technology are anticipated.

In this chapter, the Brazilian nuclear market is discussed. The introduction of advanced recycling technologies with a lower limit instantaneous mass loading factor of 0.5 for advanced fuel facilities, and for a lower limit cumulative mass loading factor of 0.8, is evaluated. The cumulative mass loading factor is calculated for the entire fleet during the period of simulation. In addition, the impact of a nuclear partnership between U.S. and Brazil on the U.S. nuclear requirements is evaluated.

Table 7-1 – Identified uranium resources - cost range < US$130/kg U (source OECD 2006)

Country	Identified uranium resources [MT U]	Percentage world wide
Australia	1,143,000	24.09
Kazakhstan	816,099	17.20
Canada	443,800	9.35
USA	342,000	7.21
South Africa	340,596	7.18
Namibia	282,359	5.96
Brazil	278,700	5.88
Niger	225,459	4.76
Russia	172,402	3.64
Uzbekistan	115,526	2.43
Other Countries	582,912	12.3
World Total	**4,742,853**	**100**

Table 7-2 – Uranium hexafluoride conversion facilities (source OECD 2006)

Country	Owner/Controller	Plant name/location	Capacity [MT/Year]
Brazil	IPEN	São Paulo	40
Canada	Cameco	Port hope, Ontario	10,500
China	CNNC	Lanzhou	400
France	COMURHEX	Pierrelatte	14,000
	Areva NC	Pierrelatte TU5	350
Iran	AEOI	Isfahan	193
Russia	Rosatom	Ekaterinburg	4,000
		Angarsk	20,000
United Kingdom	British Nuclear Fuels	Springfield, Lancashire	6,000
United States	Honeywell	Metropolis, Illinois	17,600
Total			**73,133**

Table 7-3 – World commercial enrichment facilities (source: IEEE 2006)

Country	Capacity [MT SWU]	Percentage world wide	Technology
Russia	15,000	31.5	Centrifuge
United States	11,300	23.7	Diffusion
France	10,800	22.7	Diffusion
England, Germany & Netherlands (Urenco consortium)	8,300	17.5	Centrifuge
Japan	1,050	2.2	Centrifuge
China	1,000	2.1	Centrifuge
Brazil	120	0.3	Centrifuge
Total	**47,570**	**100**	**---**

7.1.1. General information about Brazil

The Republic Federative of Brazil covers nearly half of South America with an area of 8,514,215.3 km^2 and a shore of almost 7,500 km. It is the fifth largest country in the world and it has a population of more than 180 million people, most of them living in the high-density areas of eastern Brazil, along the coast or the major rivers. In addition, about 85% of the population lives in urban areas and highly unequal income distribution remains a pressing problem. Moreover, Brazil's *Gross Domestic Product (GDP)* is one of the top ten in the world. Exploiting vast natural resources and a large labor pool, Brazil's economy outweighs that of all other South American countries, and is expanding its presence in the world markets, as presented in Table 7-4. The Brazilian economy is based on large and well-developed agricultural, mining, manufacturing and service sectors.

In Brazil, almost all reserves of fossil fuel are found in the ocean, and the country attained self-sufficiency in oil production in 2006 due to the *Brazilian Petrol Company* (PETROBRAS) technology in deepwater oil production, reaching depths of more than 1,000 meters. The country has reached energy independence due to an extensive program of diversification of a fuel matrix based on "*Fossil & Renewable – Alcohol & Biodiesel*" [22]. As a result, more than 75% of all vehicles sold nationwide can run with gas or ethanol in any proportion -- it represents more than 41% of all gasoline sold every day. Moreover, Brazil started the addition of 2% of bio-diesel in mineral diesel, and all gasoline commercialized in Brazil has 25% of ethanol, and the country has been recognized as the world leader in the use of renewable resources and green energy.

Table 7-4 –General information about Brazil

Area	8,514,215.3 km^2	
GDP (2006 purchasing power parity)	US$ 1.655 trillion	
GDP (2006 official exchange rate)	US$ 967 billion	
GDP - per capita (2006 estimated)	US$ 8,800	
Inflation rate (consumer prices)	3%	
Labor force per occupation	agriculture: 20% industry: 14% services: 66%	
Exchange rates: **(Brazilian Real *per* U.S. dollar)**	3.0771 (2003) 2.9251(2004) 2.4344 (2005) 2.1761 (2006) 1.802 (October 2007)	

7.1.2. Electric Power System in Brazil

The Brazilian energy supply portfolio, presented in Figure 7-1, has large hydro plants, thermoelectric plants running on natural gas, coal, oil and biomass, and nuclear power reactors. The electric power system is hydro dominated. Moreover, the hydro electricity generation is one of the largest Brazil's competitive advantages, because it is a carbon-free renewable resource, and it can be implemented with 100% of national technology and services. Furthermore, the Brazilian environmental legislation is one of the most demanding in the world, and it guarantees the construction of hydro plants according to international sustainable rules.

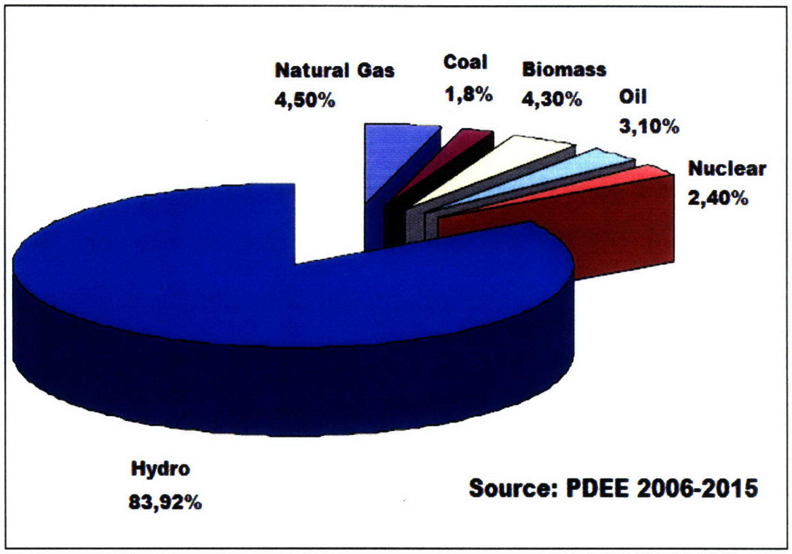

Figure 7-1 - Brazil electricity supply (source: PDEE 2006-2015)

Nuclear power plays a small role in Brazil. Less than 2.5% of all electric energy is provided by the two LWRs located in Angra dos Reis, a beautiful city on the Atlantic coast, midway between Rio de Janeiro and Sao Paulo -- two of the most populous cities in the country. The construction of more reactors has been discussed and postponed for decades due to political issues and financial problems. More than a matter of public attitude, the construction of new power reactor wasn't an economically competitive choice until recently. Besides, concerns about safety, proliferation risk and waste have been discussed by the government and industry in order to increase public support for nuclear expansion. Table 7-5 presents the installed capacity by source of electricity according to the *Decennial Plan of Electric Energy (PDE) 2006-2015* [23]. The Brazilian electric installed capacity is the world's tenth.

Table 7-5 – Installed Capacity in 12/31/2005 (source: PDE 2006-2015)

Source	Installed capacity (MWe)
Large Hydro	69,631
Thermo	19,770
Nuclear	2,007
Small Hydro	1,330
Itaipu (Hydro)	7,778
TOTAL	100,516

Thermal power plants, which run mainly with natural gas, biomass and oil, generate large fraction of electricity. The utilization of biomass is explained due to the high domestic availability -- the main biomass sources are sugarcane products: ethanol and bagasse. The utilization of natural gas instead of fossil liquid fuel, and the improvement of more efficient and clean burning [23] decreased the greenhouse emission and brought important benefits to the electrical system of the country increasing the reliability of the system due to crisis in the hydro reservoir. Nevertheless, the thermal plants can be installed near or in the load centers, where they can act in the stabilization of the power levels.

Brazil's hydroelectric potential is one of the largest: it was estimated at 260,000 MWe in 2004. The three major river systems are the Parana-Paraguay-Plata in the South, the Sao Francisco in the East, and the Amazon in the North. The Amazon, well known because of its forest, is the second longest river in the world, 4,000 miles long, and it has the greatest total flow of any river, carrying more than the Mississippi, the Nile, the longest river in the world, and the Yangtze rivers combined. It is responsible for 20% of all fresh water entering in the oceans worldwide. The hydro resources located in the Northeast, Southeast and South have already been thoroughly surveyed. The hydroelectric potential of the North and Central-West regions, which cover practically Brazil's Amazon Forest area, can meet the national electric needs, but the construction of large hydroelectric plants, besides the high investment at the beginning and the floating of a large area, must following sustainability rules.

Therefore, the average area flooded over installed power is 0, 52 km^2/MWe and the reservoir area represents about 0, 4% of the country territory. The hydro system is characterized by larger reservoirs organized in a complex topology over several rivers. Besides, 47% of the flood areas are located in the Parana River basin. In this basin, at the southeast and south of the country, there are 52 plants, totaling 40,222 MWe. Itaipu, seen in Figure 7-2, is one of the biggest hydroelectric plants in the world, with an installed capacity of 12 GWe, and it is located on the Parana River [24].

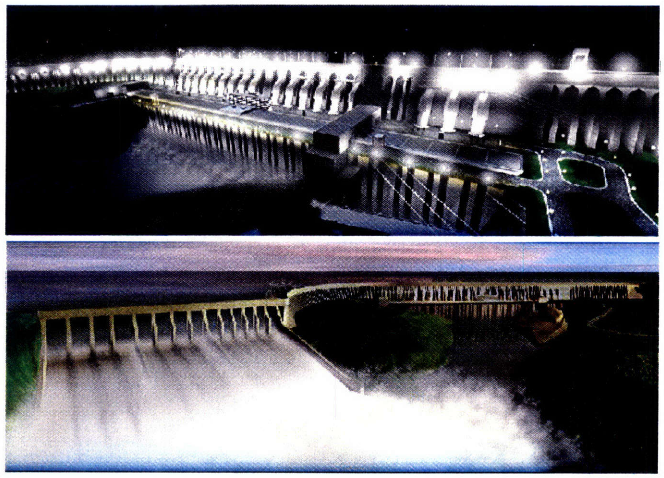

Figure 7-2 – Itaipu 12 GWe hydroelectric plant (source: www.itaipu.gov)

Although the hydro damns are responsible for almost 84% of the electricity, Brazil still has substantial hydropower potential undeveloped. The current exploited hydropower potential compared with other countries is plotted in Figure 7-3. Therefore, in July 2007, the government approved the construction of two more hydro plants with a combined installed capacity of 10,000 MWe, which should start commercial operation in 2012. For the next ten years, the government has planned the construction of eight new hydroelectric plants in the Amazonian basin, total 12,494 MWe – three of them have been already included in the 2006's electricity auction. Furthermore, an intense exploration of the Tocantins basin is also registered, with fourteen new hydroelectric planned, totaling 7,021 MWe – four of them already under construction. For the Parana River basin, 29 new hydro plants are planned -- six of them are under construction, totaling 4,848 MWe. The increase in the thermoelectric generation by natural gas should be 6,100 MWe. The participation of biomass should add more 1,800 MWe to the energetic matrix.

In December 2005, when the government sold the rights of exploration for energy, the average cost of thermal energy was US$ 61.70/MWh. For the hydroelectric energy, the average cost was US$ 45.50/MWh for the plants to be ready in 2008, and US$ 51.10/MWh for the plants to be ready in 2010. However, for the energy that will be generated in the North of the country, more US$ 4.00/MWh for the transmission costs must added. On the other hand, the *Eletrobras Thermonuclear S.A* (ELETRONUCLEAR) estimation of the *Angra 3* electric energy cost is

US$ 62.20, very close to the values reached last December for the thermal power plants. With this value, the activation of *Angra 3* became more economically attractive for the country.

To summarize, the *Brazilian Interconnected System* (SNI) has a total installed capacity of about 100,500 MWe [23] (2005) with 114 hydro plants with capacity greater than 30 MWe, 47 thermal plants, and 2 power reactors, *Angra 1* e *Angra 2*, with an installed capacity of 2,007 MWe. The government should increase the generation capacity by 40,000 MWe in the next ten years at the total cost of US$ 40 billions. About 60,000 km of high voltage transmission lines should be added to the SNI in this period.

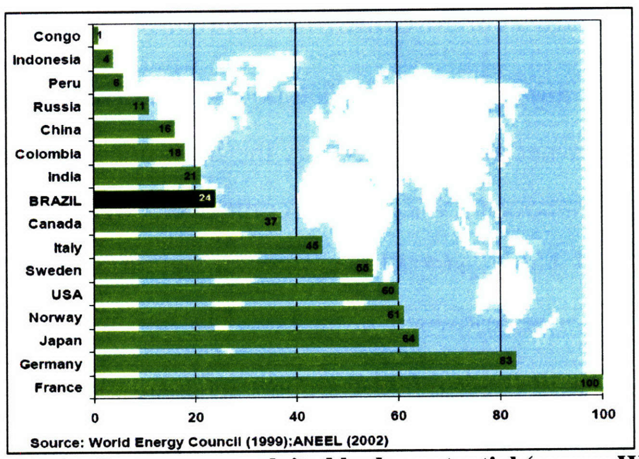

Figure 7-3 – Percentage exploited hydro potential (source:WEC)

7.2. Nuclear industry in Brazil

The Brazilian *National Nuclear Energy Commission* (CNEN) has R&D facilities for fuel cycle, reactor technology, radioisotopes, medicine and industrial nuclear applications, and few research reactors [15]. At the *Nuclear and Energy Research Institute* (IPEN), Sao Paulo, there are two research reactors: a five MW pool type, and a cyclotron, with radioisotope production, at the *Nuclear Engineering Institute* (IEN), Rio de Janeiro, there is an *Argonaut* research reactor, and at the *Center for the Development of Nuclear Technology* (CDTN), Belo Horizonte, there is a *Triga* research reactor. At the *Navy Technology Center at Sao Paulo* (CTMSP), a dual program for a prototype reactor for naval propulsion, and for small power plants is being developed. Moreover, Brazil has been involved in the *Generation IV International Forum*, and in the IAEA *International Project on Innovative Nuclear Reactors and Fuel Cycles* (INPRO) program, both developing new-generation reactor designs and nuclear technology. The CNEN is also involved with *Westinghouse Electric Company* in developing the *International Reactor Innovative and Secure* (IRIS) modular reactor.

Brazil has large uranium resources, and extracts uranium ore and concentrates it in yellowcake at a mining and milling unit. In addition, it has a pilot enrichment plant, located in the *Brazilian Navy Experimental Center of Aramar* (CEA), at 100 kilometers from Sao Paulo, which has been working since the eighties, and a newly commercial enrichment facility located in Resende, Rio de Janeiro, which will be responsible for enrichment of the fuel for its reactors -- Brazil ships its uranium to be enriched in Europe, and gets it back to fabricate the nuclear fuel. By doing the enrichment at home, Brazil expects saving US$ 16 million per year [25]. The centrifuges installed at Resende were developed and produced by the *Brazilian Navy*.

The two commercial nuclear power reactors are operated by ELETRONUCLEAR, a mixed-economy company, owned in its majority by the Brazilian government. The power reactor *Angra 1*, a 657 MWe Westinghouse LWR, started commercial operation in 1985, and *Angra 2*, a 1,350 MWe Siemens-KWU LWR, started commercial operation in 2001 [26]. The *Nuclear Industries of Brazil* (INB), a state-owned company, has the monopoly to mine uranium and produce nuclear fuel. The main mining and processing plant is located at Caetite and it started operation in 2000 -- only 25% of the country territory was surveyed for uranium resources in the 70s. Also, the *Brazilian Navy* has under construction a UF_6 plant at CEA, which should start commercial operation in 2008. In Resende, there are two INB plants (*Unit I* and *Unit II*) for fuel fabrication, and for fabrication of fuel elements. The storage of spent fuel is undertaken at the site on a long term [26]. In addition, the government is planning to have more 13 GWe nuclear units until 2035 [27]. Nuclear power must play a more significant role in the Brazilian energy matrix because it is impossible to build more hydroelectric plants near the higher electricity demand areas, like the *Sao Francisco River*, but commercial power reactors could be constructed near the river [28]. Moreover, the country expects to build light water reactors with a 100% Brazilian technology.

The construction of the first two reactors was slowed down and was halted several times due to political problems, and because the public's attitude was against the construction. To avoid delays during the construction of the next reactors, all issues related to the construction, operation and waste management have been discussed with the population. Therefore, Brazil decided to build a new reactor, denominated *Angra 3*. The construction of *Angra 3* should cost US$ 4.54 billion (2007 estimated) -- Brazil has already spent US$ 750 millions in equipment which have been in storage at the cost of US$ 20 million/year [29]. In addition, at the CTMSP and CEA, the Navy project remains active but at low government priority and budget. The initial intention to build nuclear powered submarines is placed far away in the future, but a LWR, with Brazilian technology, is under construction. The reactor, a prototype nuclear installation which should reach criticality in 2010 [30], will be one more tool for R&D activities for the development of commercial nuclear reactors. In addition, Brazil has managed to assure the international community that its intentions are industrial and commercial, not military, and an enrichment plant has been transformed into a commercial venture that should reach the production of 120,000 SWU/Year [26], enough for the current Brazilian nuclear power reactors. The total cost of the plant was US$180 million, and the electromagnetic controlled centrifuges, with rotors that levitate spinning frictionless, were developed by the *Brazilian Navy*.

In 2004, the Brazilian's centrifuges were at the heart of a major controversy. As party to the *Nuclear Non-Proliferation Treaty* (NPT or NNPT), the IAEA used to inspect the pilot enrichment plant, a navy facility, without problems even with a cover of panels to protect some aspects of its centrifuges. But when Brazil and IAEA began discussing inspections at the new facility in the city of Resende, presented in Figure 7-4, the agency insisted that it must have full visual access to the complete centrifuges installation. Brazil's arguments were the protection of some aspects of the centrifuges, which includes the unique design, shape, materials and the control system. Accordingly to Brazilian Officials, the centrifuges were designed with electromagnetic bearings which eliminated all points of contact and friction between rotating and fixed parts in the machine and it makes the machines more efficient and durable. Moreover, the centrifuge's third generation, installed in the enrichment facility in Resende are made of carbon-fibber [31].

The negotiations between Brazil and IAEA pulled along for a while. Worldwide experts argued that Brazil was setting a dangerous precedent [32] saying that the facility must be closed and compared the situation with Iran. But Brazilian Officials denied these charges for many reasons:

- Brazilian Constitution banned the use of nuclear energy for all other purposes but peaceful applications;

- Brazil has safeguards of IAEA and *Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials* (ABACC) for more than 15 years without any kind of incident or misunderstanding;
- The domain of nuclear technology is part of a broader industrial policy necessary for the country's growth; and
- There is no illegal transfer of technology involving the Brazilian facility.

Figure 7-4 – Resende enrichment facility (source: IEEE)

By the end of 2004, the size of the shielding panels was reduced and other procedures were taken to guarantee that there is no diversion of uranium. Consequently, IAEA and Brazil agreed on inspection terms. With this new facility, Brazil became one of the few countries that operate commercial centrifuge facilities. According to Brazilian Officials, the first reason behind acquiring the enrichment facility is that Brazil has large uranium reserves, as presented in Table 7-1, and commercial enrichment capability will give Brazil nuclear fuel autonomy. The two power reactors and the construction of more LWRs justify the country desire to make its own fuel. The second reason is economic. The enrichment services for about 90 percent of the world's nuclear power plants --397 of a total of 441 -- is a US $5-billion-a-year global market in which Brazil hopes to participate sometime in the future.

7.3. Assessment of nuclear technology in Brazil

In this section, the impact of the introduction of advanced technologies in the nuclear energy market in Brazil is evaluated. SWU requirements and uranium resources are discussed for three technologies over one hundred years. In addition, the sensitivity analysis for uranium prices of 60, 120 and 180 US$/kg is addressed. The annual growth rate under this scenario is 7.3% per year for the first fifty years, which is very close to 7.8% found in the reference [8]. After 2057, an annual growth rate of 4.1%, as seen in Figure 7-5, is assumed. The age distribution of the two commercial power reactors in Brazil is assumed to be 22 years old (*Angra 1*), and six years old (*Angra 2*). Moreover, the amount of spent fuel in interim storage is taken as 500 MT, considering an averaged discharged rate of 20 MT/Year/LWR.

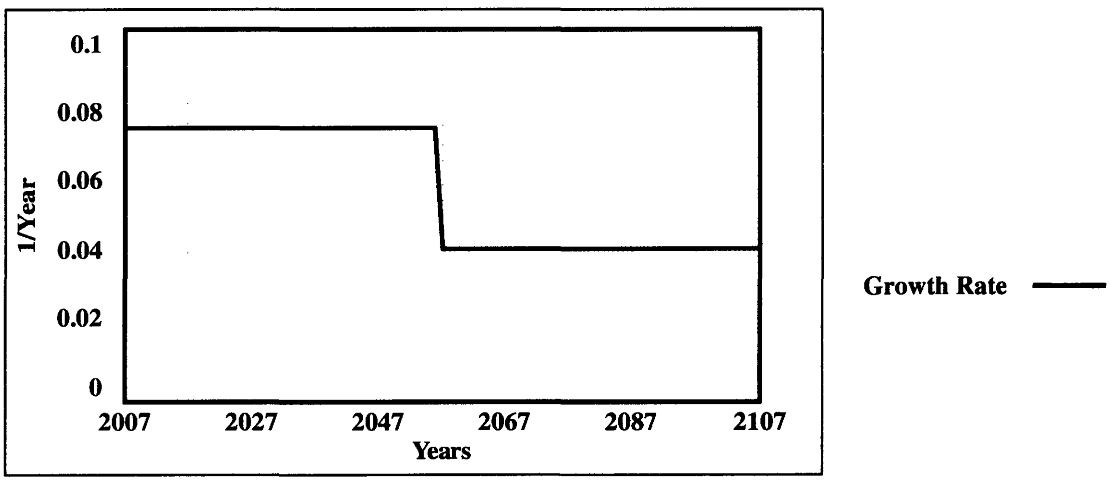

Figure 7-5 - Assumed nuclear annual growth rate

The impact of the introduction of the technology is also evaluated under the assumption that separation and reprocessing plants must have a lower limit mass loading factor of 0.5, and for a lower limit cumulative mass loading factor of 0.8. The cumulative mass loading factor is calculated for the entire fleet during the horizon of simulation. Furthermore, the introduction date of the technology was delayed until the minimal loading factor can be reached. Indeed, the construction delay is expected due to small amount of spent fuel legacy, and the initial installed nuclear power of two power reactors. Therefore, advanced recycling technologies are introduced in 2050.

The size of the separation plants is taken as 500 MT, and the industrial capacity is taken as 250 MT/Year/Year. Also, the industrial capacity doubles after 25 years of the introduction of the technology. The separated fuel cost is taken as 1.6 x10^3 \$/kg. The size and the industrial capacity of GFR reprocessing plants are taken identical to those for separation plants. However, the GFR reprocessed U/TRU cost is taken as 3.2 x10^3 \$/kg, twice more expensive than the UO_2 spent fuel separation. The nominal capacity of FFF reprocessing plant is taken as 25 MT/Year, and its industrial capacity is taken as 12.5 MT/Year/Year. In addition, the reprocessed FFF fuel cost is considered 11.5 x10^3 \$/kg.

7.3.1. The impact of advanced technologies on uranium resources

As can be seen in Figure 7-6, Figure 7-7, and Figure 7-8 for the annual growth on nuclear power demand presented in Figure 7-5, which represents an installed capacity of 585 GWe after 100 years of simulation, as plotted in Figure 7-15 and Figure 7-16, the GFR recycling scheme has the most significant reduction of the uranium ore mining rate, the uranium resources consumption, and delays the depletion date of uranium resources. Indeed, little difference in U consumption is expected from TRU burning in low conversion ratio reactors. Therefore, the GFR technology requires less uranium resources due to U recycling and near unity conversion ratio. Furthermore, the need for SWU requirements for the GFR strategy is 72.8% of the total separative work units required for the once-through cycle. Nevertheless, in a non-breeding fuel system, is expected an eventual increase in the consumption of U due to lack of TRU.

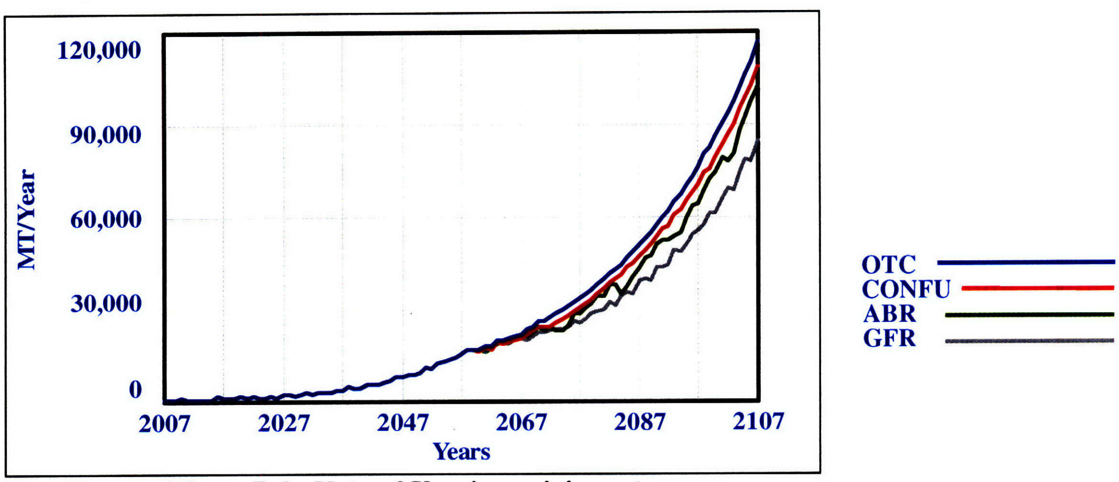

Figure 7-6 – Natural Uranium mining rate

As revealed by Figure 7-9, the SWU requirements for Brazil should reach 82x10^6 MT SWU/Year if no recycling strategy is adopted. Therefore, the country should expect a significant investment on enrichment facilities due to the current uranium enrichment capacity.

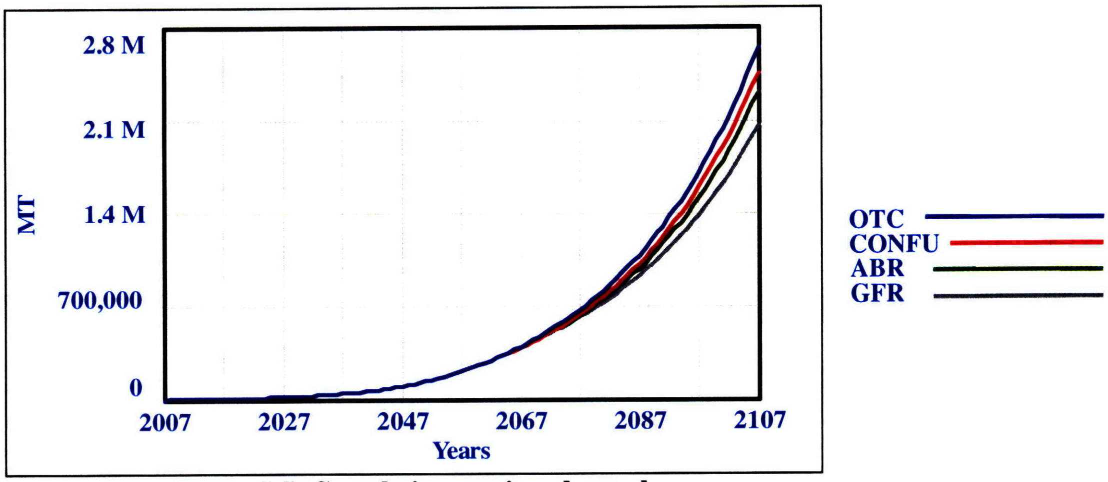

Figure 7-7 -Cumulative uranium demand

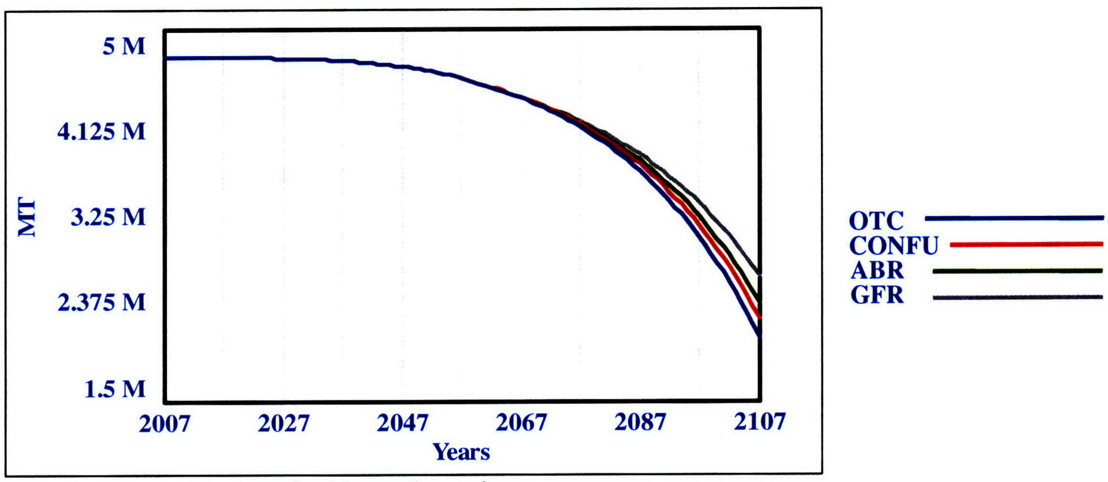

Figure 7-8 – Natural uranium resources

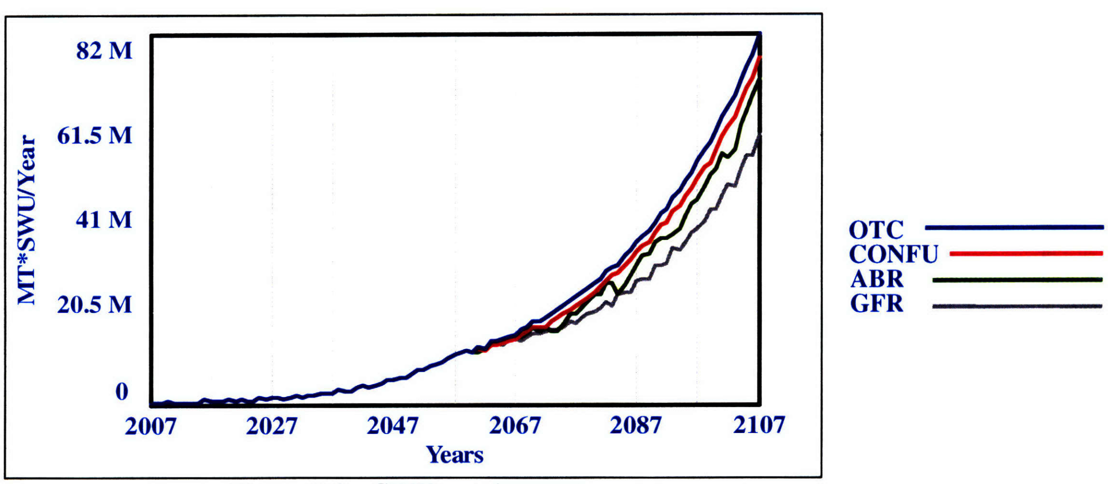

Figure 7-9 – SWU requirements

As show in Figure 7-10, the simulation results indicate that all three technologies are able to deplete the TRU inventory at interim storage. However, the CONFU strategy is the most flexible technology since its batches can be mixed with traditional UO_2 batches in the current

LWR fleet. Therefore, the deployment of the CONFU recycling scheme keeps the inventory below reasonable level, and guarantees equilibrium between the generation and consumption of TRU without further investments in the construction of fast reactors. After 100 years of simulation, the amount of TRU in interim storage for the OTC is 3,584 MT. The TRU peak for CONFU is 337.71 MT (2060), and for GRF/ABR technologies is 359.11 (2062), which represents 9.42% and 10.01% of the total TRU in interim storage for the OTC. The introduction of advanced recycling technologies reduces the amount of TRU for storage by a factor of 10. Nevertheless, the results demonstrate that the CONFU technology has no significant impact on the amount of uranium resources needed neither on the SWU requirements.

Figure 7-11 shows the fleet of separation plants to deplete the TRU inventory in interim storage, and Figure 7-12 presents the mass loading factor for all separation facilities under commercial operation. The cumulative mass loading factor for the CONFU scheme is 0.9506, for the ABR strategy is 0.9127, and for the GFR technology is 0.9109 after one hundred years of simulation. Figure 7-13 gives the number of FFF reprocessing plants to be build to reprocess FFF spent fuel from CONFU and ABR technology. The instantaneous mass loading factor has a lower limit of 0.5, and the cumulative mass loading factor for the CONFU scheme is 0.7704 and 0.9491 for the ABR technology.

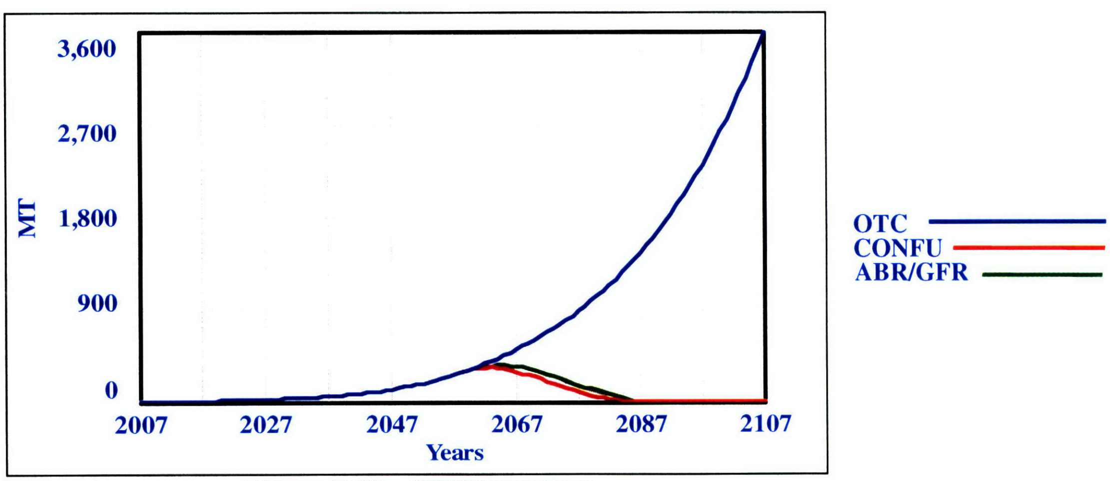

Figure 7-10 – TRU inventory

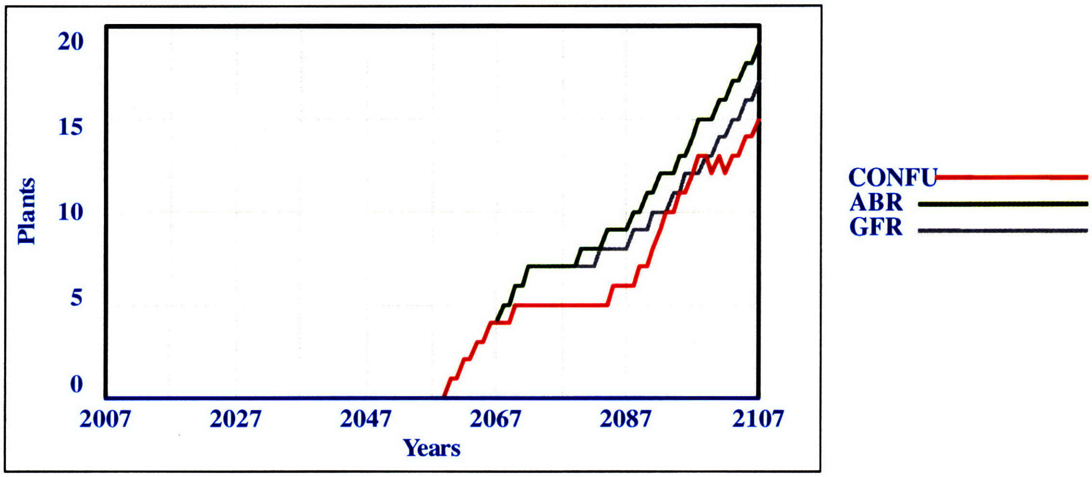

Figure 7-11 – Fleet of separation plants

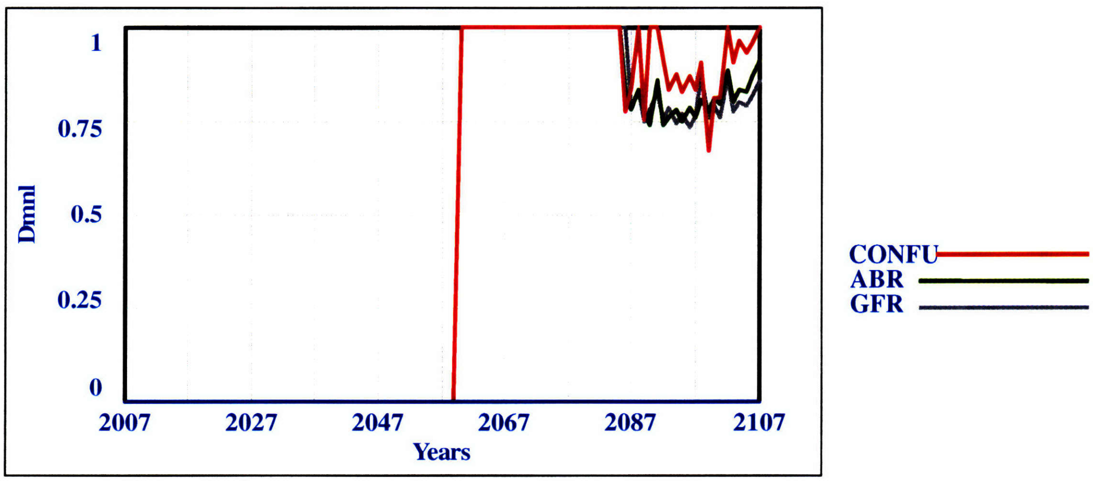

Figure 7-12– Separation plants mass loading factor

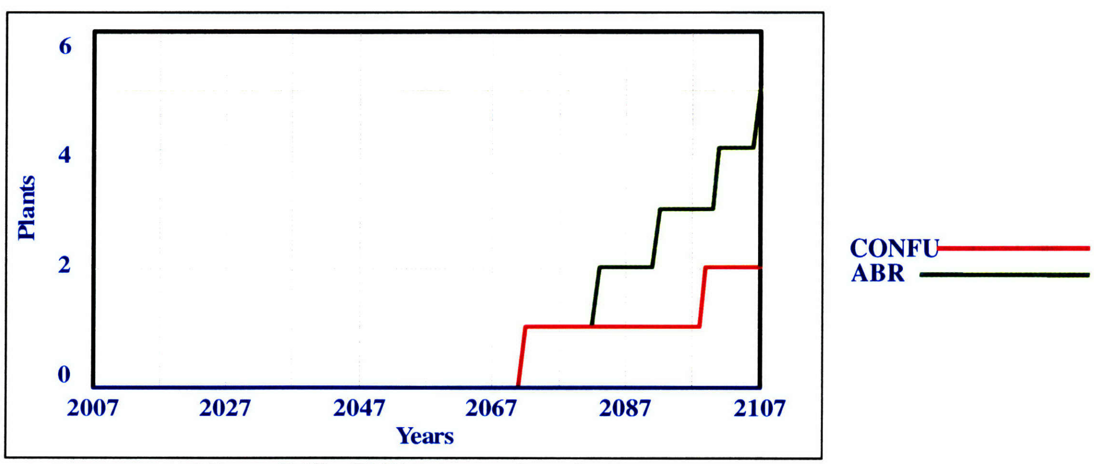

Figure 7-13 – FFF reprocessing plants

As has been demonstrated, the delayed introduction of advanced actinide burning technology, which cannot be introduced early due to small spent fuel legacy, will end up requiring a faster buildup of fuel facilities to burn down the interim TRU inventory. The introduction of the GFR technology results on the construction of only one reprocessing plant, as shown in Figure 7-14, with a lower limit instantaneous mass loading factor of 0.5, and a cumulative mass loading factor of 0.8635.

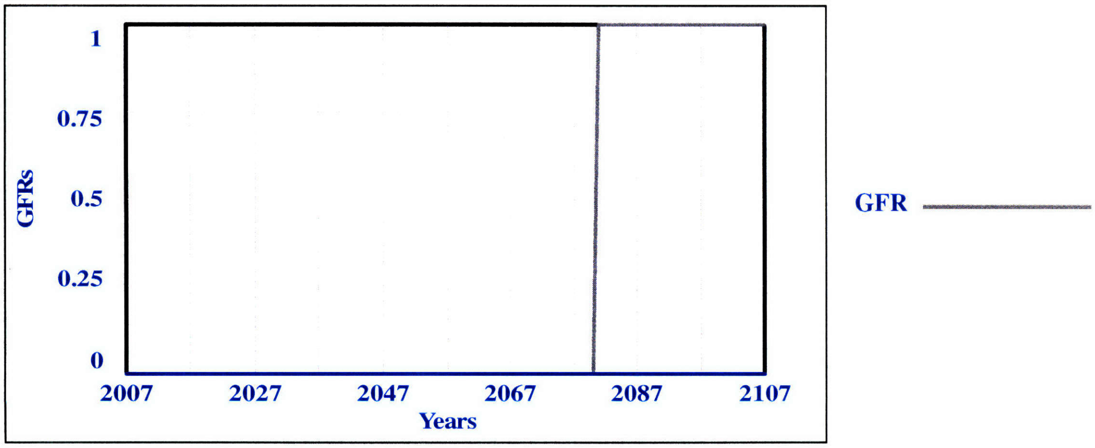

Figure 7-14 – GFR reprocessing plants

Last, the installed nuclear capacity and the ratio of fast to thermal reactors nuclear capacity are presented in Figure 7-15 and Figure 7-16.

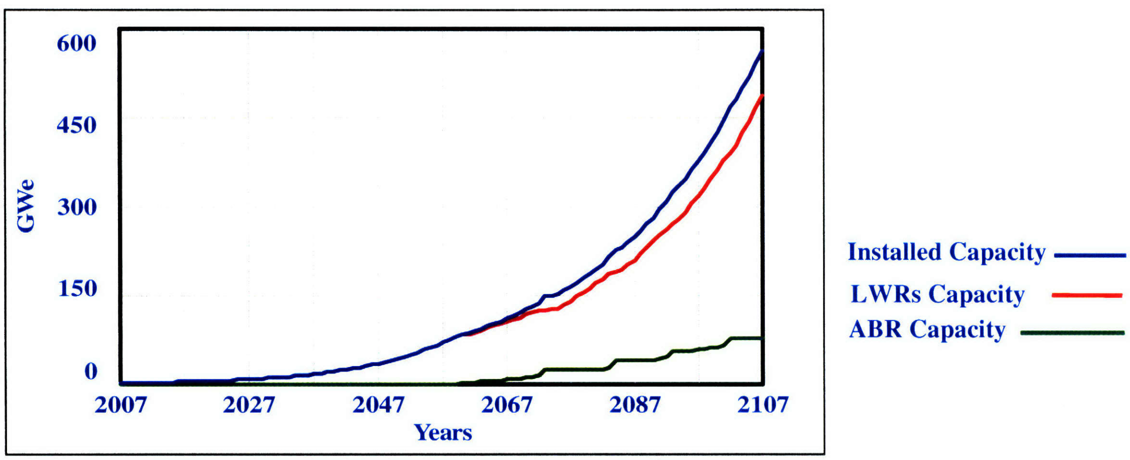

Figure 7-15 – ABR - Installed nuclear capacity

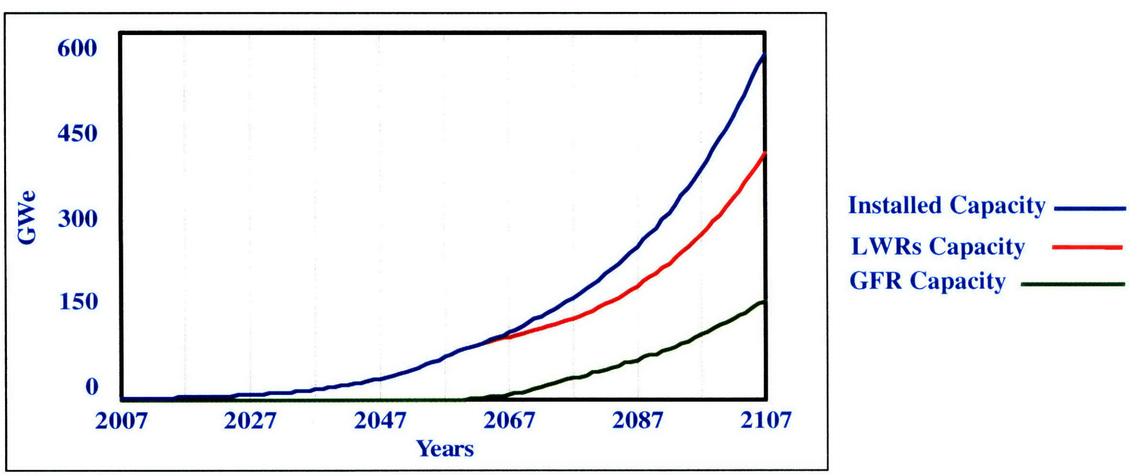

Figure 7-16 –GFR - Installed nuclear capacity

7.3.2. Sensitivity analysis of uranium prices

Brazil has one of the largest hydro potential in the world, and more than 83 new hydro plants should be built in the next fifteen years [23]. Thus, the supply of electricity will be generated, in the next years, predominantly by hydroelectric plants. However, the government is expanding the use of renewables, such as wind and biomass in the energy portfolio supply, and nuclear power should be a regulator element in this new strategy. In the December 2005 auction, when the Brazilian government negotiated the rights of exploration of electricity under a consumer final price, the averaged value of thermoelectric energy was US$ 61.70/MWh. On the other hand, the ELETRONUCLEAR projection for the electric nuclear power price from *Angra 3* is US$ 62.20/ MWh, very close to the values reached last December for the thermoelectric plants. With this value, the activation of *Angra 3* became more economically attractive, and justifies its higher capital cost. Here, the economic impact of uranium price on the fuel cycle cost, and on the total cost of the electricity, is evaluated through the case studies summarized in Table 7-6.

The introduction of the technology occurs in 2050. The price of uranium is taken as 60, 120 and 180 US$/kg for all strategies and for the once-through cycle. The simulation results for the mass flow, SWU requirements, advanced fuel facilities, and reactors are the same as presented in Section 7.3.1 since the simulation parameters are identical. Therefore, only the economics results are discussed here.

Table 7-6– Case study for sensitivity analysis of uranium prices

Case study	Introduction date of the technology	Uranium prices [US$/kg]		
Once-Through Cycle (OTC)	---	60	120	180
CONFU Technology	2050	60	120	180
Nominal ABR	2050	60	120	180
Nominal GFR	2050	60	120	180

Figure 7-17 shows the capital costs for uranium prices of 60, 120 and 180 US$/kg. As expected, the capital costs do not change with changes on uranium price. The simulation indicates that first the capital costs assume an upward trend as new reactors are built and no reactor leaves the stock of reactors going behind the 20 years age. In addition, the small number of reactors, which means no advantage due to economy of scale, makes the capital costs reach a peak of 29.32 mills/kWh in 2022 when a new reactor starts commercial operation without stopping paying overnight construction annuities. After equilibrium, the capital cost for the GFR technology is higher than for ABR. Figure 7-18 gives the O&M cost for uranium prices of 60, 120 and 180 US$/kg. As expected, the operating and maintenance cost has the same value, 9 mills/kWh, for all technologies.

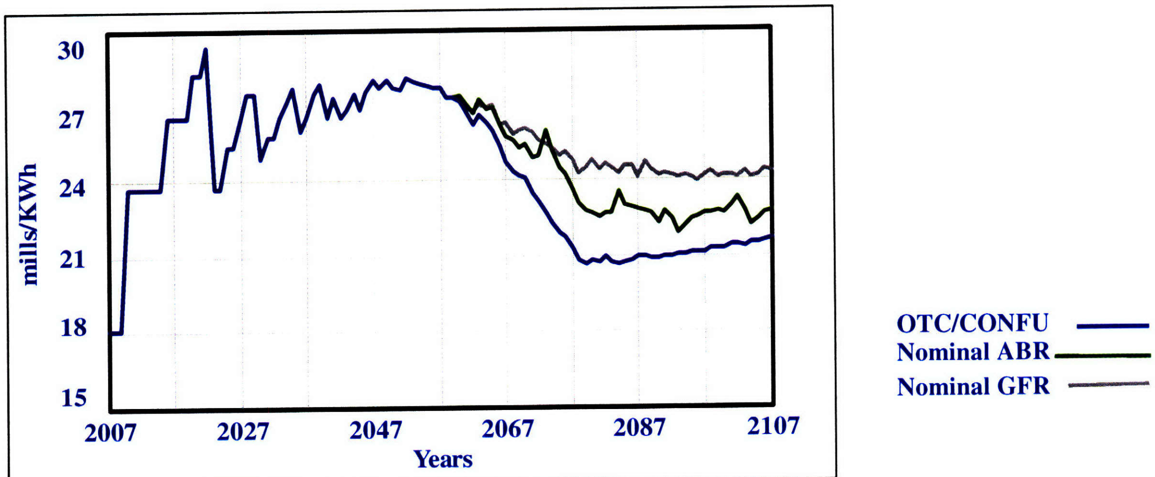

Figure 7-17–Capital cost for uranium prices of 60, 120 and 180 US$/kg

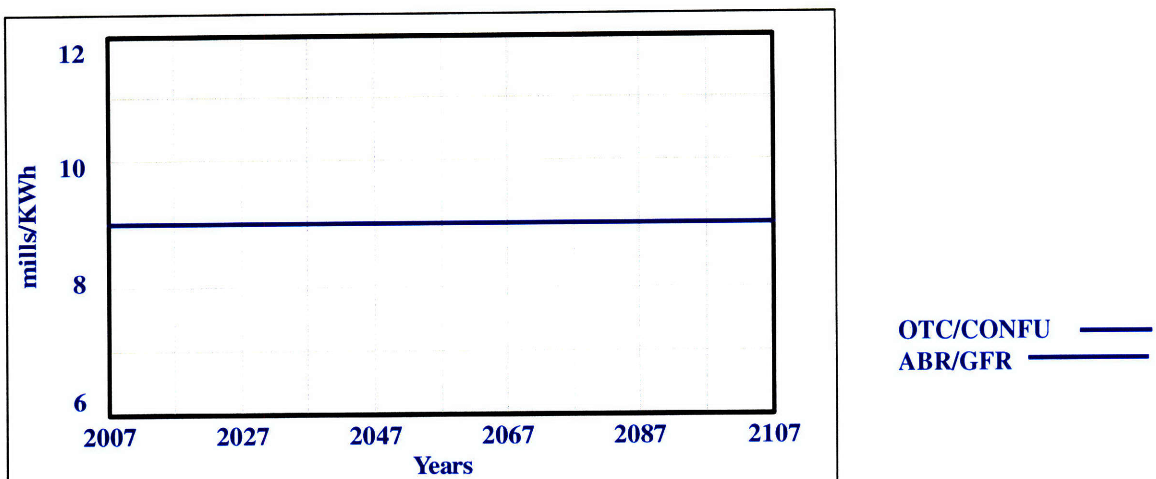

Figure 7-18 – O&M cost for uranium prices of 60, 120 and 180 US$/kg

As have been demonstrated in Figure 7-19 for the first thirty years of simulation, the fuel cycle cost for a small number of LWRs reactors presents peaks due to the load of new cores and the small installed nuclear capacity – by 2035, there are fourteen light water reactors. Moreover, the introduction of GFRs for uranium prices of 60 US$/kg becomes economically interesting, from the fuel cycle point of view, after 2089. However, for more than 20 years, the thermal technology is able to deplete TRU inventory in interim storage and it is more economically attractive. Also, the fuel cycle cost for the once-through cycle remains steady at 5.22 mills/kWh, with peaks due to the commissioning of new LWRs after 2050.

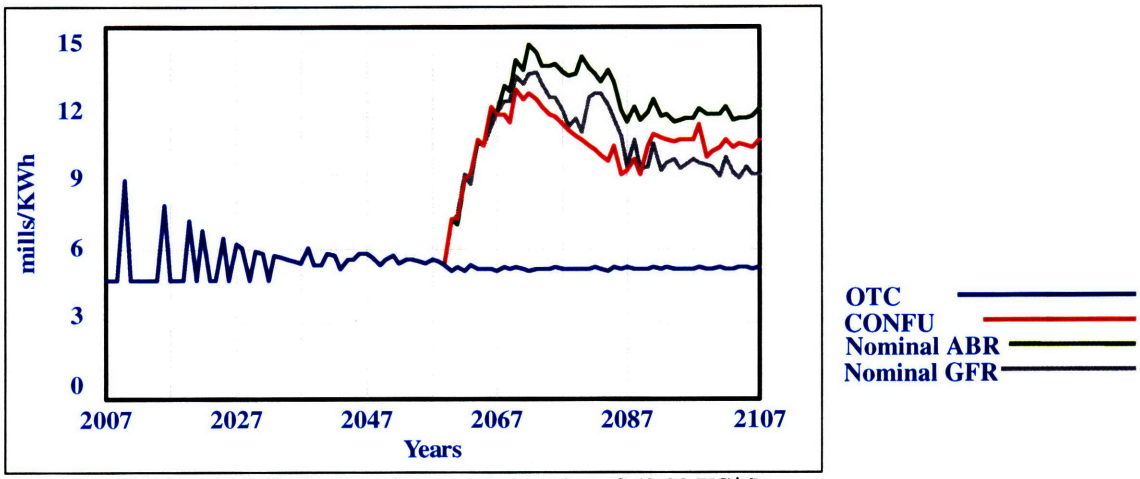

Figure 7-19 – Fuel Cycle Cost for uranium price of 60.00 US$/kg

Figure 7-20 and Figure 7-21 give the fuel cycle cost for uranium prices of 120 and 180 US$/kg respectively.

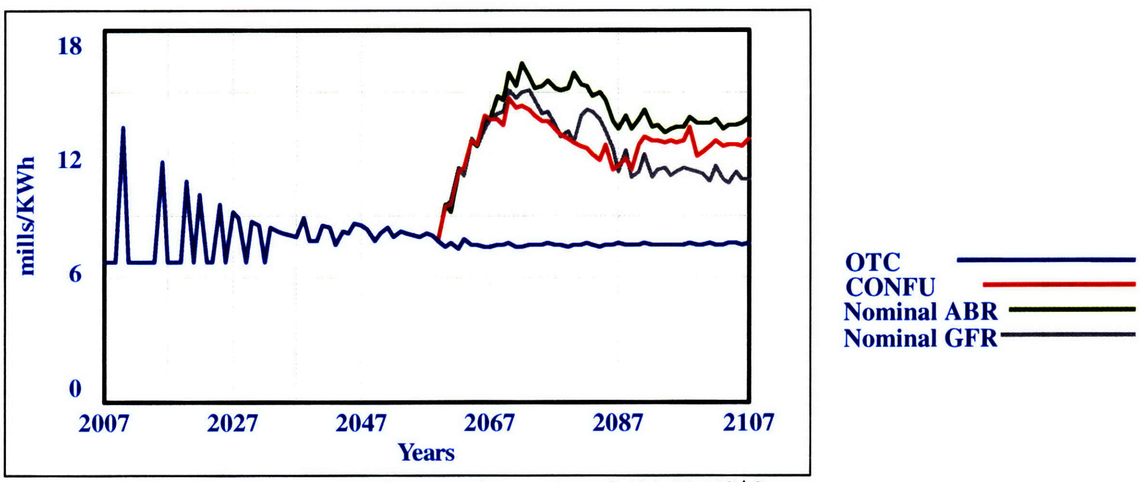

Figure 7-20 – Fuel Cycle Cost for uranium price of 120.00 US$/kg

As can be seen, the fuel cycle cost for the once-through cycle increases to 7.56 mills/kWh when the uranium price doubles from 60 to 120 US$/kg, and to 9.98 mills/kWh when it goes from 120 to 180 US$/kg. Moreover, the increase in the price of uranium makes the economics of the GFR strategy more attractive for two reasons. First, the fuel cycle costs for GFR gets close to the OTC fuel cycle cost at equilibrium. Second, the cross over point when the GFR technology is more attractive gets close to the introduction date of the technology. As shown in Figure 7-20, the cross over point is 2087 for uranium prices of 120 US$/kg. As plotted in Figure 7-21, the cross over point is 2085 for uranium prices of 180 US$/kg. For uranium prices of 60 US$/kg, the cross over point is 2089.

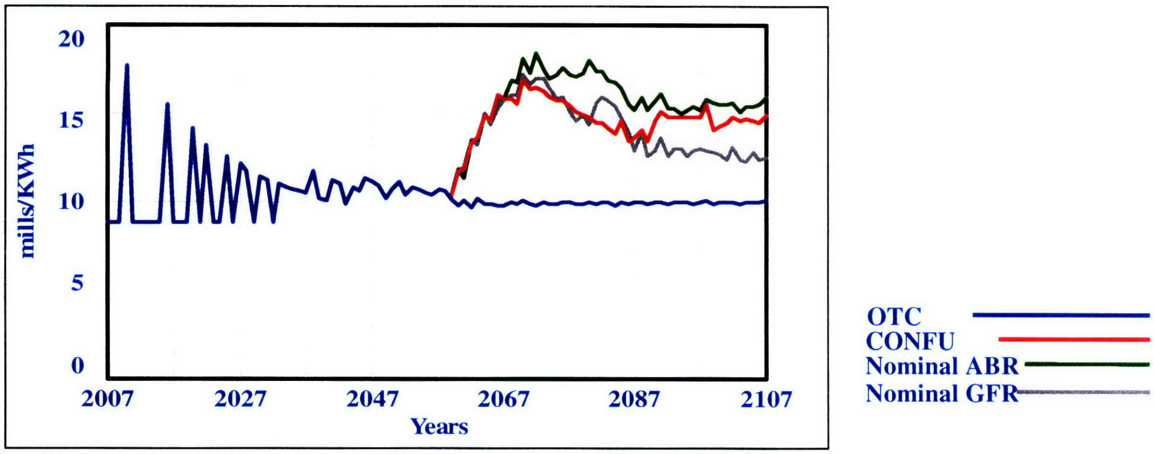

Figure 7-21 - Fuel Cycle Cost for uranium price of 180.00 US$/kg

The increase in the uranium prices makes the economics of recycling of TRU in GRFs more attractive than recycling in ABRs, as presented in Figure 7-22, Figure 7-23 and Figure 7-24. The fast recycling of TRU in GFRs presents advantages compared to ABR recycling scheme because the economic advantage due to fuel cycle cost surpass the disadvantage due to capital-related cost for ABRs.

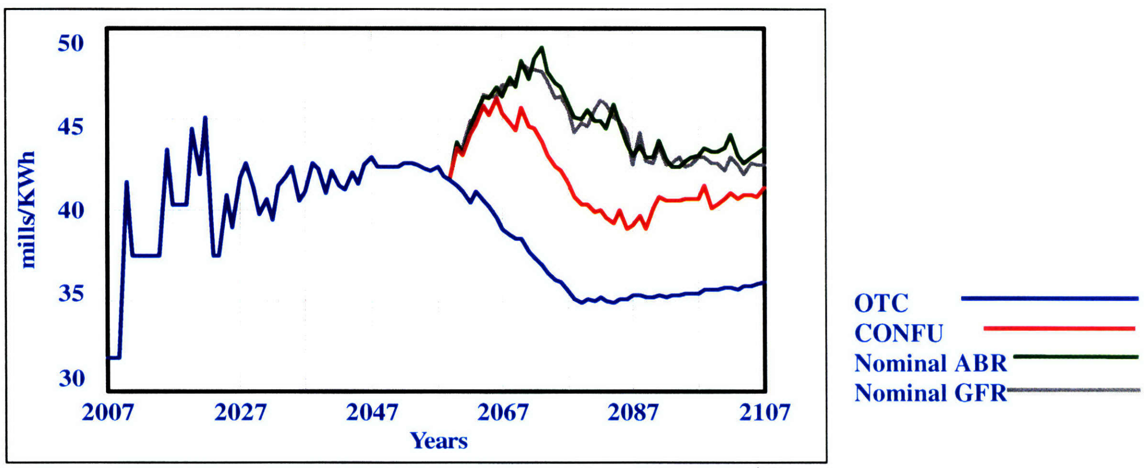

Figure 7-22 – Cost of Electricity for uranium price of 60.00 US$/kg

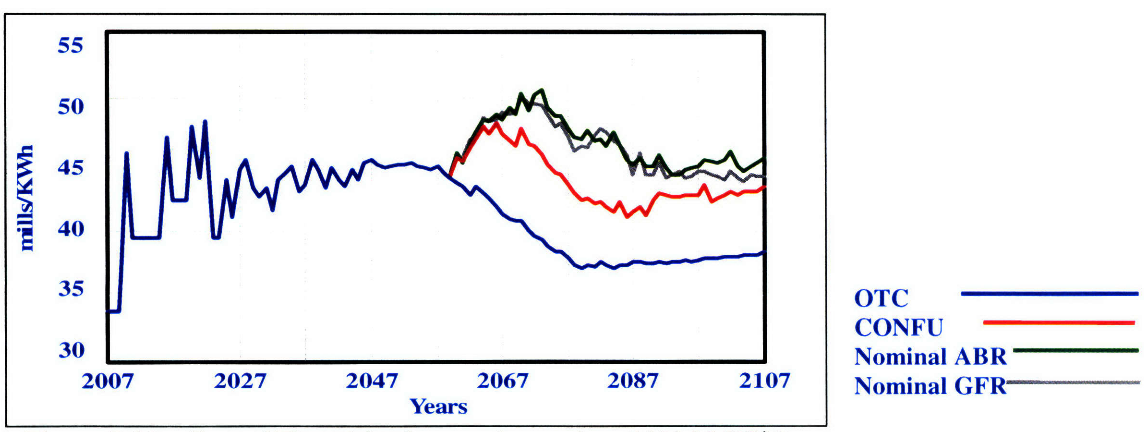

Figure 7-23 – Cost of Electricity for uranium price of 120.00 US$/kg

Figure 7-24 – Cost of Electricity for uranium price of 180.00 US$/kg

7.4. Assessment of the U.S. nuclear market under a partnership with Brazil

The U.S. is the advanced nuclear country with the largest fleet of reactors, and is leading the research in the field. Twenty percent of its electricity market relies on nuclear power, and advanced reactors and fuel facilities should be built to meet the electricity demand in the next forty years. Moreover, the U.S. is a *fuel cycle state* providing fuel for several *reactors states* that do not have fuel manufacturing industry. On the other hand, Brazil, as one of the countries of the BRIC, is expected to play an important role in the energy market in the next few decades. Although the electric power system in Brazil is hydro dominated, it has been diversifying its energy supply portfolio, and it has invested on nuclear R&D facilities. Moreover, after 28 years of nuclear research at CTMSP, with international agreements and under the inspections of the IAEA, a nuclear program based on advanced light water reactors and advanced fuel facilities, would likely be the option to follow as demand for electricity grows.

Here, we evaluate the impact of a nuclear partnership between the U.S. and Brazil through the case study presented in Table 7-7. The U.S. nuclear electricity demand annual growth rate is taken as 2.4%, and the Brazilian nuclear annual growth rate follows the trend presented in Figure 7-5 (7.3% for fifty years and than dropping to 4.1%). Therefore, the Brazilian installed nuclear capacity is identical to that for the once-through cycle presented in Section 7.3. The impact on uranium resources, SWU requirements, and number of advanced nuclear facilities to be constructed is evaluated for the U.S. as a fuel cycle state. Furthermore, Brazil is considered a reactor state that uses front and back-end fuel services from the U.S., i.e. there is no fuel facility in Brazil, it buys fresh fuel from the U.S. and sends back UO_2 spent fuel after the cooling time.

Table 7-7 – Case studies for assessment of uranium resources in the U.S.-Brazil partnership

Case study	Introduction date of the technology
Once-Through Cycle (OTC)	---
CONFU technology	2027
Nominal introduction of ABR	2047
Nominal introduction of GFR	2047

Figure 7-25 presents the U.S. uranium consumption if it has to provide uranium to fulfill the needs of both countries. In addition, as can be seen in Figure 7-26, the impact of a nuclear collaboration on the U.S. SWU requirements is significant if no recycling strategy is adopted. The necessary U.S. cumulative uranium by the end of the simulation is 22.47% higher, and the extra SWU requirements needed is 32.52% higher for the nuclear partnership.

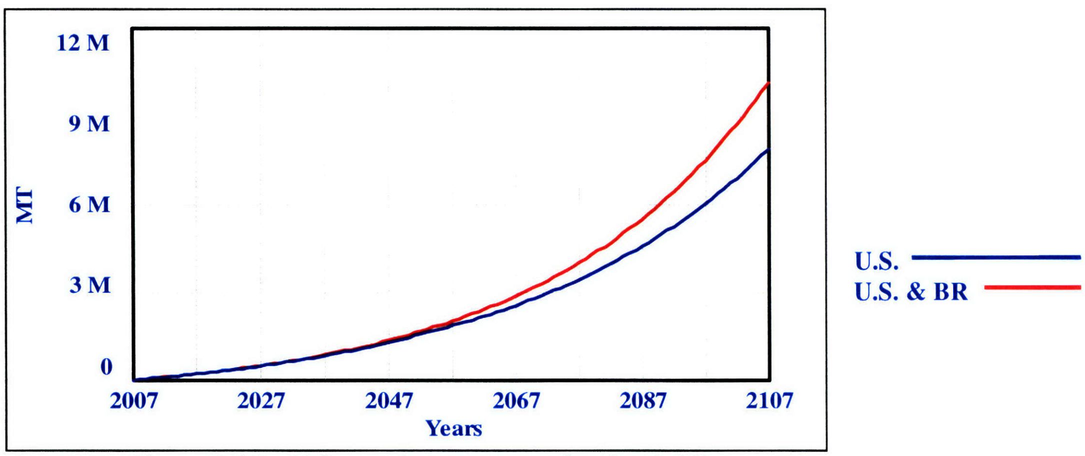

Figure 7-25 – U.S. uranium consumption for OTC

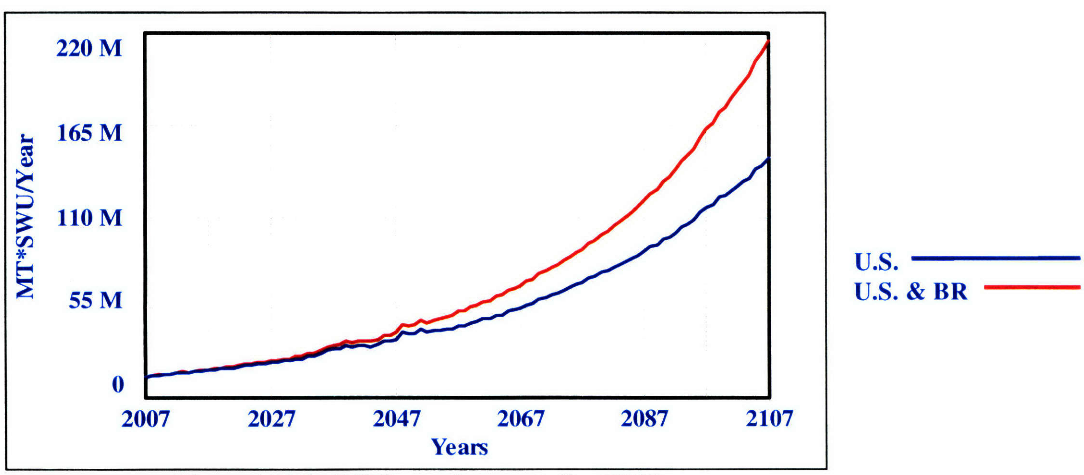

Figure 7-26 - SWU requirements for OTC

Figure 7-27 plots the U.S. cumulative TRU inventory in interim storage if the U.S. gets back the UO_2 spent fuel from Brazil and maintains the OTC scheme. In the case of the nuclear collaboration without recycling scheme, the amount of TRU in storage in the U.S. is 20.43% higher at the end of the century.

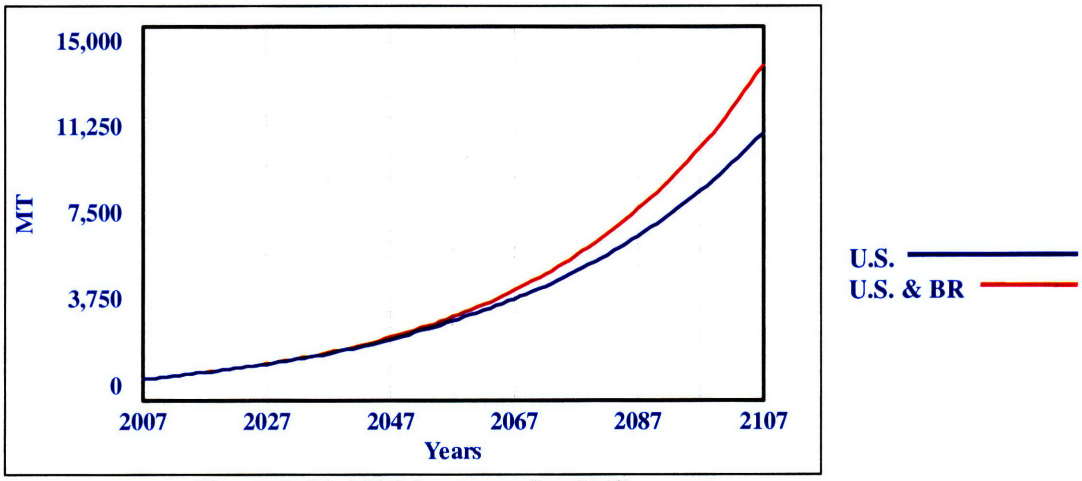

Figure 7-27 - TRU inventory for OTC

Figure 7-28 and Figure 7-29 shows the uranium consumption and SWU requirements for the CONFU strategy. As can be seen there is no significant reduction in the amount of uranium needed or in the separative work unit requirements compared to the OTC.

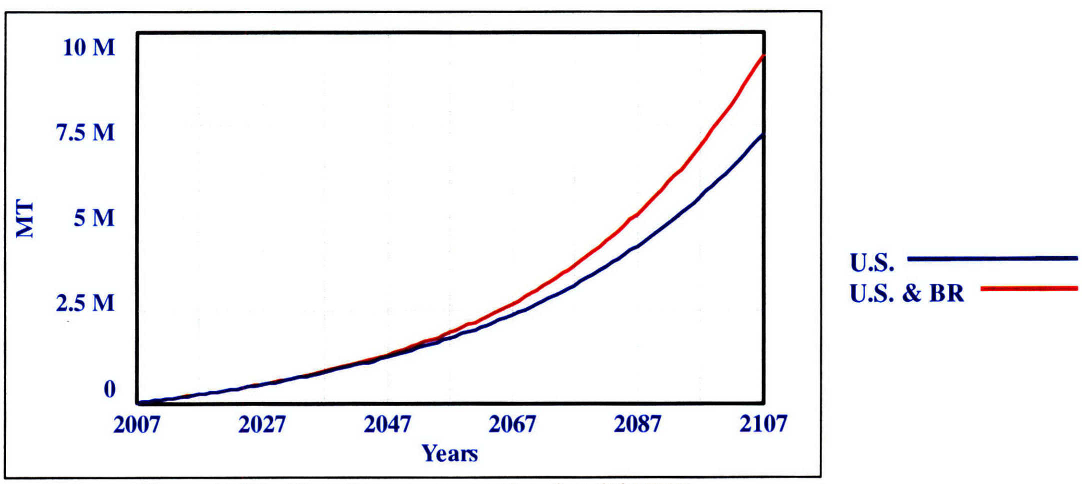

Figure 7-28 - Uranium consumption for CONFU

As shown by Figure 7-30, the thermal recycling is able to keep the transuranic inventory under reasonable levels for both cases. However, as presented in Figure 7-31, the extra number of separation plants to deplete the TRU inventory is significantly higher. By 2107, there are 22 separation plants for the partnership as opposite to 15 for the U.S. case alone. Figure 7-32 plots the SP mass loading factor for both cases.

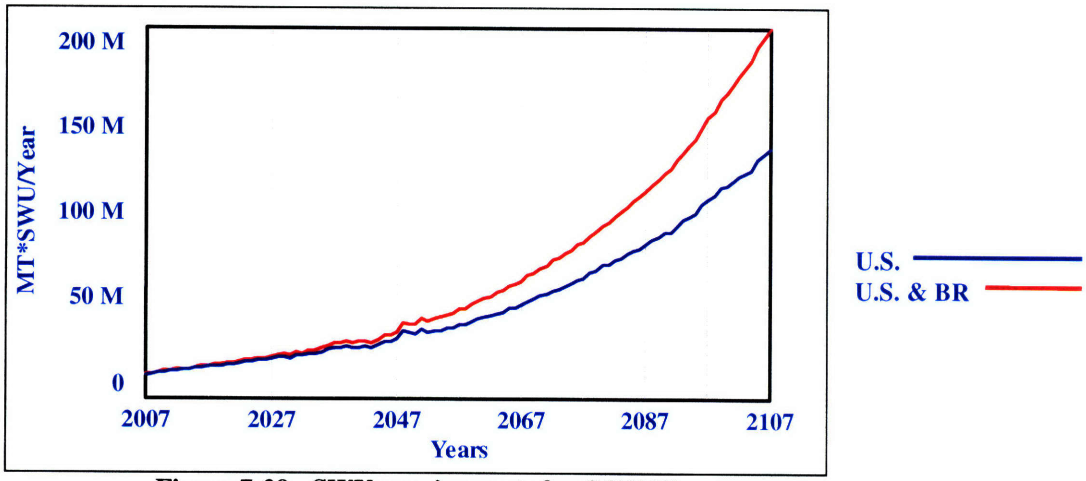

Figure 7-29 - SWU requirements for CONFU

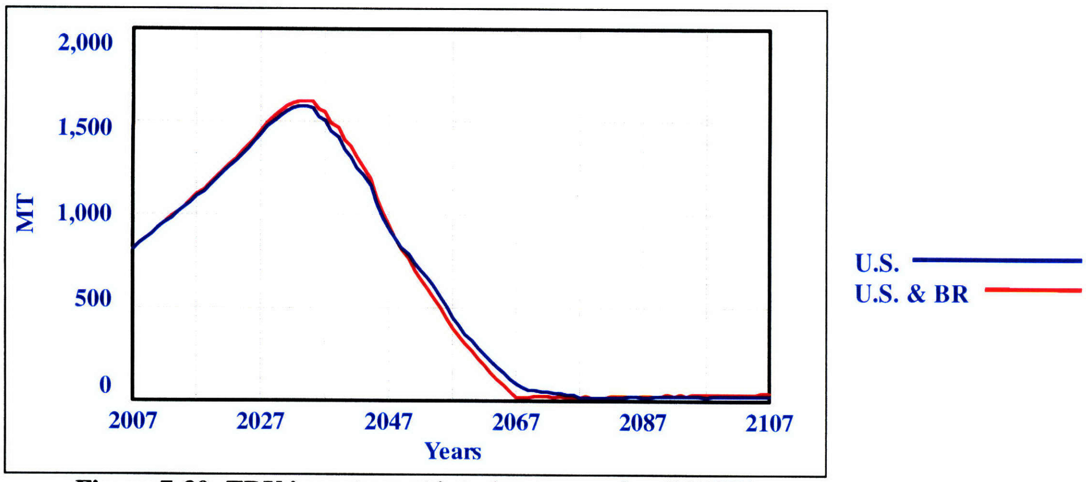

Figure 7-30 -TRU inventory at interim storage for CONFU

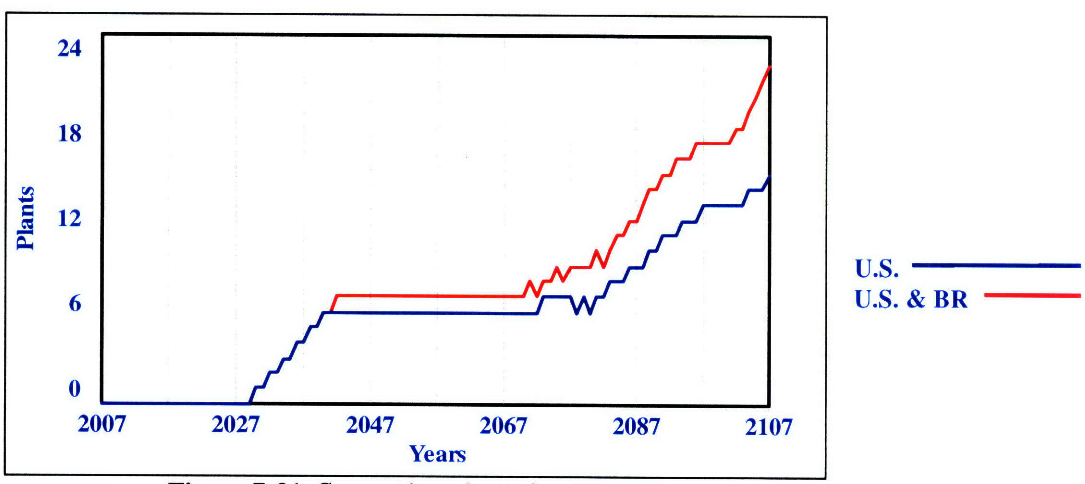

Figure 7-31 -Separation plants for CONFU

Figure 7-33 shows the number of FFF reprocessing plants, and Figure 7-34 presents the FFF mass loading factor. The number of reprocessing plants needed is the same from the introduction date of the technology for up to forty years for both cases. As a consequence, the mass loading factor is better as there is more mass available for reprocessing for the partnership case (higher FFF mass loading factor for the US&BR case).

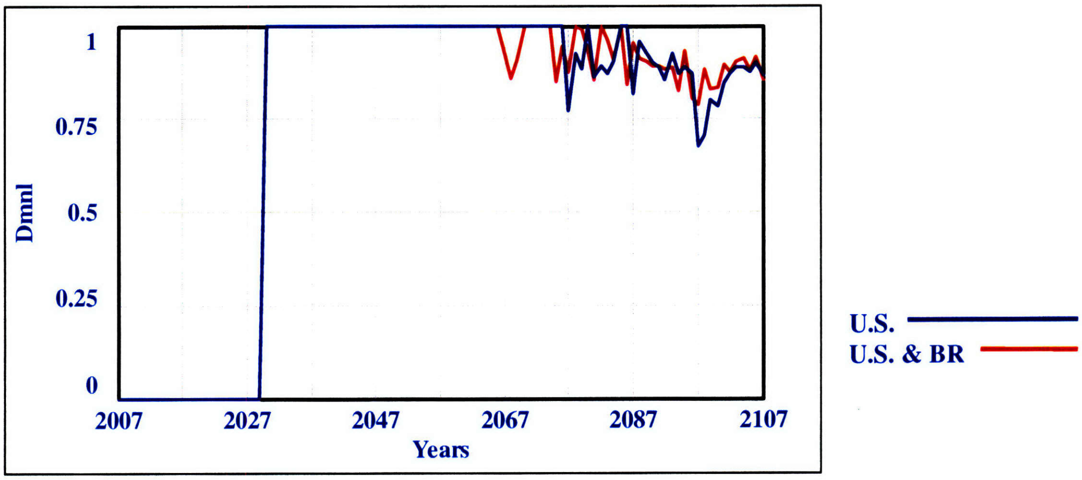

Figure 7-32 - Separation plants mass loading factor for CONFU

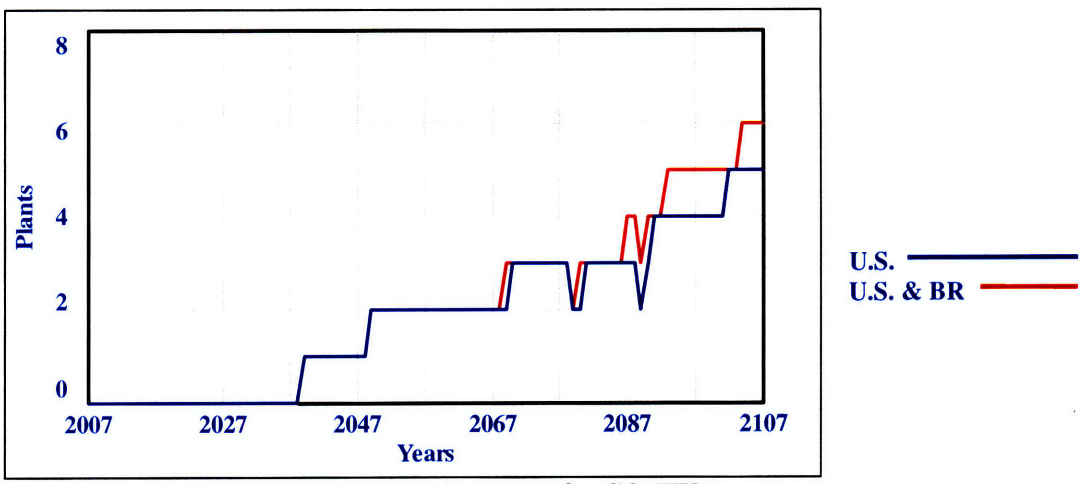

Figure 7-33 - FFF reprocessing plants for CONFU

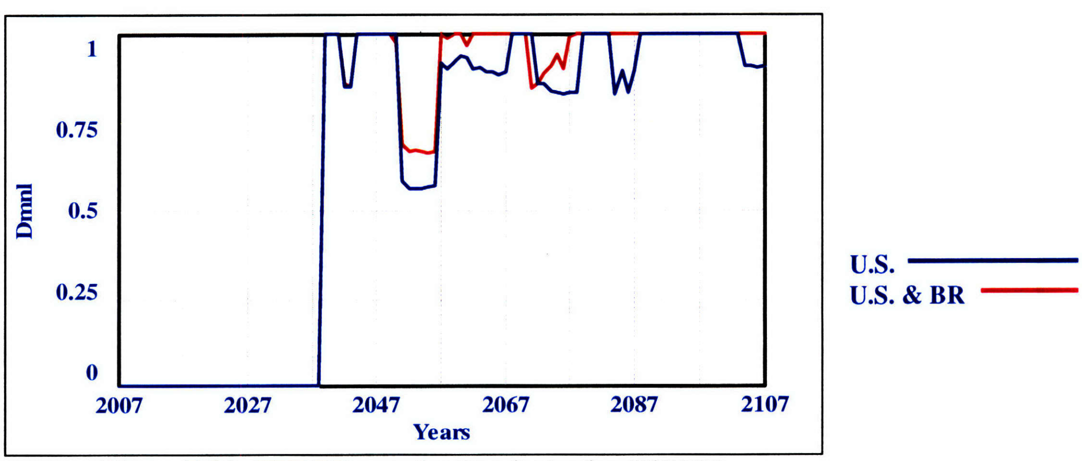

Figure 7-34 - FFF RP mass loading factor for CONFU

Figure 7-35 and Figure 7-36 show the cumulative uranium consumption and the SWU requirements for the ABR scheme. As revealed by Figure 7-35, there is a 13.20 % reduction in the uranium consumption compared to the OTC by the end of the simulation. Furthermore, the SWU requirement is 13.68% lower for the ABR strategy than for the OTC for the US&BR case. Nevertheless, the uranium consumption is 22.78% higher, and the SWU requirement is 34.79% higher for the nuclear collaboration.

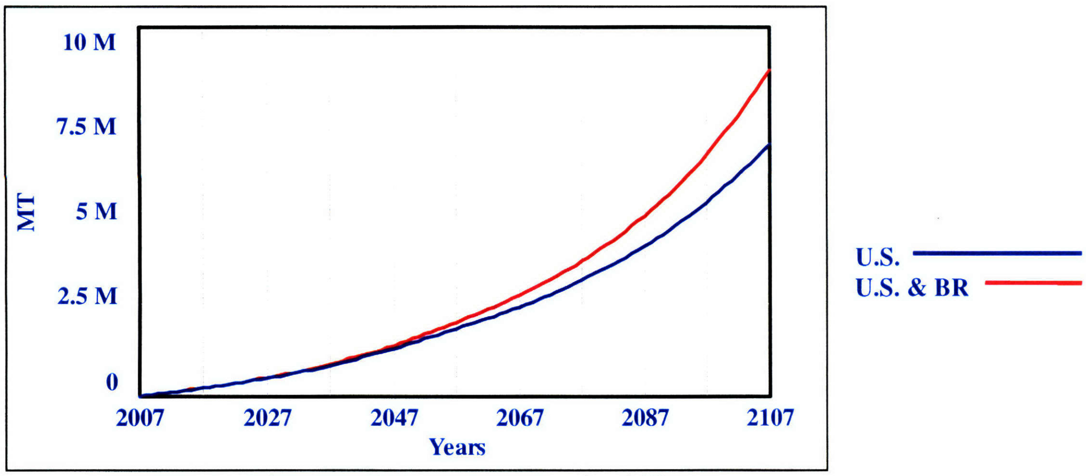

Figure 7-35 - Uranium consumption for ABR

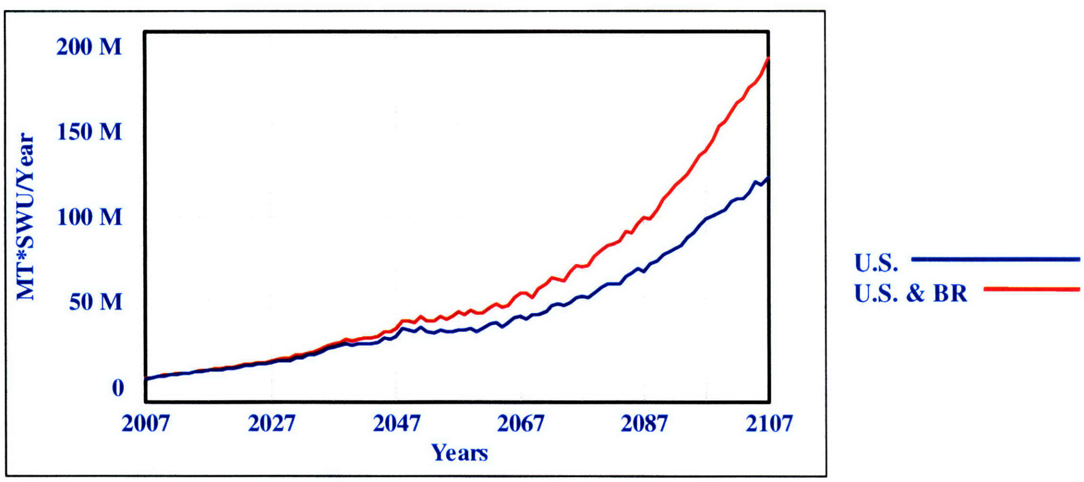

Figure 7-36 - SWU requirements for ABR

Figure 7-37 plots the TRU inventory at interim storage, Figure 7-38 shows the fleet of separation plants, and Figure 7-39 presents the SP mass loading factor. As can be seen, the ABR scheme allows a higher burn up of the transuranic inventory at interim storage for both cases, and the number of separation plants that must be built is significantly higher from 2061 to 2102. Figure 7-40 presents the FFF reprocessing plants needed, and Figure 7-41 shows the FFF mass loading factor. As expected, the number of reprocessing facilities is higher for the nuclear partnership than for the U.S. case alone.

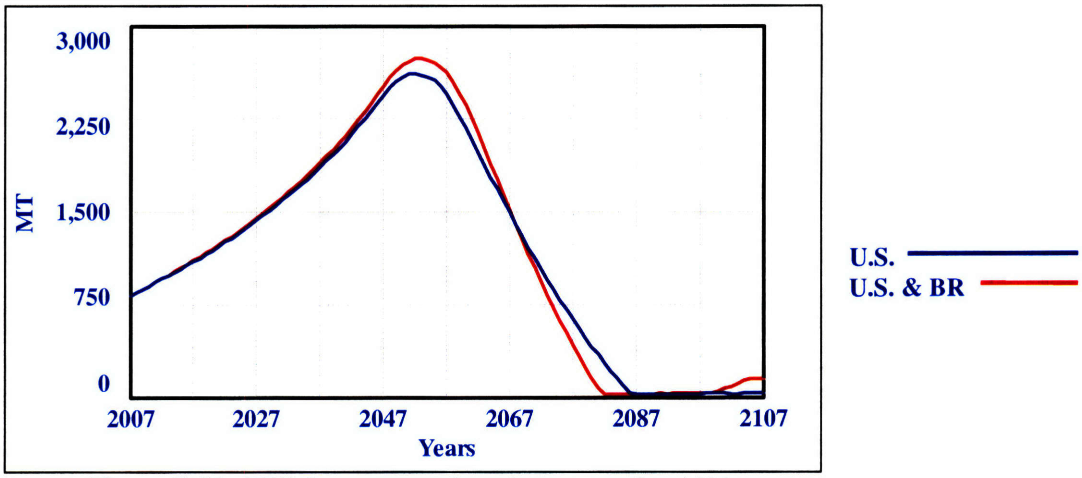

Figure 7-37 - TRU inventory at interim storage for ABR

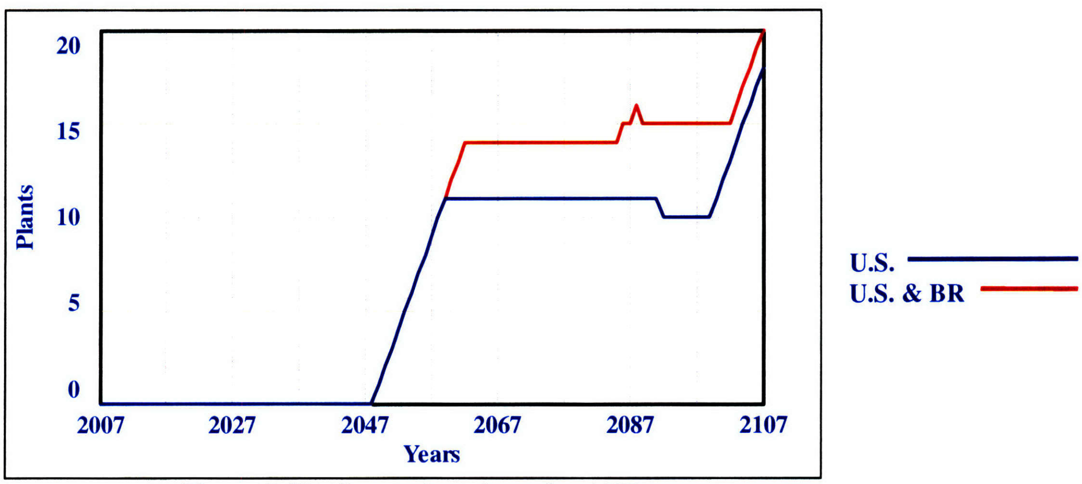

Figure 7-38 - Separation plants for ABR

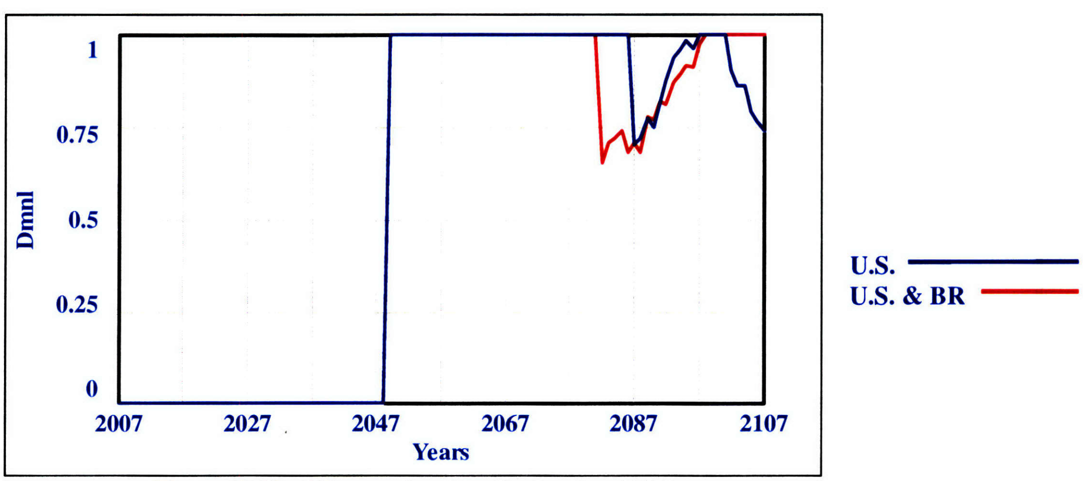

Figure 7-39 - SP mass loading factor for ABR

As can be seen in Figure 7-42, the installed nuclear capacity in the U.S. follows the power demand, and it relies more on the fast reactor fleet for the US&BR case than for the U.S. alone. Still, the ratio of thermal reactors installed capacity to total nuclear installed capacity is 78.42% for the US&BR case.

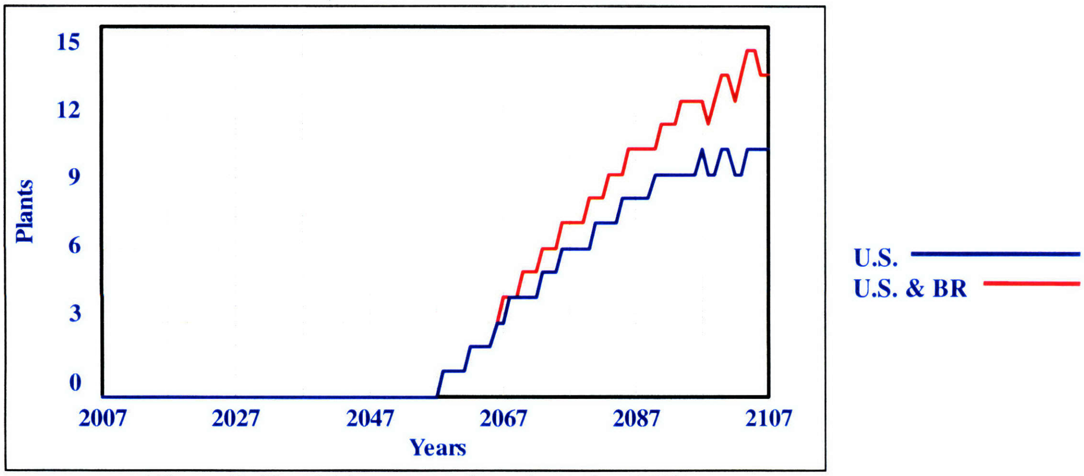

Figure 7-40 - FFF reprocessing plants for ABR

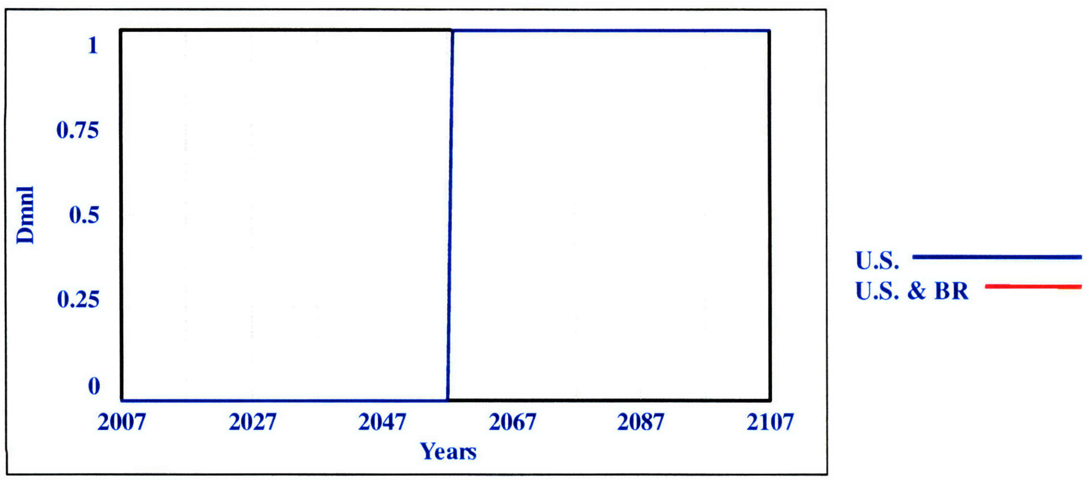

Figure 7-41 - FFF RP mass loading factor for ABR

As revealed by Figure 7-43, the amount of uranium needed to assure fresh fuel for both countries in the partnership is 23.52% higher than for the U.S. alone. On the other hand, the US&BR uranium consumption is significantly lower for the GFR strategy than for the CONFU and ABR schemes. As presented in Figure 7-44, the GFR technology also requires less SWU as GFR allows for uranium recycling.

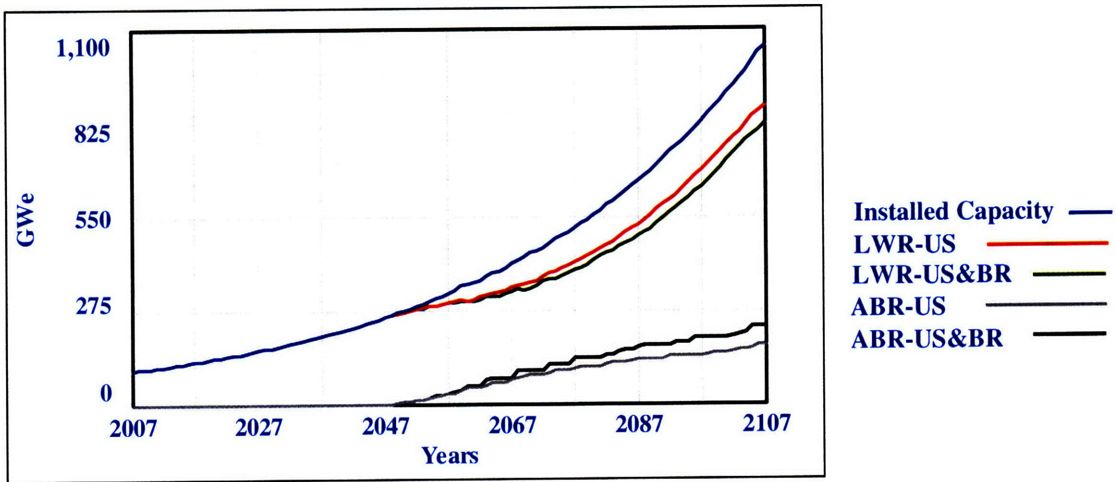

Figure 7-42 -U.S. installed nuclear capacity for ABR

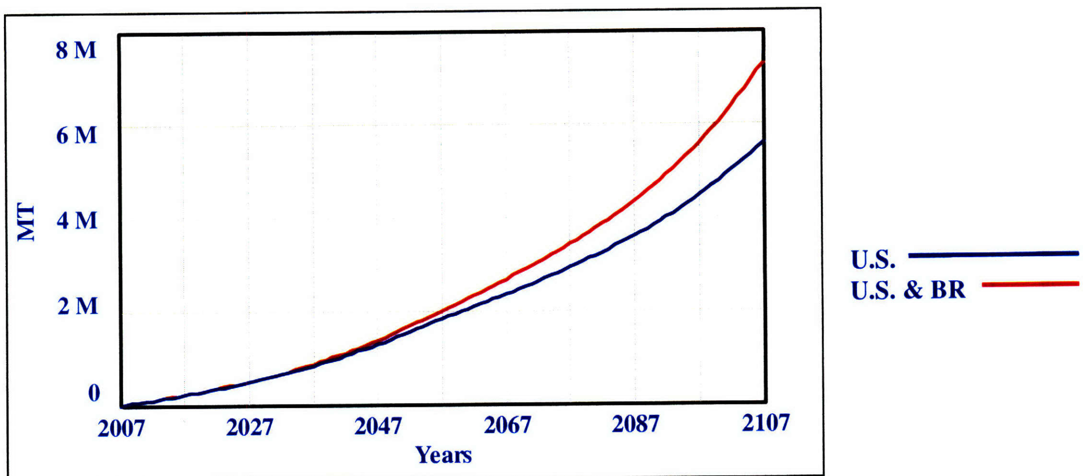

Figure 7-43 - Uranium consumption for GFR

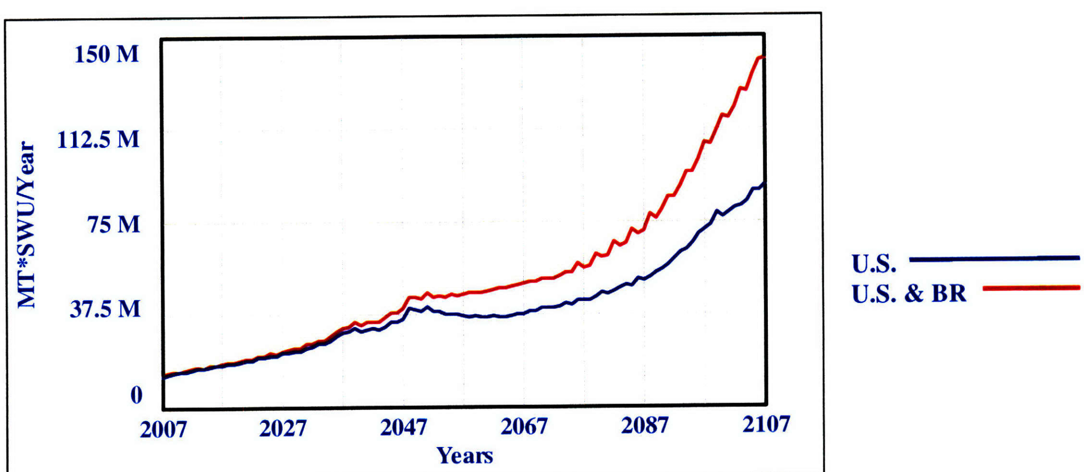

Figure 7-44 – SWU requirements for GFR

Figure 7-45 shows that the GFR scheme allows the burn up of the TRU inventory at interim storage for both cases. The number of separation plants that must be built is significantly higher after 2057, as revealed by Figure 7-46. Figure 7-47 presents the SP mass loading factor, which is improved for the partnership case.

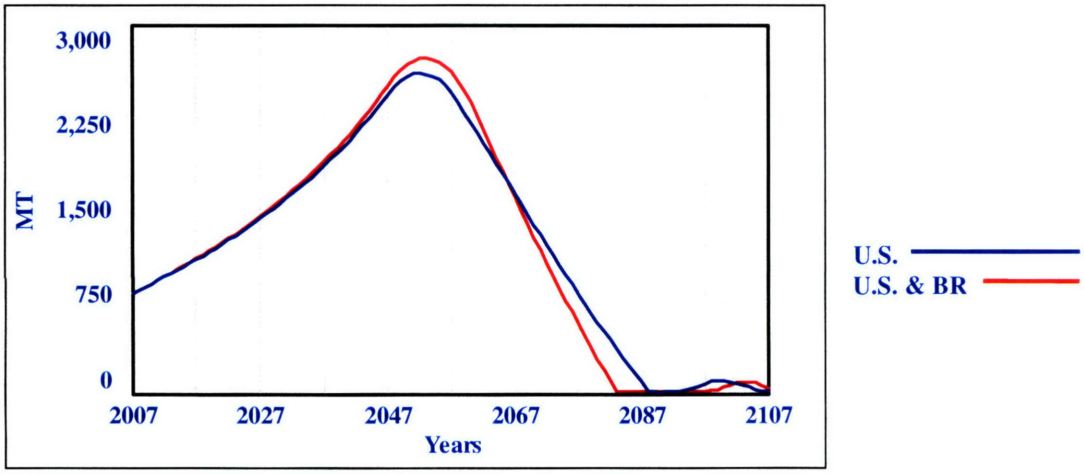

Figure 7-45 – TRU inventory for GFR

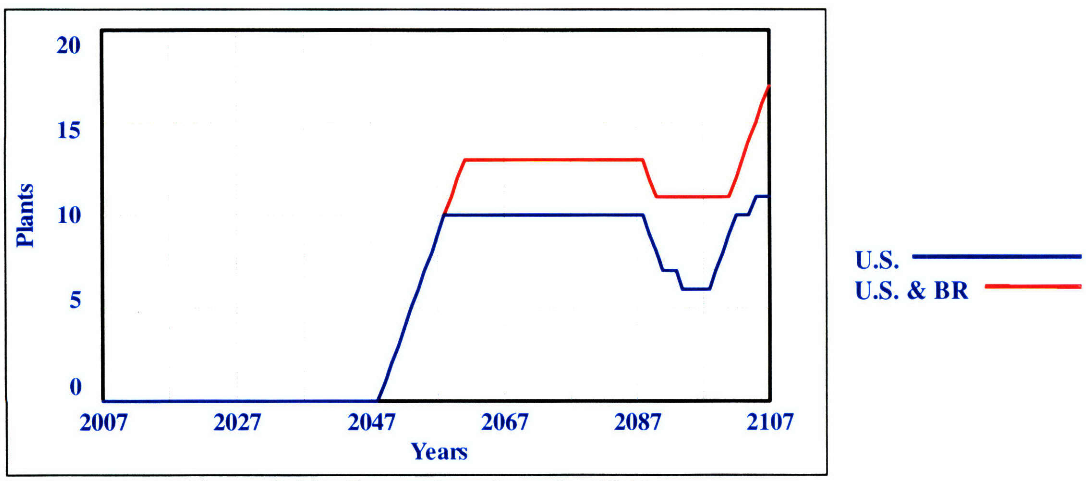

Figure 7-46 – Separation plants for GFR

As shown in Figure 7-48, the number of GFR reprocessing plants to be built is higher for the US&BR case than for the U.S. alone, as expected. Figure 7-49 presents the GFR RP mass loading factor. Note that the partnership allows building the reprocessing plants earlier than in the case of the U.S. alone.

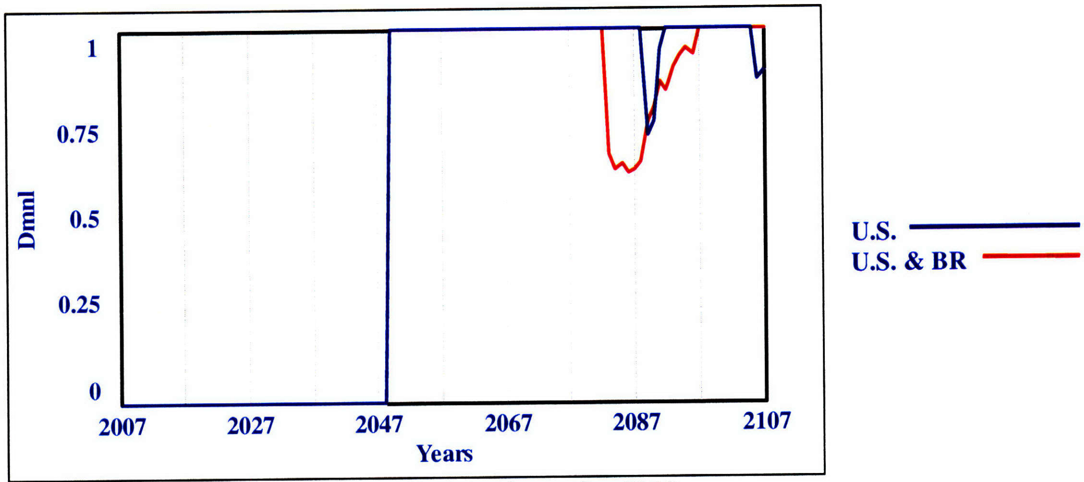

Figure 7-47 – SP mass loading factor for GFR

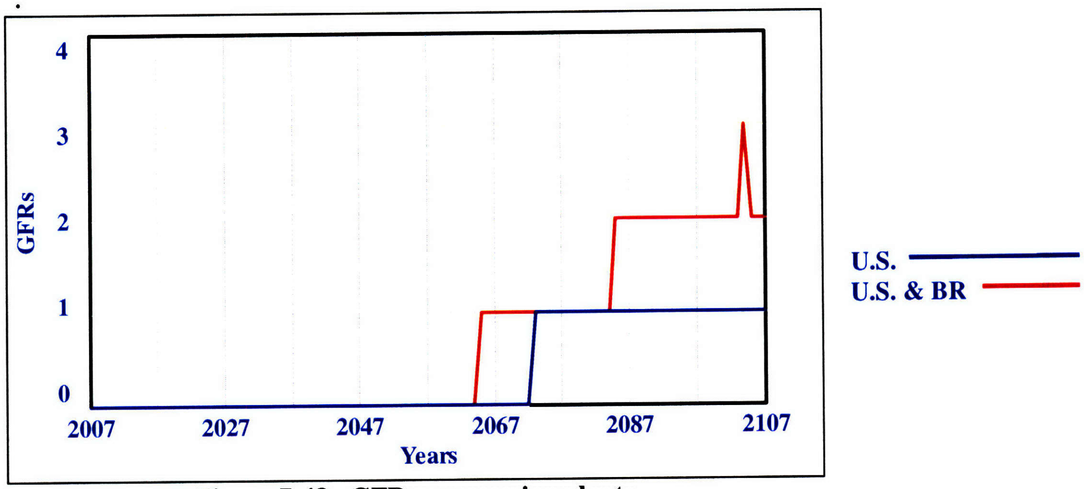

Figure 7-48 - GFR reprocessing plants

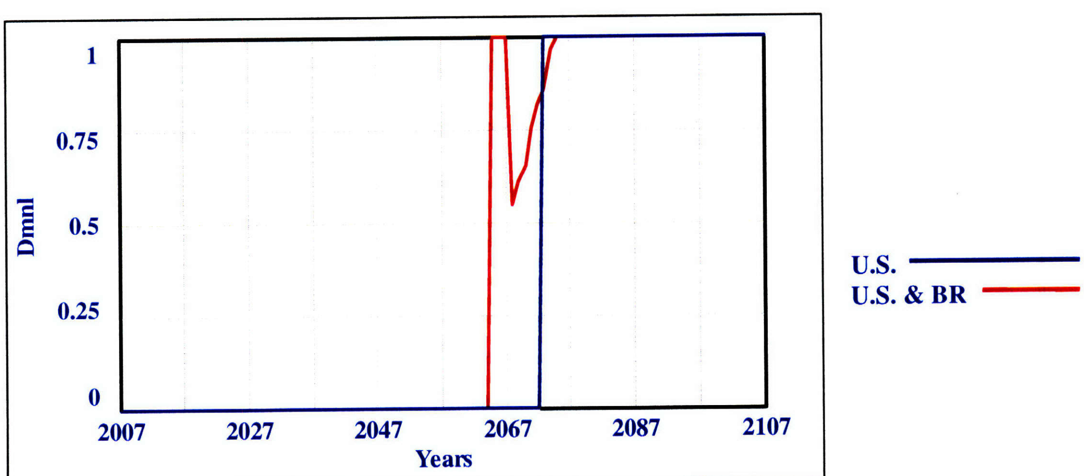

Figure 7-49 – GFR RP mass loading factor

As can be demonstrated by Figure 7-50, the installed nuclear capacity in the U.S. follows the power demand, and it relies more on the fast reactor fleet for the US&BR than for the U.S. alone.

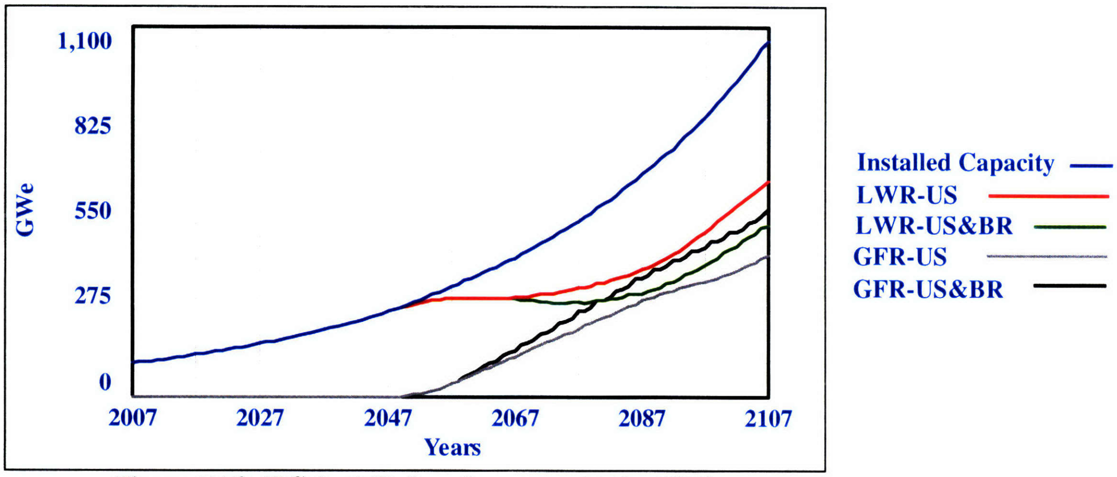

Figure 7-50 -U.S. installed nuclear capacity for GFR

In addition, after 2080 the contribution of fast reactor in the U.S. total nuclear installed capacity surpasses the contribution of LWRs. Furthermore, the nuclear collaboration allows for a 0.552 ratio of fast reactors installed capacity to total nuclear installed capacity for the US&BR case by the end of the simulation. This behavior is expected since the amount of UO_2 spent fuel available for separation, and the amount of TRU available to start a new GFR core, is higher for the nuclear collaboration.

7.5. Summary

Brazil has one of the largest hydro potential in the world. Thus, the supply of electricity will be generated, in the next years, predominantly by hydroelectric plants -- more than 83 hydro plants are expected to be built in the next decade [23].The generation of electricity from fossil fuels, a major and growing contributor to the emission of CO_2, will play a small role as a source of electricity. On the other hand, the increase in efficiency of electricity generation, the expanded use of renewable energy sources, and the increased use of nuclear power will become a more significant element in the Brazilian energy supply portfolio. Moreover, the construction of small hydro is one solution, but with small reservoir the generation becomes more dependent of the weather [33]. Furthermore, several projects can be stopped due to increasing environmental constraints. In fact, the development of the hydro potential in the North area could face serious difficulties [34] due to environmentally sensitive *Amazon forest*, and the necessity to transfer electricity over more than 2,500 km to reach the most populated areas.

As described in Section 7.3, Brazil does not have a significant nuclear spent fuel legacy , and its nuclear installed capacity may not justify the introduction of commercial recycling nuclear technologies before 2050. However, the government plans to increase from 2.4% to 4% the nuclear power contribution in the electricity supply portfolio, adding 13 GWe. The Brazilian significant inferred uranium resources; the uranium mining, conversion and enrichment facilities; and the increase in uranium prices, justify investments in the nuclear energy field. Moreover, the peak in the capital and fuel cycle costs due to the small number of LWRs, as presented in Section 7.3.2, disappears as the nuclear industry remains steady.

As has been demonstrated in Section 7.4, there is a significant impact on the U.S. nuclear market if a nuclear *fuel cycle state/reactor state* collaboration with Brazil is started. In addition, the simulation results suggest that a nuclear partnership without the introduction of advanced nuclear technologies will not have advantages for the U.S. There are other issues related to the fresh and used fuel *supply chain* which must be addressed before starting a nuclear collaboration. In contrast, Brazil has been investing in nuclear R&D facilities in the last 28 years (with low government priority and budget), and the government should start a nuclear program based on advanced light water reactors and advanced fuel facilities. Mined uranium from Brazil has been transported to Canada for conversion, and then to the United Kingdom for enrichment. The LEU returns to Brazil for fabrication into fuel elements. By doing the enrichment in a Brazilian enrichment facility, Brazil saves US$ 16 million per year. Consequently, a nuclear partnership should consider a combination of nuclear services in both countries due to the distinct energy markets.

8 Conclusions and Recommendations

8.1. Conclusions

A system dynamics version of CAFCA is developed and is shown to correctly predict the mass flow in the nuclear fuel cycle, to estimate the number of reactors and advanced facilities to fulfill the nuclear power demand under the constraints of a prescribed industrial capacity to add new fuel treatment facilities. The introduction of advanced recycling fuel to close the nuclear fuel cycle is an option to follow the open-cycle scheme. There are benefits for the closed cycle, such as maximization of resource utilization, reduction of the waste radio-toxicity, reducing the demand for ore and enrichment capacity, and limiting the rise of the price of fuel services. One or more of these justify the investment in advanced fuel facilities treatment and fast reactors.

The main points of this work can be summarized as following:

1. The use of system dynamics for modeling and simulating the nuclear fuel cycle is motivated by the growing complexity of the nuclear energy system and the necessity of adding a modular ability for development of the code that should facilitate further use as a decision analysis tools.
2. The simulation results indicate that early introduction (2027) of the self-sufficient GFR recycling scheme has the most significant impact on reduction of the uranium consumption, and the SWU requirements. The GFR technology requires less uranium resources due to U recycling and near unity fissile conversion ratio. However, at some point in the second half of the century after depletion of the TRU inventory, the demand for uranium increases again due to need for LWRs to fulfill the power demand. The lack of TRU suggests that advanced fast reactors with conversion ratio greater than one should be built around that time.
3. The CONFU recycling scheme keeps the TRU inventory in interim storage at reasonable levels of about twice the current inventory, and guarantees equilibrium between the generation and consumption of transuranics without investments in fast reactors. Therefore, the CONFU strategy is the most flexible technology in the next few decades since its batches can be mixed with traditional UO_2 batches in the LWR

fleet, and it can be deployed earlier. Furthermore, it incinerates more TRU than the GFR and ABR strategies. However, the CONFU technology has no significant impact on the amount of uranium resources needed or on the SWU requirements.

4. Economic analysis indicates that the CONFU technology is more attractive for the current uranium price (here assumed 120 US$/kg), and that the fast recycling scheme becomes as attractive as thermal recycling with the rise of the price of uranium to a much higher level. Moreover, the increase in the price of uranium makes the economics of the GFR strategy more attractive for two reasons: First, the fuel cycle costs for early introduction of GFRs gets close to the OTC fuel cycle cost at equilibrium. Second, the cross over point when the GFR scheme is more economically attractive gets closer to the introduction date of the technology.

5. The TRU consumption rate should also be considered under cost analysis. A high fuel cycle and capital-related costs for the construction of fast reactors and advanced fuel facilities would be needed for high consumption rate of TRU. Therefore, simulation results indicate that a lower TRU depletion rate results in a lower peak in the cost of electricity just after the introduction of the advanced technology.

6. According to the simulation outcomes, simultaneous introduction of a thermal and a fast recycling technology, and dedicating 25, 50 and 75% of separated TRU for the fast scheme, maintains the uranium consumptions, advanced fuel facilities, and enrichment requirements at a level between the needs of the CONFU scheme and that of the fast technology. Furthermore, the higher the percentage of TRU dedicated for the fast scheme, the more delayed is the date of depletion of known uranium resources. In addition, as the percentage of TRU available for fast fuel fabrication goes from 25 to 50 and then 75%, the amount of incinerated TRU decreases and gets closer to the stand-alone deployment of the advanced technology.

7. As explained in Section 7.3, Brazil does not have a large nuclear spent fuel legacy or a nuclear installed capacity which justifies the introduction of commercial recycling technologies before 2050. However, the government plans to increase from 2.4% to 4% the power contribution in the electricity supply portfolio, adding more than 13 GWe. The Brazilian significant uranium resources, the current mining, conversion

and commercial enrichment facilities; and the increase in uranium prices, may justify investments in the field. Moreover, a peak in the capital and fuel cycle costs due to the initial number of LWRs, as found in the simulation results, disappears as the nuclear industry remains steady and economy of scale is applied.

8. The uncertainties about reserves and prices which surround the world's oil production and the issues related to global warming and greenhouse gas emissions make nuclear power an option in Brazil as the "regulating power term". Therefore, following the overall strategy to meet the Brazilian growing needs for electricity supply, construction of the nuclear power reactor *Angra 3* was approved in 2007. However, Brazil is likely to consider all electricity sources, focusing on the carbon-free options of hydro as the dominant source of production of electricity; nuclear, as the regulating power term in the electric power sector; and renewable biofuel resources, source of transportation energy.

9. There is a significant impact on the U.S. cumulative TRU inventory at interim storage, enrichment requirements, uranium consumption, and number of advanced fuel facilities if a nuclear *fuel cycle state/reactor state* collaboration with Brazil is established. In addition, a nuclear partnership without the introduction of advanced nuclear technologies would not have advantages for the U.S. There are other issues related to the fresh and used fuel *supply chain* which must be addressed before starting a nuclear collaboration. In contrast, Brazil has been investing in nuclear R&D facilities for the last 28 years, and the government expects to start a nuclear program based on advanced light water reactors and advanced front-end fuel facilities. Consequently, based on the Brazilian energy market features, a nuclear collaboration should consider a combination of front- and back-end nuclear services in both countries.

8.2. Recommendations

The recommendations for further studies are the following:

1. Benchmarking CAFCA-SD against VISION, DANESS, and COSI would be useful to define the degree of differences among these fuel cycle simulation tools.

2. Optimization techniques should be applied locally in each structure-policy diagram. Next, a minimization of a cost functional should be applied globally to minimize the cost of electricity, i.e. given the system dynamic with the time-varying input *power demand*, the time-varying output *cost of electricity*, and time-varying states *number of reactors or fuel facilities*, a cost function that minimizes the total cost of electricity should be defined.

3. A more detailed forecast method for fuel facilities and fast reactors should be developed considering not only the facility lifetime but also all constraints in the system. In addition, more reactor types and recycling technologies should be aggregate to the model.

4. The system should be coupled with ORIGEN, and the mass flow should account for radioactive decay calculations. A simplified decay calculations model can be developed, but coupling CAFCA-SD with different nuclear codes should give more flexibility. In addition, the code should be able to access databases and excel spreadsheets for more options of reactors and fuels.

5. Due to the growing interest in global or regional cooperation, a more complete economic analysis of a nuclear partnership is needed by including transportation costs for the fresh and spent fuel. In addition, the capital and O&M costs for advanced fuel facilities should disaggregate from the back-end fuel services costs.

6. The system dynamic VENSIM simulation environment allows for high flexibility during the development and the simulations. However, a Graphic User Interfaces (GUI) should be developed.

7. In CAFCA-SD it's possible to run one case study, save results and load them as input parameters for assessment of a nuclear partnership. The use of subscripts, or matrix, to simulate a nuclear collaboration should aggregate more flexibility to the code.

9 Appendix: Stock-Flow Diagrams

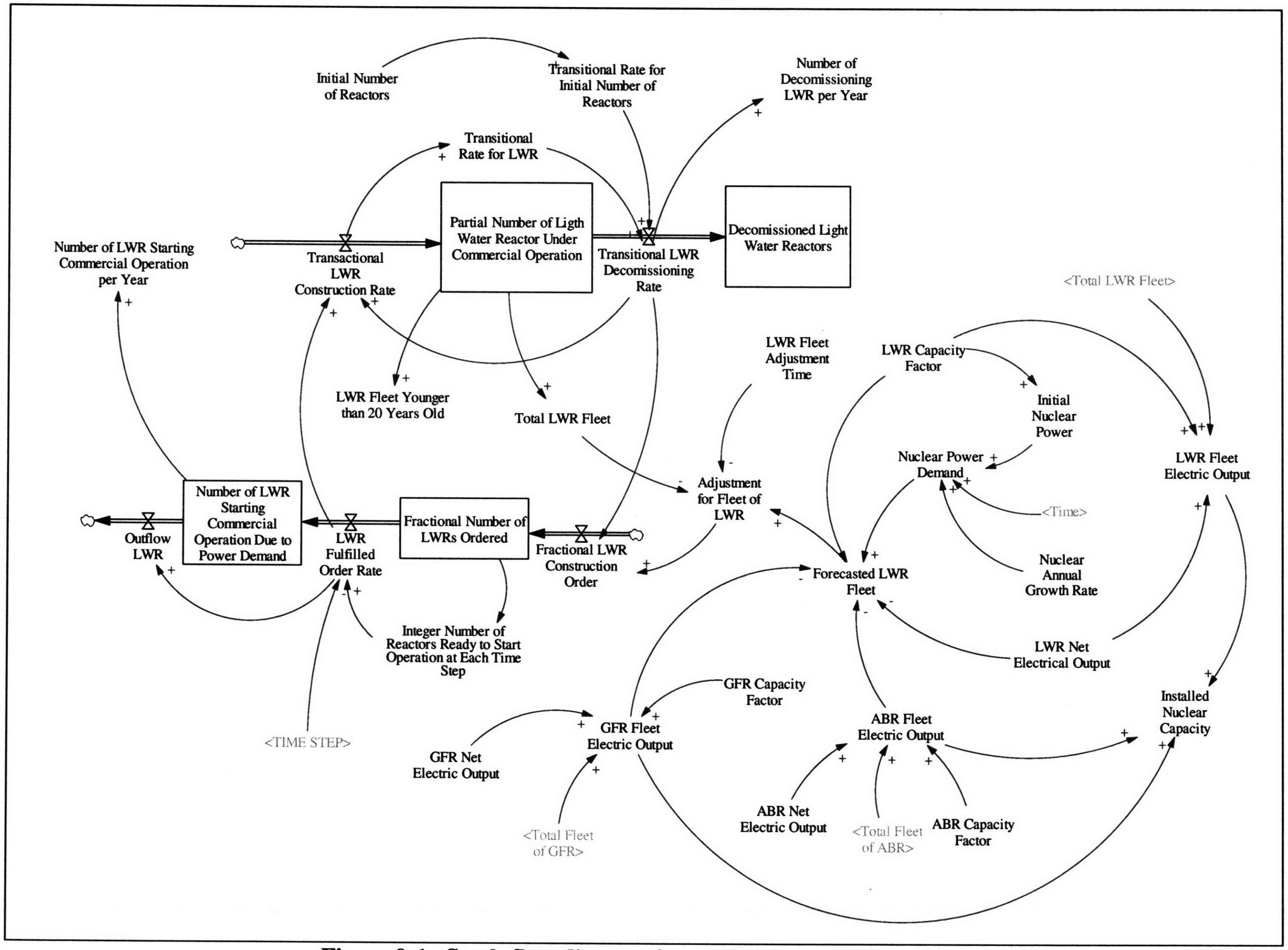

Figure 9-1 –Stock-flow diagram for the LWRs structure-policy

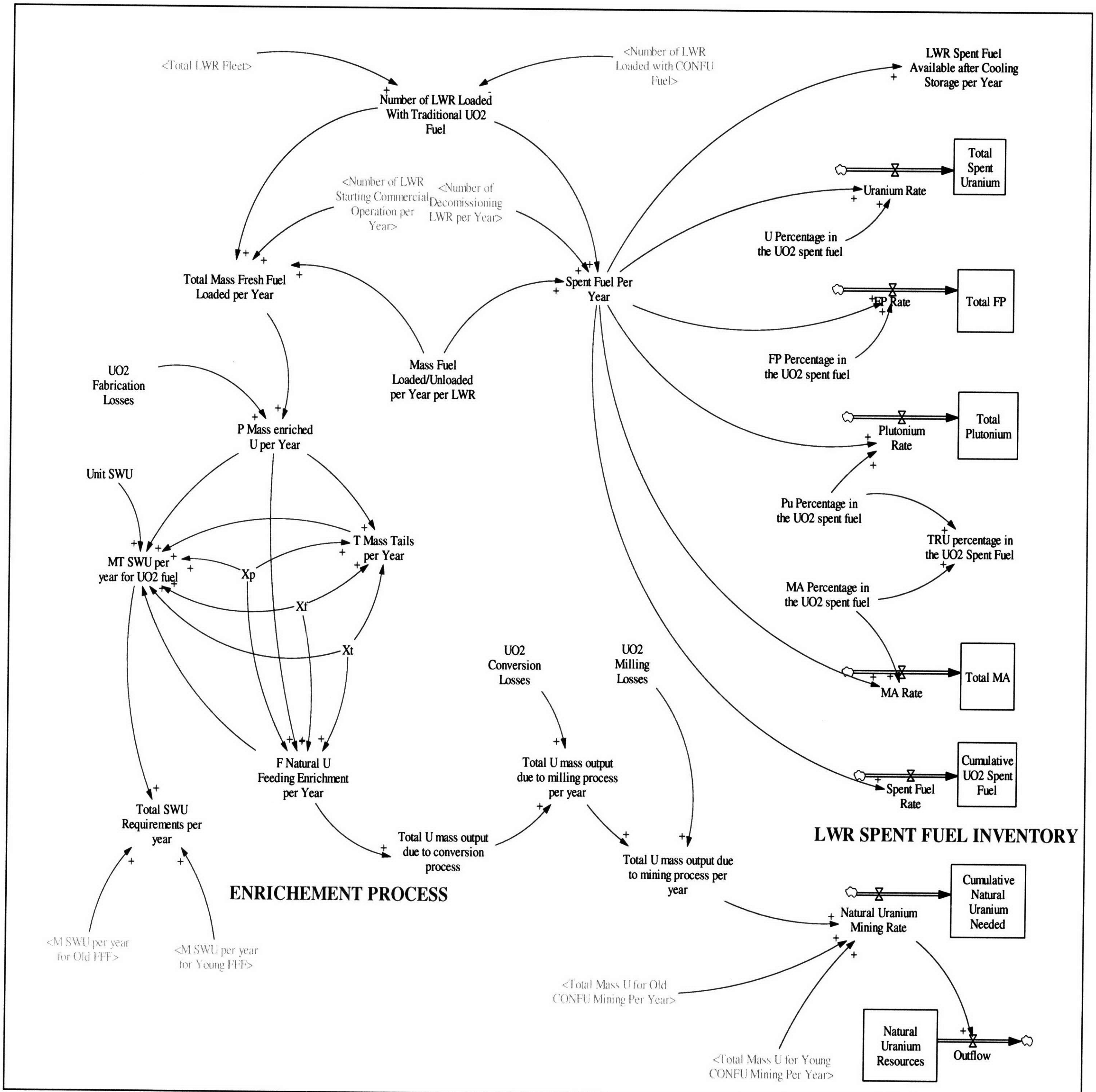

Figure 9-2 – Stock-flow diagram for front-end steps structure-policy

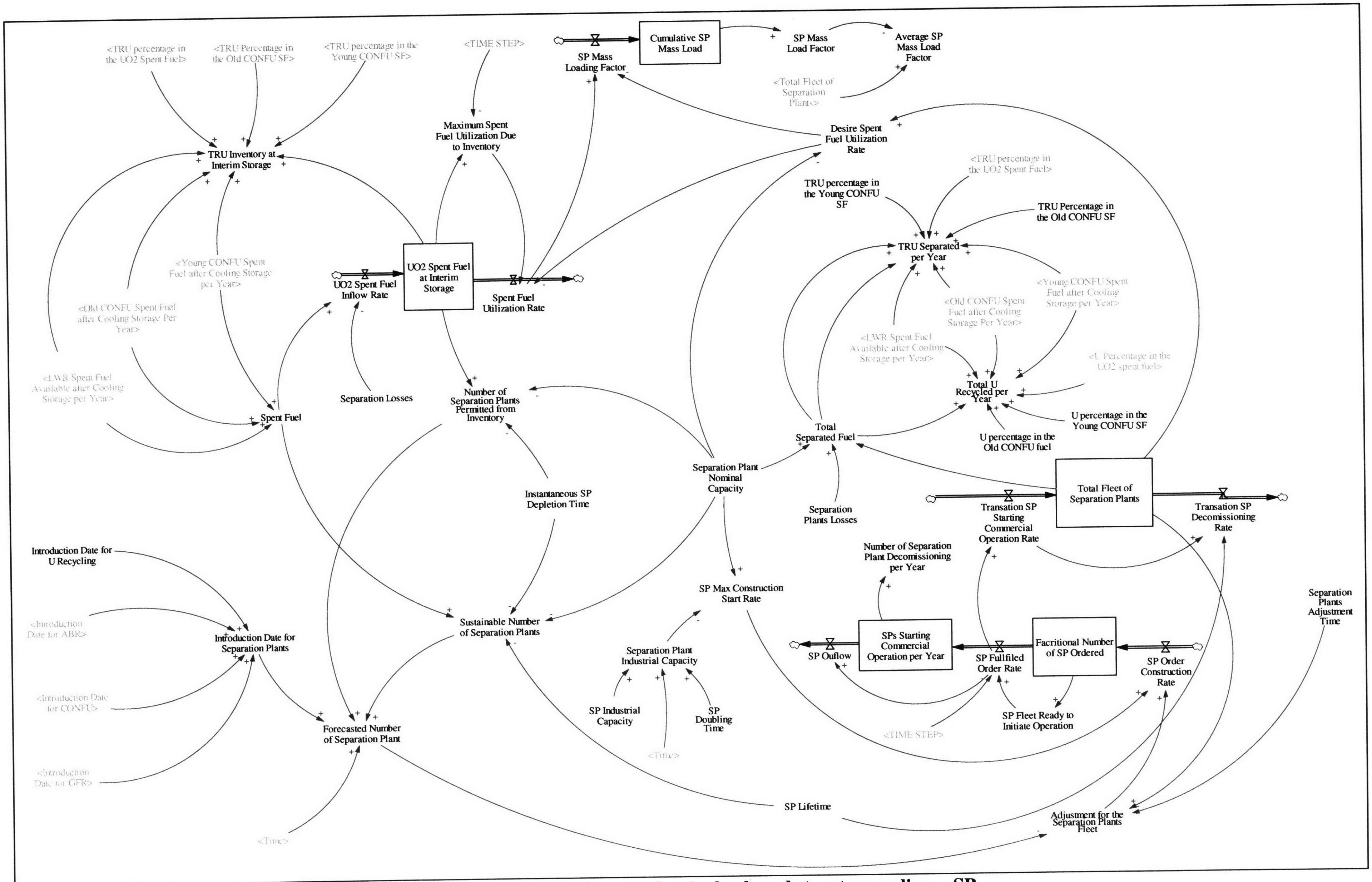

Figure 9-3 – Stock-flow diagram for the back-end structure-policy -- SP

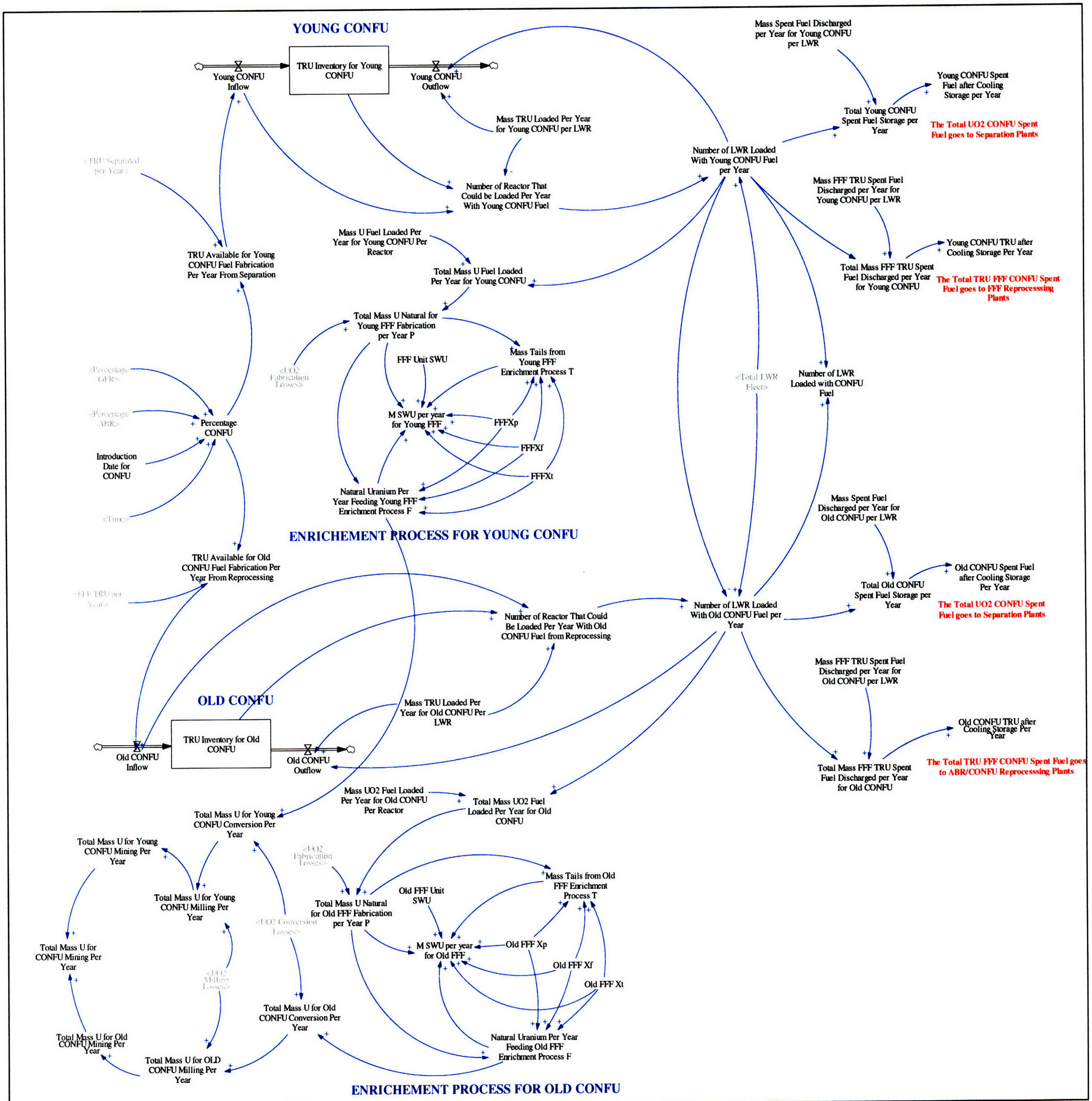

Figure 9-4 - Stock-flow diagram for the for CONFU fuel structure-policy

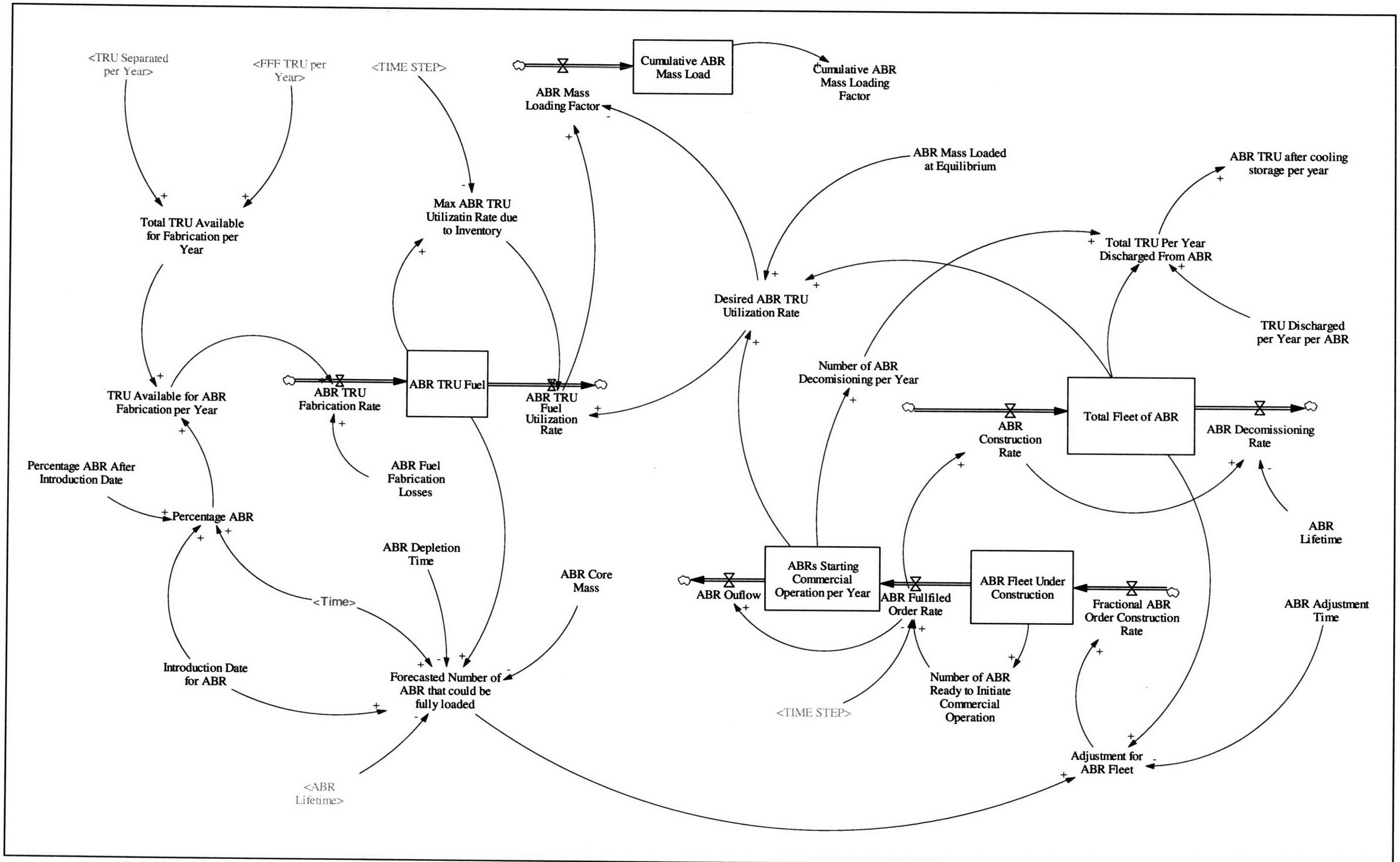

Figure 9-5 – Stock-flow diagram for the back-end structure-policy -- ABRs

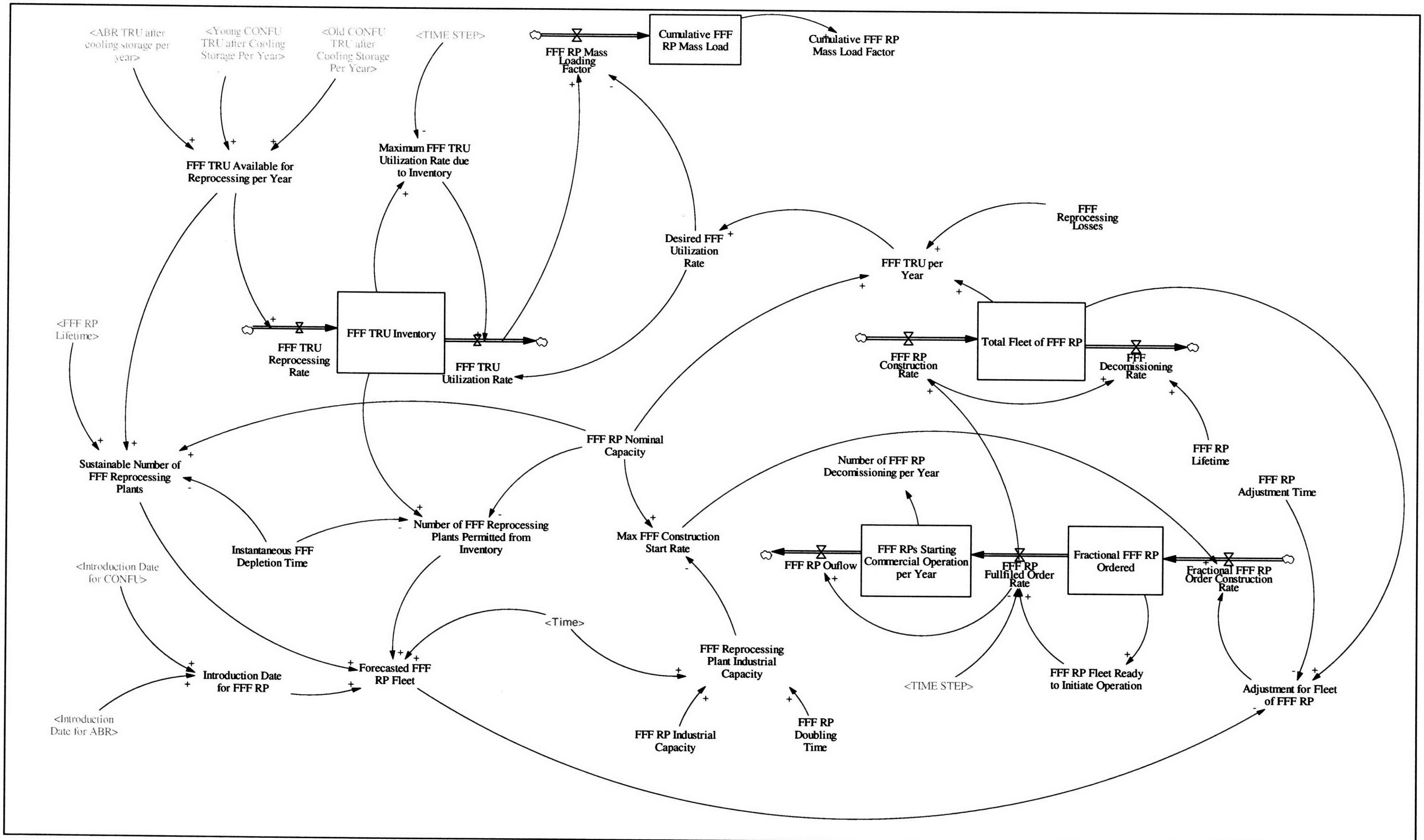

Figure 9-6 - Stock-flow diagram for the back-end structure-policy -- FFF RP

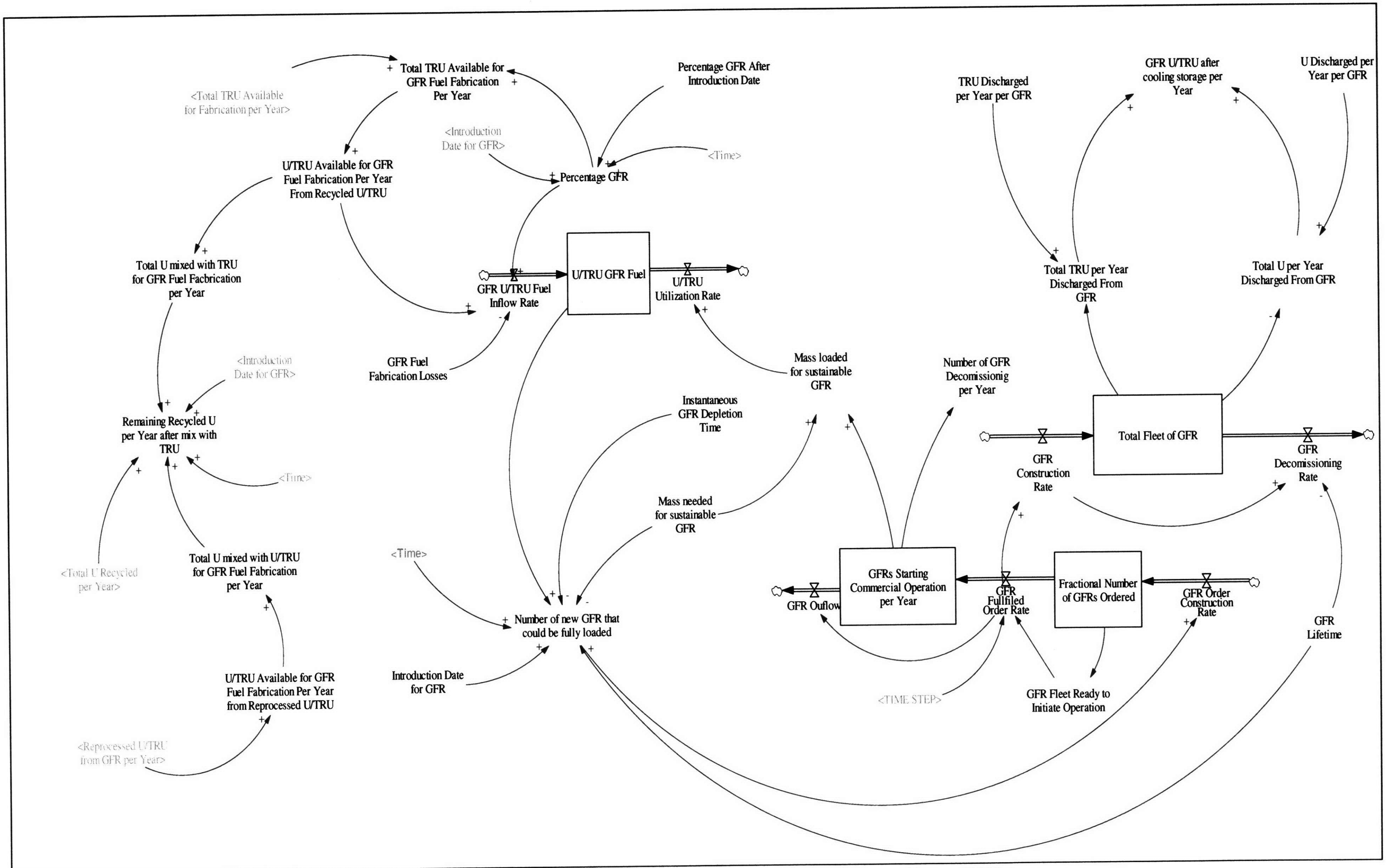

Figure 9-7 - Stock-flow diagram for the back-end structure-policy -- GFRs

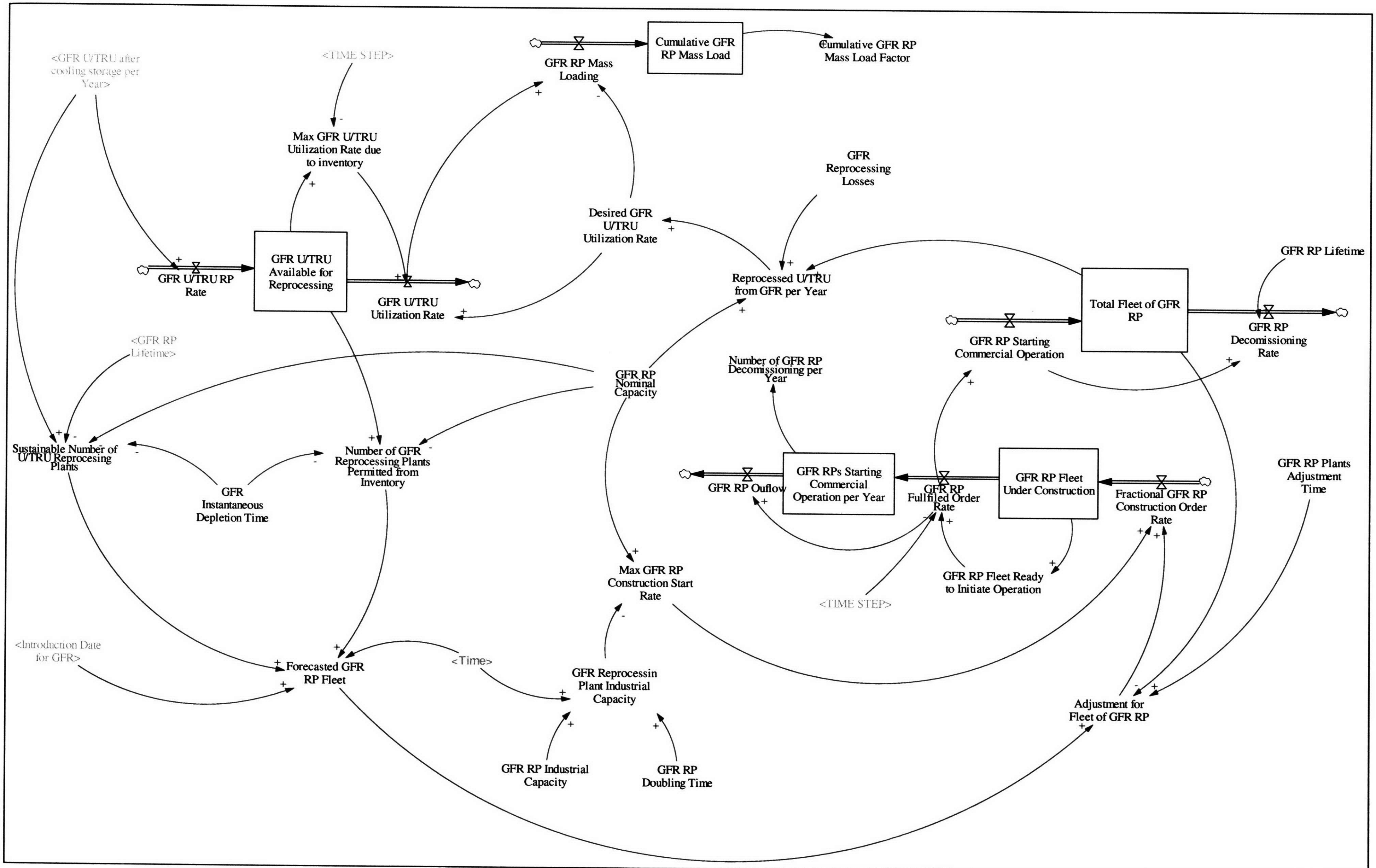

Figure 9-8 - Stock-flow diagram for the back-end structure-policy -- GFR U/TRU RP

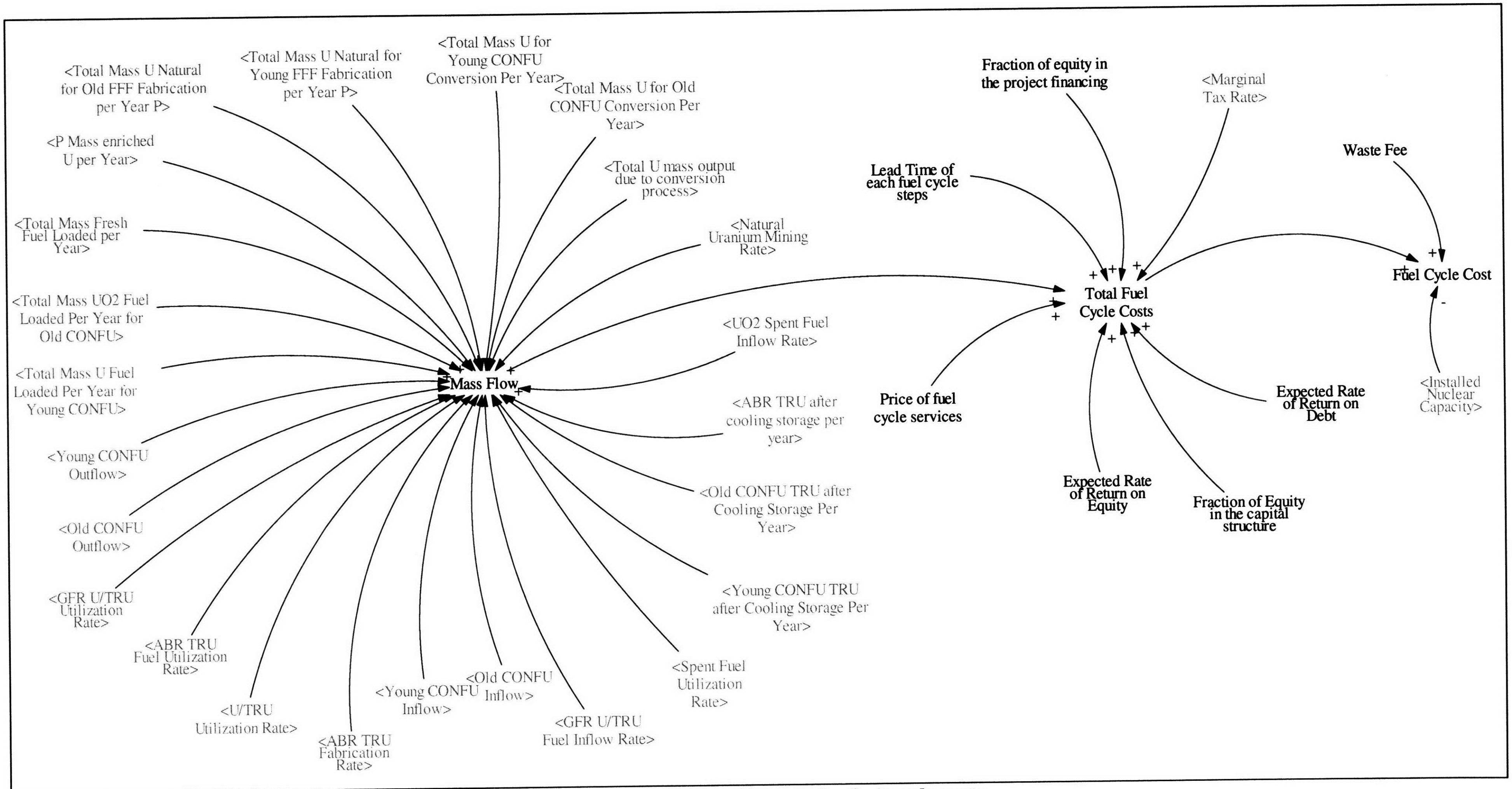

Figure 9-9 – Stock-flow diagram for fuel cycle costs

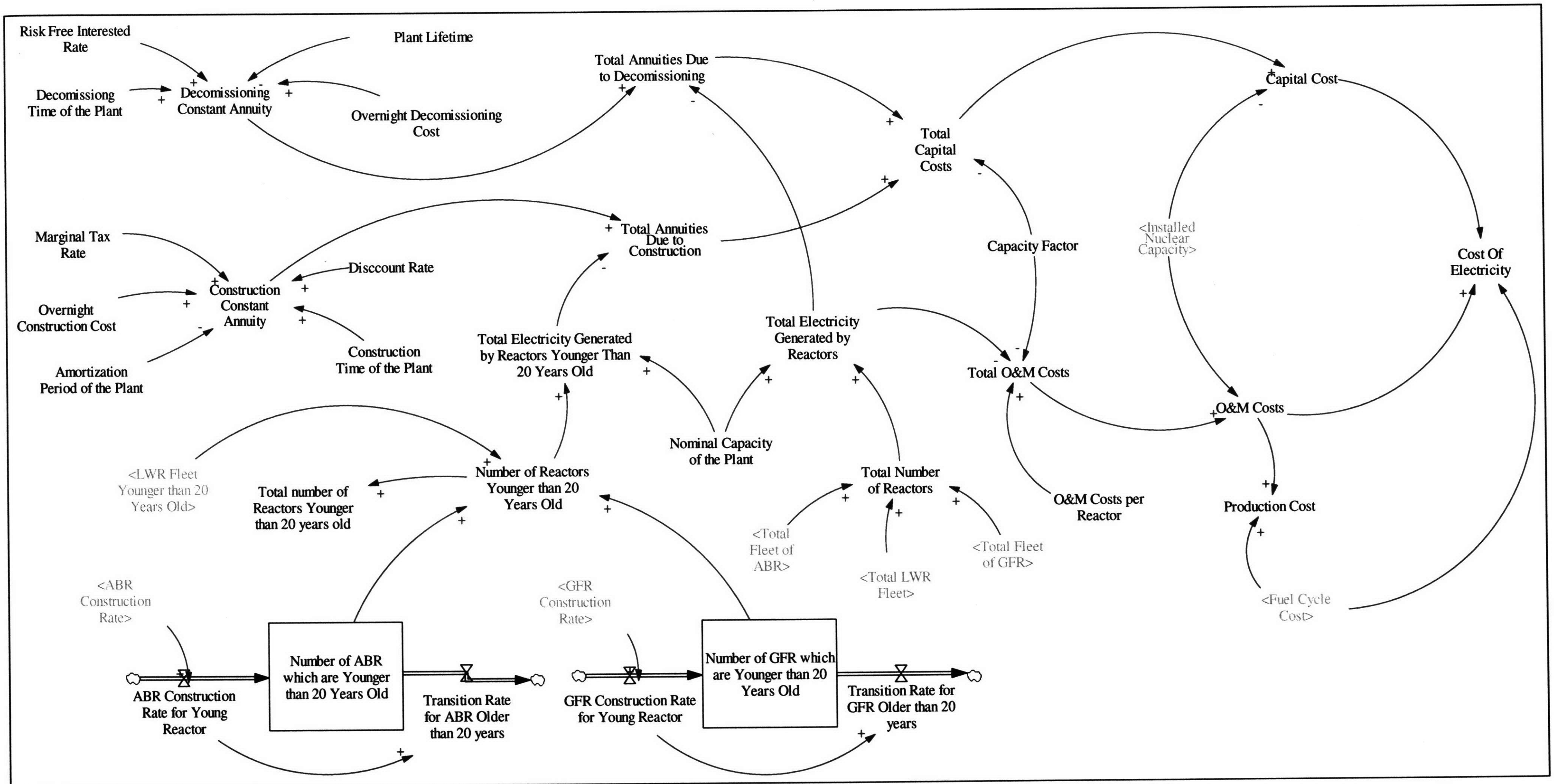

Figure 9-10 – Stock-flow diagram for capital costs, production costs and costs of electricity

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