ECONOMICS OF NUCLEAR FUEL CYCLES: OPTION VALUATION AND NEUTRONICS SIMULATION OF MIXED OXIDE FUELS

by

GUILLAUME DE ROO

Diplôme d'Ingénieur
École Polytechnique (France), 2007

Submitted to the Engineering Systems Division and the Department of Nuclear Science and Engineering in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Technology and Policy
and
Master of Science in Nuclear Science and Engineering

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Abstract

In most studies aiming at the economic assessment of nuclear fuel cycles, a primary concern is to keep scenarios economically comparable. For Uranium Oxide (UOX) and Mixed Oxide (MOX) fuels, a traditional way to achieve this is to evaluate both fuels on the deterministic premise that the fuel will be sent to geologic disposal once spent. This methodology often leads to higher costs for cycles using MOX fuel.

Geologic disposal is not the sole possible ending for spent Light Water Reactor (LWR) fuel. Fast Reactors (FRs), which feed on transuranics (TRUs) extracted from LWR spent fuel, are seriously considered as a future technology. If it is cheaper to extract TRUs from spent MOX than from UOX, then the relative cost of a fuel cycle using MOX fuel may be less than in the case of their geologic disposal. However, the commercial development of FR cycles is uncertain. The value of UOX and MOX is therefore not the deterministic value in case of geologic disposal or in case of reprocessing into FRs.

This thesis develops a method to assess the cost of thermal reactor fuel cycles in the presence of uncertainties in back-end management. The representation of future progress in FR technology through a resulting value of TRUs exhibits the properties of MOX as a financial option on the marginal TRU extraction cost. The framework establishes a significant modification of the back-end costs for countries using MOX, compared to traditional valuations. However, these savings do not completely offset the higher costs of recycling in the reference case.

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Contents

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Last but certainly not least, I would like to thank the persons who shaped my experience at MIT and indirectly this thesis, Lauren Culver and Laurent Guérin.

Acronyms

CF Capacity Factor

CR Conversion Ratio

EFPD Effective Full-Power Day

FR Fast Reactor

HEU Highly Enriched Uranium

IFBA Integral Fuel Boron Absorber

LCOE Levelized Cost of Electricity

LWR Light Water Reactor

MOX Mixed Oxide

OTC Once-Through Cycle

PPP Purchasing Power Parity

SDM Shutdown Margin

SFME Spent Fuel Management Entity

TRU Transuranic

TTC Twice-Through Cycle

UOX Uranium Oxide

Chapter 1

Introduction

In traditional approaches to the cost of nuclear fuel cycles, a primary concern is to keep scenarios economically comparable. For Uranium Oxide (UOX) and Mixed Oxide (MOX) fuels, a common way to achieve comparability is to make both fuels undergo a similar burnup and a similar ending, e.g. geologic disposal. This methodology often leads to higher costs for cycles using MOX fuel.

Geologic disposal is not the sole possible ending for spent Light Water Reactors (LWR) fuel. Fast Reactors (FRs) are seriously considered for future steps in many countries with a nuclear program. These FRs have been mostly designed to feed on transuranics (TRUs) extracted from spent LWR fuel. If it is cheaper to extract TRUs from spent MOX than from UOX, then the relative cost of a fuel cycle that includes MOX fuel may be less than in the case of their geologic disposal.

Nevertheless, a third possibility is more realistic, in which the management of spent fuel is uncertain: fast reactors are not yet commercially attractive and may never be built. In this context, the value of UOX and MOX is not the deterministic value in case of geologic disposal or in case of reprocessing into FRs. The choice of thermal reactor fuel cycles must take into account the valuation across all possible scenarios.

1.1 Defining a best cycle

Presently in the United States, uranium ore is mined, enriched, and manufactured into Uranium Oxide fuel rods. Once irradiated these rods are stored until their intended disposal. No material is reused to produce energy. This energy extraction process is called the Once-Through Cycle (OTC). Other cycles are possible, such as thermal recycling, implemented in France, Japan, and other countries in the past. In the latter, which we will

detail in Chapter 2, spent UOX is reprocessed and separated into a uranium (95%), a plutonium (1%) and a waste stream (4% of wt.). The uranium and plutonium are recycled respectively into UOX and MOX fuel assemblies, which can be used in thermal reactors again.

Since some radioactive elements are recycled, the second cycle consumes less uranium and produces less waste.[1] The two gains offset part of the cost added by recycling, but not enough to make it economically attractive according to many authors in the field.[2]

Besides these classical arguments, another argument, which received little consideration in the past, should be added. Using Areva proprietary data, BCG [2006] undertook an economic study of the recycling strategy and its implementation in the US. Some critics drew attention to the management of spent MOX, pointing out that BCG's analysis allocated an inadequate cost (Bunn [2006]):

> *[BCG] assumes that the management cost for spent MOX fuel would be the same as for spent LEU fuel, despite the far higher heat generation of spent MOX fuel, the greater difficulty in reprocessing it, and the much more radioactive nature of the fuel that would be manufactured from it.*

In fact BCG [2006] provides four management scenarios in a short appendix: disposal of MOX, multiple thermal recycling with or without removal of Americium, and recycling of used MOX into fast reactors. The resulting MOX management cost estimates are centered around the spent UOX management cost, $ 520/kgHM, and ranging from $ 0/kgHM to $ 1,600/kgHM. However disposal of MOX is excluded from this range:

> *Disposal of used MOX in a geologic repository is not considered a viable option, because it could increase recycling costs up to 40 percent by undermining any advantage gained on repository capacity, while also wasting valuable material with a high energy content that could be used by future generations.*

In this appendix, the reader is only provided with little details on economic and technical assumptions underlying these numbers, which do not completely address M. Bunn's concerns.

However, this part of the BCG study is innovative in two regards:

[1] The expression "less waste" has to be understood loosely here. The fission products separated at the reprocessing step present less decay heat, less radioactivity and radiotoxicity than the spent UOX and should hence be cheaper to dispose of. Spent MOX is not included in such statement.

[2] Bunn et al. [2003] reports a difference of 1.3 mill/kWh, MIT [2003] 2.8 mill/kWh, and EPRI [2007] 0.7 mill/kWh.

- it claims that spent MOX is not meant to be disposed of (in contrast to what most studies assume) but rather that there are alternative and more desirable scenarios.
- as a consequence it introduces an (uncertain) value for spent MOX management that is not necessarily the cost for compulsory geologic disposal. Notably BCG claims that the management costs are lower than for UOX in case of multiple recycling with Americium removal and recycling into FRs.[3]

And indeed, to the extent that the TRUs present in LWR spent fuel have a value for other cycles, since spent MOX has a higher concentration of these TRUs than spent UOX for a similar reprocessing price, there could exist conditions under which spent MOX is attractive, and is more attractive than spent UOX.

Whether these conditions are met in the perspective of fast reactors needs to be assessed properly. However, before carrying any quantitative assessment, let us note that the MOX cycle needs not even be the least expensive cycle in any specific scenario to be the best one overall. The preferred cycle is rather the one able to mitigate the losses/benefits across future scenarios.

Example Let us consider a schematic reality, in which spent UOX can either be directly disposed of, stored or recycled into MOX. After some time T, a decision is taken for the accessible spent fuel (ie. spent fuel which has not yet been disposed of) among 3 possible outcomes

- Economic and technical changes make recycling into FRs commercially attractive;
- Recycling into FRs is not commercially attractive, but forced in order to "burn" the most troublesome radionuclides;
- Recycling into FRs is not commercially attractive, and spent fuel is disposed of.

In this representation, the fuel cycle in which spent fuel is being disposed of directly has a constant cost, which we set arbitrarily to $C_{FC} = 1$. Figure 1.1 provides us with fictional fuel cycle costs for the different spent UOX management strategies.

[3]In Visosky et al. [2006], the isotopic vector of plutonium is showed to degrade quickly in multiple recycling and to become unattractive for LWRs. There is little knowledge of the parameters assumed by BCG to assess multiple recycling. Therefore this thesis will focus solely on recycling in FRs and geologic disposal as possible spent MOX management. It will appear later that correcting for this restriction is equivalent to changing the probability distribution of the price of TRUs in Chapter 4.

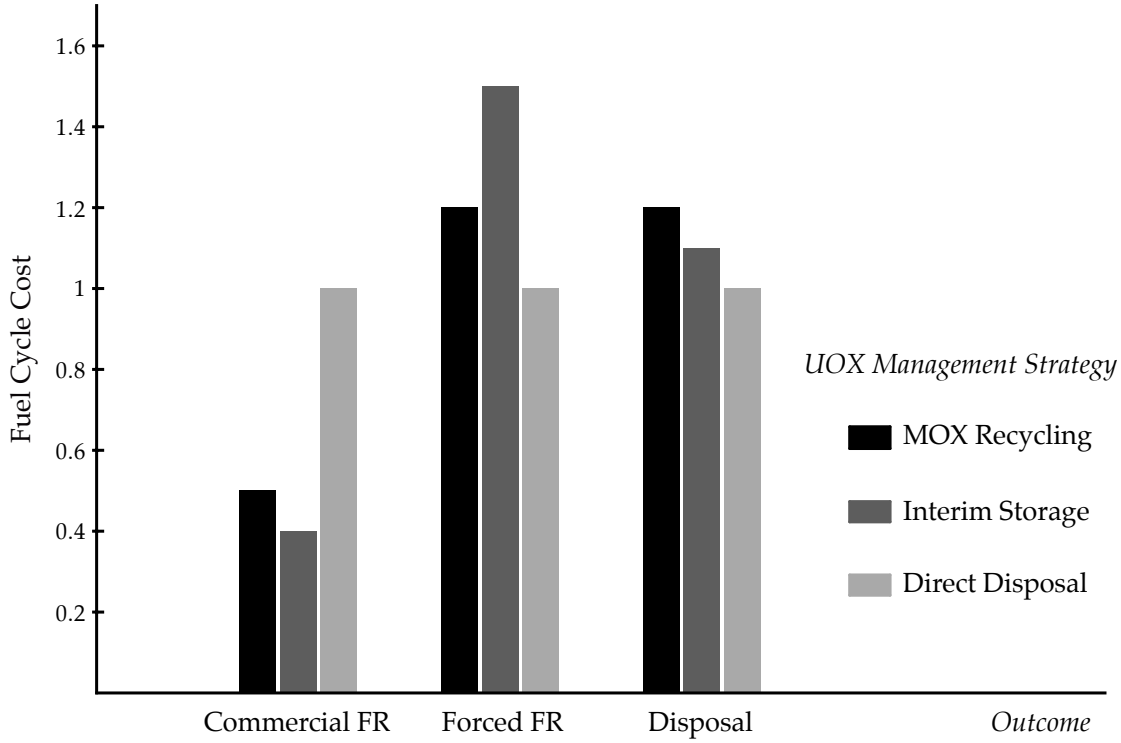

Figure 1.1 – *Fictional costs for the 3 management strategies, depending on the outcome*

Let us assume that all outcomes have equal probability. The corresponding expected cost incurred for each fuel management strategy is calculated in Table 1.1.

Table 1.1 – *Expected fuel cycle cost ("best" strategy indicated in bold)*

	MOX Recycling	Interim Storage	Direct Disposal
$\mathbb{E}(C_{FC})$	**0.97**	1.0	1.0

This example shows how MOX can be the best cycle on average without being the best option for any specific outcome.[4]

So far, most studies have focused on the comparison of different cycles - recycling or absence of recycling - in specific waste management scenarios - such as disposal. Such methodology can present efficiently some economic tradeoffs, but our simple example illustrates that there can be value in taking account of the various scenarios in order to properly assess the desirability of a particular cycle.

[4]Here we arbitrarily assume that the actors in charge of spent fuel management are risk neutral. Other metrics on cost probability distributions can be designed to represent risk aversion, e.g. $\mathbb{E}(C_{FC}) + \alpha\text{Var}(C_{FC})$. Their use would not fundamentally impact the approach of this thesis.

1.2 Parallels in strategy choices

Examples of similar prospects, where extra costs are justified as having a strategic value, exist in various industries. For instance, consider a manufacturer unsure what demand will be for car A or car B. If future demand were known in advance, his cheapest solution would be to buy plant A or plant B, producing car A or B respectively. But as a result of the uncertainty, and the fact that investments are irreversible, the manufacturer could be ready to pay more for a plant AB capable of producing car A and car B depending on the future demand. An analogous problem exists for firms with multiple inputs, e.g. a utility ready to pay for a more expensive coal plant able to burn coal of different qualities.

These cases are an illustration of flexible design of output/input (He and Pindyck [1989]). Other examples common to most projects involving timely choices of technologies and investments include options to expand, options to abandon, or timing options. The nuclear industry can present many of its decisions as having strategic value. In the nuclear industry, two examples of options can be formulated:

- Using ground surface storage during the first years when decay heat is high, before moving to a repository, can have a certain economic advantage. Loubergé et al. [2002] investigate it as an optimal stopping problem, in the face of random costs of unanticipated accidents (geologic disposal) and random costs of institutional control and hazard management (surface storage).
- Due to the importance of capital cost in the nuclear electricity cost (Du and Parsons [2009]), adapting the size of reactors in the face of the uncertain price of electricity or consumption growth is another problem which received attention (Golliera et al. [2005]), and can play in favor of designs such as the Pebble Bed Modular Reactor.

These cases are good illustrations of what the nuclear industry can perceive as "options", but without necessarily analyzing them thoroughly as such.

1.3 Option value representation

Due to their widespread nature, the quantification of the strategic value embedded in industrial options has received much interest and produced formalisms such as decision trees and "real" options. In decision trees, "all" possible events and the consequent possible management decisions generate "branches" that the company can follow. The action path corresponding to the highest probable value is chosen and corresponds to the value

of the project. Real option analyses use more systematic financial tools, like binomial options models, and generally correspond to projects contingent on an underlying variable, on which assumptions of price dynamics are made (e.g. impact of oil market price on oil field development).

Later in this thesis, decisions are made depending on the price of TRUs. The anticipation of this price could lead to continuous adjustments of reprocessing capacity, or duration of interim storage. However, to keep tractable the modeling of reality, we restrain the number of possible states of the system and make little use of financial options formalism. Therefore our analysis can mostly be assimilated to a decision tree analysis. This simplified framework is enough to build economic intuition on the value of the call option created by the use of MOX.

1.4 Policy impact of an economic approach

When comparing fuel cycles, economics are only one factor, and not necessarily the main one: energy security, health, safety, technological advantage, and other strategic considerations are significant in the often politicized discussions about energy. This is all the more true as fuel costs account for only a fraction of the total energy cost.

To the extent that economics is one of the present modes of debate, and a rather "transparent" one to the public, it is desirable to make the economic discussion more complete and incorporate into its metric as many significant "strategic factors" as possible. This thesis deals with one of these factors, namely the interest of thermal recycling for future cycles, and tries to clarify some of its technical and economical aspects by using decision tree tools and neutronics simulations. By doing so, it tries to bring a new argument into the debate.

Chapter 2

Description of Potential Fuel Cycles

Many fuel cycles were conceived in the 70's and 80's, some differing from others by the kind of reactors they use, and others only by the thoroughness of their separation process or the length of cooling periods. Therefore a complete detailing of each step from ore mining, to reactors, to waste management must be specified so as to adequately compare the various cycles. As a consequence, this thesis only focuses on four cycles regarded as the main ones, and thereafter restrains the possible decisions to these cycles.

These cycles can be separated into three kinds:

i *open cycles*, in which fuel fabricated from raw ore undergoes a single pass in a reactor and is then sent directly into a final repository

ii *semi-closed cycles*, in which this spent fuel is recycled to extract part of the remaining energy through a limited number of passes into reactors

iii *fully-closed cycles*, in which this spent fuel recycling can last an unlimited amount of time

To describe each cycle, one uses generally three main stages, by which they can be characterized:

i the *front-end*, which encompasses mining of uranium ore, and fabrication of the fuel by assembly of its different components

ii the *fuel use*, where the assemblies produce electricity (or simply heat) through fission, and are then stored in pools to cool down

iii the *back-end*, which covers means of prolonged interim storage (dry casks), shipping, reprocessing, and disposal of the spent fuel or its separated elements. The possible reassembly of the separated elements will be considered as a front-end process.

The categories are very adequate for open cycles, which are sequential. It will however be used more carefully when talking about closed fuel cycles.

2.1 Thermal reactor cycles

Thermal reactors constitute the vast majority of present reactors in the world. These reactors are designed such that the energy releasing process, fission, happens mainly between fissile atoms and neutrons with a low energy level. These neutrons are essentially in thermal equilibrium with the ambient medium ($\sim$.025eV) like a gas in a room, hence the "thermal" designation.

To reach this level of energy, neutrons are slowed down by a moderator. In most cases, this moderator is water: either light water or heavy water.[1] The first type being dominant, it will be the central reference hereafter.

Fuel Cycle 1 : Once-Through Cycle (OTC) *Open cycle, in which the spent fuel discharged from the reactor is considered as waste. It is currently the cycle of reference in the US (corresponding to Cycle 1 in MIT [2003] and illustrated in Figure 2.1)*

The OTC starts with the mining and milling of uranium. Uranium is recovered from areas where geological processes have increased its local concentration, either by open-pit mining and milling or solution mining (in which weak acids are pumped through the deposit). The leachate is then subjected to precipitation, solvent extraction, and ion exchange. The resulting uranium concentrate (U_3O_2), called yellowcake, contains between 60% and 85% uranium in weight. Yellowcake can then be calcined to remove impurities before refining and conversion.

After a chemical process producing 99.95% pure uranyl nitrate ($UO_2(NO_3)_2$), uranium is converted to the volatile uranium hexafluoride (UF_6). At this step, uranium still has the isotopic composition of the initial ore, i.e. only 0.71% of ^{235}U its fissile and lightest isotope. In contrast to CANDU reactors, Light Water Reactors (LWRs) require an enrichment of the fuel, i.e. an increase of its composition in the fissile isotope ^{235}U (4.5 wt. % in the reference case). Using the differences in molecular masses, enrichment is obtained currently by gaseous diffusion through porous membranes or gas centrifugation. The process results in the production of two streams: a large fraction depleted in ^{235}U (enrichment tails) stored until later usage, and one enriched in this isotope.

[1] Light Water Reactors are either pressurized (PWR) or boiling (BWR). The main example of pressurized heavy water reactor is the Canadian design, CANDU.

The latter stream is then converted back to a UO_2 powder, pressed into pellets, sintered in a furnace, and stacked in tubes made of zirconium alloy to withstand the conditions in the reactor core. These tubes, named fuel pins, are then assembled in a lattice of similar alloy.[2] They are then loaded in a LWR core, in which they stay 3 cycles of 18 months and produce an amount of heat depending on the operating conditions and the initial enrichment (50MWd/kgHM burnup in the reference case). During the irradiation, a number of uranium atoms undergo fission to produce energy. Absorption of some released neutrons by ^{238}U leads to the creation of ^{239}Pu, which in turn partially undergoes other fissions.

After its stay in the reactor, the fuel is discharged, and will be designated as spent fuel. Due to its irradiation, the spent fuel notably produces decay heat for subsequent years. During the first years after unloading (5 years), this decay heat is removed by an interim storage in reactor pools. Spent fuel is then transported to an interim storage for another cooling of 20 years, usually in dry casks. Finally it is encapsulated for final disposal in a geological repository.

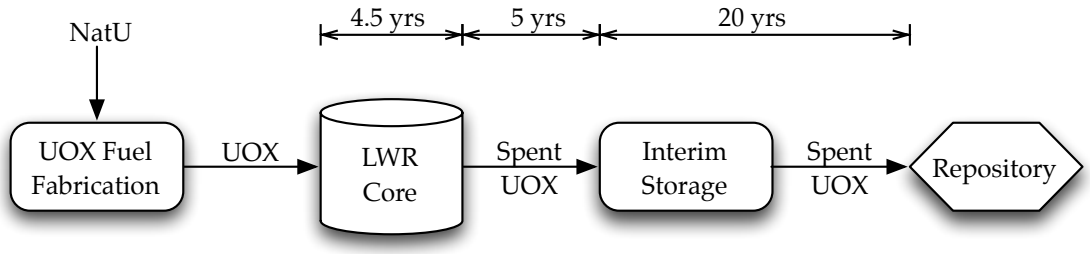

Figure 2.1 – *Fuel Cycle #1 ∼ Once-Through Cycle*

Fuel Cycle 2 : Twice-Through Cycle (TTC) *Semi-closed cycle in which the thermal reactor spent fuel is reprocessed, and some of its components reused in thermal reactors before being disposed of (corresponding to Cycle 2 in MIT [2003] and illustrated in Figure 2.2)*

The nuclear fuel cycle follows similar steps as described above, until the discharge of the thermal reactor fuel. After 5 years cooling in the reactor pools, the fuel is then shipped to a reprocessing facility where it is dissolved in acid and separated from its cladding. The solution is then treated chemically to produce to three main streams using the PUREX process: a plutonium nitrate, a uranyl nitrate, and a waste product (other actinides, fission products, impurities and the unremoved U/Pu) stream.

The latter stream is stored in stainless steel casks and then blended in an inert glass matrix which goes to a geologic disposal, along with the treated cladding, after a cooling

[2] 17x17 in our simulations, typical of a PWR.

period of 20 years. The uranium stream can be converted to uranium dioxide for the production of new fuel through through conversion and enrichment.[3] Lastly, the plutonium is converted into plutonium dioxide. It is then blended with depleted uranium, pressed into pellets, sintered and stacked in pins in a dedicated plant using glove boxes to shield the installation from the radiations emitted by the plutonium. The produced assemblies can then be used in a thermal reactor.

A concern with MOX fuel is that its use in thermal reactors produces a different neutron spectrum than regular UOX assemblies. As a consequence, some adaptation of the reactor may have to be made, but many reactors are now designed to be able to use 100% MOX cores (e.g. EPR). A simulation of MOX composition and loading pattern for a core with 30% MOX, which maintain the performance within the typical PWR operations conditions, can be found in Appendix A.

Once irradiated, the assemblies are cooled 5 years in reactor pool, then stored interimely in dry casks for 20 years, before their geologic disposal. Due to different initial materials, the final spent MOX has a different composition than spent UOX. As a result a mass of spent MOX produces a higher decay heat than the same mass of UOX.

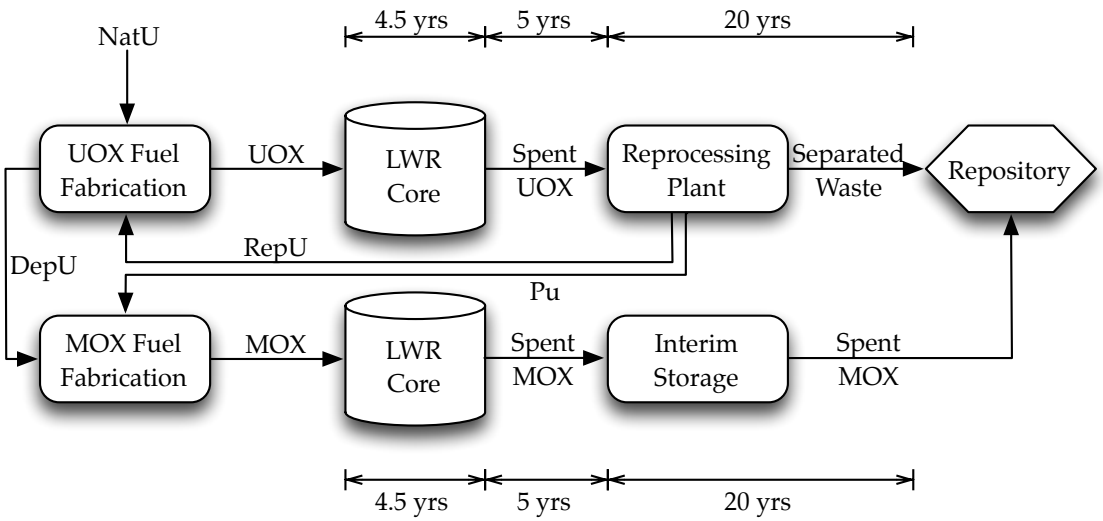

Figure 2.2 – *Fuel Cycle #2 ∼ Twice-Through Cycle*

Also called Pu-Recycling, this cycle is generally the one considered by studies assessing the economics of MOX (Bunn et al. [2003], MIT [2003], EPRI [2007]). There are however other definitions of Mixed Oxide Fuels in which americium, and neptunium, are re-

[3]This reprocessed uranium is more enriched than natural uranium, but is irradiated and contains ^{236}U a neutron absorber. Therefore, it needs to be converted and enriched in separate plants, with different ^{235}U enrichment targets, see Appendix B.2.

cycled along with plutonium in a matrix of the recovered uranium (Wigeland and Bauer [2004]). Therefore, one must be careful when comparing studies.

2.2 Fast reactor cycles

In contrast to thermal reactors, neutrons are here kept at the high energy at which they were emitted by previous fissions. A higher neutron energy spectrum allows the reactor to increase the average number of neutrons released by fission as well as the probability of fission of some actinides that cannot be fissioned in thermal reactors.

Therefore TRUs can be used as a fuel component for fast reactors. Such fast reactors may be designed to produce new fissile material at a rate that exceeds or falls short of its rate of consumption by the neutron chain reaction. With a focus on the plutonium rather the whole TRU vector, the "standard conversion ratio" was defined as the ratio of the rate of production of fissile Pu (^{239}Pu, ^{241}Pu) to its rate of destruction at equilibrium (Ott and Borg [1980]). Depending on this ratio FRs are named:

- *burner* reactors, if the ratio is smaller than 1
- *"self-sustainable"* reactors, if the ratio is 1
- *breeder* reactors, if the ratio is greater than 1

The growth rate of the TRUs in the system is linked to this conversion ratio.

Fuel Cycle 3 : 1-Tier Recycling (1-Tier) *Fully-closed cycle in which spent UOX fuel is reprocessed and some of its components are recycled infinitely in FRs (corresponding to Cycle 3 in MIT [2003] and illustrated in Figure 2.3)*[4]

The 1-Tier Recycling furthers the process of the semi-closed cycle introduced earlier. Here, the reprocessing of the LWR spent fuel does not only extract the uranium and the plutonium to reuse them, but also minor actinides. The reprocessing technique is TRUEX, which separates the initial solution into a TRU, a uranium and a waste stream. The uranium and waste streams are treated as before and are sent to a LWR and a geologic repository respectively. The TRUs are blended with depleted uranium to produce a metallic fuel, the composition and loading time of which depend on the conversion ratio.

Once spent, the fuel from FRs is cooled for 5 years and then undergoes pyroprocessing. The latter process separates the fuel into a mix of uranium and transuranics (U/TRU) and

[4]MIT [2003] focuses on burner reactors for this cycle. This work considers the "self-sustainable" reactor as the reference case.

a waste stream. The waste stream is disposed of, like in the TRUEX process. The U/TRU mix is blended with more depleted uranium and TRU to produce new fresh fuel, which will be further used in fast reactors.

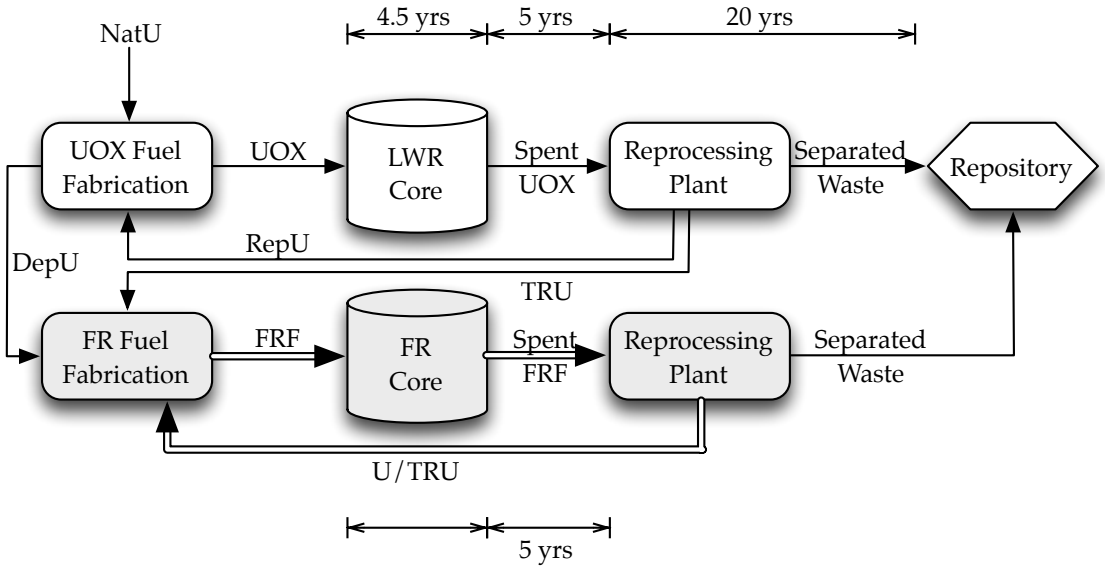

Figure 2.3 – *Fuel Cycle #3 ∼ 1-Tier Recycling*

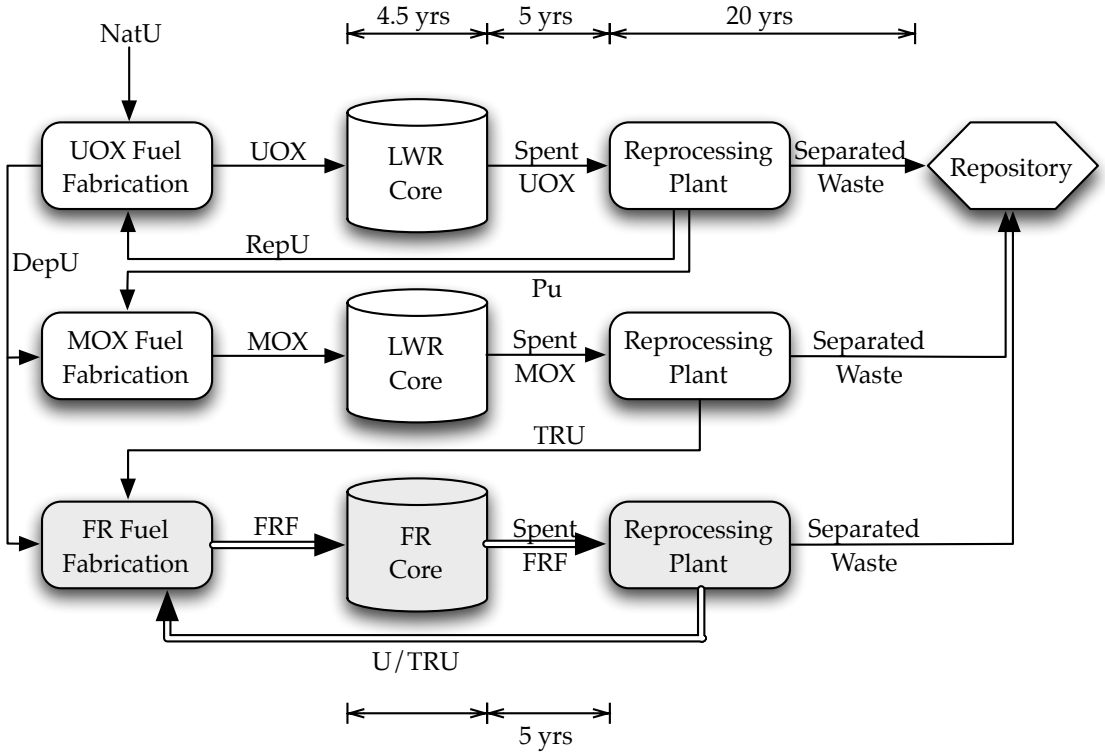

Figure 2.4 – *Fuel Cycle #4 ∼ 2-Tier Recycling*

Fuel Cycle 4 : 2-Tier Recycling (2-Tier) *Fully-closed cycle cycle in which spent MOX is recycled, and some of its components are recycled infinitely in FRs (illustrated in Figure 2.4)*

The 2-Tier Recycling is the combination of the previous scenario, and the Twice-Through Cycle: the spent UOX from the thermal reactor is recycled once into MOX. Once irradiated, this MOX is reprocessed through the TRUEX process for its use into fast reactors.

2.3 Comparison of open & closed cycles

Closing the fuel cycle, namely separating the components of spent fuel for further use, has served multiple purposes, whose relative importance has changed over time: reprocessing was initially developed for military purposes, and was later adapted to civil usages and supported as a way to extract more energy from uranium (recycling in LWRs and FRs), as well as a waste management strategy.

Mixed Oxide fuel, as a possible product of such reprocessing, has shown similar changes in the justification of its use and in its comparison to other cycles. These comparisons exhibit the intrinsic trade-offs between the various cycles designed by nuclear research. Their respective merits can be compared along 4 main axes:

- the uranium ore consumption, which conditions the resource consumption for a given power generation
- the amount and type of waste produced, which conditions the complexity of their disposal, and part of the proliferation resistance of the cycle
- the use of nuclear services (enrichment, reprocessing, fabrication), which entails an industrial fabric, research efforts, and proliferation safeguards
- the types of reactors involved

Through their needs in these categories, the various cycles show different trade-offs. For example, the Once-Through Cycle can be expected to have higher uranium ore consumption and probably waste management services requirements. However, it can also be expected that, because closing fuel cycles involves the costly handling of irradiated materials, the nuclear services costs will be smaller than for the Twice-Through Cycle or Recycling into Fast Reactors.

Uranium Ore Consumption Nuclear energy is not renewable: there are limited resources of uranium in the same way that there are limited resources of coal and oil. Therefore, uranium ore consumption planning and geographic distribution were among the

concerns of decisions makers.[5] With uncertainty about the available uranium resources, studies in the late 1970's were pointing out the need for new sources of uranium to sustain the expected consumption. Figure 2.5, extracted from a 1978 EPRI study on foreign uranium supply for the US, illustrates this gap.

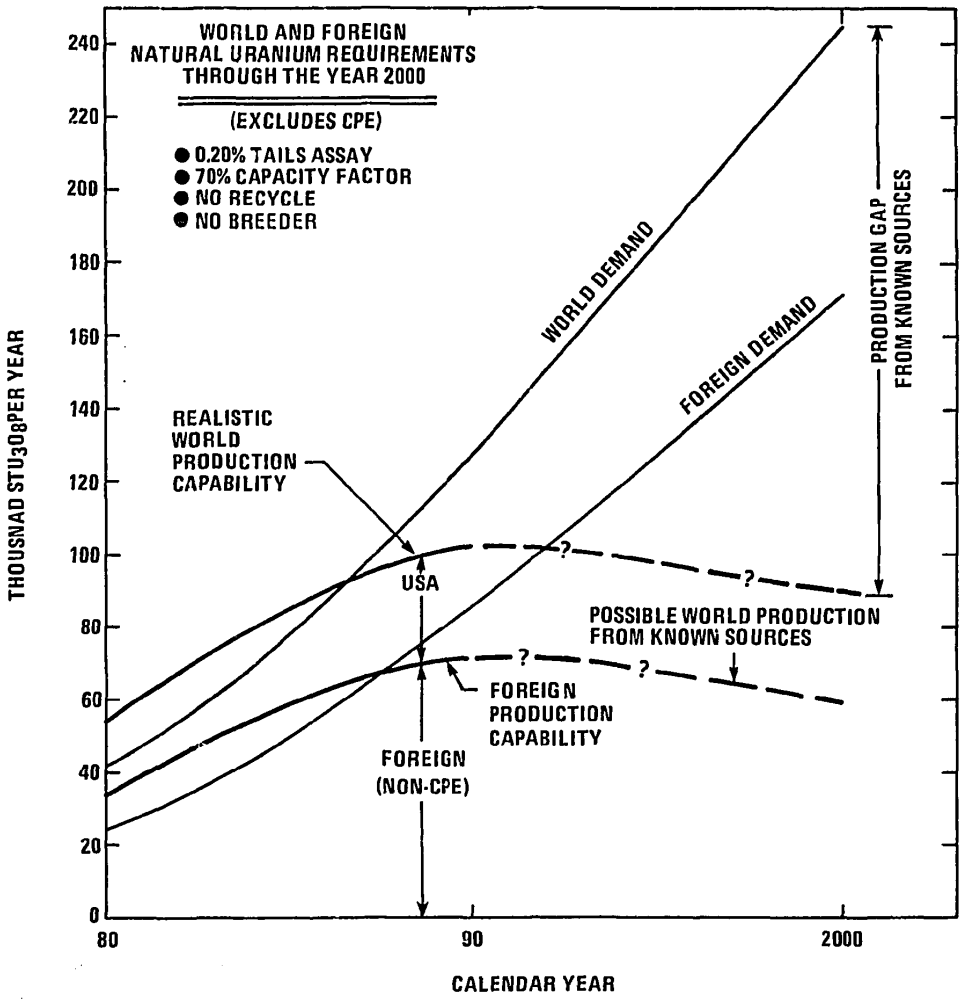

Figure 2.5 – *World and foreign natural uranium requirements until year 2000 (McLeod and Stoyn [1978])*

In this context, recycling could emerge as an interesting way to reduce uranium consumption. Moreover, it also reduced the need for conversion and enrichment services of the saved amount. The difference between uranium consumption in the different cycles is significant:

[5]For instance, energy dependency was a major concern when deciding the size of the French program, according to A. Lauvergeon, CEO of Areva. In her book, *La troisième révolution énergétique* (2008, ed. Plon, p.109), she writes: "I realized that the generation in power in the 70's had been directly exposed to this conflict [Algeria] which had produced a deep trauma [...]. These men hence came to refuse the idea of any srategic dependence from this part of the world."

- the Once-Through Cycle with the assumptions detailed in Appendix B uses 25.7 kg of natural uranium per GWh of electricity
- the Twice-Through Cycle uses 19.1 kg of natural uranium for the same amount of electricity, i.e. 23% less
- all Fast Reactor Recycling strategies with a self-sustainable reactor asymptotically use 1.2 kg of depleted uranium per GWh of electricity

However, historically, reduction of uranium ore consumption became a secondary concern: uranium resources proved to be larger than anticipated, and consumption lower than anticipated as a result of the slowdown of the industry (cost escalations, accidents...). Moreover, the effects of the introduction of such cycles on uranium ore consumption only become significant after 50 years (Guérin and Kazimi [2009]).

Waste Management Another great concern in nuclear fuel cycles is the difficulty of dealing with the waste they produce.[6] Nuclear generation produces waste with some unusual characteristics compared to waste from other human activities. For instance, it takes in the order of 10 million years for untreated fuel discharged from current reactors to reach the radiotoxicity level of the natural uranium from which it was fabricated. Disposal therefore has to be done through conditioning and final storage in geologic repositories carved in clay, salt or granite.

It can be of interest to design fuel cycles, which minimize the required size or number of these repositories, their noxiousness to the environment, and the appeal of their content to malevolent actors. The repository design requirements depend on the mass and volume of the material, its radioactivity, decay heat, radiotoxicity, and the mobility of specific radionuclides it contains (like Iodine). None of these requirements, individually, is a direct proxy to the disposal cost. Moreover, over time, different components of the irradiated material are the dominant contributors to these factors. Nevertheless, separating the spent fuel into different waste streams of similar characteristics for their separate disposal or transmutation into more benign material can potentially lead to benefits.

To partially illustrate this point, Figure 2.6 shows that most of the long term radiotoxicity comes from the TRU and not the fission products of spent UOX. Keeping TRUs in the reactors and burning them through MOX fuels or fast reactors could therefore have a significant impact on waste management. The greatest impact is achieved by the burning of Pu, as noted by Westlén [2007].

[6] Currently no final repository for commercial spent fuel exists in the world.

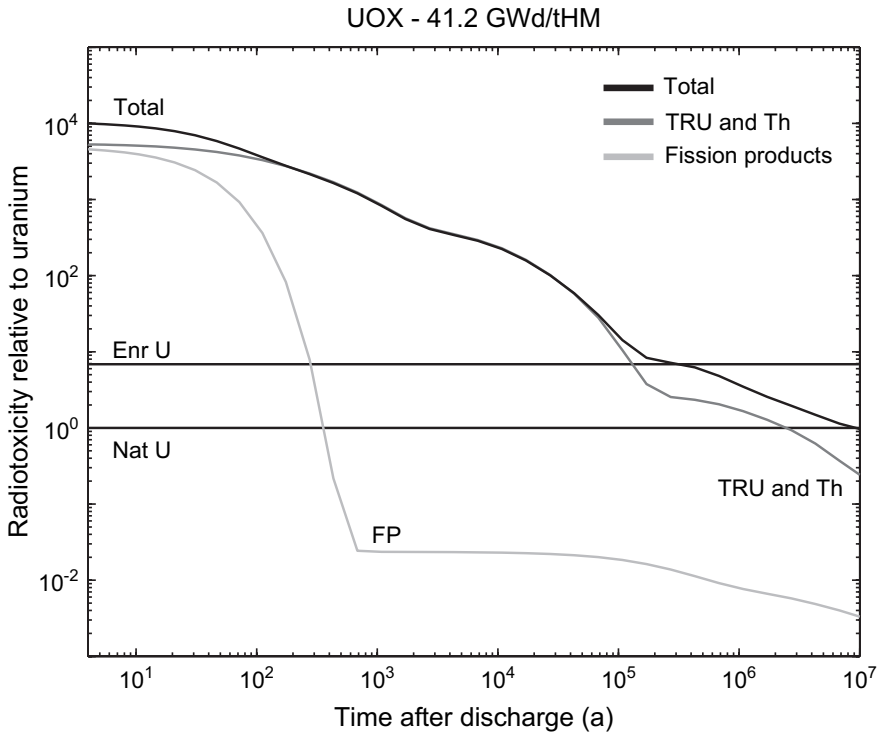

Figure 2.6 – *Time evolution of the radiotoxicity from spent UOX, from Westlén [2007]*

As a consequence, the separation of the waste into different streams, some being reused (Plutonium and Uranium), changes the final storage needs. In a fixed repository, the ratio of the repository volume required to store a kg of initial spent UOX, to the one required by the conditioned waste can therefore be greater than one. This ratio is called the densification factor, and varies in the literature from a neighborhood of 2 or 2.5 (Bunn et al. [2003], INL [2008]) to 4 (BCG [2006]).

However, the burning of Pu and other TRUs is not necessarily complete. For instance spent MOX fuel resulting from LWR Recycling still contains 73% (wt.) of its initial TRUs, and produces much more decay heat than the spent UOX assembly. If the spent MOX fuel is disposed of, the radiotoxicity reduction benefits anticipated in Figure 2.7 are not achieved. Therefore, the benefits from recycling are cancelled.[7] Compared to this case, cycles keeping the transuranics in the reactors, such as fast reactors, and potentially burning them have greater benefits.[8]

[7]BCG [2006] considers that "if used MOX were to be directly disposed into the repository after 20-25 years of interim storage, due to the temperature constraints in the repository, it would not be disposed as densely as used regular fuel. In this case, the densification factor for used MOX is 0.15".

Wigeland and Bauer [2004] find that MOX with one recycling has an overall densification factor of 1.09.

[8]Provided that they burn the TRUs contained in the cycle at the end the nuclear program.

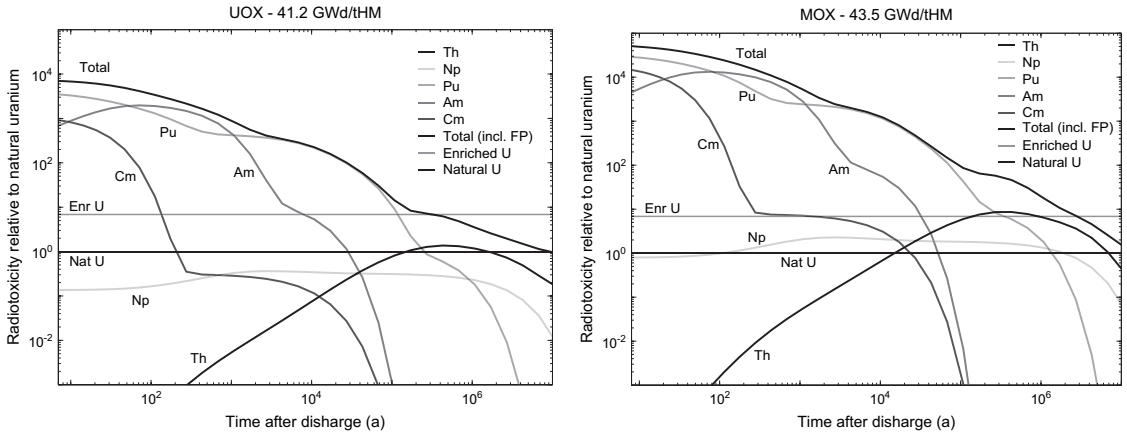

Figure 2.7 – *Time evolution of the radiotoxicity of the actinides in spent UOX and MOX, from Westlén [2007]*

Nuclear Services The term "nuclear services" in this thesis encompasses conversion, enrichment of uranium, manufacturing of the fuel (oxide, metallic, thermal or fast reactor), as well as fuel reprocessing. "Recycling services" will designate a subset of this category, containing fuel reprocessing and the fabrication of new fuel from the separated Pu/TRU.

The needs for these services vary in a more complex manner across cycles than the uranium consumption:

For the Once-Through Cycle, conversion and enrichment, linked to the amount of uranium consumed, are higher than for all other cycles. However, the cycle entails no recycling. On the contrary, semi- and fully-closed fuel cycles involve the use of less demonstrated technology, often involving glove boxes or hot cells to shield operators during maintenance from the irradiated materials. One can expect the recycling costs to increase as the cycle is closed since the materials are more difficult to handle.

Reactors Reactors have a great importance since they are among the least flexible elements in the cycle: built to be used for decades without much modifications and among the most capital intensive elements in the process.

The Twice-Through Cycle uses the same kind of reactor as the Once-Through Cycle, accordingly, there is no difference between the two thermal cycles in this regard. However, fast reactors are expected to be significantly more expensive than thermal reactors. The intensity of their use will, therefore, increase the cost of electricity: one can hence expect that 1-Tier Recycling will have higher reactor costs than 2-Tier Recycling.

2.4 "Heard of" arguments for semi-closure

On top of the tradeoffs outlined in the previous section, and which will be quantified in Chapter 3, other arguments, minor at first sight or hard to quantify, have been evoked over time in the literature on Mixed Oxide fuels. In contrast to the previous arguments, they do not limit themselves to the evaluation of the cycle per se but try to incorporate some of the benefits it provides to the whole nuclear industry, over a broader time horizon. For instance,

- *Technical preparation of FR recycling*:

  Many fast reactor designs have been developed, which can be categorized by their type of fuel: oxide fuels (like the fuel used in LWRs) or metallic fuel. It is unclear what type will dominate the market, but oxide fuels have been given a head-start, being notably the choice of France and Japan. To the extent that part of the knowledge they accumulated in MOX fuel fabrication and reprocessing can be used for fast reactor technologies, one could say that the development of the MOX technology entails reduced cost of future oxide fuel fast reactors. However, even countries doing 1-Tier Recycling will have to develop TRUEX, and will be able to benefit from this experience before developing FR fuel recycling if they are considering oxide FR fuels.

  Without MOX, the recycling experience will be shorter but the quantification of a learning curve (when so much uncertainty on reprocessing cost exists), and the assumption of its non-transferability from one country to another seem shaky bases on which to define a comparative advantage for semi-closure.

- *Industrial reprocessing capacity limitations*:

  It can also be argued that developing MOX reduces the need for reprocessing capacity for the startup of a fast reactor program. Indeed it is unlikely that countries will have the will or capacity to reach big reprocessing capacities, within short time frames. On the other hand, the amount of TRUs present in the core of a 1GWe self-sustainable FRs designed by Hoffman et al. [2006] is about 6 MTHM. On top of this, to launch the full cycle, reprocessing included, more TRUs are needed. If fuel irradiation and cooling both last 5 years, it seems reasonably conservative to require about 15 MT of TRUs for the *full lifetime* of a self-sustained reactor.

  The latter amount corresponds approximately to 165 MT of spent UOX, or 35 MT of spent MOX. Therefore a reprocessing plant which could reprocess indifferently UOX or MOX, with 1,700 MTHM/year capacity like La Hague, would produce

enough fuel for the full-cycle operation of 11 GWe of FR per year, if fed by spent UOX, and 52 GWe, if fed only by spent MOX.[9] The difference is significant but it seems more likely that the limiting factor will be countries' fast reactor construction capacity or needs rather than reprocessing capacity. Consequences of limited capacity, and induced delays in reprocessing, on the quality of the TRU vector extracted should also be limited.

- *Avoid mishaps of Yucca Mountain*

  Recycling does not suppress the need for a repository, at best it delays it. As a consequence, discussions on the incorporation of law suits into disposal costs and past problems linked to the specific repository of Yucca Mountain do not seem adequate to determine the most adapted cycle. Lawsuit considerations are only valid if they have a higher probability of occurring in a OTC than in a recycling context, which is not obvious. It is more likely that delays in waste management solutions development are linked to institutional features of the state and not a binding feature of the OTC.

- *Option value of TRU concentration*

  The last "heard of" argument is that extracting TRUs for FR is "less expensive" from spent MOX than from spent UOX. This problem is linked to the issues of spent fuel valuation introduced in Chapter 1. The consequence of MOX, however, is that some TRU is burnt in the process. Fortunately, this valuation can be detailed economically and will be presented in Chapter 5.

[9] Using a UOX reprocessing plant for MOX is possible under certain conditions. As noted by NEA [2002], for technical and economical reasons, "MOX assemblies would necessarily have to be reprocessed in plants primarily intended for reprocessing UOX. [...] UOX and MOX assemblies are reprocessed together with a 3:1 ratio advised as being a technically sound value".

Chapter 3

Economic Modeling of Deterministic Cycles

Past studies on nuclear fuel cycle economics (e.g. Bunn et al. [2003], MIT [2003]) have focused on the comparative assessment of one fully determined cycle with another fully determined cycle.

To allow for benchmarking with these studies and to see the relative impact of the valuation approach introduced by this thesis, the present chapter suggests an economic model in the spirit of previous work on fuel cycle economics. It explains the economic methodology used to assess the cost of the four cycles detailed previously. It will serve as a basis for the assessment of cycles in a non-deterministic environment, in Chapter 5.

3.1 Economic methodology

To each cycle described previously are attached a uranium consumption profile, a waste generation profile, a nuclear services requirement profile, and a reactor usage profile. These timely streams of mass and associated services contain all the cost information about a cycle. From this point, the rigorous way to economically compare the different cycles is to compare their cost profiles for the same electricity production profile. The matching of costs and revenues allows the calculation of a levelized cost of electricity (LCOE) for each cycle, which can be written

$$l = \frac{\int_0^T C\,(t)\ e^{-rt}\,dt}{\int_0^T Q\,(t)\ e^{-rt}\,dt}$$

where T is the time period considered, $Q(t)$ the electricity profile over that period, $C(t)$ the associated cost profile, and r the continuous discount rate.

Levelized Cost Calculation The simplest conceptual way to calculate the LCOE is to choose a fixed electricity production profile and calculate for each cycle the necessary number of reactors and plants of each type, using each fuel, which should be used at every moment in time to meet this specific electricity production. The problem with this physical representation is that reactors and reprocessing plants are discrete and time constrained units, the capacity of which cannot vary at will. Therefore, even the less complex cycles introduce non constant mass flows, which cannot be solved for without more assumptions and historical legacy considerations.[1]

An equivalent and more tractable manner to calculate the LCOE is to abstract from these frictions and follow a mass of fuel, as it goes through the system according to a predetermined schedule. Instead of representing a reactor and the associated plants, one can think of this initial fuel as renting reactors and reprocessing plants, which are assumed readily available. This methodology translates into electricity production and cost profiles. The LCOE can then be calculated as

$$l = \frac{\sum_{i=1}^{\infty} \int_{A_i}^{B_i} C_i(t)\ e^{-rt}\, dt}{\sum_{i=1}^{\infty} \int_{A_i}^{B_i} Q_i(t)\ e^{-rt}\, dt} \tag{3.1}$$

where i indexes the different passes in reactors undergone by the initial mass of fuel and its by-products, (A_i, B_i) are the start and end date of these passes, and $(C_i(.), Q_i(.))$ are the cost and construction profiles respectively for each pass.[2]

[1] This is the approach of Guérin and Kazimi [2009] who use a System Dynamics representation.

[2] To be rigorous, this schedule entails a certain "elementary" discontinuous pattern of electricity production, which cannot meet every possible electricity production profile by scaling and delaying:

Let $Q^*(t) = \sum_{i=1}^{\infty} \int_{A_i}^{B_i} Q_i(t)\ dt$ be this elementary pattern. There exists an infinity of $Q(.)$ (electricity profiles), such that

$$\nexists a \in \mathcal{S}\left(\mathbb{R}, \mathbb{R}^+\right) : Q(t) = \int_0^{\infty} a(t-u)\, Q^*(u)\ du$$

where $\mathcal{S}$ is the set of positive functions of $\mathbb{R}$, including Dirac functions.

If each cycle has a different pattern, it can be hard to compare them on the basis of a unique electricity profile. However, as the size of the considered reactor fleet increases and their construction times are distributed, the size of the reactor fleet then varies continuously and it can be shown that the LCOE doesn't change with the electricity profile chosen (De Roo and Parsons [2009a]). This thesis uses this mathematical result to simplify the representation of costs.

This method has several advantages compared to traditional steady state analyses: they represent the transitional cost of reaching the steady-state in the LCOE, and they allow for systems without clearly defined steady-states, e.g. 1-Tier with breeder reactors.

Data and Currencies The following step is to describe the timing of each step of the different cycles and to detail the cost and electricity production profile corresponding to a mass of initial ore going through the cycle.

Some of these costs and prices are accessible, such as uranium ore or enrichment services which are offered in liquid and competitive markets. Reprocessing and MOX fuel fabrication industries by contrast are at best an oligopoly of state-owned firms, which makes costs more difficult to assess. The most uncertain cost data lie within less developed processes such as fast reactors and full-actinide recycling technologies. For the latter, only estimations based on few partially disclosed prototypes can be done.

The cost are expressed in constant 2007 dollars.

3.2 Key input values

This section only details the values used for key inputs summarized in Table 3.1. All inputs used by the economic modeling can be found in Appendix D.[3]

Discount rate and taxes In this study, we use a 5% real discount rate, the only exception being geologic disposal and recycling facilities for which we use 3%, as done by the Office of Management and Budget. Depreciation schedules are only taken into account for reactors and recycling plants.[4]

Uranium and Enrichment The price of uranium is considered constant in the model, although its possible escalation is one of the arguments in favor of recycling. This method is used in most studies and particularly adapted to constant uranium consumption profiles, for which it is equivalent to use an "adjusted" price of uranium.

In this thesis, we take the spot value in July 2009 for the cost of uranium and its enrichment.

[3] Most of them are discussed in De Roo and Parsons [2009b].

[4] For information, BEA requires fuel depreciation: "For missiles and nuclear fuel rods, depreciation is estimated using a straight-line pattern (to reflect the pattern of rotation and replacement of nuclear fuel) and a Winfrey retirement pattern." http://www.bea.gov/national/FA2004/Tablecandtext.pdf

However, since these rules have been created for the OTC, and do not seem adapted to fuel with negative value for instance, it seems complex and arbitrary to extend it to other cycles. As a consequence it is neglected throughout the study.

Fuel Fabrication The fabrication cost is extrapolated from previous studies. The farbication cost for Mixed Oxide Fuel (LWR) and the Metallic Fuel (FR) are assumed to be the same in the absence of sufficient data on the process. The former comes from the estimation of the cost of a 100 MTHM/year plant operating for 40 years, with an overnight construction cost of $3 billion dollars and an operating cost of $80 million dollars per year. It also corresponds to 12% per year escalation from Bunn et al. [2003].

Reprocessing The reprocessing cost covers all the expenditure linked to reprocessing of the waste, including the possible storage of waste before its disposal. The various aqueous reprocessing costs (PUREX, TRUEX) are assumed to be the same, and derived from a 800 MTHM/year plant with an overnight construction cost of $17 billion dollars and an operating cost of $420 million dollars per year. It also corresponds to 12% per year escalation from Bunn et al. [2003]. The pyroprocessing cost is assumed to be the double of this cost.

Waste Management The interim storage cost is taken from Bunn et al. [2003]. The disposal cost is to be paid 5 years after unloading, at the same time as interim storage. It is based on the levelized cost of the Yucca Mountain project cash flow, as defined in OCRWM [2008], and an estimation of future nuclear electricity production.

The densification factors are taken to be 2.5 for separated UOX-HLW (INL [2008]), and 0.15 for spent MOX (BCG [2006]). A cost of disposal of $5,900/kgFP is derived for fast reactors.

Reactors and Operation LWR cost and the associated construction and depreciation schedules are taken from Du and Parsons [2009], following MIT [2003]. The fast reactor used is a self-sustainable fast reactor, i.e. conversion ratio of 1, the cost of which is assumed to be 20% higher than for a LWR of same capacity. Its cost of operation is scaled up accordingly.

Finally, fast reactors usually have shorter cycle lengths than light water reactors, likely to lead to lower capacity factors. Given the uncertainties on cycle lengths, maintenance requirements and learning curve for fast reactors, we use a fixed capacity factor of 85% independent of the type of reactor type.[5]

[5]It is common to see a capacity factor of 90% applied to LWRs to reflect their present performance. However such number does not take into account the historical performance, which seems the most relevant in the context of our analysis.

Table 3.1 – *Key Inputs*

Real Discount Rate	5%	
Uranium	90	$/kgHM
Enrichment	160	$/SWU
UOX Fabrication	250	$/kgHM
MOX Fabrication	2,400	$/kgHM
FRF Fabrication	2,400	$/kgHM
UOX Reprocessing	1,600	$/kgiHM
MOX Reprocessing	1,600	$/kgiHM
FRF Reprocessing	3,200	$/kgiHM
UOX/MOX Interim Storage	200	$/kgiHM
Spent UOX Disposal	1.34	mill/kWh
	755	$/kgiHM
HLW/UOX Disposal	300	$/kgiHM
Spent MOX Disposal	5,030	$/kgiHM
HLW/MOX Disposal	320	$/kgiHM
HLW/FR Disposal	458	$/kgiHM

3.3 LCOE results

The result of the calculations in Appendix D are summarized in Table 3.2.

Table 3.2 – *Levelized Cost of Electricity*

Cost (mill/kWh)	OTC	TTC	1-Tier	2-Tier
Fuel Cost	8.52	10.43	9.53	9.84
O&M Cost	7.81	7.81	8.10	7.93
Reactor Cost	42.65	42.65	44.23	43.27
Total	58.98	60.89	61.86	61.04
Increase wrt OTC		3.2%	4.9%	3.5%

Classically, we see that the introduction of recycling, whether in LWRs or FRs introduces a significant increase in the LCOE. Therefore, the OTC appears as the most economic solution with the chosen parameters. The TTC and its extension into 2-Tier Recycling also seem cheaper than the 1-Tier Recycling. This result should be moderated,

since it is due to the higher use of the expensive FRs made in the 1-Tier and their early introduction compared to 2-Tier Recycling.

To see the impact of different parameters on the cost of the different cycles, we can perform a sensitivity analysis. The results are shown in Figures 3.1-3.5. They show that the order of economic preference among these four cycles does not change very much with any of the key inputs.

In Figure 3.1, the sensitivity of the LCOE to the price of uranium is represented for the four cycles. The gap between cycles is barely modified as the price varies, such that the price of uranium does not appear as the main driver of cycle choice. It takes a price of uranium of \$620/kgHM for the OTC and the TTC to be equal. With such high price, the 1-Tier and 2-Tier Recycling would actually become attractive before the TTC, with a breakeven price of \$550/kgHM and \$480/kgHM respectively. Lastly if TTC is the cycle of reference, 2-Tier Recycling becomes attractive at only \$170/kgHM.

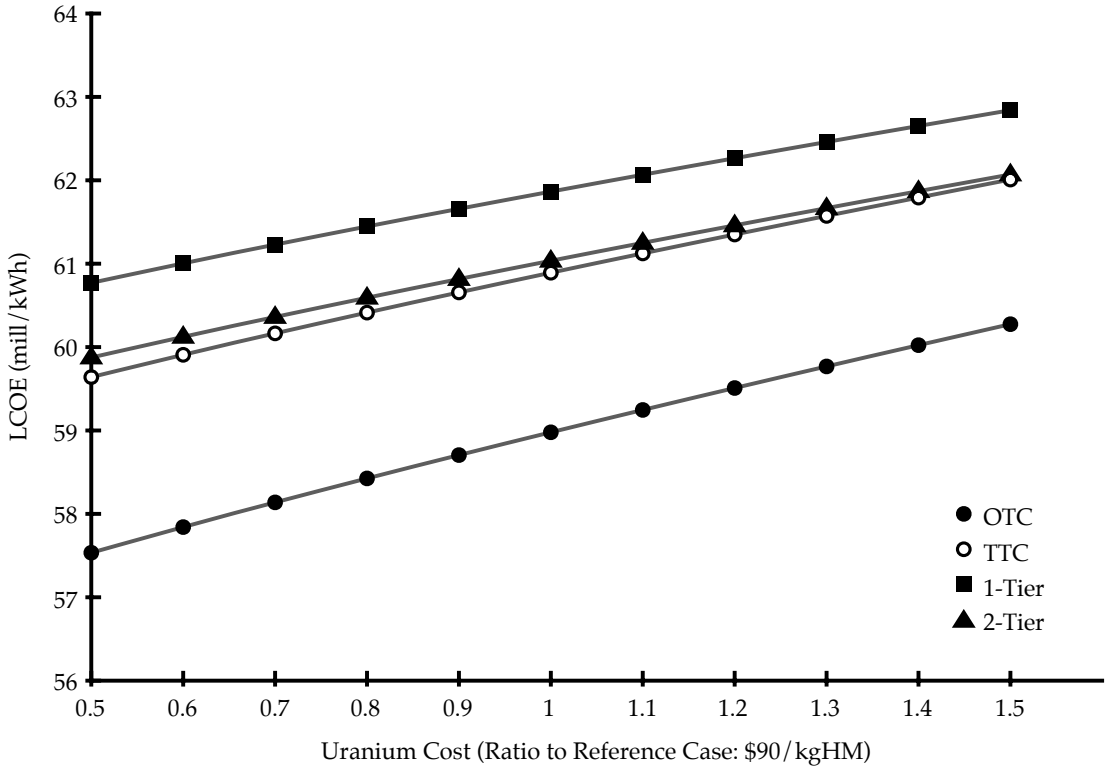

Figure 3.1 – *LCOE as a function of uranium price*

The major factor in the cost comparison, before the size of the premium on FRs (Figure 3.3), is the cost of recycling (i.e. reprocessing, and fabrication from the separated Pu/TRU), see Figure 3.2. A division of these costs by 2 would bring thermal and fast recycling within the same cost as the OTC.

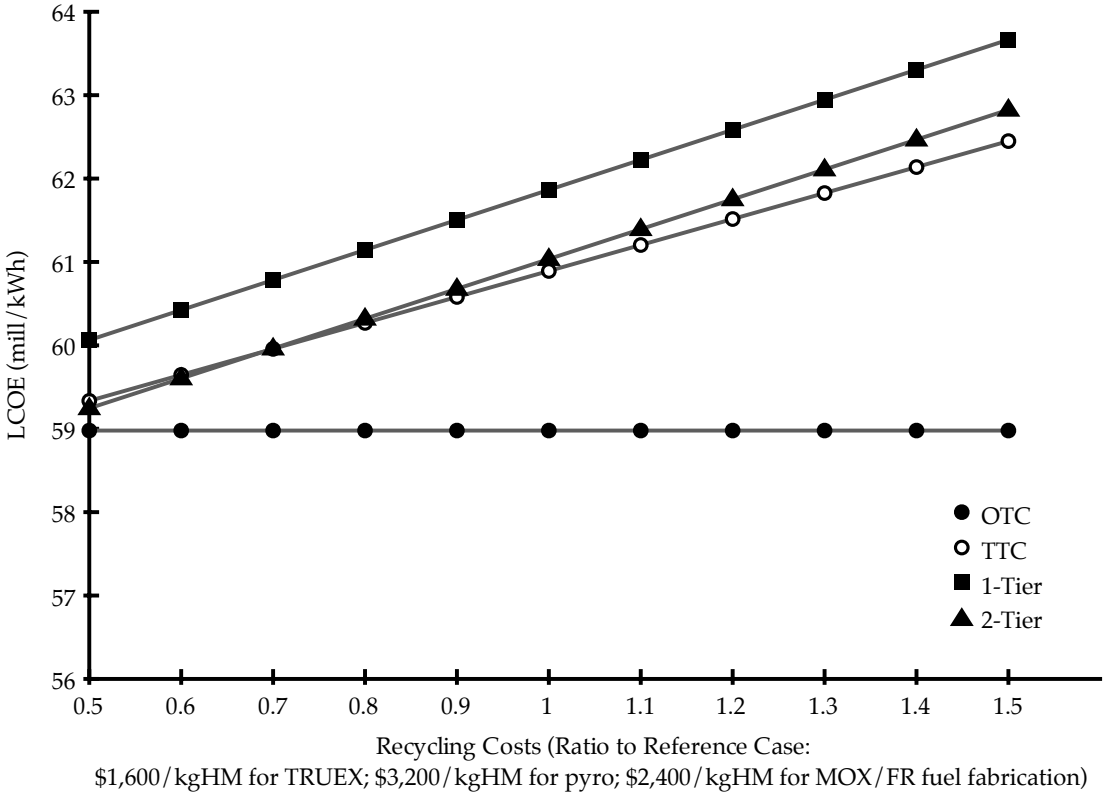

Figure 3.2 – *LCOE as a function of recycling costs (reprocessing, fuel fabrication)*

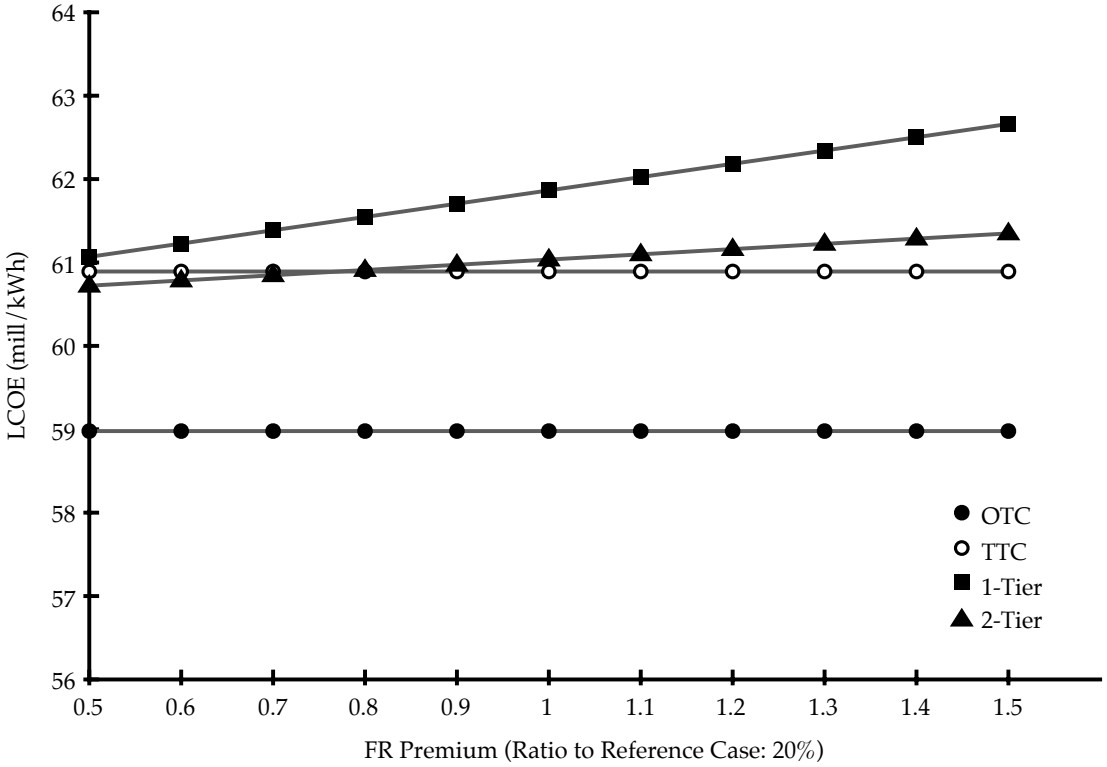

Figure 3.3 – *LCOE as a function of FR premium*

The cost of disposal appears to have little influence on relative cost of one solution to another. But it has more influence than the price of uranium in which breakeven values are often expressed (e.g. Bunn et al. [2003]). For instance, it would take a disposal fee of 4.75 mill/kWh (3.5 times the reference case) for the OTC and the 2-Tier Recycling to be comparable.[6]

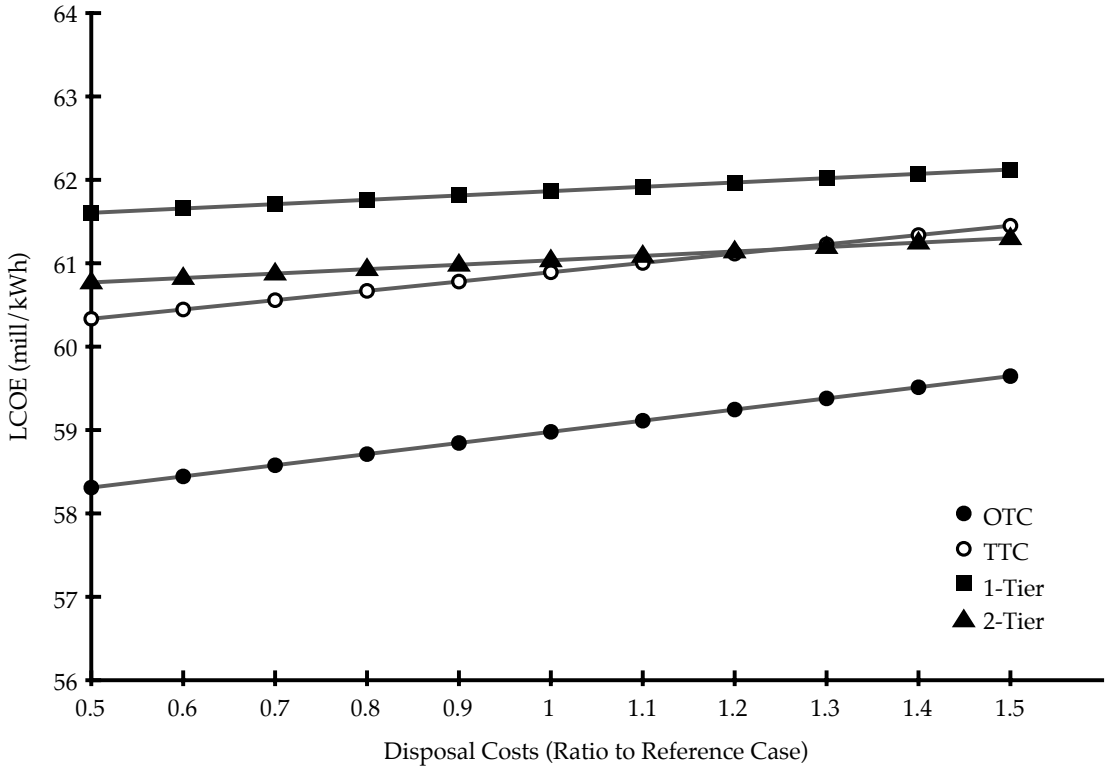

Figure 3.4 – *LCOE as a function of disposal costs*

Finally, the sensitivity of the total LCOE to the discount rate is the greatest, as can shown in Figure 3.5. Although the relative difference in LCOE decreases as the interest rate increases, its absolute value does not change, and the ranking of costs of the different cycles does not change either.

[6]It would take 5.3 times the reference uranium price to reach breakeven.

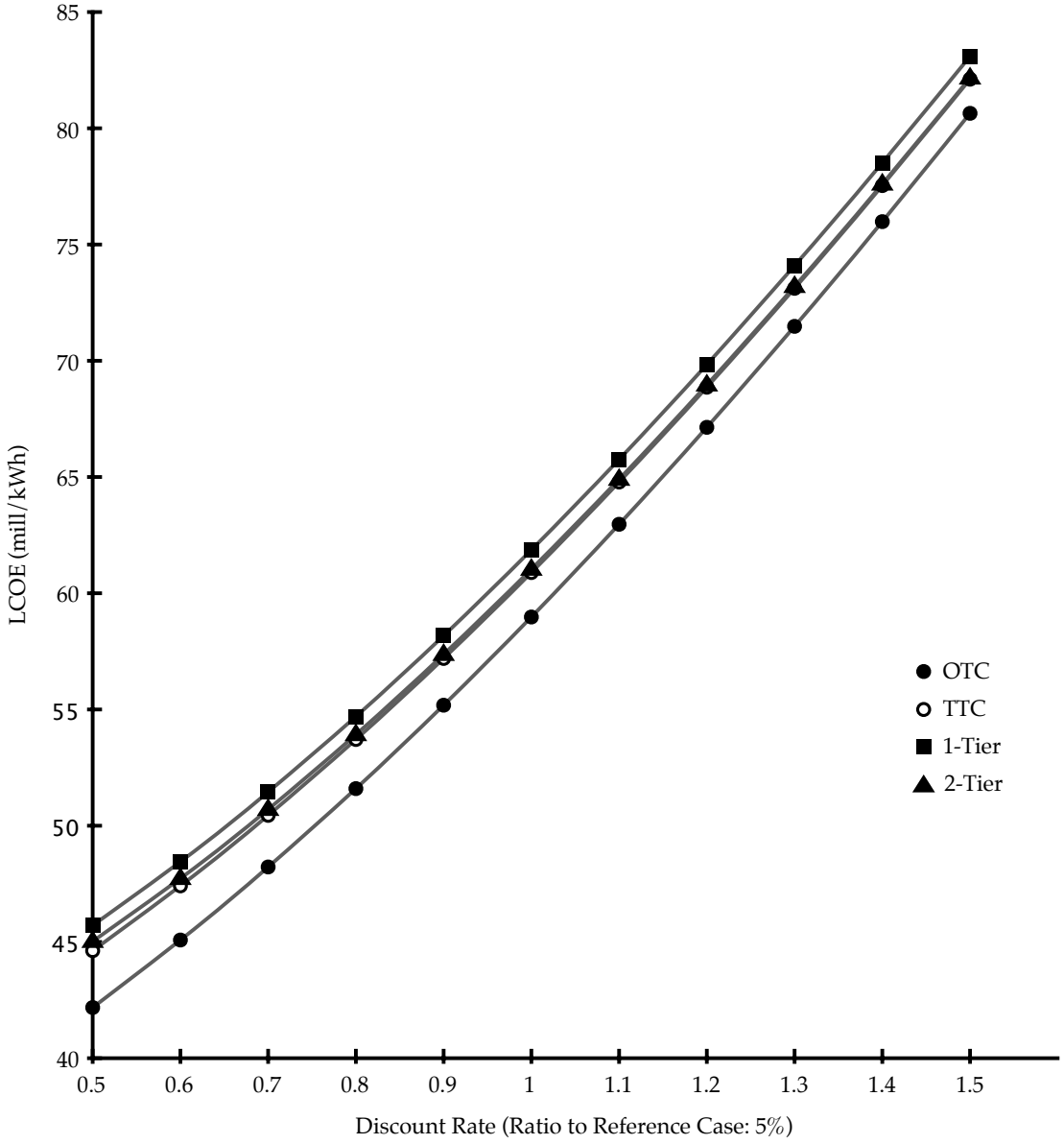

Figure 3.5 – *LCOE as a function of discount rate* [7]

[7]The calculation of the levelized costs of recycling and disposal remains subjected to a 3% discount rate.

Chapter 4

Value of TRU

In the previous chapter, an economic model was used to compare different deterministic cycles. A single metric, the levelized cost of electricity, was used to describe the cost of the entire cycle, without detailing the interactions and equilibriums that exist within the system.

Indeed, a material coupling exists between thermal and fast reactors, or between thermal reactors using UOX and MOX. To the mass flows are attached a financial transaction which implicitly gives a measure of the attractiveness of the transferred element, i.e. TRUs or Plutonium. The present section studies this value across cycles, and develops it as an indicator of future progress in nuclear technology.

4.1 Implicit valuation of TRU

In recycling strategies, material with a market value is passed from one reactor to another in order to extract more energy. Nevertheless, to express the LCOE of these strategies in Equation 3.1, there was no need to introduce any implicit price for the transferred elements: the transfer of material within the cycle does not represent any incurred cost. Therefore, any arbitrary price given to Plutonium or TRUs only appears as an internal transfer and leaves the LCOE unaffected.

Hence for any set of $(p_i)_{i\in\mathbb{N}^*}$, prices of the transferred elements, Equation 3.1 can be rewritten

$$l = \frac{\displaystyle\int_{A_1}^{B_1} C_{1,t}\, e^{-rt}\, dt - q_1 p_1 e^{-rB_1} + \sum_{i=2}^{\infty}\left(q_{i-1}p_{i-1}e^{-rB_{i-1}} + \int_{A_i}^{B_i} C_{i,t}\, e^{-rt}\, dt - q_i p_i e^{-rB_i}\right)}{\displaystyle\sum_{i=1}^{\infty}\int_{A_i}^{B_i} Q_{i,t}\, e^{-rt}\, dt}$$

where p_i and q_i are the price and quantity of material passed from reactor i, respectively.

The consequence of any payment is to allocate a certain cost to each part of the cycle: depending on the price of the material transferred, the LCOE of each reactor is expressed by

$$l_1(p_1) = \frac{\int_{A_1}^{B_1} C_{1,t}\, e^{-rt}\, dt - q_1 p_1 e^{-rB_1}}{\int_{A_1}^{B_1} Q_{1,t}\, e^{-rt}\, dt} \tag{4.1}$$

$$l_i(p_{i-1}, p_i) = \frac{q_{i-1}p_{i-1}e^{-rB_{i-1}} + \int_{A_i}^{B_i} C_{i,t}\, e^{-rt}\, dt - q_i p_i e^{-rB_i}}{\int_{A_i}^{B_i} Q_{i,t}\, e^{-rt}\, dt} \text{ for } i > 1 \tag{4.2}$$

There always exists a set of prices such that the LCOE of each reactor is the same as the total LCOE (De Roo and Parsons [2009b]).

The reason for this uniform LCOE throughout the cycle is that costs are entailed by the entire cycle. Therefore, it is arbitrary to allocate particular costs to different parts of the same cycle: in 1-Tier Recycling, for instance, the requirement of UOX reprocessing is not the consequence of fast reactor usage more than thermal reactor usage. Moreover the product generated, sometimes simultaneously, either by FRs or LWRs, using UOX or MOX, is a homogeneous good: electricity. Therefore there is no economic reason to differentiate its price depending on its source. To the extent that there is no alternative for the utilities other than the deterministic cycle considered, thermal reactors have no other option than to provision for the recycling of their waste, up to the level where other thermal or fast reactors will be able to produce electricity competitively, i.e. at the same cost.

As a result, the LCOE and materials prices are not only such that the revenue and cost profiles of the entire cycle reach a net present value of zero, but also such that this present value is equal to zero for each generator using each kind of fuel in the cycle. This determines a unique price of Transuranics as well as Plutonium as they are transferred. The following part of this chapter focuses on TRUs.

In a physical system, the isotopic composition of the TRU vector passed along the chain of reactors varies after each irradiation, eventually reaching an equilibrium composition. The consequence is that the neutronic properties of the mass of TRUs changes and so does the enrichment of the FR fuel in these TRUs. The corresponding prices of TRUs,

p_i, should reflect these changes in properties.

To simplify the calculation, a first assumption is made that TRUs have the same economic value before or after irradiation into FRs. This is equivalent to assuming that they have constant physical properties at their extraction from LWRs. In other words,

$$\forall i > j,\ p_i = p_j \text{ with } j = 1 \text{ or } 2 \text{ for 1-Tier and 2-Tier respectively}$$

This approximation is only reasonable if equilibrium core characteristics are close to startup characteristics. Hoffman et al. [2006] find that the TRU concentration in fast reactor fuel varies by approximately 10% from startup to equilibrium. This is significant but since it is unclear how TRU compositions evolve until equilibrium, this effect is neglected.

Secondly the assumption is made that fresh TRUs have the same value whether coming from UOX or MOX. This is consistent with results found by Hoffman et al. for the PRISM-based reactors used in this study. It is mainly the consequence of a certain homogeneity in the TRU absorption cross section profiles at high energy. Without changing the design and operation of the reactor, Hoffman et al. assessed different streams for a fast reactor with CR=0.5, including streams from UOX with 50MWD/kgHM and single pass MOX with a bypass. They concluded that there was little impact on the equilibrium conversion ratio, and the TRU enrichment requirement.[1]

In the worst case, ie. TRU from MOX, Hoffman et al. [2006] found that

> *For the Case 1B external feed, the equilibrium conversion ratio would be reduce to approximately 0.45 and the TRU enrichment increased by approximately 5% relative to the reference ABR designs. This would require a small increase in fuel volume fraction in order to achieve the target CR if the equilibrium GNEP scenario would include a single pass of the plutonium in an LWR.* (see Figure 4.1)

Hoffman et al. also conclude

> *This all suggests that the ABR should have sufficient flexibility to operate with a wide range of TRU feeds [...] with little effect on the ABR performance.*

With the constant TRU valuation approximation explained above, the problem of spent fuel valuation can be simplified. Using the same economic modeling as in Chapter 3 results in the following implicit TRU prices:[2]

[1] A difference in valuation of the order of 10% could be applied. However, it would have little impact on the call options exhibited in the next chapter.

In general, one should be able to determine, for a specific reactor, the price of TRU as a function of its content (mostly its Pu fissile isotopes). Reactors could also be optimized to flatten this function.

[2] Please note that the methodology described above can also be used to extract the implicit Plutonium

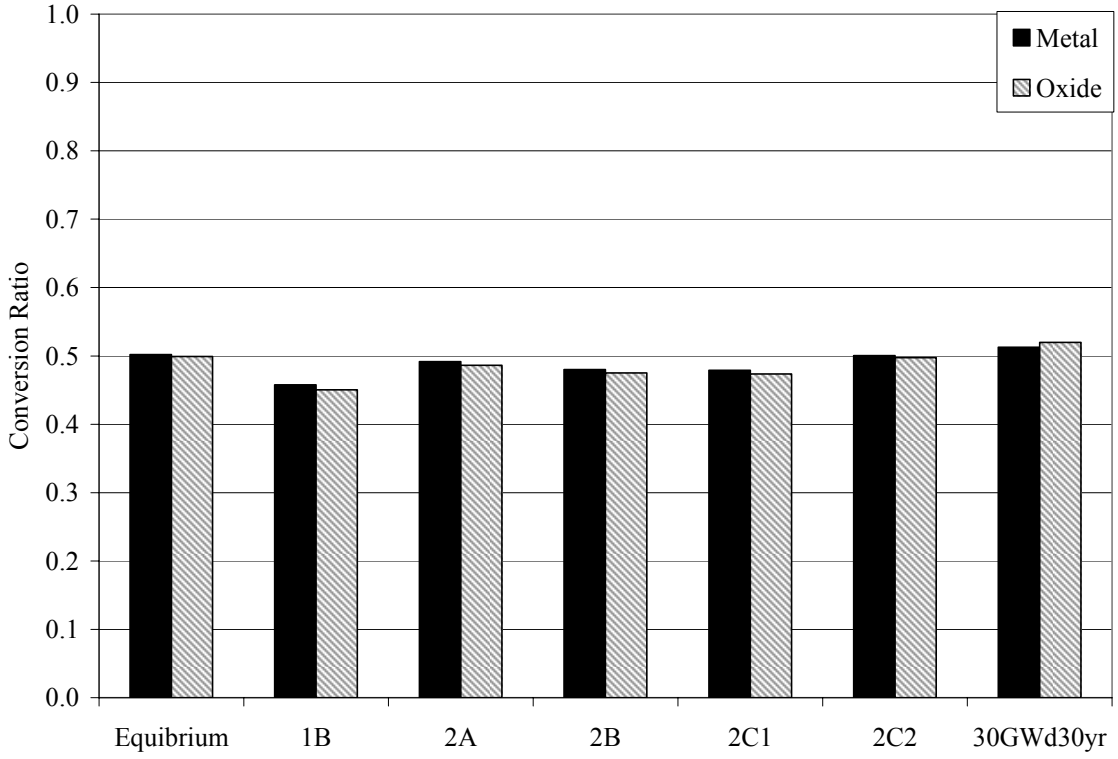

Figure 4.1 – *Equilibrium conversion ratios of a reactor designed to have CR=0.5 and feed on spent UOX, for different TRU feed streams, for initial CR=0.5. "Equilibrium" = 1-Tier Recycling; "1B" = 2-Tier Recycling; "2A/2B/2C" = Variants of 2-Tier Recycling with Pu-Np-MOX with different Am and Cm separations (Hoffman et al. [2006])*

Table 4.1 – *Implicit Pu and TRU prices for the different cycles*

Fuel Cycle	OTC	TTC	1-Tier	2-Tier
LCOE (mill/kWh)	58.98	60.89	61.86	61.04
Pu (k$/kgHM)	/	-22.3	/	-29.8
TRU (k$/kgHM)	/	/	-64.8	-73.6

Where the LCOE gave a direct measure of the competitiveness of a cycle compared to another, the price of TRUs informs us on the competitiveness within the cycle. Indeed, it tells us the level of compensation necessary between reactors so that each step produces electricity at the same cost.

In the reference scenarios, the value of TRUs appears to be highly negative. In this context, TRUs must be seen as a waste, which needs to be disposed of. Very much like incinerators producing electricity from our daily waste, fast reactors would then have to

price in the TTC and 2-Tier Recycling. The following table exhibits the result for completeness. All corresponding calculations can be found in Appendix D.

be paid to take the TRUs and produce electricity competitively.

Sensitivity of TRU price To see the variability of the TRU price to the cost inputs, the variation of the implicit TRU price is plotted for 1- and 2-Tier Recycling as the discount rate, disposal cost, uranium and recycling costs vary. In Figures 4.2-4.3, it appears that the two parameters determined by progress in advanced fuel cycle development, i.e. recycling and fast reactor costs, are the main drivers of the evolution of the TRU price.

- As the uranium price increases, the thermal cycles become more expensive, hence making the fast reactor cycle comparatively cheaper and reducing the payment needed to make them economical. Therefore, the price of TRU increases.
- The cost of disposal appears to have a moderate impact on the price of TRU, for 1- and 2-Tier Recycling. As a matter of fact, whether produced by thermal reactor or fast reactors, the quantity of fission products produced is approximatively the same per kWh.[3] The consequence is that thermal and fast reactors are affected by changes in the disposal cost, on a similar basis per kWh.
- The influence of the discount rate is more complex: for low values, the added cost of recycling are less discounted and dominate the variation driving the TRU price down; for high values, the fast reactors becomes more expensive, driving the TRU price down as well. In between lies a maximum.
- Lastly, the increase in recycling services and fast reactor prices decrease the competitiveness of fast reactor cycles, increasing the payment that LWRs have to make, and reducing the value of TRU.

[3]If fission events produce the same amount of energy and the same amount of fission products, then the only significant factor to impact the kgFP/kWh produced by reactors is the thermal efficiency.

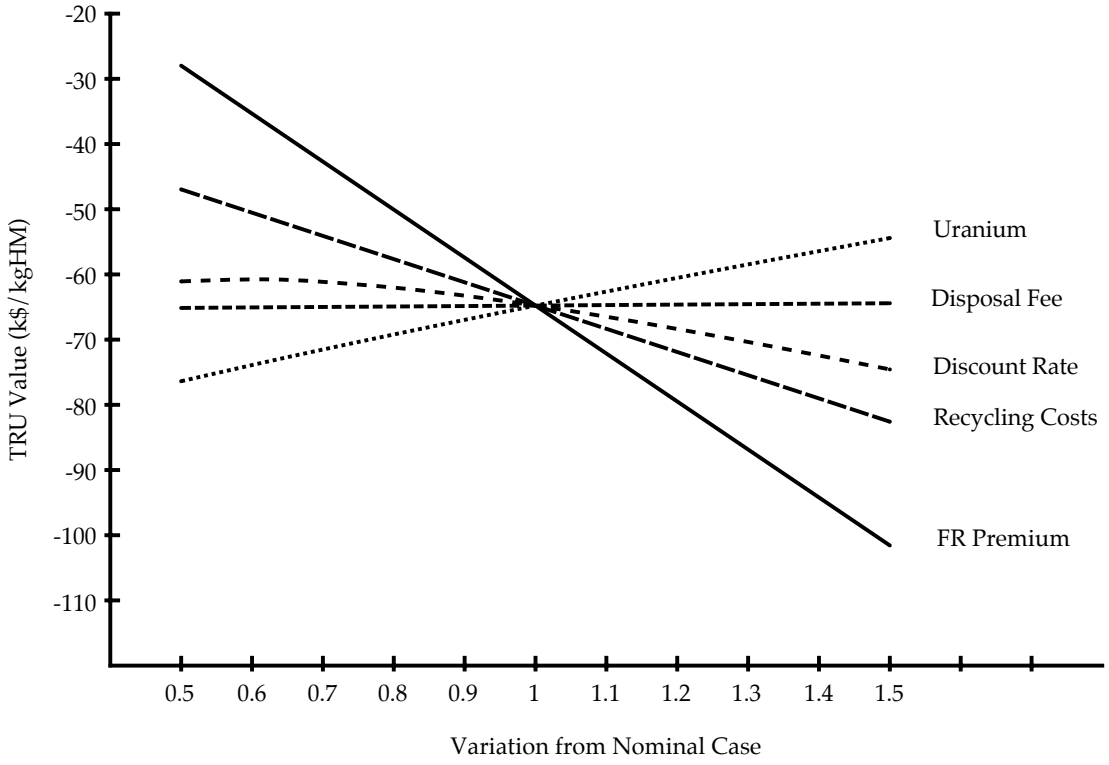

Figure 4.2 – *TRU price variation ~ 1-Tier Recycling*

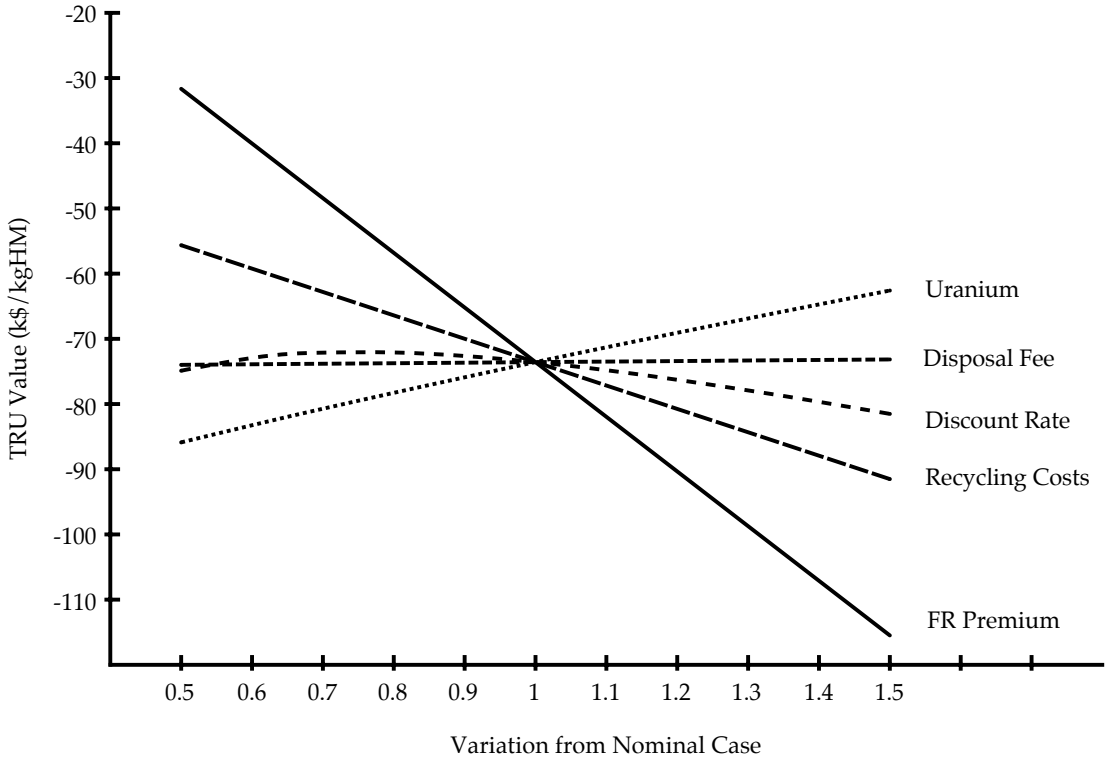

Figure 4.3 – *TRU price variation ~ 2-Tier Recycling*

4.2 Cycle choice in price-taking model

In the previous section, the economic assessment of a specific cycle led to an equilibrium and defined a correspondence between the levelized cost of electricity and a price of TRU derived implicitly. In this context, the price of TRU appeared correlated with the choice of thermal cycle, and its constituting costs (Figures 4.2-4.3). Therefore any analysis, which considers the price of TRU as purely external to thermal cycles, within a specific country, is somehow flawed.[4]

However, as we have seen in the previous section, the sensitivity of the price of TRU is the greatest for the fast reactor cost components. Therefore a first approximation could be that the price of TRU is mostly driven by the choices and costs in fast reactor cycles and not in thermal cycles. On top of this, let us consider a multi-country market, in which not all countries have committed to the same thermal cycle strategy. Provided that we have a homogeneous good and an atomistic market, countries could take this price of TRU as a reference for their fuel cycle choices.

As a consequence, we make the approximation that the price of TRUs is external to choices and evolutions in the thermal cycles. Countries are considered as price-takers: their fuel cycle choices have no impact on the competitive market price. There is a unique price of TRUs which reflects the global progress in full-actinide recycling development. This market representation has two advantages: it decouples the thermal and fast reactor cycles and allows a comparison between thermal cycles producing different amounts of TRUs on a transparent basis.

For each generator, the price of TRUs now determines the LCOE of its production through the relation established by Equations 4.1-4.2. Depending on the price of TRU, the LCOE of one reactor using a specific strategy is then compared to another. This price of TRU becomes the strategic parameter on which to base cycle choices:

- there is a market value of TRU below which FRs are able to produce electricity at a competitive price.
- there is a market value of TRU above which LWRs will be ready to extract the TRUs contained in their spent fuel, instead of disposing of them

If the latter is lower than the former, a transaction is possible in which LWR will switch from spent fuel disposal to its reprocessing. The extracted would then be sold to FRs at

[4] If the LWRs studied were using all the parameters entering in the implicit equation of the TRU value, it would be mathematically impossible to change the value of TRUs while assuming the generator parameters fixed. However, this is never the case.

a price which would still make them competitive. If this condition is not met, LWRs will dispose of their fuel and FRs will not be built.[5] Figure 4.5 illustrates these 2 cases.

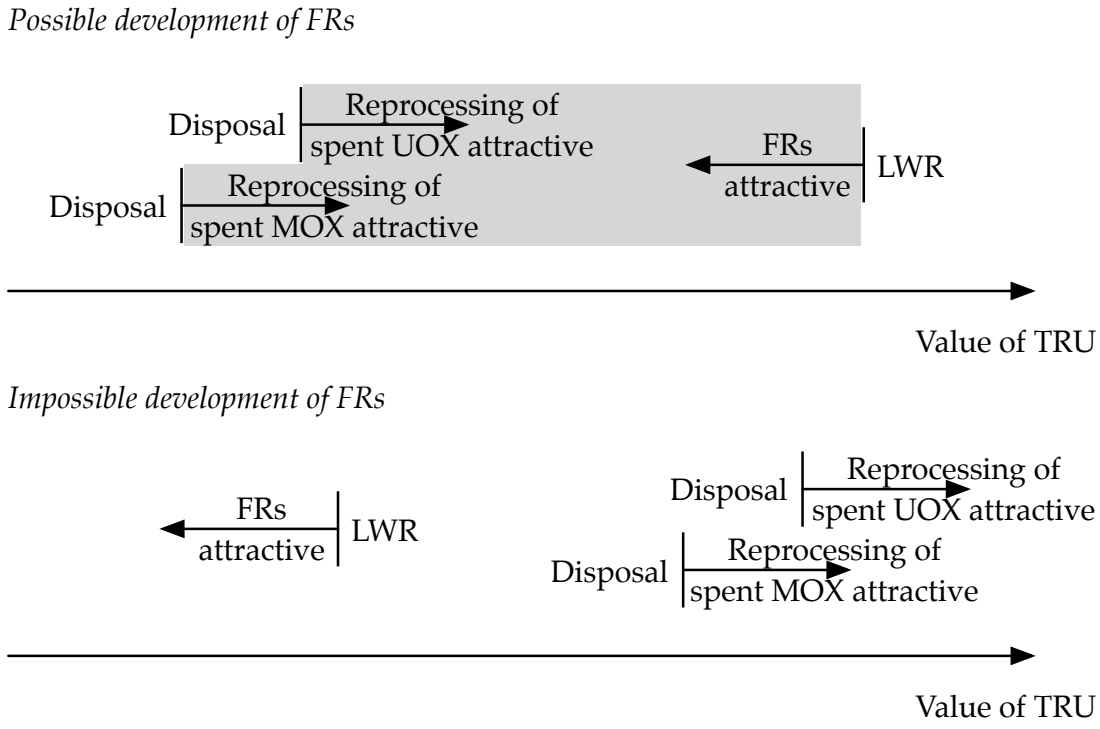

Figure 4.4 – *Dominant solutions depending on the price of TRU: 2 cases*

4.3 Modeling of potential outcomes

From Chapter 3 results, it appeared that although countries like Japan, China, Russia, France and others, are reviving or accelerating their fast reactor programs, there is no certainty as to the fact that these reactors will be commercially attractive in any near term future scenario. As a result, this thesis considers 3 "outcomes" of the fast reactor development programs:

- The technical developments (leading to a reduction of the fast reactor and recycling

[5]This representation can also be used to determine which FR design to choose.
Let us consider a breeder reactor and a burner reactor. All other things equal, if TRUs are a valuable good, then the reactor producing electricity at the least cost is the one producing the biggest amount of TRUs within a period of time, i.e. the breeder. On the contrary, if TRUs has a very negative value, it will be better to burn them so that less come out of the reactor, i.e. use a burner reactor. In fact what matters is not only the conversion ratio but also the amount of TRU stored in a reactor. This amount increases as the conversion ratio decreases. Therefore, the dynamic described above is reinforced.
Between these two extremes lies a value at which the 2 technologies have the same cost. By this way, one can determine the dominant FR design depending on the value of TRUs.

costs), the price of uranium, and the cost of disposal are such that FRs are commercially attractive.

- These conditions are not met, and the accumulated spent fuel simply has to be finally disposed of.
- Non-economic factors (security of supply, fuel management, etc.) are such that FRs are imposed independently of their commercial attractiveness.

Based on the previous section, we model the outcome of fast reactor programs from the thermal reactor perspective by

- a price for TRU
- the optionality of reprocessing

The price is difficult to assess, given the present state of technology, and even more so for the future. Therefore, a more accurate description of the present anticipation of future prices of TRUs is a price distribution. When calculations are necessary to illustrate our point, this thesis will assume that the distribution schematically consists in equally likely events:

- the price is equal to -$ 70,000/kgHM, which corresponds to the implicit TRU value of our reference case;
- the price is equal to $ 0/kgHM, which corresponds to an improvement of FR technology such that no transfer of money is necessary between reactors;
- the price is equal to $ 70,000/kgHM, which corresponds to the price at which sources of TRUs, different than reprocessing from thermal spent fuel, could be available. Appendix C.2 derives this cap on TRU price through the consideration of FRs using enriched uranium at start-up.

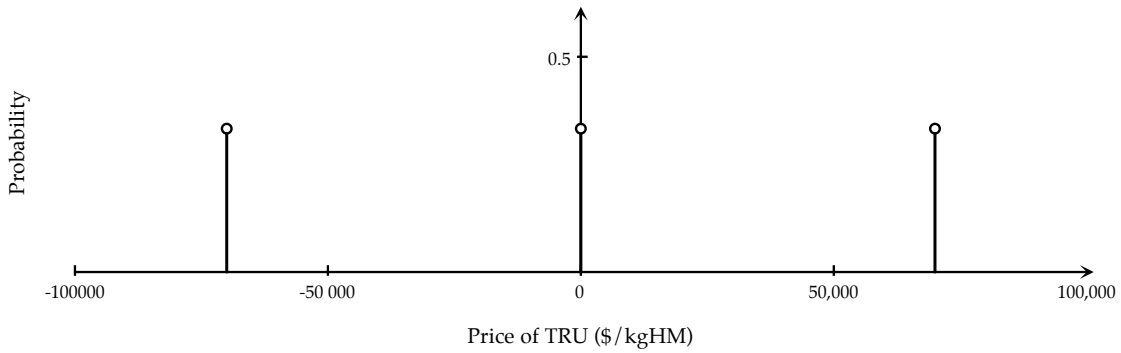

Figure 4.5 – *Example of distribution for the TRU price*

Chapter 5

Option Value of MOX in Probabilistic Cycles

In this chapter, the non-deterministic nature of technology development outcomes is introduced in the thermal fuel cycle valuation.

More precisely, this central part of the work shows a way to value LWR Recycling differently than what has been done in past studies and Chapter 3. To achieve this, the economic model developed previously is progressively extended to fit a simple probabilistic model and then a tree of decisions, in order to gradually introduce more realistic scenarios.

5.1 A simplified case

As assumed in Chapter 4, the transuranics contained in LWR spent fuel have a probabilistic value. The probability distribution reflects the possible evolutions of the fast reactor technology, and their impact on the competitiveness of the full-actinide recycling strategy. By contrast to deterministic approaches, the choice of a cycle here is not determined a priori: countries may choose to start with OTC or TTC and evolve towards 1-Tier or 2-Tier Recycling respectively, as they are given information about the value of their spent fuel. In other words, given the value of TRU, there will be a decision to make between furthering the cycle for the spent LWR fuel, or disposing of it.

Let us assume that 3 identical countries load a batch of UOX in a thermal reactor at the same moment. To settle the future of the resulting waste, they have to evaluate the possibility of going to fast reactors at some point in time. When they choose to make a decision about LWR spent fuel, they develop R&D projects which reveal the value of

TRU. Depending on this value, they must decide to pay for disposal or reprocessing into fast reactors. The time at which this decision is made will be referred to as the *time of settlement*.

In this example, one country chooses to settle the issue of spent fuel when the fuel is unloaded, this strategy is referred to as "Direct Choice". Another chooses to postpone this decision to a further date, leaving the spent fuel in storage in the meantime, this will be denoted as "Delayed Choice". Finally one decides to recycle spent fuel into MOX, hence delaying the decision about FR cycles and modifying the nature of spent fuel; this will be noted "LWR Recycling". At the moment of the choice between extracting the TRUs and disposing of the LWR spent fuel, the value of TRUs is revealed. The countries then incur the cost associated with the disposal of their spent fuel, or its reprocessing and the sale of separated TRU. This example is summarized in Figure 5.1.

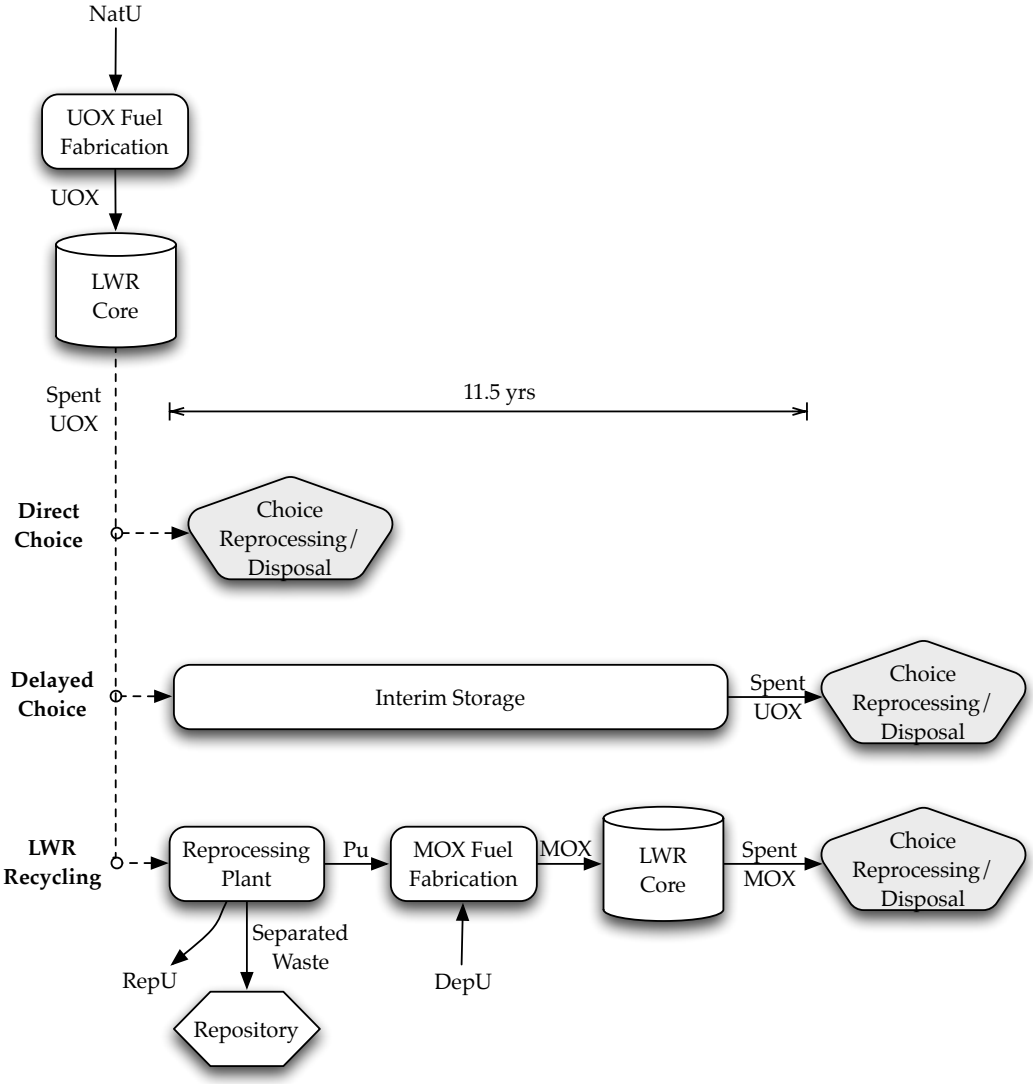

Figure 5.1 – *Comparison of 3 spent UOX management strategies*

5.1.1 Behavior at settlement

At time of settlement, countries are faced with a possible arbitrage between recycling the spent fuel to extract or dispose of the TRUs. This decision will depend on the price that they can be paid for extracted TRUs. The following paragraphs deal with the optimal choice of the different countries.

We use the time of spent UOX unloading from reactor pools as the time of reference, $t = 0$, and note $T = 11.5$ yrs the time between loading of UOX and loading of the resulting MOX. We also assume that costs are payed according to the schedule used in Chapter 3, so that TRUs are paid for one year after reprocessing expenses.

Direct Choice Let Q^{dc}_{UOX} be the mass of spent UOX, with concentration c_{UOX} in TRU, at the moment of the decision. And let p be a given price of TRU, then the profit of the owner of the spent fuel at the time of settlement, π, can be written

$$\pi\left(q_{UOX}, p\right) = q_{UOX}\left(\frac{c_{UOX}}{(1+i)^1}\, p - C_{d/sUOX} - C_{r/UOX}\right) - \left(Q^{dc}_{UOX} - q_{UOX}\right)\left(C_{d/UOX} + C_{i/UOX}\right)$$

where q_{UOX} is the amount of fuel recycled, i is the annual discount rate, $C_{d/UOX}$ and $C_{d/sUOX}$ are the cost of disposal of spent UOX and its separated HLW respectively, $C_{i/UOX}$ is the cost of interim storage and $C_{r/UOX}$ is the cost of spent UOX reprocessing (using TRUEX, and including the interim storage of separated HLW and revenues from reprocessed uranium).

Let us define p_1^-, the marginal cost of extracting TRUs from freshly unloaded fuel,

$$p_1^- = \frac{C_{r/UOX} - \left(C_{d/UOX} + C_{i/UOX} - C_{d/sUOX}\right)}{c_{UOX}\ (1+i)^{-1}} \tag{5.1}$$

If there is no obligation to recycle, the cost minimization problem leads to:

- if $p < p_1^-$, the country decides to dispose of the totality of the spent UOX,
  $\pi^{dc}_{max}(p) = \pi(0, p) = \pi^{dc}_0 = -Q^{dc}_{UOX}\left(C_{d/UOX} + C_{i/UOX}\right)$
- if $p_1^- \leqslant p$, the country develops fast reactors through the reprocessing of all spent UOX,
  $\pi^{dc}_{max}(p) = \pi\left(Q^{dc}_{UOX}, p\right) = \pi^{dc}_0 + Q^{dc}_{UOX}\frac{c_{UOX}}{(1+i)^1}(p - p_1^-)$

Let us note that the profits of the economically optimal behavior determined above, and which we will denominate "optimal unconstrained behavior", can be written for fu-

ture calculations[1]

$$\pi^{dc}_{max}(p) = Q^{dc}_{UOX}\left(\frac{c_{UOX}}{(1+i)^1}(p-p_1^-)_+ - C_{d/UOX} - C_{i/UOX}\right)$$

Delayed Choice The countries choosing the delayed or direct choice have the same amount and type of fuel at the time of settlement.[2] Therefore, the reasoning at settlement is very similar. The main difference is that the cost of interim storage has already been incurred. Similarly to p_1^-, we define

$$p_1^+ = \frac{C_{r/UOX} - \left(C_{d/UOX} - C_{d/sUOX}\right)}{c_{UOX}\ (1+i)^{-1}} \tag{5.2}$$

The optimal unconstrained behavior leads to a profit, which can be written

$$\pi^{dc}_{max}(p) = Q^{dc}_{UOX}\left(\frac{c_{UOX}}{(1+i)^1}(p-p_1^+)_+ - C_{d/UOX}\right)$$

LWR Recycling Suppose that all the initial UOX has been reprocessed into MOX, and let Q^r_{MOX} be the quantity of spent MOX, with concentration c_{MOX} of TRU, at the moment of the decision. The profit can be written

$$\pi(q_{MOX}, p) = q_{MOX}\left(\frac{c_{MOX}}{(1+i)^1}\,p - C_{d/sMOX} - C_{r/MOX}\right) - (Q^r_{MOX} - q_{MOX})\left(C_{d/MOX} + C_{i/MOX}\right)$$

where q_{MOX} is the amount of fuel recycled and the other terms are defined similarly to the previous case. If there is no obligation to recycle, let us define

$$p_2 = \frac{C_{r/MOX} - \left(C_{d/MOX} + C_{i/MOX} - C_{d/sMOX}\right)}{c_{MOX}\ (1+i)^{-1}} \tag{5.3}$$

The optimal decision at the time of settlement becomes:

- if $p < p_2$, the country decides to dispose of the totality of the spent MOX, and the maximal profit is
  $\pi^r_{max}(p) = \pi(0,p) = \pi^r_0 = -Q^r_{MOX}\left(C_{d/MOX} + C_{i/MOX}\right)$
- if $p_2 \leqslant p$, the country develops fast reactors through the reprocessing of all spent MOX, and
  $\pi^r_{max}(p) = \pi(Q^r_{MOX}, p) = \pi^r_0 + Q^r_{MOX}\frac{c_{MOX}}{(1+i)^1}(p-p_2)$

[1] $(\,.\,)_+ = \max(\,.\,, 0)$

[2] The consequences of fuel decay on the vector of TRU are neglected.

Similarly to the previous case, the optimal unconstrained behavior leads to a profit which can be written for future calculations

$$\pi^{r}_{max}\left(p\right) = \varphi_{M/U}\, Q^{dc}_{UOX}\left(\frac{c_{MOX}}{\left(1+i\right)^{1}}(p-p_2)_{+} - C_{d/MOX} - C_{i/MOX}\right)$$

where $\varphi_{M/U}$ is the ratio of the mass of MOX to the mass of corresponding initial UOX.

However, reaching the economically optimal solution is not the sole possibility anticipated in Chapter 4. In the previous calculations, the assumption was that countries would be able to choose the most economical solution once the price of TRU was revealed. They may however choose, or be forced, to implement disposal or reprocessing regardless of the price of TRUs, for non economic reasons (public acceptance, energy security...).

To summarize, the profits made at the time of settlement can be brought back to the time of unloading, and expressed mathematically to provide insight on the effect that we want to study:[3]

Systematic Disposal Decision

$$\begin{cases} \Pi_{direct} = \Pi^{0}_{direct} &=& -Q^{dc}_{UOX}\left(C_{d/UOX} + C_{i/UOX}\right) \\ \Pi_{delayed} = \Pi^{0}_{delayed} &=& -Q^{dc}_{UOX}\dfrac{C_{d/UOX}}{\left(1+i\right)^{T}} \\ \Pi_{recycl} = \Pi^{0}_{recycl} &=& -\varphi_{M/U}\, Q^{dc}_{UOX}\dfrac{C_{d/MOX} + C_{i/MOX}}{\left(1+i\right)^{T}} \end{cases} \tag{5.4}$$

which corresponds to variations on the Once-Through and Twice-Through Cycles.

Systematic TRU Extraction Decision

$$\begin{cases} \Pi_{direct} &=& \Pi^{0}_{direct} + Q^{dc}_{UOX}\dfrac{c_{UOX}}{\left(1+i\right)^{1}}\left(\mathbb{E}[p] - p_1^{-}\right) \\ \Pi_{delayed} &=& \Pi^{0}_{delayed} + Q^{dc}_{UOX}\dfrac{c_{UOX}}{\left(1+i\right)^{T+1}}\left(\mathbb{E}[p] - p_1^{+}\right) \\ \Pi_{recycl} &=& \Pi^{0}_{delayed} + \varphi_{M/U}\, Q^{dc}_{UOX}\dfrac{c_{MOX}}{\left(1+i\right)^{T+1}}\left(\mathbb{E}[p] - p_2\right) \end{cases} \tag{5.5}$$

which corresponds to variations of the 1-Tier and 2-Tier Recycling.

[3]Costs incurred before the time of settlement (recycling into MOX for instance) are not included in these formulas.

Optimal Decision

$$\begin{cases} \Pi_{direct} &= \Pi^0_{direct} + Q^{dc}_{UOX} \dfrac{c_{UOX}}{(1+i)^1} \mathbb{E}\left[\left(p - p_1^-\right)_+\right] \\ \Pi_{delayed} &= \Pi^0_{delayed} + Q^{dc}_{UOX} \dfrac{c_{UOX}}{(1+i)^{T+1}} \mathbb{E}\left[\left(p - p_1^+\right)_+\right] \\ \Pi_{recycl} &= \Pi^0_{delayed} + \varphi_{M/U}\, Q^{dc}_{UOX} \dfrac{c_{MOX}}{(1+i)^{T+1}} \mathbb{E}\left[\left(p - p_2\right)_+\right] \end{cases} \tag{5.6}$$

which corresponds to the economically optimal behavior.

The expectancy of the optimal behavior profits contains the term $\mathbb{E}\left[(p-p_i)_+\right]$, the generic formula of a financial call option. The interpretation is that the presence of TRUs in spent LWR fuel gives access to an optional resource. Very much like in finance, countries have the opportunity to exercise the option "reprocessing" if the TRU price goes above a certain value. This value is equal to the marginal cost of extraction, and different whether the spent fuel form is UOX or MOX.

This marginal cost is composed of two parts:

- the cost of reprocessing
- the avoided cost of interim storage and disposal

With the values used in Chapter 3, we find

$$\begin{aligned} p_1^+ &= \$\,113,900 - 29,100 = \$\,84,800/\text{kgHM} \\ p_1^- &= \$\,113,900 - 53,400 = \$\,68,500/\text{kgHM} \\ \text{and } p_2 &= \$\,26,300 - 80,700 = -\$\,54,400/\text{kgHM} \end{aligned}$$

As could be expected, the savings in disposal costs are an important part of the extraction price from spent MOX, but also from spent UOX. The concentration of the TRU is the main factor of extraction price difference between spent UOX and MOX.

We have,

$$\frac{c_{UOX}}{(1+i)^1} = 1.20\%,\ \frac{c_{UOX}}{(1+i)^{T+1}} = 0.52\% \text{ and } \varphi_{M/U}\frac{c_{MOX}}{(1+i)^{T+1}} = 0.34\%$$

which shows that LWR Recycling cost is potentially the least exposed to variations in the price of TRUs.

Since $p_2 < p_1^- < p_1^+$, we can also expect MOX users to choose reprocessing more often and to capture more benefits from the sale of TRU. It is also more likely for countries which have not yet paid for interim storage to reprocess their spent UOX. However, this lower marginal extraction cost is partially offset because the TRUs are accessible later and

because some of them are burnt during the new pass in LWRs. With the distribution chosen in Chapter 4, the marginal price of TRU extraction from UOX is only attractive if interim storage has not yet been paid for.

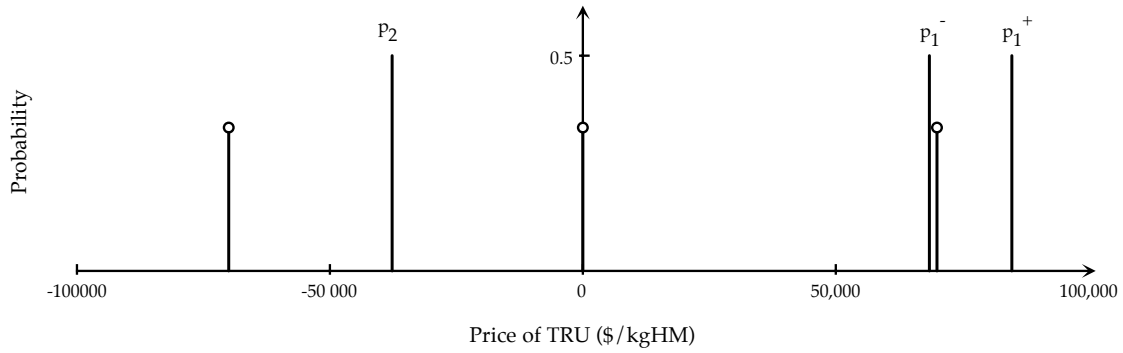

Figure 5.2 – *Distribution of the TRU price*

5.1.2 Results

The previous mathematical formulation gives insight on the arbitrage between disposal and reprocessing for FRs. However, whether recycling, delayed or direct action is chosen, each strategy entails different costs before the settlement time is reached. Notably in the case of LWR recycling, spent UOX must undergo reprocessing and be manufactured into MOX to produce electricity. By taking this into account, we can calculate the fuel component of the LCOE in each cycle (other parts of the LCOE will be constant across choices).

Table 5.1 gives the *expected* levelized cost of the fuel cycle for the 3 thermal fuel cycle strategies shown in Figure 5.1, with 3 possibilities at settlement: systematic disposal, systematic reprocessing, or optimal choice depending on the price of TRU as shown in Equations 5.4-5.6.[4]

Table 5.1 – *Expected LCOE*

Cost (mill/kWh)	Disposal	TRU Extraction	Optimal Cost
Direct Choice	8.52	10.00	8.51
Delayed Choice	7.95	8.99	7.95
LWR Recycling	10.43	10.03	9.99

[4]Note that the first and last values of the first column match the values found in Table 3.2 since they correspond directly to the OTC and the TTC respectively.

From the first LWR perspective, whose front-end cost are equal to \$6.83/MWh, the back end cost then becomes:

Table 5.2 – *Expected back-end fee for the simplified case (mill/kWh)*

Direct Choice	Disposal (OTC)	1.69
	TRU Extraction	3.17
	Optimal Cost	1.68
Delayed Choice	Disposal	1.12
	TRU Extraction	2.16
	Optimal Cost	1.12
LWR Recycling	Disposal (TTC)	3.60
	TRU Extraction	3.20
	Optimal Cost	3.16

These results show how the usual approach leads to the highest cost evaluation for LWR Recycling (3.60 mill/kWh) and that the back-end cost can be significantly reduced if other scenarios are taken into account. There are two notable effects:

- with the chosen TRU price distribution, only users of spent MOX can significantly benefit from the TRU extraction. However, this flexibility never offsets the higher initial costs of Recycling. The latter only becomes comparable to Direct Choice for compulsory reprocessing (gap of \$0.03/MWh)
- introducing the FRs at the same date as with Recycling by the use of interim storage creates a significant economic advantage: the Delayed Choice is always \$ 0.5/MWh below the others. Whether disposal decisions can be delayed is not clear; however the relative magnitude of the price variation shows the importance of the time frame.

Figure 5.3 illustrates these two points.

5.2 Decision tree model

The limitation of the previous approach is that it does not evaluate cycles with the same electricity profile nor does it represent the time constraints of technology development. Notably it assumes that technologies are readily available when needed and the choice

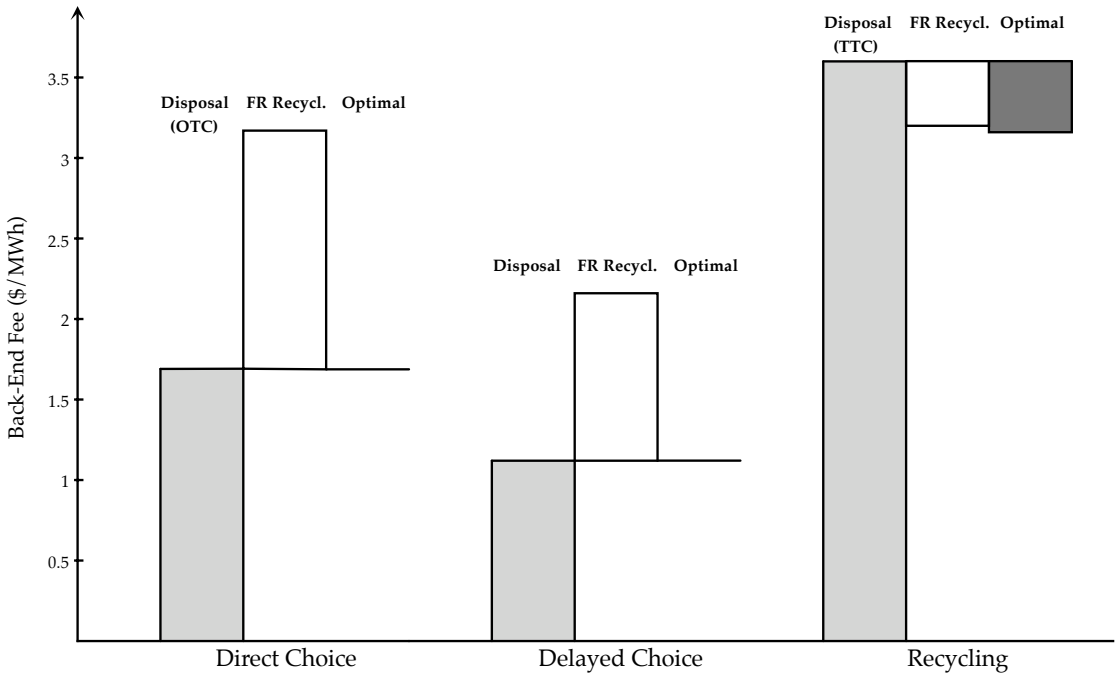

Figure 5.3 – *Back-end fees for simple example*

of a technology is non-binding (it does not have impact on future decisions). Such constraints are all the more important as the previous table demonstrated the effect of timeframe on the economic valuation of a cycle. A more realistic representation of the technological development and decision process is needed, which can be obtained through tools such as decision trees.

5.2.1 Introduction of a Spent Fuel Management Entity (SFME)

The development of a fuel cycle is a long process: a country which decides to do LWR recycling cannot hope to produce MOX instantaneously. A technology, whether a reprocessing plant, a reactor, or a geological repository, takes time to develop and reach industrial implementation. Moreover, countries are limited in their strategy by anterior decisions. Therefore, countries need to follow "tracks" in which they engage through a time constrained process.

Because the coexistence of multiple "tracks" would not be socially efficient, the strategy is generally chosen by a central planner (i.e. the state). The implementation is then led by the planner itself (development of Yucca Mountain by DOE) or an organization of private entities resulting from the legislation enacted by the central planner (Switzerland, Japan).

To represent this fact, a spent fuel management entity (SFME) is introduced. Its role is to take ownership of the spent fuel produced by LWRs in exchange for the payment of a fee by utilities. This payment represents the expected cost of the fuel management strategy defined by the central planner, evaluated on a risk free basis. Following this plan, the SFME proceeds to disposal, or reprocessing the fuel, and can sell by-products of its activity, i.e. MOX and TRUs, to the utilities at the market price.[56]

The interactions are represented in Figure 5.4.

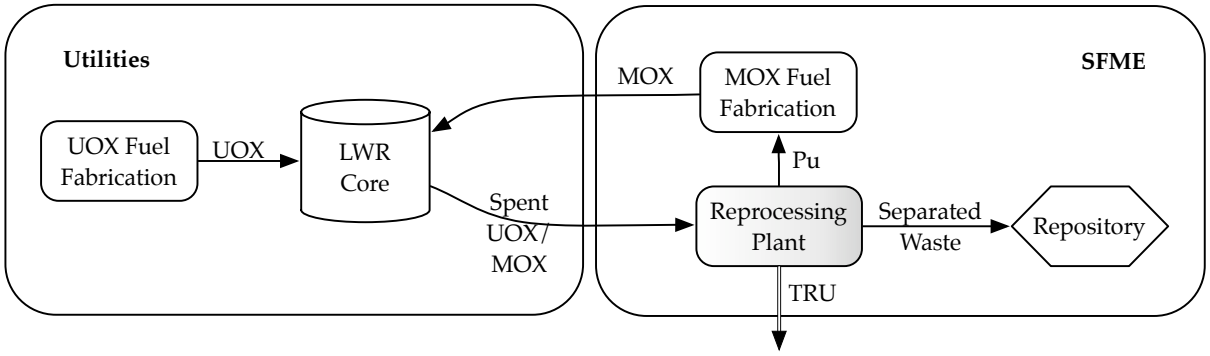

Figure 5.4 – *Interaction between utilities and spent fuel management entity*

5.2.2 Definition of a decision tree

In the economic framework of Chapter 3, the consumption of nuclear fuel services or the renting of a reactor was an idealized process: it assumed that a previously built plant would always be available, but also that the choice to construct such fast reactor or such reprocessing plant will have been made at a previous point in time. This idealization becomes unadapted when uncertain development of technologies comes into play, as in the case of fast reactors. The result is that one needs to represent the decision process affecting posterior decisions.

This thesis represents this process through a decision tree with time-step $T = 11.5$ yrs. The decision tree represented in Figure 5.5 revolves around three central time points:

- At the beginning of the exercise, thermal reactors have been built and start processing fuel. The time $t = 0$ corresponds to the moment where the first UOX assembly

[5]Providing that the same fee is applied to electricity from UOX and MOX, the SFME will sell MOX at the fabrication cost of UOX.

[6]This does not mean that TRUs should be sold or managed by a different entity than the SFME, or a different country. The fact that the TRUs leave the system in Figure 5.4 is a representation of the decorrelation of the thermal and fast cycle problems.

is loaded. The SFME's decision about what to do with the waste that will be produced is made simultaneously: either the development of LWR recycling facilities or a process to build a geological repository is begun or an interim storage solution is developed until further information arrives about the value of spent fuel. Depending on the decision at time $t = 0$, the SFME charges a fixed price \$/MWh for the management of spent UOX (and MOX), which reflects its expected costs.

- 21 years later, at $t = 2T - 2$, the solutions chosen previously start to be available: this delay is meant to mimic the R&D and construction process. A consequence is that the batches loaded at $t = 0$ and $t = T$ can be recycled for core loading at $t = 2T$. This time coincides, for the sake of simplicity, with the moment when the fast reactor outcome is decided, i.e. what is the future value of TRU and if recycling is compulsory. The country decides accordingly to build a repository if it had not been done or to develop fast reactor cycle facilities.
- Around time $t = 4T$ the fast reactor or repository construction program is completed and an advanced cycle can potentially be implemented. As a result, the fuel loaded until $t = 3T$ included can be reprocessed, if necessary, and the TRU paid at the value determined at $t = 2T$.

The branches of this decision tree are detailed in Figures 5.6-5.10.

We assume that waste can only go to the repository $2T$ after unloading from reactor pools. This is the reason why in Figures 5.10, repository construction starts at $t = T$. Moreover, although our analysis covers the entire cost, some spent LWR fuel or the resulting HLW will need to be stored until after $5T$. Our Figures do not illustrate this period.

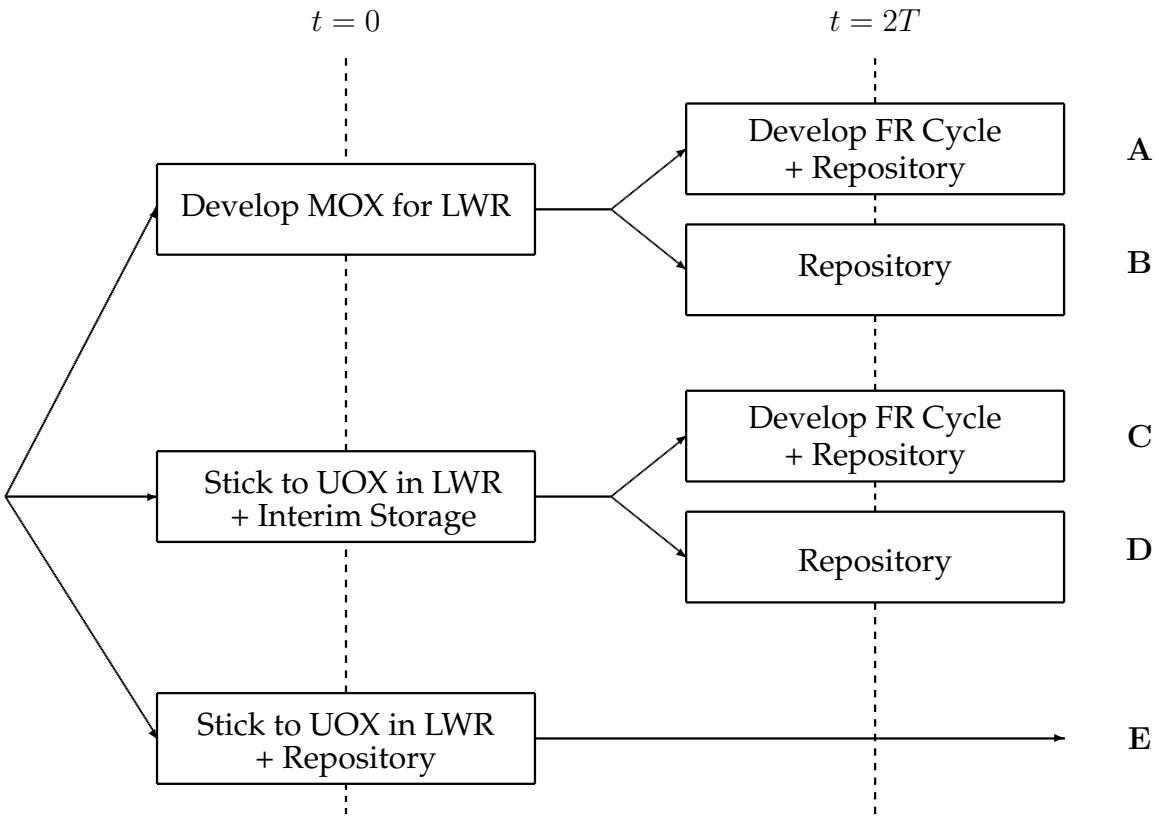

Figure 5.5 – *Decision process for non-deterministic cycles*

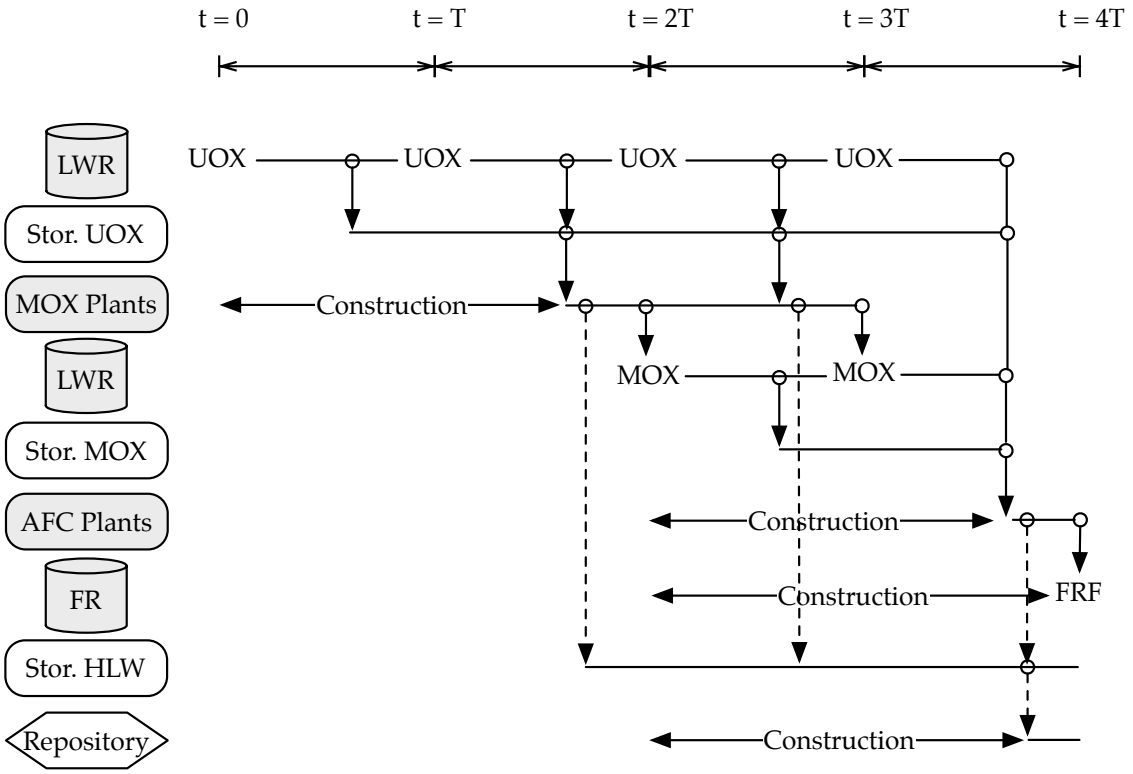

Figure 5.6 – *Details of path* **A** *(full reprocessing case)*

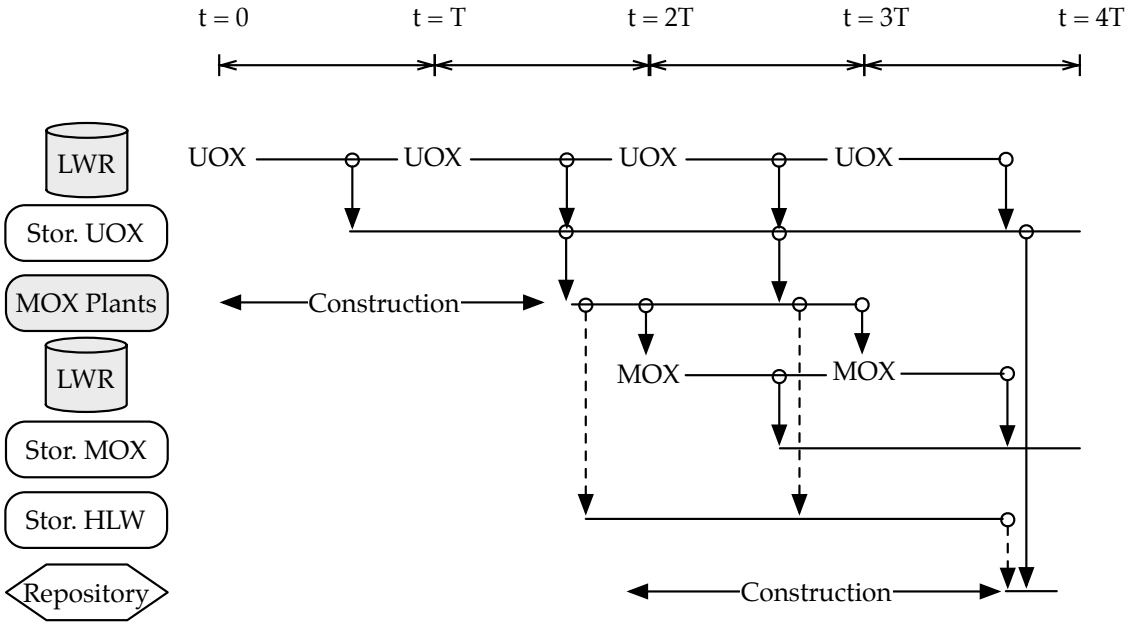

Figure 5.7 – *Details of path* **B**

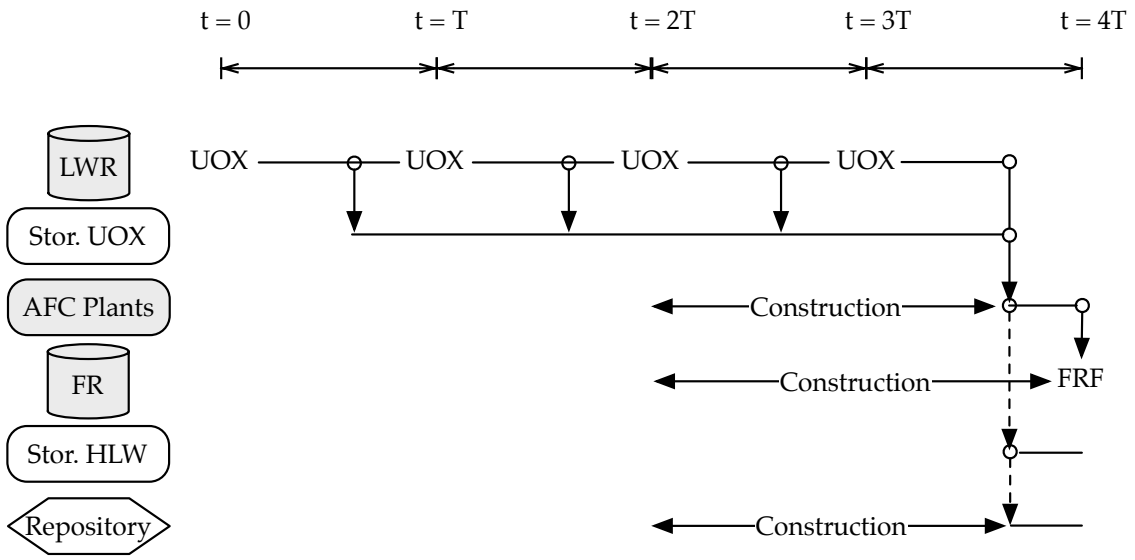

Figure 5.8 – *Details of path* **C** *(full reprocessing case)*

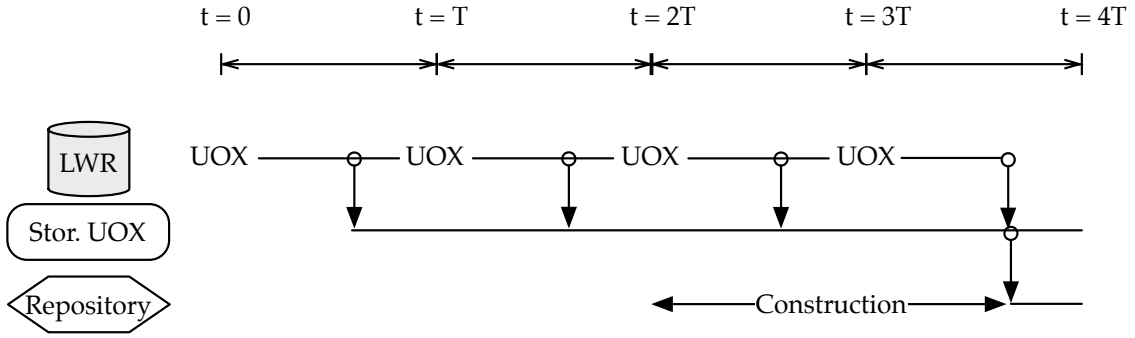

Figure 5.9 – *Details of path* **D**

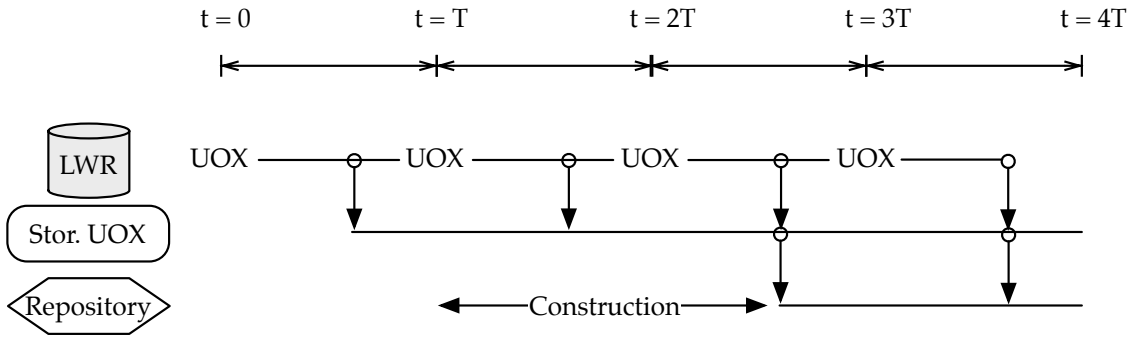

Figure 5.10 – *Details of path* **E**

5.2.3 Limitations

This representation is very stylized, mostly for the sake of clarity in the calculations, but also to be relevant to various situations in different countries over time. Therefore several limitations can already be acknowledged, which should have limited impact:

- Human decisions are made in continuous time, and the choices are not limited to the ones presented here (for instance, disposal could be aborted and recycling developed at $t = 2T$).
- The fact that the spent fuel remaining after time $t = 3T$ should be reprocessed or disposed of, at one single point in time (and not delayed) only corresponds to the necessity of an economic endpoint. This assumption should give an advantage to MOX since the payment of TRU happens sooner.
- The time scale of some 50 years between the first loading of UOX and loading in fast reactor may seem optimistic, but it can coincide with early versions of French program and may still be applicable to China. This compactness results in the coincidence of MOX loading with knowledge about TRU value and favors MOX.
- The fuel consumed between each point $t = nT$ is not represented. Generally speaking, this tree is only the representation of the trajectory of some amount of fuel and not of a full reactor-scale cycle. The restriction to a discrete flow of material can be justified similarly to Chapter 3.
- Finally, it was assumed that at the time of construction, the repository was built for all expected fuel. Therefore, MOX or its separated products would not be cooled enough to enter the repository once completed, and their cost of disposal could be postponed. This fact is detrimental to MOX but also applies to UOX burnt after $t = 2T$. Moreover spreading a repository construction over time could cancel economies of scale.

5.3 Economic modeling of $t = 2T$ decisions

In the designed tree, the SFME is taking a decision at $t = 0$ about the management of spent fuel. Only one strategy remains unaffected by the information given at $t = 2T$: direct disposal, which is assumed irreversible. For the other strategies however, another decision has to be made at $t = 2T$, which depends on the price of TRU.

To calculate the cost of the fuel cycle for each branch, one needs to first determine the optimal behavior which will be adopted. The next section builds on Section 5.1.1 to

describe the behavior and corresponding cost.

Note on Interim Storage In this decision tree, a time dependence for the interim storage cost is introduced, such that we should introduce $C_{i,t}$, the cost of interim storage during a period t.[7] However, as could be seen in the simple case, interim storage costs introduce more complexity in the analysis. They are temporarily left out of this section, for sake of clarity in the mathematical modeling.

We define q^* as the mass of thermal reactor fuel (whether UOX or MOX) consumed at each step, ψ^* as the total production of electricity discounted to $t = 0$, and Π as the profit of the SFME discounted to the same date.

5.3.1 Cost for the MOX branch

In contrast to the other branches, or to the simplified example, at the time of sale or disposal of the remaining fuel, there are two kinds of spent fuel: spent UOX (with low TRU content) and spent MOX (with high TRU content). Therefore, there are more potential strategies which can be adopted than in the previous section.

Reprocessing capacity This thesis assumes arbitrarily that the country schedules and builds a facility which supports a steady-state cycle with MOX. Since a spent UOX assembly can be recycled into $\varphi_{M/U}$ unit of MOX fuel, the adequate reprocessing capacity q_r is such that $UOX + MOX = q_r + \varphi_{M/U}\ q_r = q^*$.[8]

The impact of this reprocessing capacity on the quantities of TRU produced throughout the cycle can be seen in Tables 5.3-5.4.[9]

Table 5.3 – *TRU production in the different cycles and its repartition at* $t = 4T$

Cycle	Q_{UOX}	Q_{MOX}	TRU$_{UOX}$	TRU$_{MOX}$
Interim Storage	$4\ q^*$	0	$4\ c_{UOX} q^*$	0
LWR Recycling	$2\ q^*$	$2\frac{\varphi_{M/U}}{1+\varphi_{M/U}} q^*$	$2\ c_{UOX} q^*$	$2\frac{\varphi_{M/U}}{1+\varphi_{M/U}} c_{MOX} q^*$

[7] $C_{i,T}$= \$100/kgHM and $C_{i,t}$= \$200/kgHM for $t \geqslant 2T$.

[8] This leads to $q_r = 0.88\ q^*$.

[9] Indeed, $Q_{UOX} = 4\ q^* - 2(1 + \varphi_{M/U}) q_r = 2\ q^*$ and $Q_{MOX} = 2\varphi_{M/U}\ q_r = 2\frac{\varphi_{M/U}}{1 + \varphi_{M/U}} q^*$

Table 5.4 – *Numerical calculations normalized by q^**

Cycle	Q_{UOX}	Q_{MOX}	TRU_{UOX}	TRU_{MOX}
Interim Storage	4	0	5.2×10^{-2}	0
LWR Recycling	2	0.23	2.6×10^{-2}	1.5×10^{-2}

where TRU_{MOX} and TRU_{UOX} are the quantities of TRU contained by spent UOX and spent MOX respectively. Table 5.4 shows the reduction of mass of spent fuel that has to be processed at the time of settlement. The amount of TRUs, in the case of LWR Recycling, is 21 % smaller through 2 effects: TRUs are burnt in MOX, while UOX would have created TRUs.

Behavior at $t = 2T$ Assume that the price of TRU is a given p, then the profit of the SFME can be written in the following way. Let C_{UOX} be the cost of a UOX assembly at time of loading, and let Π_r be the invariable profits entailed by the choice of recycling.

$$\Pi_r = q_r \left(1 + \frac{1}{(1+i)^T}\right) \times \left(-\frac{C_{r/UOX}}{(1+i)^{2T-2}} - \varphi_{M/U}\frac{C_{f/MOX}}{(1+i)^{2T-0.5}} + \varphi_{M/U}\frac{C_{UOX}}{(1+i)^{2T}}\right)$$

where $C_{f/MOX}$ is the cost of MOX manufacturing, and the other costs are defined as in the previous section.

The total profits can then be written,

$$\begin{aligned}\Pi(q_{MOX}, q_{UOX}) = {} & \psi^* f + \Pi_r + q_{MOX}\left(\frac{c_{MOX}}{(1+i)^{4T-1}}p - \frac{C_{gd/sMOX}}{(1+i)^{2T}} - \frac{C_{r/MOX}}{(1+i)^{4T-2}}\right) \\ & + q_{UOX}\left(\frac{c_{UOX}}{(1+i)^{4T-1}}p - \frac{C_{gd/sUOX}}{(1+i)^{2T}} - \frac{C_{r/UOX}}{(1+i)^{4T-2}}\right) \\ & - \left(2\varphi_{M/U}q_r - q_{MOX}\right)\frac{C_{gd/MOX}}{(1+i)^{2T}} - \left(2q^* - q_{UOX}\right)\frac{C_{gd/UOX}}{(1+i)^{2T}}\end{aligned}$$

where q_{MOX} and q_{UOX} are the amount of fuel recycled at the time of settlement, and $C_{gd/X}$ indicates the cost of building a repository for a unit of waste of type X. Let us note p_M and p_U the marginal extraction cost of TRU from MOX and UOX respectively,

$$p_M = \frac{C_{r/MOX} - \left(C_{gd/MOX} - C_{gd/sMOX}\right)(1+i)^{2T-2}}{c_{MOX}\ (1+i)^{-1}} \tag{5.7}$$

$$p_U = \frac{C_{r/UOX} - \left(C_{gd/UOX} - C_{gd/sUOX}\right)(1+i)^{2T-2}}{c_{UOX}\ (1+i)^{-1}} \tag{5.8}$$

The optimal unconstrained behavior will then lead to recycling according to the following strategy.[10]

- if $p \leqslant p_M$, then the country decides to dispose of all the fuel, i.e.

$$\Pi_{\max} = \Pi(0,0) = \psi^* f + \Pi_r - 2q_r \frac{C_{gd/MOX}}{(1+i)^{2T}} - 2q^* \frac{C_{gd/UOX}}{(1+i)^{2T}}$$

  We define f_d as the fee such that this profit is equal to 0.

- if $p_M \leqslant p \leqslant p_U$, then the country decides to reprocess only spent MOX, i.e.

$$\Pi_{\max} = \Pi(2\,q_r, 0) = \psi^*(f - f_d) + 2\,q_r \frac{c_{MOX}}{(1+i)^{4T-1}}(p - p_M)$$

- if $p_U \leqslant p$, then the country decides to reprocess all spent fuel (UOX and MOX), i.e.

$$\Pi_{\max} = \Pi(2\,q_r, 2\,q^*) = \psi^*(f - f_d) + 2\,q_r \frac{c_{MOX}}{(1+i)^{4T-1}}(p - p_M) + 2\,q^* \frac{c_{UOX}}{(1+i)^{4T-1}}(p - p_U)$$

Marginal cost of extraction Very much like in Section 5.1.1, one can notice that in fact the profit can be written

$$\Pi = \psi^*(f - f_d) + 2\,q_r \frac{c_{MOX}}{(1+i)^{4T-1}}(p - p_M)_+ + 2\,q^* \frac{c_{UOX}}{(1+i)^{4T-1}}(p - p_U)_+$$

Since the fee is set such the expect profit of the SFME is equal to 0, we can directly calculate this fee in the case of different optimization policies at settlement,

- Constant disposal decision: $f_{\mathbf{B}} = f_d$
- Constant TRU Extraction decision:

$$f_{\mathbf{A}} = f_{\mathbf{B}} - 2\,q_r \frac{c_{MOX}}{(1+i)^{4T-1}}(\mathbb{E}[p] - p_M) - 2\,q^* \frac{c_{UOX}}{(1+i)^{4T-1}}(\mathbb{E}[p] - p_U)$$

- Optimal decision :

$$f_{\min(\mathbf{A},\mathbf{B})} = f_{\mathbf{B}} - 2\,q_r \frac{c_{MOX}}{(1+i)^{4T-1}} \mathbb{E}\left[(p - p_M)_+\right] - 2\,q^* \frac{c_{UOX}}{(1+i)^{4T-1}} \mathbb{E}\left[(p - p_U)_+\right]$$

The difference with the simplified case of the previous section notably lies in the fact there is not only one, but two call options, represented by the two types of fuel.

[10] p_M can be assumed smaller thant p_U as in the simplified example.

5.3.2 Direct disposal and interim storage

For direct disposal, since the repository has already begun construction at the time the TRU price is revealed, we consider that the process is not reversible and no fuel is left to manage by $t = 4T$. There is no specific behavior for the countries to adopt other than continuing the engaged process. As a consequence

$$f_{\mathbf{E}} = \frac{4\,q^*}{\psi^*}\,\frac{C_{gd/UOX}}{(1+i)^T}$$

In the case of interim storage, the country is left with a unique kind of fuel, hence this is a simplification from the MOX case, and it yields

- Constant disposal decision:
$$f_{\mathbf{D}} = \frac{4\,q^*}{\psi^*}\frac{C_{gd/UOX}}{(1+i)^{2T}}$$

- Constant TRU Extraction decision:
$$f_{\mathbf{C}} = f_{\mathbf{D}} - \frac{4\,q^*}{\psi^*}\frac{c_{UOX}}{(1+i)^{4T-1}}\left(\mathbb{E}[p] - p_U\right)$$

- Optimal decision :
$$f_{\min(\mathbf{C},\mathbf{D})} = f_{\mathbf{D}} - \frac{4\,q^*}{\psi^*}\frac{c_{UOX}}{(1+i)^{4T-1}}\mathbb{E}\left[(p-p_U)_+\right]$$

5.3.3 Synthesis

In the previous sections, we showed that the cost of the different branches could in fact be represented by a fixed price and a call option. The strike of these call options is the marginal cost of extraction of TRUs from the different materials.

Representing the cost of interim storage does not change the previous approach, but would lead to the definition of new marginal extraction prices. By extension of Equations 5.7-5.8, let us define

$$\begin{aligned} p_M^i &= p_M - \frac{\left(C_{i/MOX}(2T) - C_{i/MOX}(iT)\right)(1+i)^{iT-2}}{c_{MOX}\ (1+i)^{-1}} \\ p_U^j &= p_U - \frac{\left(C_{i/UOX}(2T) - C_{i/UOX}(iT)\right)(1+i)^{iT-2}}{c_{UOX}\ (1+i)^{-1}} \end{aligned}$$

with $i = 0$ or 1, and $j = 0$,1 or 2.[11] These prices introduce the avoided storage cost of the spent LWR fuel.[12]

In this context, each LCOE is composed of a fixed component, and an option composed of 5 weighted call options whose underlying strikes are the different marginal costs of TRU extraction. In fact, the marginal cost of extraction profile represents in an insightful way what LWR Recycling does through TRU concentration. Let p be the market price, Figure 5.11 illustrates the simplified profile of marginal costs.

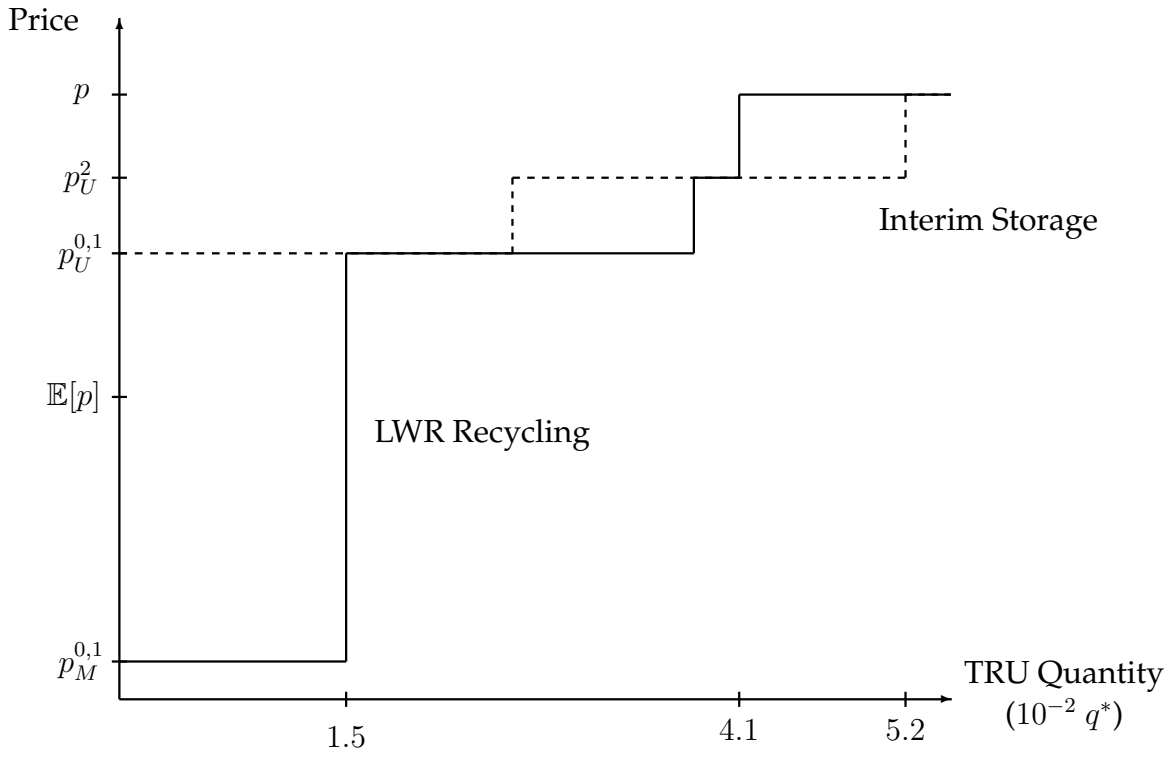

Figure 5.11 – *Marginal cost of TRU extraction*

A striking result is that although the quantity of TRUs is inferior with recycling, choosing the MOX branch will always allow to capture more benefits for the sale of TRU, as long as the price p is inferior to $p =$\$280,000/kgHM. This price is unlikely to ever be met since FRs can use highly enriched uranium.[13]

We see in Figure 5.12, that with the chosen TRU price distribution, spent UOX is actually rarely worth reprocessing while MOX always is. Significant earnings can only be expected with spent LWR fuel, for which interim storage has not yet been fully paid for.

[11] Note that p_M^2 would be equal to p_M and $p_U^2 = p_U$

[12] If this fuel were reprocessed, its separated elements would be stored at the recycling plant, the cost of which is included in C_r.

[13] See Appendix C.2

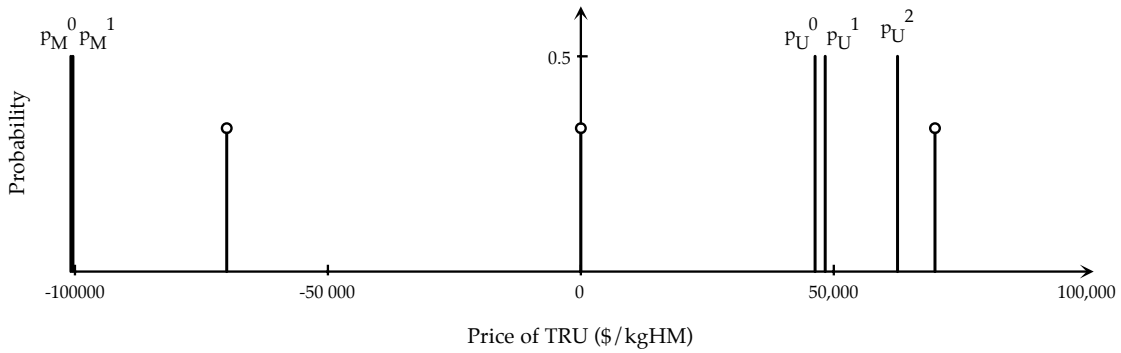

Figure 5.12 – *Distribution of the TRU price*

The question, therefore, becomes how much this expectation of higher future benefits in the case of LWR Recycling is worth in terms of present cost. Since the fixed costs are hard to detail mathematically, we complement the theoretical approach by the quantification of the studied effects. The calculations are based on the costs used in Chapter 3 and detailed in Appendix D.2.[14]

They lead to the following SFME fees:

Table 5.5 – *Levelized SFME fee*

Choice at $t = 0$	Choice at $t = 2T$	Cost (mill/kWh)
Disposal		1.69
Interim Storage	Disposal	1.12
	TRU Extraction	1.54
	Optimal Cost	1.08
LWR Recycling	Disposal	2.05
	TRU Extraction	2.02
	Optimal Cost	1.80

Before commenting these results in the next chapter, let us note that the effect of LWR Recycling, i.e. its ability to capture benefits of TRU extraction for FR cycles, has been reduced between Tables 5.2 and 5.5. The main two reasons are that, in contrast to the simplified example, not all spent UOX is recycled into MOX in our decision tree, moreover the impact of TRU sale is postponed to the introduction of FRs. The value of call options therefore becomes smaller than in the simple case of Section 5.1.

[14] $C_{gd/UOX}$ is determined such that $f_{\mathbf{E}}$=1.69 mill/kWh as in Chapter 3.
We find $C_{gd/UOX}$=\$540/kgHM. The other costs of disposal are deduced from this cost, in the same way as with $C_{d/UOX}$.

Chapter 6

Conclusions

In most of the studies referenced, fuel cycle modeling has been done through steady-state representations of deterministic scenarios. These models have given much insight into the parameters at stake, but have limited their analysis of uncertainties to sensitivity studies. On top of this, they have often sought to make all scenarios comparable by assuming a common ending. The latter method is not adapted to MOX fuels since their cost of disposal is very high, and this ending is rarely contemplated by MOX advocates (cf. BCG [2006]).

To solve this issue, this thesis relied on the intuition that the value of a particular spent fuel does not only encompass its cost of disposal but its value across future scenarios. As a consequence spent fuel management strategies should be assessed based on their results in all possible scenarios, using an economic options framework. In this paper, we developed a method relevant to all types of fuel and all their possible uses, and applied it specifically to the valuation of spent UOX and MOX in the context of FR development.

From Chapters 3 to 5, several models were presented, gradually introducing a probabilistic environment and a constrained decision model. This chapter summarizes the final results.

6.1 Results and interpretation

For the sake of clarity, the concept of a Spent Fuel Management Entity in charge of the back-end of Light Water Reactors was only introduced for the decision tree. Nevertheless, it is also applicable to traditional approaches of nuclear fuel cycle economics.

For the four cycles described in Chapter 2 and assessed deterministically in Chapter 3, the back-end charge of LWRs are summarized in Table 6.1.

Table 6.1 – *SFME fee for deterministic case (Chapter 3)*

	Cost (mill/kWh)
OTC	1.69
TTC	3.60
1-Tier	4.58
2-Tier	3.75

In Chapter 5, we modified the idealized fuel cycles to make them more realistic and comparable. As a result, we introduced several changes:

- the valuation of TRUs was modified to take into account potential progress in full-actinide recycling technologies. As a result, the average TRU price was raised;
- the initial schedules were modified in order to make 1-Tier and 2-Tier Recycling more comparable by the simultaneous introduction of FRs;
- when MOX was introduced, the reprocessing capacity was limited.

As a consequence, let us denote

- OTC*, the adapted Once-Through Cycle, in which the decision of direct disposal is taken (path **E** of the decision tree);
- TTC*, the adapted Twice-Through Cycle, in which a Thermal Recycling plant is built and the spent UOX and MOX disposed of (path **B**);
- 1-Tier*, the adapted 1-Tier Recycling, in which some spent UOX goes to interim storage, and all spent UOX is reprocessed for FRs (path **C** with full reprocessing);
- 2-Tier*, the adapted 2-Tier Recycling, in which some spent UOX goes to interim storage, some is recycled into MOX, and all spent LWR fuel is reprocessed for FRs (path **A** with full reprocessing).

The impact on the costs of Table 6.1 is shown in Table 6.2.

Table 6.2 – *SFME fee for adapted cycle (Chapter 5)*

	Cost (mill/kWh)
OTC*	1.69
TTC*	2.05
1-Tier*	1.54
2-Tier*	2.02

In contrast to the estimation of Chapter 3, we see that if FRs are introduced at the same point in time, 1-Tier Recycling could be cheaper than 2-Tier Recycling. The costs of the TTC, and its extension into 2-Tier Recycling, are also significantly reduced by the change in schedule and because only part of the spent UOX is recycled into MOX.

Finally, the choices of the SFME were extended into a set of 2 decisions in Chapter 5. The SFME first chooses between direct disposal, interim storage, or the building of a thermal recycling plant. In a second phase, when possible, the SFME chooses systematically to dispose of the fuel or systematically to recycle it in FRs (for non economic reasons), or to make the most economical decision based on the revealed price of TRU (optimal behavior described in Section 5.3).

Table 6.3 shows the resulting expected back-end fee.[1]

Table 6.3 – *SFME fee for decision tree (Chapter 5)*

Choice at $t = 0$	Choice at $t = 2T$	Cost (mill/kWh)
Direct Disposal		**1.69**
Interim Storage	Disposal	1.12
	TRU Extraction	**1.54**
	Optimal Behavior	1.08
LWR Recycling	Disposal	**2.05**
	TRU Extraction	**2.02**
	Optimal Behavior	1.80

Figure 6.1 illustrate these results. The light grey area represents the cost if the systematic decision at $t = 2T$ is to implement disposal, the white area, the added cost if the systematic decision is to extract the TRUs and recycle them into FRs, and the dark grey area, the savings resulting from the optimal behavior.

The latter is the direct illustration of the call options identified in Section 5.3, which correspond to the storage of TRUs in spent UOX and spent MOX.

[1] The numbers in bold are the ones introduced in Table 6.2.

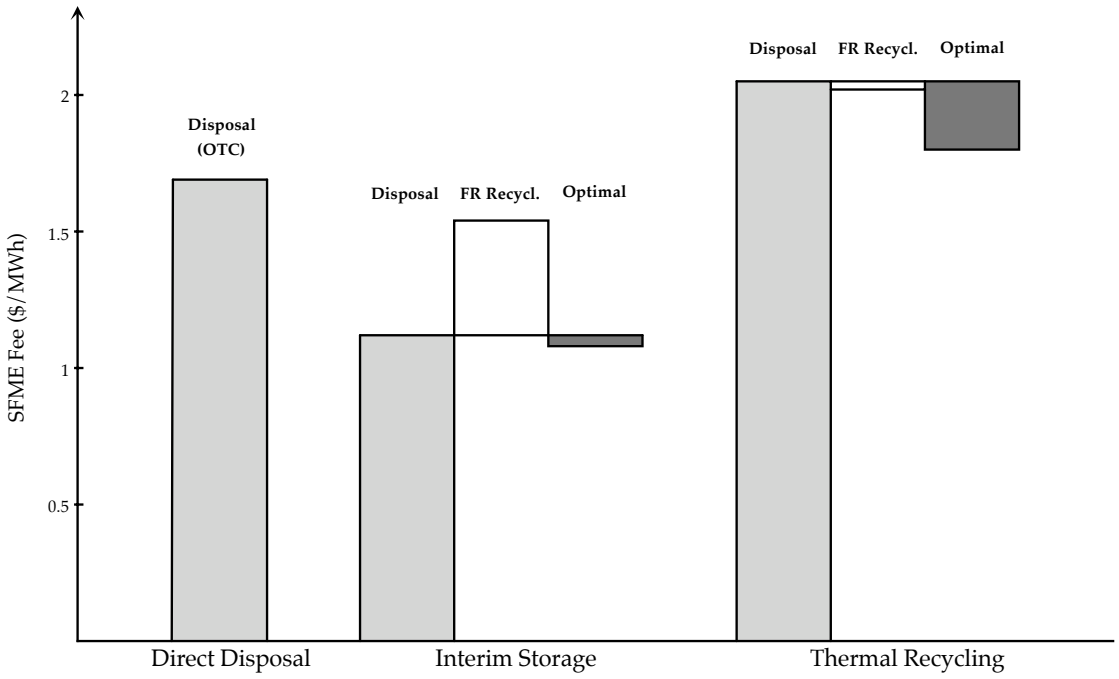

Figure 6.1 – *SMFE fees for decision tree*

Interpretation of MOX Value Figure 6.1 shows that even with partial recycling of UOX into MOX, the countries using MOX gain greater benefits from the potential development of full-actinide recycling:

- the cost added to disposal cost by the systematic development of FRs is 0.42 mill/kWh with interim storage and -0.03 mill/kWh with MOX;
- the optimal behavior based on the price of TRUs leads to savings of 0.04 mill/kWh with interim storage and 0.25 mill/kWh with MOX, compared to systematic disposal.

The sample price distribution hence highlights the fact that by lowering and diversifying the prices at which extracted TRUs are available (see Figure 5.11), the introduction of MOX allows a country to capture more potential benefits from the development of FRs.

Countries having already developed MOX are, therefore, more likely to benefit from future FR developments. However, in our reference case, it remains that the cost of a strategy using Mixed Oxide Fuels is greater than a strategy without recycling. If the SFME actions are based upon the price of TRU, the added cost of MOX would range from 0.11 mill/kWh (compared to direct disposal) to 0.72 mill/kWh (compared to interim storage), representing an increase of 7% and 67% of the LWR back-end costs respectively.

6.2 Perspective

The major points illustrated by this thesis are, therefore, that:

- the schedule of expenses is the main driver of back-end costs
- the introduction of MOX makes more likely the introduction of FRs in the future. These future expectations significantly change the valuation of MOX compared to the classical approach, although not enough to close the gap with interim storage.

The importance of time frame highlights sensitivity to discount rates as a point for further investigation. The second point is contingent on the assumed inputs: the distribution of TRU prices and the costs of recycling are sensitive inputs on which little data is available, and subject to changes. Moreover, little attention was devoted to uranium price escalation, and its impact on the value of TRUs.

However, refinements on the strategic value of TRU concentration in MOX should have limited impact: in both probabilistic models, the value of the call option created by MOX represented a saving of 12% of back-end costs, compared to the traditionally assessed TTC. Figure 6.2 shows how this relates to the total LCOE of a LWR.

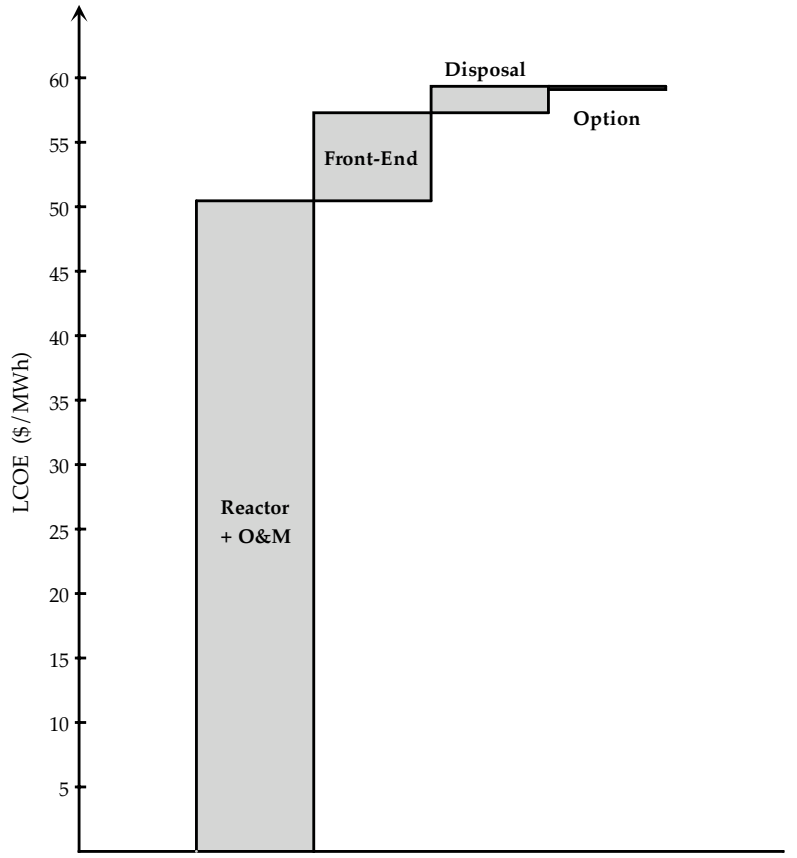

Figure 6.2 – *LCOE break-down for optimal behavior in MOX branch*

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Appendix A

Modeling of MOX fuel

This chapter summarizes results obtained in a study aiming at the modeling of a typical PWR core loaded with about 30% of Mixed Oxide (MOX) fuel assemblies, and is very indebted to the framework of a simultaneous study led by Shwageraus [2009]. The main focus was on the composition and mass flows necessary to a reactor operating with mixed fuel in order to provide meaningful numbers for economic analyses, and scenario simulations.

A.1 Methodology

A.1.1 Design guidelines

The following analysis was pursued with a twofold aim:

- maintaining the core performance within the typical PWR operations conditions
- providing values meaningful for the economics of MOX

The latter concern corresponds to the design of a MOX assembly that would be "technically equivalent" to a UOX assembly, i.e. designed to sustain the same burnup as UOX without significant safety impact, and without impairing the performance of UOX fuel.

Cycle length

The target reference fuel cycle length was chosen to be 466 Effective Full Power Days (EFPD), which corresponds to a 18-month cycle assuming 85% capacity factor, in consistence with MIT [2003]. Higher capacity factors can be obtained through a change in the

fuel composition or, as we will assume for later normalization, through an increase of the mass flow into the reactor.

The target fuel cycle length was achieved through variations in the fraction of fuel assemblies reloaded each cycle, loading pattern, and in the enrichment of the MOX assemblies while keeping UOX enrichment constant to what is common practice for full UOX cores. The target discharge burnup for both UOX and MOX fuel is 50 MWd/kgHM.

Loading pattern

With some departures from Shwageraus [2009], the fuel assemblies loading and reshuffling strategy was based on the following guidelines

- the loading strategy should minimize neutron fluence to the reactor vessel by avoiding the loading of fresh assemblies in the core periphery
- the relative fraction of MOX assemblies should be at most 30% of the total number of fuel assemblies in the core
- one quarter mirror core symmetry should be maintained
- adjacency of MOX assemblies and positioning at the control rods emplacement should be limited as much as possible for power peaking and control rod reactivity worth concerns respectively
- assembly radial power peaking factors and pin peaking factors should be limited to 1.5 and 2.0 respectively
- spread in discharge fuel burnup values should be minimal in order to keep the discharge burnup values within the current licensing limits

Soluble boron concentration

The concentration of soluble boron is limited to about 2000 ppm, since large soluble boron concentration can result in positive moderator temperature coefficient. The maximum critical boron concentration required during the irradiation cycle can be influenced by the use of burnable poison loading in UOX assemblies.

Shutdown margin (SDM)

The shutdown margin is the instantaneous amount of reactivity by which a reactor would become subcritical from its operating condition, assuming all control rods were fully inserted except for the rod with the highest reactivity worth. As this margin evolves with

burnup, it is necessary to ensure minimal shutdown margins at all times during the core lifetime.

The minimum shutdown margin should be 1.3% $\Delta\rho$ for a Westinghouse PWR operating at full power. It is calculated by

$$\text{SDM} = 0.9\ (\rho_{allCRD} - \rho_{maxCRD}) - \rho_{HFPtoHZP} - \rho_{IA} \tag{A.1}$$

with ρ_{allCRD}, the reactivity worth of all fully inserted control rods, ρ_{maxCRD}, the reactivity worth of the control rod with the highest worth, $\rho_{HFPtoHZP}$, the difference between core reactivities at hot full power and at hot zero power, and ρ_{IA}, the rod insertion allowance.

A.1.2 Computational tools

The following description is meant to be brief since more details on the codes can be found in each code's reference.

The analysis was performed using Studsvik Core Management System (CMS). This code is commonly used by the nuclear power industry for in-core fuel management and loading pattern optimization, evaluation of fuel cycle length, burnable poison design and requirements, various fuel and adequacy to regulatory requirements.

CMS is composed of a two-dimensional transport code CASMO-4 used to generate macroscopic cross-sections library. For further usage, this library is subsequently transformed by TABLES-3, which generates a macroscopic cross-sections library. The latter is used in SIMULATE-3, a two-group three-dimensional nodal diffusion code for the whole core coupled with neutronic-thermal hydraulic analysis.

A.2 Core description

The core serving as a reference for this analysis was a typical 4-loop Westinghouse PWR, the characteristic of which are summarized in Table A.1. This core was loaded with assemblies of two types: UOX and MOX (UO_2-Pu/AmO_2). Both fuel types are designed in identical 17x17 pins geometry with 25 guide tube positions. Schematic view of one quarter of the fuel assembly is presented in Figures A.2-A.3.

As in Shwageraus [2009], all UOX fuel pins have a burnable poison coating. Usually, the burnable poison loading per assembly can be adjusted through variation in the number of Integral Fuel Boron Absorber (IFBA) rods, i.e. rods containing uranium pellets with a thin coating of zirconium diboride (ZrB_2). For sake of simplicity, adjustment

is only done in this study through variation of the IFBA coating thickness, which is not expected to have a significant impact on the mass flows and compositions. The uranium enrichment was assumed to be fixed at 4.5 wt. % to reach the target burnup.

MOX fuel assemblies do not have any burnable absorbers. This is due to the fact that excess reactivity of the MOX fuel is typically lower than that of the UO2 fuel, with a harder neutron spectrum. Loading of Pu/Am in the MOX fuel is adjusted to match approximately the single-batch core reactivity limited burnup of UOX fuel, as shown in Figure A.1. It was also further refined, as a loading pattern was chosen, in order to match the target value for burnup, which resulted eventually in the choice summarized in Table A.2. The Pu/Am isotopic vector used in this analysis corresponds to a typical spent UOX fuel with 4.5% initial enrichment, 50 MWd/kg discharge burnup, cooled 5 years after discharge, from which the sole Pu is extracted and left to decay for 2 more years. At the end of this process, the Pu/Am mix is composed of 66.2 wt. % of fissile Plutonium (the presence of ^{241}Am is due to the decay of ^{241}Pu). Depleted uranium was used as UO_2 component in the MOX fuel. Several Pu enrichment levels were then used in MOX fuel assemblies in order to minimize the pin power peaking factors as shown in Figure A.3.

Figure A.4 presents the core map with the location of the control rods (control rod clusters in black). Eight banks of control rods are used, 4 (from A through D) are dedicated to power maneuvering and 4 (from SA through SD) are used exclusively for shutdown. Letter "S" in the name indicates that the control rod belongs to the shutdown bank.

Table A.1 – *Core design parameters*

Plant description	
Core thermal power, MW	3411
Plant thermal efficiency, %	33.71
Plant electric power output, MWe	1150
Core description	
Power density, W/cm3	104.5
Average linear heat generation rate, W/cm	182.91
Primary system pressure, MPa	15.5
Total core flow rate, Mg/sec	18.63
Core coolant mass flux, kg/m2-sec	2087.6
Core inlet temperature, °C	292.7
Fuel Rod	
Total number of fuel rod locations	50,952
UO2 Fuel density, % of theoretical	94
Pellet diameter, mm	8.192
Cladding material	Zircaloy-4
Cladding thickness, mm	0.572
Cladding outer diameter, mm	9.5
Active fuel height, m	3.66
Fuel Assembly	
Total number of fuel assemblies	193
Assembly lattice geometry	Square 17 x 17
Number of fuel rods locations per assembly	264
Number of grids per assembly	7
IFBA rods per assembly	264
Total IFBA loading, g ^{10}B/cm	0.103
Fuel rod pitch, cm	1.26
Assembly pitch, cm	21.5 x 21.5
Control Rod Cluster	
Neutron absorbing material	Ag-In-Cd
Cladding material	304 SS
Cladding thickness, mm	0.46
Number of clusters	53
Number of absorber rods per cluster	24

Table A.2 – *Fuel Composition*

MOX fuel composition

Pu/Am density, g/cm3	10.76
Average fuel density, g/cm3	10.34
Depleted UO2 enrichment, wt.%	0.25
Average Pu/Am mix, wt.%	8.73
Composition of Pu/Am mix, wt. %	
Pu238	2.65
Pu239	55.47
Pu240	22.81
Pu241	10.69
Pu242	6.73
Am241	1.64

UO2 fuel composition

Fuel density, g/cm3	10.30
Uranium enrichment, wt.%	4.5
IFBA Coating	ZrB_2
ZrB2 density, g/cm3	6.1
IFBA Coating thickness, μm	15.0

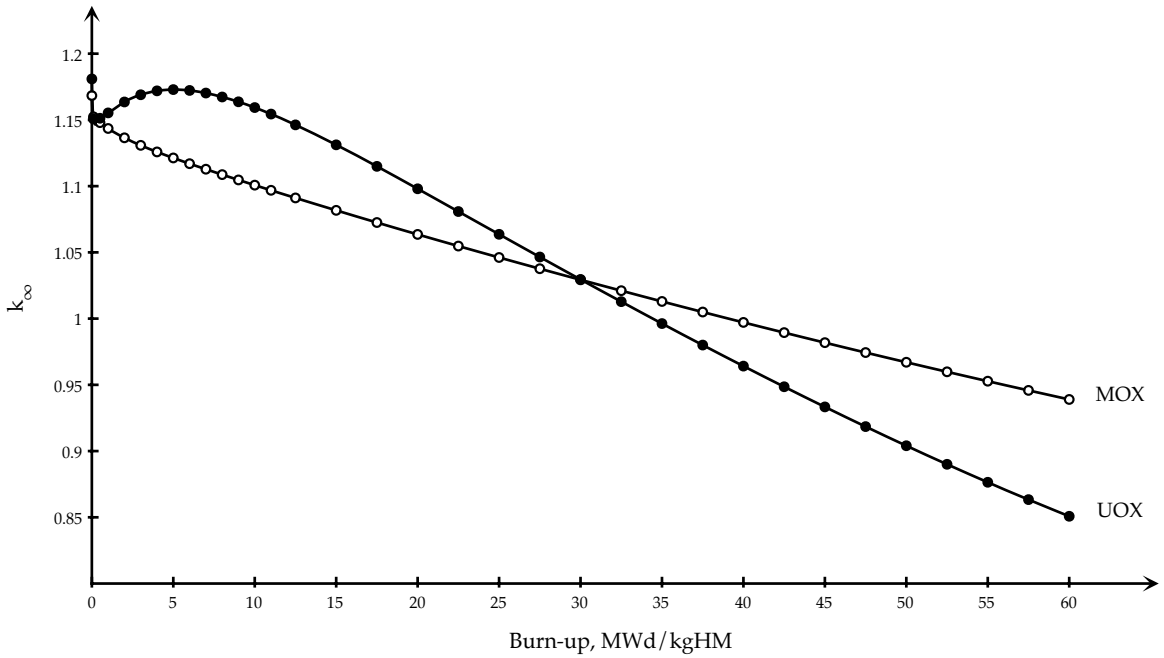

Figure A.1 – *Evolution of k_∞ of designed UOX and MOX with burnup (at 600ppm boron)*

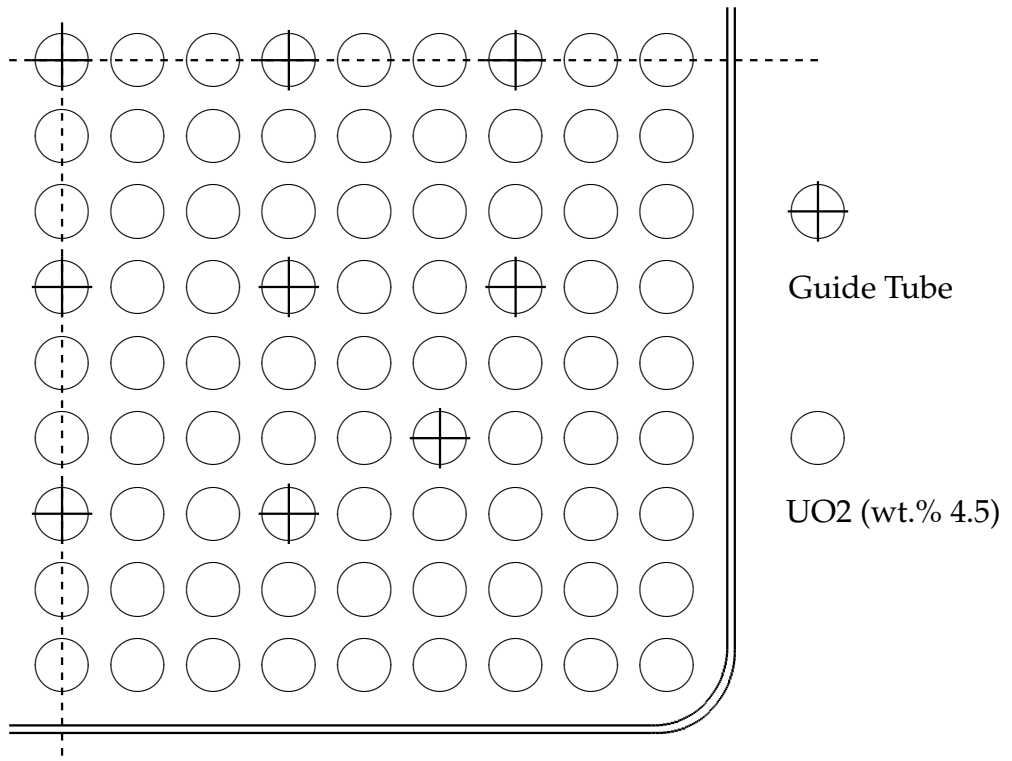

Figure A.2 – *Schematic view of 1/4 UOX fuel assembly*

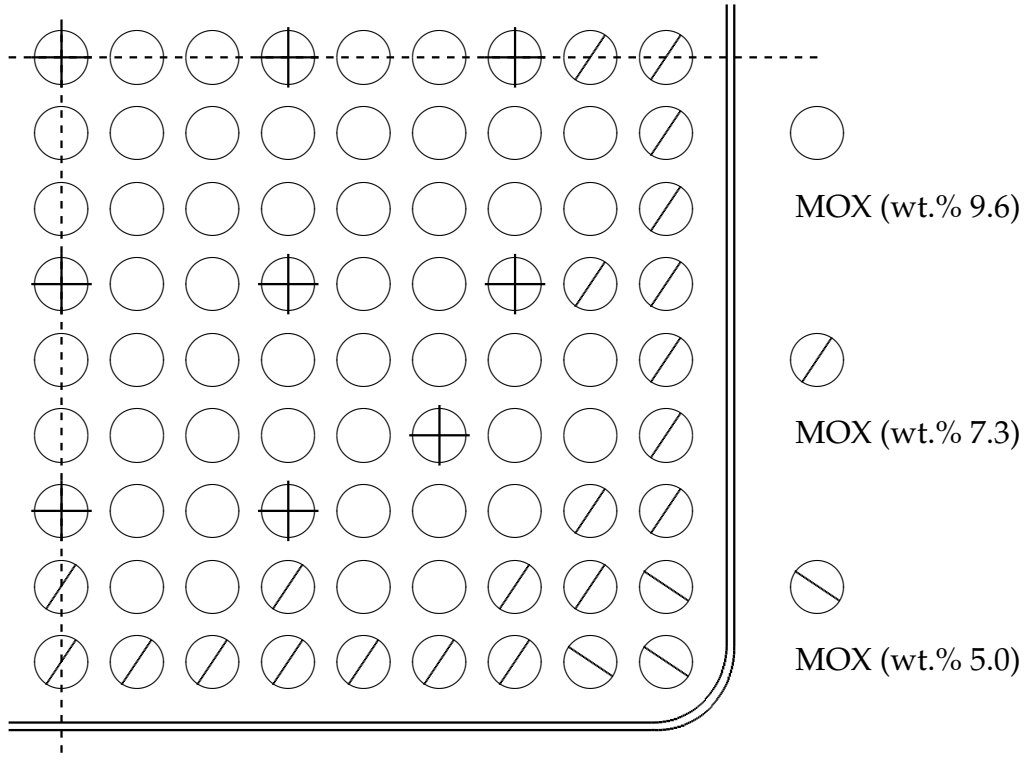

Figure A.3 – *Schematic view of 1/4 MOX fuel assembly*

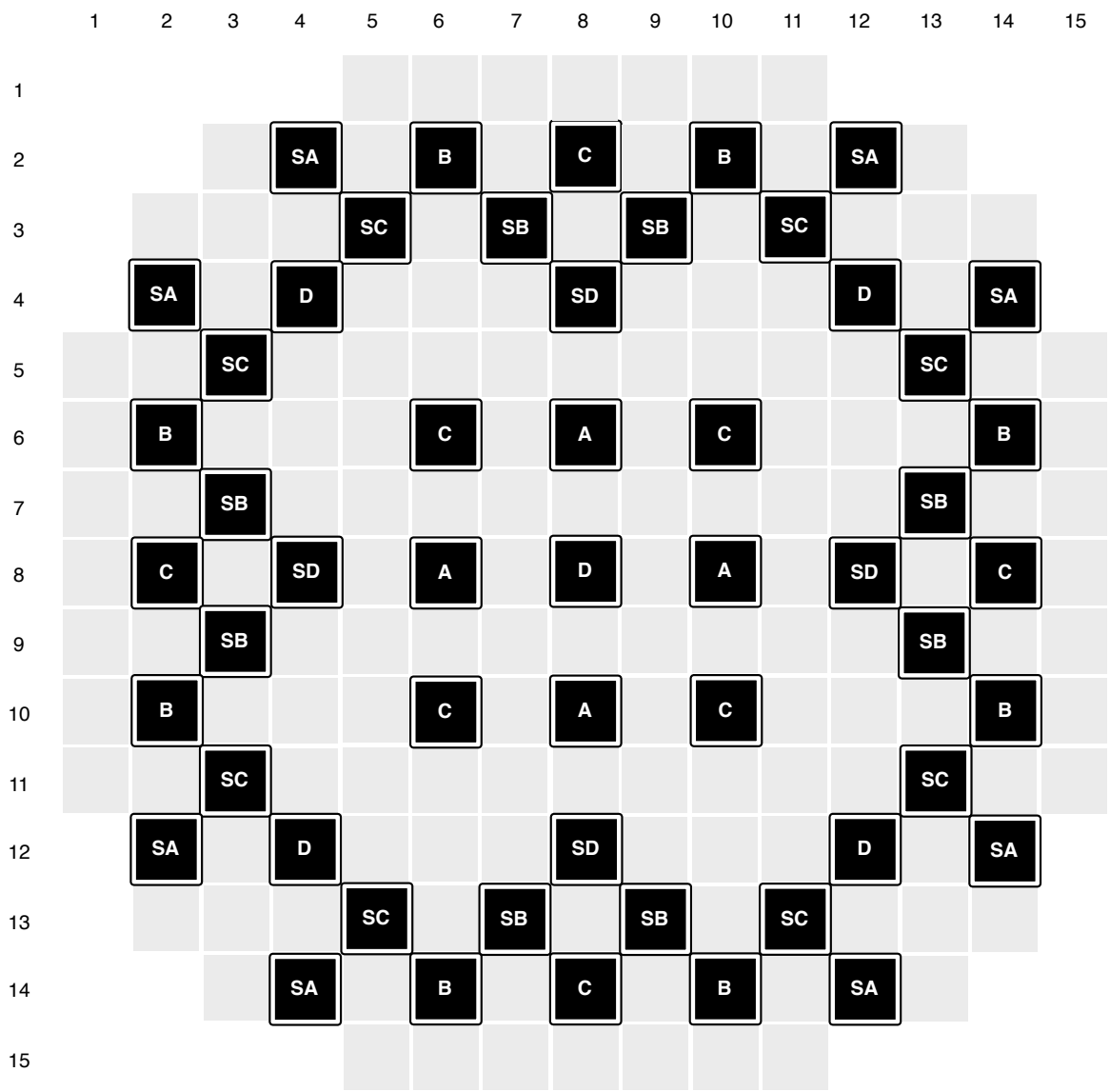

Figure A.4 – *Control rod banks location*

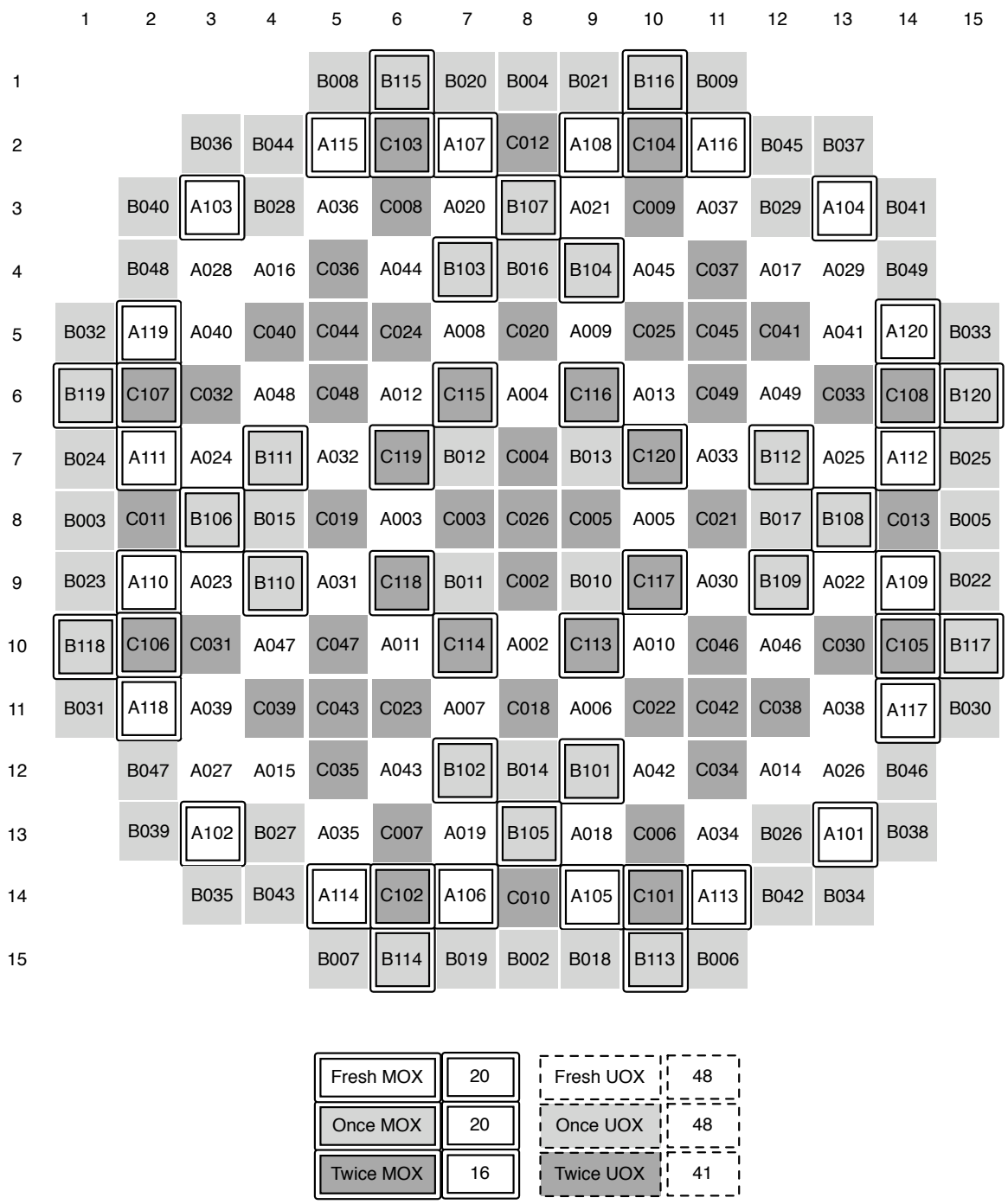

Figure A.5 – *Core loading pattern*

A.3 Results

The developed fuel loading map and reshuffling strategy is presented in Figure A.5. The core has one quarter symmetry and satisfies the restrictions on the fraction of MOX fuel assemblies: the total number of MOX assemblies is 56, which is slightly lower than 30%. In terms of location of the MOX assemblies, the reader should note that the loading pattern entails the presence of MOX assemblies at the position of bank "B" rods (dedicated to power maneuvering). The same assemblies lead to the formation of zones where MOX assemblies are adjacent, departing from Shwageraus [2009].

20 MOX assemblies are reloaded every cycle, while only 16 of them remain in the core for 3 consecutive cycles (80%). The assemblies, which accumulate the highest burnup after two irradiation cycles, are discharged after the second cycle. The same principle also applies to the UOX assemblies: 48 fresh assemblies are reloaded every cycle, out of which only 41 undergo 3 cycles (85%). A total of 68 fresh fuel assemblies are hence loaded each cycle to achieve a 463 EFPD cycle length as can be seen in Figure A.6. This is only 3 days short of the target 466 EFPD. The subsequent reactivity coefficient, materials flows, and other calculations are based on the results of the simulation of cycle 7.

The evolution of the critical boron concentration is represented in Figure A.7 and follows the guideline recommendations indicated earlier, with a concentration below 1,600ppm throughout the cycle.

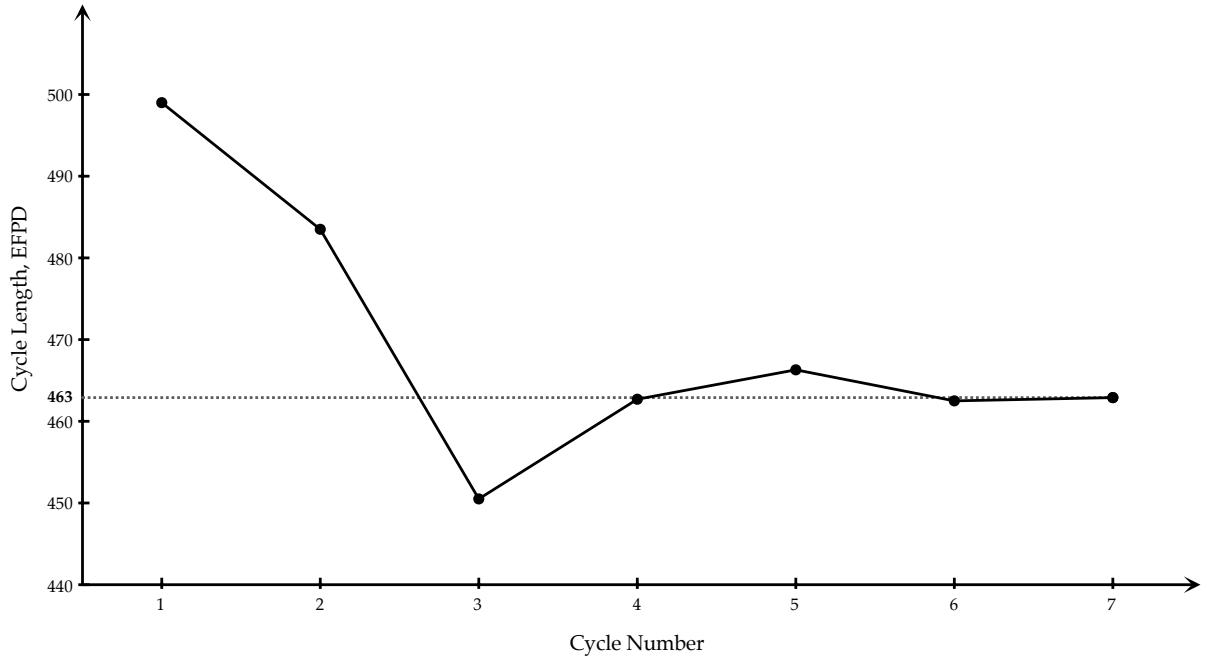

Figure A.6 – *Approach to equilibrium core cycle length*

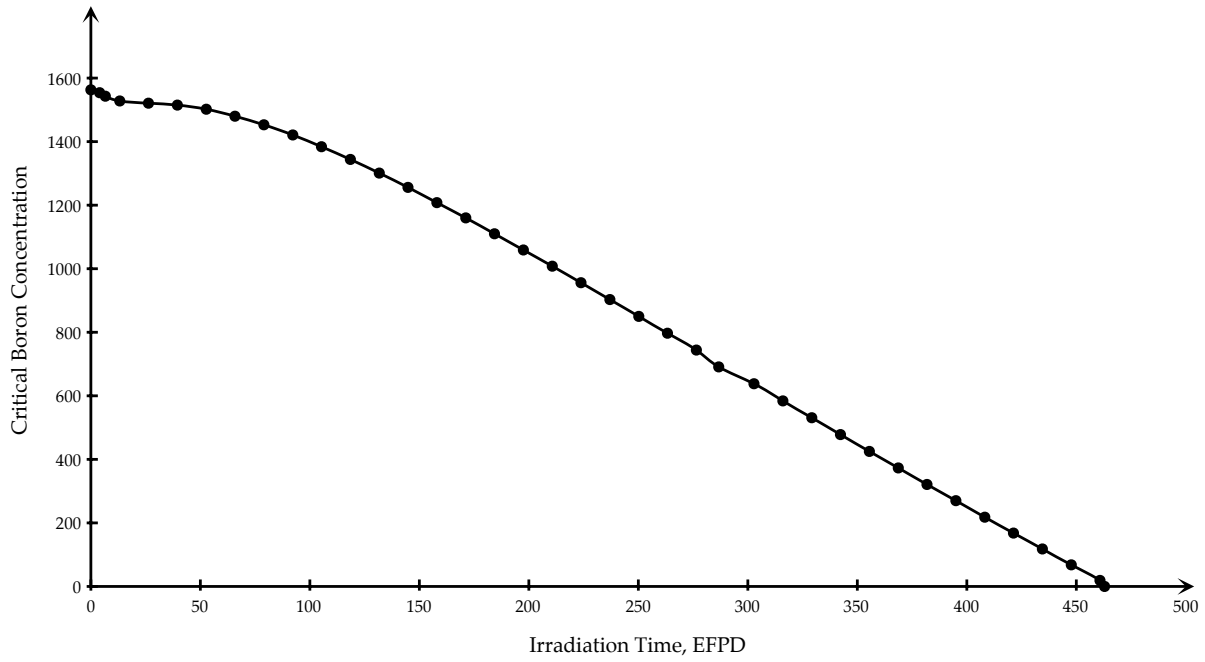

Figure A.7 – *Evolution of the critical boron concentration with time*

Figure A.8 presents the Beginning and End of Cycle (noted BOC and EOC respectively) power and burnup distributions. The loading pattern has been optimized so as to limit the spread between assemblies (see also Table A.5). As a result, the discharged assemblies of UOX have burnups ranging from 40.7 to 55.3 MWd/kgHM and discharged MOX assemblies have burnups ranging from 42.8 to 56.0 MWd/kgHM. The highest values seem compatible with the licensing peak rod burnup limit of 62 MWd/kgHM. Furthermore, the average burnup is close to the target of 50MWd/kgHM (50.3 for both UOX and MOX).

The average fuel burnup for the total core, calculated as total energy produced by all fuel assemblies divided by all the Heavy Metal mass loaded, was found to be 50.3MWd/kgHM, close to the target value.

The radial power peaking factors presented in Figures A.8-A.9 miss by very little the 1.5 and 2.0 guideline values for the radial peaking and pin peak respectively (maximum values: 1.51 and 2.03). It is however a minor concern since:

- this could be mitigated by the use of burnable poison such as Gadolinium, which was neglected in this study
- a very direct and effective way to reduce these factors would be to decrease the enrichment of the MOX assemblies closer to 50MWd/kgHM.

  However, this would reduce the burnup of MOX. When looking at fuel compositions for cycle comparisons, having UOX and MOX with the same burnup seems a

more desirable target than the correction for residual gap in peaking factors.

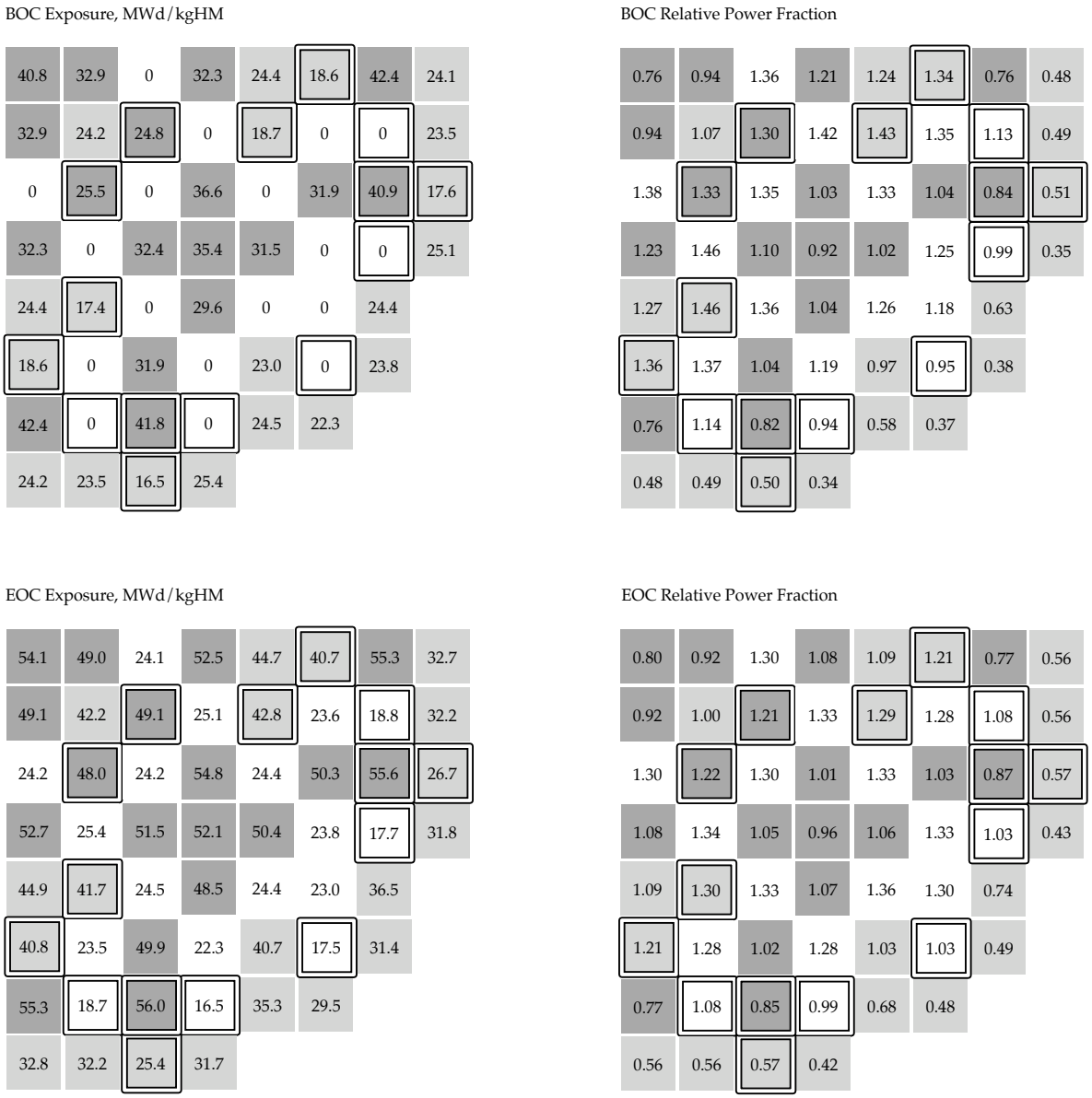

Figure A.8 – *Equilibrium cycle assembly exposure and power fraction*

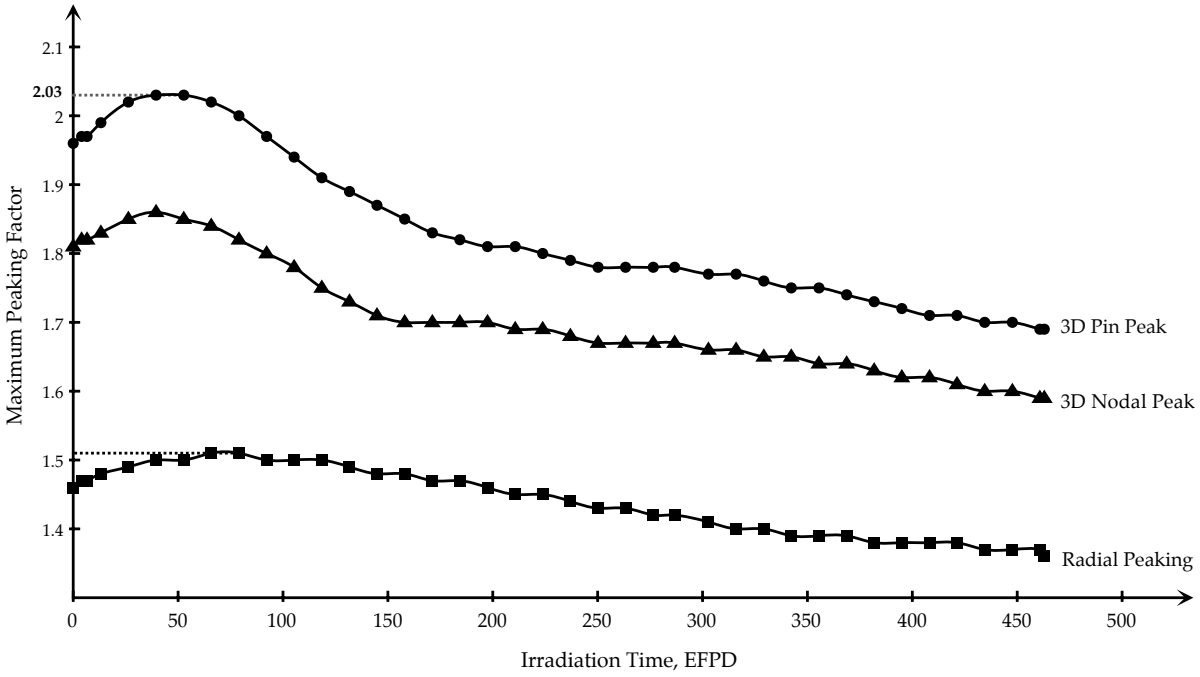

Figure A.9 – *Power peaking factors*

In contrast to Shwageraus [2009], the safety focus has been put here mostly on the shutdown margin (SDM) since it is where the differences in loading patterns, namely the emplacement of MOX assemblies at some control rods positions, is expected to have the most impact.

The calculations were made along the following principles:

- the Xenon reactivity effect was excluded from all SDM calculations because the changes in Xe concentration can be considered slow enough, so that there is sufficient time to compensate for its reactivity effect by flooding the core with soluble boron. For information, the Xe worth is 2145 and 2396 pcm at beginning of cycle (BOC) and end of cycle (EOC) respectively.
- the reactivity worth of individual control rods was calculated for the full core model (without symmetry) assuming that all rods are fully inserted. Then, the rods were withdrawn one at a time and reactivity difference was taken as the rod worth
- the difference between core reactivities at hot full power and at hot zero power was calculated with all rods in conservatively
- the control rod insertion allowance was calculated at HFP with all the shutdown banks fully withdrawn while all the other control rod banks conservatively assumed to be inserted to 30% length

The results can be seen in Tables A.3-A.4

Table A.3 – *Summary of individual control rod worths (in pcm)*

Position (i,j)	BOC	EOC
(8,8)	148	164
(10,8)	336	289
(12,8)	263	223
(14,8)	99	144
(13,9)	237	243
(10,10)	**348**	**311**
(14,10)	79	112
(13,11)	203	245
(12,12)	236	274
(14,12)	58	99

Table A.4 – *Calculation of shutdown margin (in pcm)*

	BOC	EOC
ρ_{allCRD}	7034	8133
ρ_{maxCRD}	348	311
$\rho_{HFPtoHZP}$	2836	4587
ρ_{RIA}	530	894
SDM	**2832**	**1691**

The high power region around (10,10) leads to a high reactivity of the control rod at this point. The SDM, calculated as in Equation A.1, seems appropriate for the beginning and end of cycles and one can extrapolate that it is for all points in the cycle. The SDM is more restrictive at EOC because of the higher HFP to HZP reactivity decrement which is not fully compensated by the higher control rods worth.

As a conclusion, with almost 1.7% $\Delta\rho$ throughout the cycle, the loading pattern still seems to allow an operation of the reactor under proper safety conditions.

Finally, material flow through the studied 30% MOX core can be found in Table A.5. The materials mass balance normalized per cycle and per unit energy is presented in Table A.6.

Material Flows:

Table A.5 – *Detail of the assemblies' burnup and composition*

UOX	Load	Discharge													
No. ASSY	48	3	4	4	4	4	4	4	4	4	4	1	4	4	**Average**
Burnup	0	40.73	44.87	48.51	49.07	49.92	50.28	50.40	51.54	52.14	52.68	54.10	54.82	55.28	**50.30**
Mass/ASSY, kg (5yrs cooling)															
Total HM	452.7	433.8	431.9	430.2	429.9	429.5	429.4	429.3	428.8	428.5	428.3	427.6	427.3	427.1	429.4
U	452.7	428.6	426.4	424.5	424.2	423.7	423.6	423.5	422.9	422.6	422.3	421.6	421.2	421.0	423.5
Pu	0	4.7	4.9	5.1	5.1	5.2	5.2	5.2	5.2	5.3	5.3	5.3	5.4	5.4	5.2
MA	0	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6

MOX	Load	Discharge					
No. ASSY	20	4	4	4	4	4	**Average**
Burnup	0	42.75	48.05	49.10	55.58	56.04	**50.30**
Mass/ASSY, kg (7yrs cooling)							
Total HM	454.6	434.7	432.3	431.8	428.8	428.6	431.2
U	414.9	403.0	401.5	401.2	399.2	399.1	400.8
Pu	39.0	28.6	27.7	27.5	26.3	26.2	27.3
MA	0.7	3.0	3.1	3.1	3.3	3.3	3.2

Table A.6 – *Normalized Mass Flows (with CF = 84.5%)*

	At Loading			After 7yrs Cooling		
	MOX	UOX	Total	MOX	UOX	Total
Mass balance, kg / cycle						
HM	9,092	21,729	30,280	8,624	20,610	29,234
U	8,298	21,729	30,027	8,016	20,330	28,346
Pu	781		781	545	249	794
MA	13		13	63	31	94
Mass balance, kg / GWeEFPY						
HM	6,354	15,186	21,541	6,028	14,405	20,432
U	5,800	15,186	20,986	5,602	14,209	19,811
Pu	546		546	381	174	555
MA	9		9	44	22	66
Mass balance, kg / GWeY						
HM	5,369	12,831	18,200	5,093	12,170	17,263
U	4,900	12,831	17,731	4,733	12,005	17,916
Pu	461		461	322	147	502
MA	8		8	37	18	59

Appendix B

Fuel Cycle Flows

B.1 Fuel compositions

The following compositions were established by core simulations using CASMO and SIMULATE. For details of the MOX simulation, see Appendix A.

Table B.1 – *LWR fuel composition wt. % (50 MWd/kgHM)*

	Fresh UOX	Spent UOX	Fresh MOX	Spent MOX
^{234}U	0.036	0.018	0.002	0.018
^{235}U	4.5	0.956	0.228	0.119
^{236}U	0	0.583	0	0.026
^{238}U	95.464	92.009	91.04	87.999
^{238}Pu	0	0.031	0.232	0.225
^{239}Pu	0	0.634	4.843	2.514
^{240}Pu	0	0.261	1.991	1.791
^{241}Pu	0	0.141	0.934	0.774
^{242}Pu	0	0.079	0.587	0.695
^{241}Am	0	0.044	0.143	0.143
Other TRU	0	0.098	0	0.266
Total Act	100	94.854	100	94.57
Total U	100	93.566	91.27	88.162
Total Pu	0	1.146	8.587	5.999
Total TRU	0	1.288	8.730	6.408
FP	0	5.146	0	5.43
Total	100.0	100.0	100.0	100.0

B.2 Enrichment

To release a certain energy, i.e. to reach a certain burnup, uranium has to be enriched beforehand in its only fissile isotope: ^{235}U. This required concentration increases with the target burnup. Simulation of a PWR core with 3 batches of UOX fuel irradiated for 1.5 year per cycle show that the necessary enrichment for a UOX fuel made from natural uranium is 4.5% for 50 MWd/kgHM.

However, UOX fuel can also be made from reprocessed uranium. If this uranium were used to fabricate UOX and enriched to the same percentage, it would not be able to reach the same burnup. The reason is that irradiation of the UOX in the core produces a synthetic isotope, ^{236}U, a neutron absorber, which is extracted together with the reprocessed uranium by the aqueous reprocessing. Therefore, a higher enrichment of the reprocessed uranium in ^{235}U must be reached, to compensate for this absorber.

Bunn et al. use the following formula:[1]

$$x_{rp} = \frac{x_p}{1 - 0.21\dfrac{x_{r236}}{x_{rf}}}$$

where x_{rp} is the equivalent enrichment, x_p the regular enrichment, x_{r236} the concentration of the reprocessed uranium in ^{236}U, and x_{rf} the concentration of the reprocessed uranium in^{235}U.

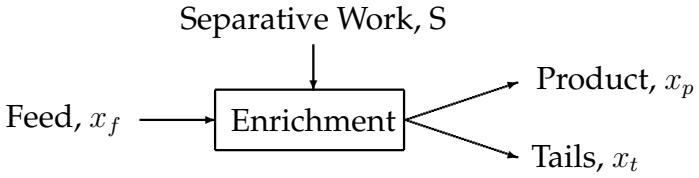

Figure B.1 – *Flows in the enrichment process*

Given the composition of a spent UOX assembly designed to sustain a 50MWd/kgHM burnup (see Table B.1), the reprocessed uranium would have to be enriched at 5.16% in ^{235}U in order to reach the same burnup.

B.3 Optimal tails

Once the proper enrichment of uranium determined, whether for natural or reprocessed uranium, there are many ways to produce such a fuel. Indeed, you can extract most of the

[1]Rearranged from Plutonium Fuel: An Assessment (NEA, 1989), p.129, similarly to Bunn et al. [2003].

^{235}U present in a small quantity of uranium, or just a little of the ^{235}U present in a bigger amount of uranium.

This choice depends on the relative cost of uranium to enrichment. This problem can be formulated in terms of finding the optimal enrichment of the tails, x_t, which leads to the minimal cost of fabrication. The cost of a fresh UOX assembly has 4 components:

- the cost of fabrication itself, C_f (\$/kgHM)
- the cost of enrichment, $S\ C_s$, where S is the number of separative working units (SWU) and C_s the cost of enrichment (\$/SWU)
- the cost of ore and of conversion, $R\,C_u + R\,C_c$, where R is the feed which will be enriched (kgU/kgEU), C_u the cost of uranium (\$/kgHM) and C_c the cost of conversion (\$/kgHM)

Once we account for the loss at the respective steps, f_f, f_s, f_c, it yields

$$C_{UOX} = \frac{1}{1-f_f}\left[\frac{R}{1-f_s}\left(\frac{C_u}{(1-f_c)(1+i)^{t_u}} + \frac{C_c}{(1+i)^{t_c}}\right) + \frac{S\,C_s}{(1+i)^{t_s}}\right] + \frac{C_f}{(1+i)^{t_f}}$$

where $R = \dfrac{x_p - x_t}{x_f - x_t}$

and $S = \phi(x_p) + (R-1)\phi(x_t) - R\phi(x_f)$ with $\phi(x) = (2x-1)\ln\left(\dfrac{x}{1-x}\right)$

If we want the minimum C_{UOX} with respect to x_t, the first-degree condition gives

$$\frac{1}{x_f - x_t} = \lambda \times \left(\frac{\phi(x_f) - \phi(x_t)}{x_f - x_t} + \frac{2\phi(x_t)}{1-2x_t} + \frac{1-2x_t}{x_t(1-x_t)}\right)$$

where $\lambda = \dfrac{(1-f_s)C_s}{\dfrac{C_c}{(1+i)^{t_c-t_s}} + \dfrac{C_u}{(1-f_c)(1+i)^{t_u-t_s}}}$

Since this equation is implicit, only an approximate formula, or solutions for specific numerical parameters, can be given. One point worth noticing is that the optimal enrichment of the tails does not depend on the product enrichment, but only on the feed enrichment and on λ. The optimal tails assay, we note x_t^*.

Note that the previous calculation is done for natural uranium but is similar for reprocessed uranium. In the latter case, we add use the subscript "r" in the variables denomination: x_t becomes x_{rt}, C_u becomes C_{ru}, and so on.

B.4 Flows

With the economic framework used in Chapter 3, and losses of 0.2% at each step, we find the following mass flows with self-sustainable fast reactors.

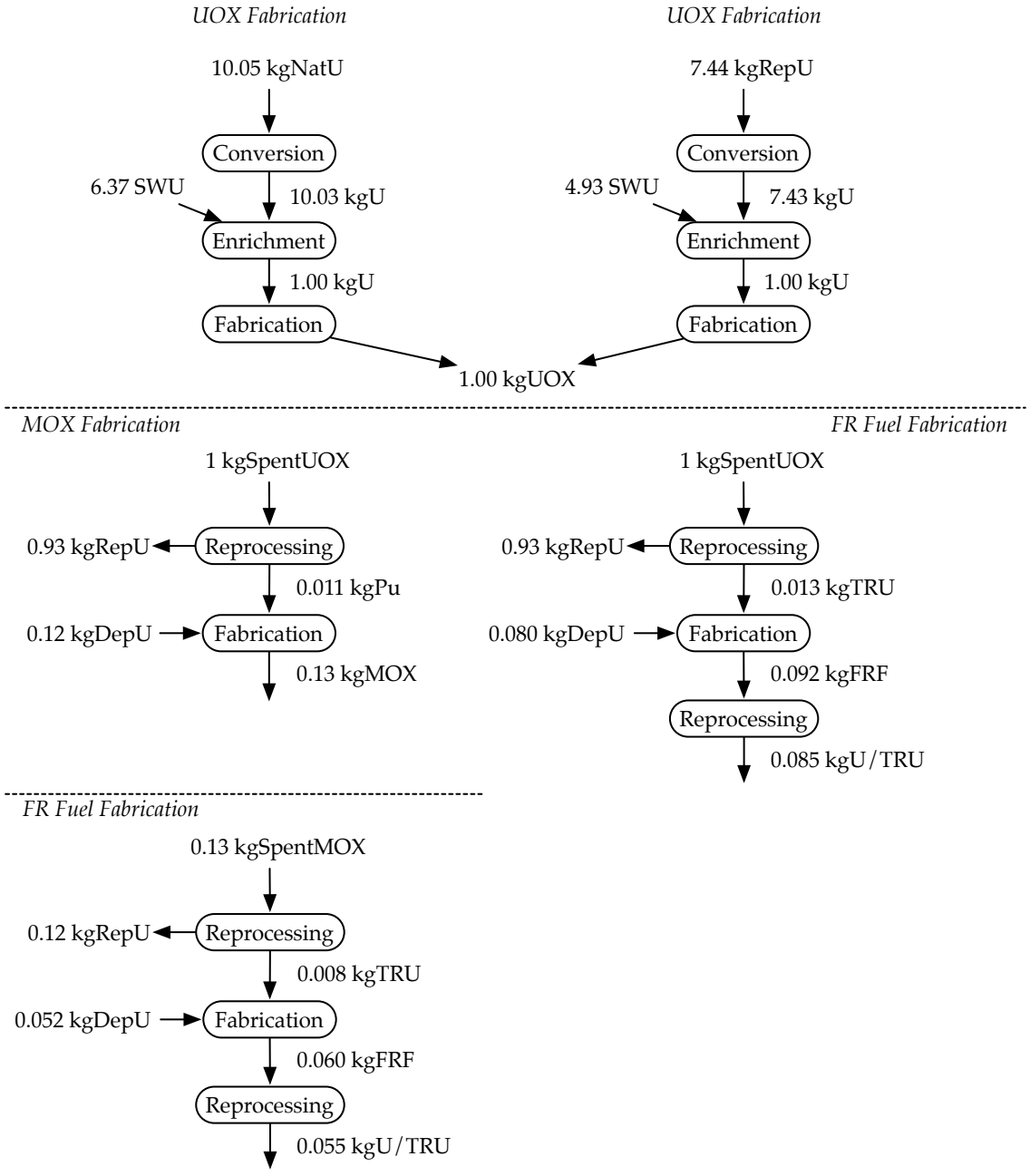

Figure B.2 – *Schematic mass flow of the system for economic analysis*

Appendix C

Details of Economic Model

C.1 Table of inputs

General Economic Parameters		
General Discount Rate	5.0%	
Rate for Disposal	3%	
Rate for Reprocessing	3%	
Tax Rate	37%	
Inflation Rate		
Real Fuel Escalation		
Fuel Cycle Economic Parameters		
Uranium Purchase	90	$/kgHM
Depleted Uranium	10	$/kgHM
Yellow Cake Conversion	10	$/kgHM
Enrichment	160	$/SWU
Fabrication of UOX fuel for LWR	250	$/kgHM
Fabrication of MOX fuel for LWR	2,400	$/kgHM
Fabrication of Breeder FR fuel	2,400	$/kgHM
Fabrication of Self Sust. FR fuel (14% TRU)	2,400	$/kgHM
Fabrication of Burner FR fuel (33% TRU)	2,400	$/kgHM
for Reprocessed Uranium		
Premium for conversion	200%	
Premium for enrichment	10%	
Premium for fabrication	7%	
Reprocessing of Spent UOX	1,600	$/kgHM
Reprocessing of Spent MOX	1,600	$/kgHM
Reprocessing of Breeder Fuel	3,200	$/kgHM
Reprocessing of Self Sust Fuel	3,200	$/kgHM
Reprocessing of Burner Fuel	3,200	$/kgHM
Interim Storage for UOX	200	$/kgHM
Interim Storage for MOX	200	$/kgHM

Geological Disposal of Spent UOX	50 MWd/k	755	$/kgIHM
	80 MWd/k	1,290	$/kgIHM
Geological Disposal of Spent MOX	50 MWd/k	5,035	$/kgIHM
	80 MWd/k	8,598	$/kgIHM
Disposal of HLW from UOX	50 MWd/k	302	$/kgIHM
	80 MWd/k	516	$/kgIHM
Disposal of HLW from MOX	50 MWd/k	319	$/kgIHM
	80 MWd/k	319	$/kgIHM
Disposal of HLW from Breeder		458	$/kgIHM
Disposal of HLW from Self Sust		458	$/kgIHM
Disposal of HLW from Burner		458	$/kgIHM

LWRs Parameters

Lifetime	60	yrs	
Core Mass	84.7	MTHM/Gwe	
Thermal efficiency	33%		
Burnup of LWR fuel	50	80	MWd/kgHM
Fuel cycle length for LWR	1.5	2.35	
Capacity Factor	85.0%	86.8%	
Availability	90%		
Batch Replacement Time	0.08	yr	
Number of batches	3		
Time between discharge and dry storage/reproces	5	yrs	
Overnight Cost	4000	M$/Gwe	
Decommissioning ON	700	M$/Gwe	
Incremental CAPEX	40	M$/Gwe*yr	
Fixed Yearly O&M	56.44	M$/Gwe*yr	
Variable O&M	0.42	mill/kWh	

FRs Parameters

Lifetime		60	yrs	
Cross section conversion ratio		0.5	1	
TRU Mass Ratio		0.8	1.01	
Total Core Mass		23.8	43.4	MTHM/Gwe
Average Burnup		131.9	73	
Number of batches	Main Core	6	3	
	OC / Blanket	7	4.5	
Cycle Length (yrs)		0.7	1.2	yrs
Thermal efficiency		41%		
Capacity Factor		85%		
Time between discharge and reprocessing		5	yrs	
Fast Reactor ON Overcost (compared to LWR)		20%		
Overnight Cost		4800	M$/Gwe	
Decommissioning ON		840	M$/Gwe	
Incremental CAPEX		48	M$/Gwe*yr	
Yearly O&M		67.73	M$/Gwe	
Variable O&M		0.50	mill/kWh	

PUREX Plant Parameters

Lifetime	40	
Capacity (Input)	800	MTHM/year
Overnight Cost	17.0	billion$
O&M	0.42	billion$/year
Decom	1.7	billion$

MOX Plant Parameters

Lifetime	40	
Capacity (Output)	104	MTHM/year
Overnight Cost	3.0	billion$
O&M	0.08	billion$/year
Decom	0.3	billion$

Fuel Cycle Technical Parameters

Loss during conversion	0.2%
Loss during enrichment	0.2%
Loss during fabrication	0.2%
Loss during reprocessing	0.2%

UOX Fuel	50MWd	80MWd	
Enrichment	4.5%	7.1%	
Optimum Tails Assay	0.28%	0.28%	
Feed (initial kgU/enriched kgU)	9.74	15.74	
Separative Work Units	6.50	11.82	
Pu in Spent Fuel	1.1%	1.4%	% of ikgHM
TRU in Spent Fuel	1.2%	1.6%	% of ikgHM
FP in Spent Fuel			% of ikgHM

MOX Fuel	50MWd	80MWd	
Initial Pu fraction	8.7%	14.7%	
Pu in Spent Fuel	6.00	9.69	% of ikgHM
TRU in Spent Fuel	6.41	7.11	% of ikgHM
FP in Spent Fuel			% of ikgHM

SFR Fuel	0.8	1.01	
Arevage TRU enrichment of Fresh Fuel	33.3%	13.9%	% of ikgHM
Arevage TRU enrichment of Spent Fuel	27.0%	14.0%	% of ikgHM
FP in Spent Fuel	14.1%	7.8%	% of ikgHM

Reactors Construction Schedule	
Year-4	9.5%
Year-3	25.0%
Year-2	31.0%
Year-1	25.0%
Year-0	9.5%

Recycling Plants Construction Schedule	
Year-9	2.0%
Year-8	4.0%
Year-7	5.0%
Year-6	6.0%
Year-5	10.0%
Year-4	12.0%
Year-3	14.0%
Year-2	16.0%
Year-1	16.0%
Year-0	15.0%

Reactors Depreciation Schedule	
Year 1	5.00%
Year 2	9.50%
Year 3	8.55%
Year 4	7.70%
Year 5	6.93%
Year 6	6.23%
Year 7	5.90%
Year 8	5.90%
Year 9	5.91%
Year 10	5.90%
Year 11	5.91%
Year 12	5.90%
Year 13	5.91%
Year 14	5.90%
Year 15	5.91%
Year 16	2.95%

C.2 Alternative FR cycle and cap on TRU price

A cycle left out from Chapter 2 for clarity is one involving only fast reactors feeding initially on uranium enriched at levels close to Highly Enriched Uranium (HEU).

Fuel Cycle 5 : near HEU-based Recycling *Fully-closed cycle cycle in which fast reactors are started with enriched uranium (illustrated in Figure C.1)*

The specificity of this cycle is that the fast reactor uses highly enriched uranium in his initial core, whereas the previous designs used a blend of TRU and depleted uranium throughout their entire lifetime. The initial uranium is enriched in proportions close to 20% for self-sustainable fast reactors (at which uranium is considered highly enriched)

and then used in the fast reactor. During irradiation, the fast reactor produces a mix of uranium and TRUs, which will be recovered. Depleted uranium is then added for the next pass, as in the cycles described above.

Little studies have been done on such design, but it offers an alternative way to start a FR cycle, without links to the previous LWR cycle.

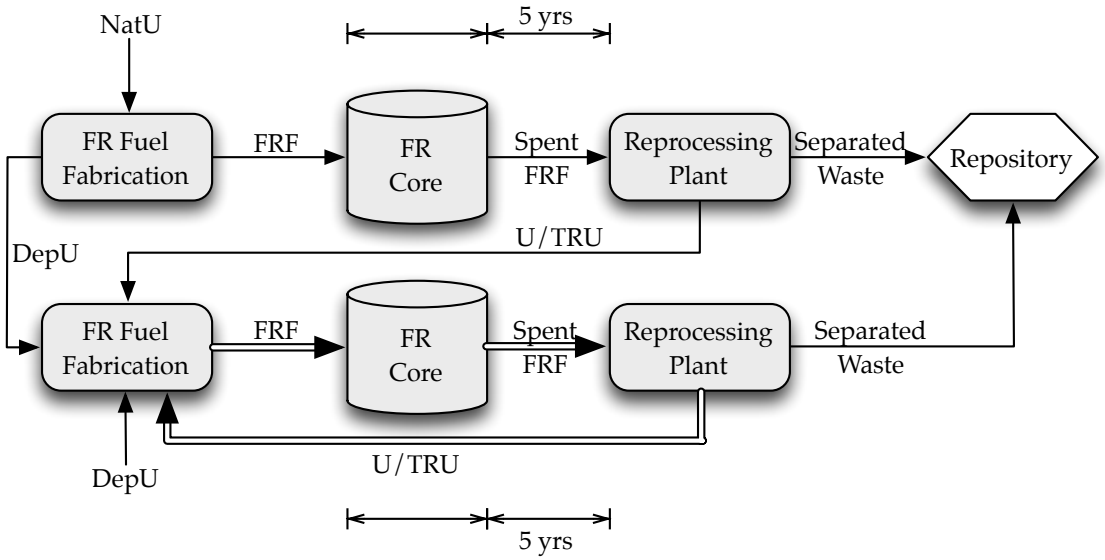

Figure C.1 – *Fuel Cycle #5 ∼ HEU-based Recycling*

Table C.1 – *Cost of Fuel for Self-Sustainable FR at Loading Time*

Enriched Uranium Based				
	Unit Cost	Units	Time	NPV
Ore Purchase	\$90/kgHM	44.65	2.0	4,312
Yellow Cake Conversion	\$10/kgHM	44.56	1.5	467
Enrichment	\$160/kgSWU	36.86	1.0	6,311
Fabrication of FR fuel	\$2,400/kgHM	1.0	0.5	2,459
Total (\$/kgHM)				13,549
Transuranic Based				
	Unit Cost	Units	Time	NPV
TRU Purchase	\$75,766/kgHM	0.139	1.0	11,080
DU Purchase	\$10/kgHM	0.863	1.0	9
Fabrication of FR fuel	\$2,400/kgHM	1.0	0.5	2,459
Total (\$/kgHM)				13,549

We make the assumption that a fuel assembly enriched at 19% is equivalent to a self-sustainable fast reactor fuel assembly composed of 13.9% of TRU, and that no significant modification in FR cost would result from the use of enriched uranium based compared to TRU based fuel. The induced price of TRU is about $ 76,000 /kgHM, as shown in Table C.1.

An enrichment of 20% would lead to a price of TRU close to $80,040/kgMTHM through a similar calculation. However, let us note that the cost of fabrication from uranium would likely be lower than from TRU. Therefore our estimate is already biased towards the attractiveness of TRUs.

C.3 Value of reprocessed uranium

Once we have determined the optimal tails assay for natural and reprocessed uranium, we define the price of reprocessed uranium, C_{ru}, such that the price of the two fuels, at their minimal cost, is equal:

$$\begin{aligned} & \frac{1}{1-f_f}\left[\frac{R}{1-f_s}\left(\frac{C_u}{(1-f_c)(1+i)^{t_u}}+\frac{C_c}{(1+i)^{t_c}}\right)+\frac{S\,C_s}{(1+i)^{t_s}}\right]+\frac{C_f}{(1+i)^{t_f}} \\ = & \frac{1}{1-f_f}\left[\frac{R_r}{1-f_s}\left(\frac{C_{ru}}{(1-f_c)(1+i)^{t_u}}+\frac{C_{rc}}{(1+i)^{t_c}}\right)+\frac{S_r\,C_{rs}}{(1+i)^{t_s}}\right]+\frac{C_{rf}}{(1+i)^{t_f}} \end{aligned}$$

where the elements with the subscript r are the equivalent of the ones described above, but for reprocessed uranium. From this equation, we extract C_{ru}, the price of reprocessed uranium. Let us note that C_{ru}, here again, is implicit, since R_r and S_r are functions of x^*_{rt}, itself dependent on λ_r and hence C_{ru}.[1] The resulting calculations lead to a value of $ 122 /kgHM of reprocessed uranium, see Table C.2.

[1]We only corrected the value of recovered uranium for the changes in enrichment, cost of conversion, fabrication and so on. We neglected the implications of using reprocessed uranium on the fuel composition and behavior in later part of the fuel cycle (like reprocessing into fast reactors). One of the reasons is that 1kgUOX once reprocessed will only produce 7-10% of a new UOX assembly.

Table C.2 – *Cost of UOX at Loading Time*

from Natural Uranium				
	Unit Cost	Units	Time	NPV
Ore Purchase	\$90/kgHM	10.05	2.0	972
Yellow Cake Conversion	\$10/kgHM	10.03	1.5	105
Enrichment	\$160/kgSWU	6.37	1.0	1,094
Fabrication	\$250/kgHM	1.0	0.5	256
Total (\$/kgHM)				2,428
from Reprocessed Uranium				
	Unit Cost	Units	Time	NPV
RepU Purchase	\$122/kgHM	7.44	2.0	1,003
Yellow Cake Conversion	\$30/kgHM	7.43	1.5	240
Enrichment	\$176/kgSWU	4.93	1.0	911
Fabrication	\$268/kgHM	1.0	0.5	274
Total (\$/kgHM)				2,428

Appendix D

Excel Spreadsheets

This chapter displays the excel calculations carried out for the economic modeling.

D.1 Valuation in deterministic cycles

Burn-up (MWd/kgHM)
50 UOX in LWRs

Cycle Capacity Factor
85.0%

Time Frame (years)	
4.5	Irradiation time of UOX in LWRs
5	Time between discharge and interim storage

0.89 Carrying Charge Factor

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Depreciation of UOX Fuel		$/kgHM	1			0
Reactor Core Occupation	11,898	$/kgHM (after tax)	1	0	11,898	11,898
Operations and Maintenance	3,459	$/kgHM	1	0	2,179	2,179
Interim Storage	200	$/kgiHM	1	-5	126	99
Geologic Disposal	755	$/kgiHM	1	-5	476	373

LCOE Calculation	
Electricity Produced by UOX (MWh)	396
Front End Cost ($/kgUOX)	1,905
Reactor Net Cost ($/kgUOX)	11,898
Operations & Maintenance Net ($/kgUOX)	2,179
Back-End Cost ($/kgUOX)	472
Total Net Cost ($/kgUOX)	16,454
Front End Cost (mill/kWh)	6.83
Reactor Cost (mill/kWh)	42.65
Operations & Maintenance (mill/kWh)	7.81
Back-End Cost (mill/kWh)	1.69
Total COE (mill/kWh)	58.98

Uranium consumption
24.7 kgHM/GWh

---->

Interim Storage (mill/kWh)	0.35
Disposal (mill/kWh)	1.34

Figure D.1 – *Once-Through Cycle*

Burn-up (MWd/kgHM)
50 Spent UOX
50 MOX in LWRs

UOX Capacity Factor
85.0%
MOX Capacity Factor
85.0%

Time Frame (years)
4.5 Irradiation time of UOX in LWRs
4.5 Irradiation time of MOX in LWRs
5 Time between discharge and interim storage

0.89 UOX Carrying Charge Factor
0.89 MOX Carrying Charge Factor

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Depreciation of UOX Fuel		$/kgHM	1			
Reactor Core Occupation	11,898	$/kgHM (after tax)	1	0	11,898	11,898
Operations and Maintenance	3,459	$/kgHM	1	0	2,179	2,179
Reprocessing of SF	1,600	$/kgiHM	1	-5	1,008	790
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-5	190	149
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-6	-72	-54
Sale of Reprocessed Plutonium	22,347	$/kgHM	0.011	-6	161	120
Plutonium Purchase	-22,347	$/kgHM	0.011	-6	-161	-120
Depleted Uranium Purchase	10	$/kgHM	0.12	-6	1	1
Fabrication of MOX fuel	2,400	$/kgHM	0.13	-6.5	198	144
Depreciation of MOX Fuel		$/kgHM	0.13			
Reactor Core Occupation	11,898	$/kgHM (after tax)	0.13	-11.5	1,556	888
Operations and Maintenance	3,459	$/kgHM	0.13	-11.5	285	163
Interim Storage	200	$/kgiHM	0.13	-16.5	16	7
Geological Disposal of Spent MOX	5,035	$/kgiHM	0.13	-16.5	415	185

Implicit Value of Separated Pu
-22,347 $/kgHM

This value is defined as the transaction price between the 2 steps, so that each step has a NPV of zero.
If you look in 'Fuel Data', you will see that the cost of MOX and UOX are different.
Indeed, the back-end costs of UOX and MOX are different. Therefore, saying that UOX and MOX have the same value does not mean that they have the same cost of fabrication.

LCOE Calculation	
Electricity Produced by UOX (MWh)	396
Electricity Produced by MOX (MWh)	52
Reactor Net Cost ($/kgUOX)	12,786
Operations & Maintenance Net ($/kgUOX)	2,342
Fuel Cycle Net Cost ($/kgUOX)	3,128
Total Net Cost ($/kgUOX)	18,255
Reactor Cost (mill/kWh)	42.65
Operations & Maintenance (mill/kWh)	7.81
Fuel Cost (mill/kWh)	10.43
Total COE (mill/kWh)	60.89

Uranium consumption
64.3 Elec. of RepU (MWh)
19.1 kgHM/GWh
-23% Consumption w.r.t OTC

LCOE for UOX			
Front-End Cost ($/kgUOX)	1,905		
Reactor Cost ($/kgUOX)	11,898		
Operations & Maintenance ($/kgUOX)	2,179		
Back-End Cost ($/kgUOX)	1,005		
Front End Cost (mill/kWh)	6.83		
Reactor Cost (mill/kWh)	42.65		
Operations & Maintenance (mill/kWh)	7.81		
Back-End Cost (mill/kWh)	3.60	---->	Reprocessing (mill/kWh) 2.83
Total	60.89		Disposal (mill/kWh) 0.53
Check	0.00		Uranium (mill/kWh) -0.19
			Pu/TRU (mill/kWh) 0.43

LCOE for MOX			
Front-End Cost ($/kgUOX)	24		
Reactor Cost ($/kgUOX)	888		
Operations & Maintenance ($/kgUOX)	163		
Back-End Cost ($/kgUOX)	193		
Front End Cost (mill/kWh)	1.17		
Reactor Cost (mill/kWh)	42.65		
Operations & Maintenance (mill/kWh)	7.81		
Back-End Cost (mill/kWh)	9.26	---->	Interim Storage (mill/kWh) 0.35
Total	60.89		Disposal (mill/kWh) 8.91
Check	0.00		

Figure D.2 – *Twice-Through Cycle*

Burn-up (MWd/kgHM)	
50	UOX
50	MOX
73	FR Fuel

FR Capacity Factor	
85.0%	

Source of TRU is MOX	
FALSE	

Time Frame (years)	
4.5	Irradiation of UOX in LWRs
4.5	Irradiation of MOX in LWRs
3.6	Irradiation time in FR for IC and MC
5.4	Irradiation time in FR for OC
5	Time between discharge and reprocessing LWR
5	Time between discharge and reprocessing FR

0.89	UOX Carrying Charge Factor
0.89	MOX Carrying Charge Factor
0.93	FR Carrying Charge Factor (Overall)

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Depreciation of UOX Fuel		$/kgHM	1			
Reactor Core Occupation	11,898	$/kgHM (after tax	1	0	11,898	11,898
Operations and Maintenance	3,459	$/kgHM	1	0	2,179	2,179
Reprocessing of SF	1,600	$/kgiHM	1	-5	1,008	790
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-5	190	149
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-6	-72	-54
Sale of Reprocessed TRU	64,775	$/kgHM	0.013	-6.0	525	391
TRU Purchase	-64,775	$/kgHM	0.013	-6.0	-525	-391
Depleted Uranium Purchase	10	$/kgHM	0.080	-6.0	1	0
Fabrication of FR fuel	2,400	$/kgHM	0.092	-6.5	140	102
Depreciation of FR Fuel		$/kgHM	0.092			
Reactor Core Occupation (IC, MC)	21,617	$/kgHM (after tax	0.061	-10.6	1,315	785
Operations and Maintenance (IC, MC	6,285	$/kgHM	0.061	-10.6	241	144
Reprocessing of Spent Fuel	3,200	$/kgiHM	0.061	-15.6	123	57
Disposal of Separated HLW	458	$/kgiHM	0.061	-15.6	18	8
Sale of Recycled U/TRU	9,827	$/kgHM	0.056	-16.6	347	155
Reactor Core Occupation (OC)	33,926	$/kgHM (after tax	0.031	-12.4	1,068	584
Operations and Maintenance (OC)	9,864	$/kgHM	0.031	-12.4	196	107
Reprocessing of Spent Fuel	3,200	$/kgiHM	0.031	-17.4	63	27
Disposal of Separated HLW	458	$/kgiHM	0.031	-17.4	9	4
Sale of Recycled U/TRU	9,827	$/kgHM	0.029	-18.4	180	73

PV Factor
2.38

Implicit Value of Separated TRU
-64,775 $/kgHM
Implicit Value of Separated Pu
$/kgHM
These values are defined as the transaction prices between the different steps, so that each step has a NPV of zero.

LCOE Overall Calculation	
Electricity Produced by UOX (MWh)	396
Electricity Produced by MOX (MWh)	0
Electricity Produced by one pass in FR (MWh)	66
Reactor Cost ($/kgUOX)	15,156
Operations & Maintenance ($/kgUOX)	2,776
Fuel Cost ($/kgUOX)	3,266
Reactor Cost (mill/kWh)	44.23
Operations & Maintenance (mill/kWh)	8.10
Fuel Cost (mill/kWh)	9.53
Overall COE (mill/kWh)	61.86

LCOE for UOX			
Front-End Cost ($/kgUOX)	1,905		
Reactor Cost ($/kgUOX)	11,898		
Operations & Maintenance ($/kgUOX)	2,179		
Back-End Cost ($/kgUOX)	1,277		
Front End Cost (mill/kWh)	6.83		
Reactor Cost (mill/kWh)	42.65		
Operations & Maintenance (mill/kWh)	7.81		
Back-End Cost (mill/kWh)	4.58	---->	Reprocessing (mill/kWh) 2.83
Total	61.86		Disposal (mill/kWh) 0.53
Check	0.00		Uranium (mill/kWh) -0.19
			Pu/TRU (mill/kWh) 1.40

LCOE for MOX
Front-End Cost ($/kgUOX)
Reactor Cost ($/kgUOX)
Operations & Maintenance ($/kgUOX)
Back-End Cost ($/kgUOX)
Front End Cost (mill/kWh)
Reactor Cost (mill/kWh)
Operations & Maintenance (mill/kWh)
Back-End Cost (mill/kWh)
Total
Check

LCOE for FR			
Front-End Cost ($/kgUOX)	-289		
Reactor Cost ($/kgUOX)	1,369		
Operations & Maintenance ($/kgUOX)	251		
Back-End Cost ($/kgUOX)	325		
Front End Cost (mill/kWh)	-10.82		
Reactor Cost (mill/kWh)	51.18		
Operations & Maintenance (mill/kWh)	9.37		
Back-End Cost (mill/kWh)	12.14	---->	Reprocessing (mill/kWh) 3.16
Total	61.86		Disposal (mill/kWh) 0.45
Check	0.00		U/TRU (mill/kWh) 8.52

Figure D.3 – *1-Tier Recycling*

Burn-up (MWd/kgHM)	
50	UOX
50	MOX
73	FR Fuel

FR Capacity Factor
85.0%

Source of TRU is MOX
TRUE

Time Frame (years)	
4.5	Irradiation of UOX in LWRs
4.5	Irradiation of MOX in LWRs
3.6	Irradiation time in FR for IC and MC
5.4	Irradiation time in FR for OC
5	Time between discharge and reprocessing LWR
5	Time between discharge and reprocessing FR

0.89	UOX Carrying Charge Factor
0.89	MOX Carrying Charge Factor
0.93	FR Carrying Charge Factor (Overall)

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Depreciation of UOX Fuel		$/kgHM	1			
Reactor Core Occupation	11,898	$/kgHM (after tax	1	0	11,898	11,898
Operations and Maintenance	3,459	$/kgHM	1	0	2,179	2,179
Reprocessing of SF	1,600	$/kgiHM	1	-5	1,008	790
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-5	190	149
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-6	-72	-54
Sale of Reprocessed Plutonium	29,773	$/kgHM	0.011	-6	215	160
Plutonium Purchase	-29,773	$/kgHM	0.011	-6	-215	-160
Depleted Uranium Purchase	10	$/kgHM	0.12	-6	1	1
Fabrication of MOX fuel	2,400	$/kgHM	0.13	-6.5	198	144
Depreciation of MOX Fuel		$/kgHM	0.13			
Reactor Core Occupation	11,898	$/kgHM*yr	0.13	-11.5	1,556	888
Operations and Maintenance	3,459	$/kgHM*yr	0.13	-11.5	285	163
Reprocessing of SF	1,600	$/kgiHM	0.13	-16.5	132	59
Geologic Disposal of Sep. HLW	319	$/kgiHM	0.13	-16.5	26	12
Sale of Reprocessed Uranium				-17.5		
Sale of Reprocessed TRU	73,573	$/kgHM	0.008	-17.5	388	165
TRU Purchase	-73,573	$/kgHM	0.008	-17.5	-388	-165
Depleted Uranium Purchase	10	$/kgHM	0.052	-17.5	0	0
Fabrication of FR fuel	2,400	$/kgHM	0.060	-18.0	91	38
Depreciation of FR Fuel		$/kgHM	0.060			
Reactor Core Occupation (IC, MC)	21,617	$/kgHM (after tax	0.040	-22.1	855	291
Operations and Maintenance (IC, MC	6,285	$/kgHM	0.040	-22.1	157	53
Reprocessing of Spent Fuel	3,200	$/kgiHM	0.040	-27.1	80	21
Disposal of Separated HLW	458	$/kgiHM	0.040	-27.1	11	3
Sale of Recycled U/TRU	11,163	$/kgHM	0.036	-28.1	256	65
Reactor Core Occupation (OC)	33,926	$/kgHM (after tax	0.020	-23.9	695	217
Operations and Maintenance (OC)	9,864	$/kgHM	0.020	-23.9	127	40
Reprocessing of Spent Fuel	3,200	$/kgiHM	0.020	-28.9	41	10
Disposal of Separated HLW	458	$/kgiHM	0.020	-28.9	6	1
Sale of Recycled U/TRU	11,163	$/kgHM	0.019	-29.9	133	31

PV Factor
2.38

Implicit Value of Separated TRU
-73,573 $/kgHM
Implicit Value of Separated Pu
-29,773 $/kgHM
These values are defined as the transaction prices between the different steps, so that each step has a NPV of zero.

LCOE Overall Calculation	
Electricity Produced by UOX (MWh)	396
Electricity Produced by MOX (MWh)	52
Electricity Produced by one pass in FR (MWh)	43
Reactor Cost ($/kgUOX)	13,995
Operations & Maintenance ($/kgUOX)	2,563
Fuel Cost ($/kgUOX)	3,182
Reactor Cost (mill/kWh)	43.27
Operations & Maintenance (mill/kWh)	7.93
Fuel Cost (mill/kWh)	9.84
Overall COE (mill/kWh)	61.04

LCOE for UOX				
Front-End Cost ($/kgUOX)	1,905			
Reactor Cost ($/kgUOX)	11,898			
Operations & Maintenance ($/kgUOX)	2,179			
Back-End Cost ($/kgUOX)	1,045			
Front End Cost (mill/kWh)	6.83			
Reactor Cost (mill/kWh)	42.65			
Operations & Maintenance (mill/kWh)	7.81			
Back-End Cost (mill/kWh)	3.75	---->	Reprocessing (mill/kWh)	2.83
			Disposal (mill/kWh)	0.53
Total	61.04		Uranium (mill/kWh)	-0.19
Check	0.00		Pu/TRU (mill/kWh)	0.57

LCOE for MOX	
Front-End Cost ($/kgUOX)	-16
Reactor Cost ($/kgUOX)	888
Operations & Maintenance ($/kgUOX)	163
Back-End Cost ($/kgUOX)	236
Front End Cost (mill/kWh)	-0.75
Reactor Cost (mill/kWh)	42.65
Operations & Maintenance (mill/kWh)	7.81
Back-End Cost (mill/kWh)	11.32
Total	61.04
Check	0.00

LCOE for FR				
Front-End Cost ($/kgUOX)	-127			
Reactor Cost ($/kgUOX)	508			
Operations & Maintenance ($/kgUOX)	93			
Back-End Cost ($/kgUOX)	132			
Front End Cost (mill/kWh)	-12.81			
Reactor Cost (mill/kWh)	51.18			
Operations & Maintenance (mill/kWh)	9.37			
Back-End Cost (mill/kWh)	13.29	---->	Reprocessing (mill/kWh)	3.16
			Disposal (mill/kWh)	0.45
Total	61.04		U/TRU (mill/kWh)	9.68
Check	0.00			

Figure D.4 – *2-Tier Recycling*

D.2 Valuation in probabilistic cycles

D.2.1 Simple case

Burn-up (MWd/kgHM)	
50	UOX in LWRs

Time Frame (years)	
4.5	Irradiation time of UOX in LWRs
5	Time between discharge and interim storage

Cycle Capacity Factor
85.0%

0.89	Carrying Charge Factor	

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-5	190	149
Reprocessing of SF	1600	$/kgiHM	1	-5	1,008	790
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-6	-72	-54
Sale of TRU	-68,481	$/kgHM	0.013	-6	-555	-414
Geologic Disposal	755	$/kgiHM	1	-5	476	373
Interim Storage	200	$/kgiHM	1	-5	126	99

LCOE Calculation

Electricity Produced by UOX (MWh): 396

Probability	TRU Price ($/kgHM)	Reprocessing (mill/kWh)	Min (mill/kWh)	Disposal (mill/kWh)
p_1^+ =	68,481	8.52	8.52	8.52
0.33	-70,000	11.52	8.52	8.52
0.33	0	10.00	8.52	8.52
0.33	70,000	8.49	8.49	8.52
Expectation		10.00	8.51	8.52

Figure D.5 – *Calculation for Direct Choice*

Burn-up (MWd/kgHM)	
50	UOX in LWRs

Time Frame (years)	
4.5	Irradiation time of UOX in LWRs
5	Time between discharge and interim storage

Cycle Capacity Factor
85.0%

0.89	Carrying Charge Factor	

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Interim Storage	200	$/kgiHM	1	-5	126	99
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-16.5	190	85
Reprocessing of SF	1600	$/kgiHM	1	-16.5	1,008	451
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-17.5	-72	-31
Sale of TRU	-84,818	$/kgHM	0.013	-17.5	-687	-292
Geologic Disposal	755	$/kgiHM	1	-16.5	476	213

LCOE Calculation

Electricity Produced by UOX (MWh): 396

Probability	TRU Price ($/kgHM)	Reprocessing (mill/kWh)	Min (mill/kWh)	Disposal (mill/kWh)
p_1^+ =	84,818	7.95	7.95	7.95
0.33	-70,000	9.86	7.95	7.95
0.33	0	8.99	7.95	7.95
0.33	70,000	8.13	7.95	7.95
Expectation		8.99	7.95	7.95

Figure D.6 – *Calculation for Delayed Choice*

Burn-up (MWd/kgHM)	
50	in LWRs

Time Frame (years)	
4.5	Irradiation time in LWRs
5	Time between discharge and interim storage

Cycle Capacity Factor	
85.0%	

0.89	Carrying Charge Factor

Fuel Cycle Expenses	Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
Uranium Purchase	90	$/kgHM	9.80	6.5	556	763
Yellow Cake Conversion	10	$/kgHM	9.78	6	62	83
Enrichment	160	$/kgSWU	6.51	5.5	657	859
Fabrication of UOX fuel	250	$/kgHM	1	5	158	201
Geologic Disposal of Sep. HLW	302	$/kgiHM	1	-5	190	149
Reprocessing of SF	1600	$/kgiHM	1	-5	1,008	790
Sale of Reprocessed Uranium	-122	$/kgHM	0.93	-6	-72	-54
Depleted Uranium Purchase	10	$/kgHM	0.12	-6	1	1
Fabrication of MOX fuel	2400	$/kgHM	0.13	-6.5	198	144
Geologic Disposal of Sep. HLW	319		0.13	-16.5	26	12
Reprocessing of SF	1600		0.13	-16.5	132	59
Sale of Reprocessed Uranium	0		0.13	-17.5	0	0
Sale of Reprocessed TRU	54445		0.008	-17.5	287	122
Geologic Disposal	5035		0.13	-16.5	415	185
Interim Storage	200		0.13	-16.5	16	7

LCOE Calculation	
Electricity Produced by UOX (MWh)	396
Electricity Produced by MOX (MWh)	52

Probability	TRU Price ($/kgHM)	Reprocessing (mill/kWh)	Min (mill/kWh)	Disposal (mill/kWh)
p_2 =	-54,445	10.43	10.43	10.43
0.33	-70,000	10.55	10.43	10.43
0.33	0	10.03	10.03	10.43
0.33	70,000	9.50	9.50	10.43
Expectation		10.03	9.99	10.43

Figure D.7 – *Calculation for Recycling*

D.2.2 Decision tree

SFME		Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
	Interim Storage UOX (3T)	200	$/kgHM	0.12	-5	15	11
	Interim Storage UOX (T)	100	$/kgHM	0.88	-5	56	44
	SFME Fee	-1,488	$/kgHM	1	-5	-938	-735
	Interim Storage UOX (2T)	200	$/kgHM	0.12	-16.5	15	7
	Interim Storage UOX (T)	100	$/kgHM	0.88	-16.5	56	25
	SFME Fee	-1,488	$/kgHM	1	-16.5	-938	-419
	Reprocessing of SF	1600	$/kgHM	0.88	-16.5	891	399
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-17.5	-64	-27
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-17.5	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-18	175	73
	Sale of MOX	-2428	$/kgHM	0.12	-18.5	-177	-72
	Repository for UOX-HLW	216	$/kgiHM	3.77	-23	513	167
	Repository for MOX-HLW	228	$/kgiHM	0.23	-23	33	11
	Interim Storage UOX/MOX (1T)	100	$/kgHM	1.00	-28	63	16
	SFME Fee	-1,488	$/kgHM	1	-28	-938	-239
	Reprocessing of SF	1600	$/kgHM	0.88	-28	891	227
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-29	-64	-15
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-29	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-29.5	175	41
	Sale of MOX	-2428	$/kgHM	0.12	-30	-177	-41
	Interim Storage UOX/MOX (0T)	0	$/kgHM	1	-39.5	0	0
	SFME Fee	-1,488	$/kgHM	1	-39.5	-938	-136
	Reprocessing of SF	1600	$/kgHM	2.23	-39.5	2,249	327
	Sale of Reprocessed Uranium	-122.3	$/kgHM	1.87	-40.5	-144	-20
	Sale of Reprocessed TRU	100,800	$/kgHM	0.04	-40.5	2,572	357
						Total	0
	Interim Storage UOX (3T)	200	$/kgHM	0.12	-5	15	11
	Interim Storage UOX (T)	100	$/kgHM	0.88	-5	56	44
	SFME Fee	-1,161	$/kgHM	1.00	-5	-731	-573
	Interim Storage UOX (2T)	200	$/kgHM	0.12	-16.5	15	7
	Interim Storage UOX (T)	100	$/kgHM	0.88	-16.5	56	25
	SFME Fee	-1,161	$/kgHM	1.00	-16.5	-731	-327
	Reprocessing of SF	1600	$/kgHM	0.88	-16.5	891	399
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-17.5	-64	-27
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-17.5	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-18	175	73
	Sale of MOX	-2428	$/kgHM	0.12	-18.5	-177	-72
	Repository for UOX-HLW	216	$/kgiHM	1.77	-23	241	78
	Repository for UOX	540	$/kgiHM	2	-23	680	221
	Repository for MOX-HLW	228	$/kgiHM	0.23	-23	33	11
	Interim Storage UOX (2T)	200	$/kgHM	0.88	-28	111	28
	Interim Storage MOX (1T)	100	$/kgHM	0.12	-28	7	2
	SFME Fee	-1,161	$/kgHM	1	-28	-731	-187
	Reprocessing of SF	1600	$/kgHM	0.88	-28	891	227
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-29	-64	-15
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-29	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-29.5	175	41
	Sale of MOX	-2428	$/kgHM	0.12	-30	-177	-41
	Interim Storage UOX (2T)	200	$/kgHM	0.88	-39.5	111	16
	Interim Storage UOX/MOX (0T)	0	$/kgHM	0.12	-39.5	0	0
	SFME Fee	-1,161	$/kgHM	1	-39.5	-731	-106
	Reprocessing of SF	1600	$/kgHM	0.23	-39.5	233	34
	Sale of Reprocessed Uranium	0	$/kgHM	0.22	-40.5	0	0
	Sale of Reprocessed TRU	100,800	$/kgHM	0.01	-40.5	939	130
						Total	0
	Interim Storage UOX (3T)	200	$/kgHM	0.12	-5	15	11
	Interim Storage UOX (T)	100	$/kgHM	0.88	-5	56	44
	SFME Fee	-1,161	$/kgHM	1.00	-5	-731	-573
	Interim Storage UOX (2T)	200	$/kgHM	0.12	-16.5	15	7
	Interim Storage UOX (T)	100	$/kgHM	0.88	-16.5	56	25
	SFME Fee	-1,161	$/kgHM	1.00	-16.5	-731	-327
	Reprocessing of SF	1600	$/kgHM	0.88	-16.5	891	399
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-17.5	-64	-27
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-17.5	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-18	175	73
	Sale of MOX	-2428	$/kgHM	0.12	-18.5	-177	-72
	Repository for UOX-HLW	216	$/kgiHM	1.77	-23	241	78
	Repository for UOX	540	$/kgiHM	2	-23	680	221
	Repository for MOX-HLW	228	$/kgiHM	0.12	-23	17	5
	Repository for MOX	3598	$/kgiHM	0.12	-23	262	85
	Interim Storage UOX (2T)	200	$/kgHM	0.88	-28	111	28
	Interim Storage MOX (2T)	200	$/kgHM	0.12	-28	15	4
	SFME Fee	-1,161	$/kgHM	1	-28	-731	-187
	Reprocessing of SF	1600	$/kgHM	0.88	-28	891	227
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-29	-64	-15
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-29	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-29.5	175	41
	Sale of MOX	-2428	$/kgHM	0.12	-30	-177	-41
	Interim Storage UOX (2T)	200	$/kgHM	0.88	-39.5	111	16
	Interim Storage MOX (0T)	0	$/kgHM	0.12	-39.5	0	0
	SFME Fee	-1,161	$/kgHM	1	-39.5	-731	-106
	Reprocessing of SF	1600	$/kgHM	0.12	-39.5	117	17
	Sale of Reprocessed Uranium	0	$/kgHM	0.11	-40.5	0	0
	Sale of Reprocessed TRU	100,800	$/kgHM	0.01	-40.5	470	65
						Total	0

Probability	TRU Price ($/kgHM)	Reprocessing All (mill/kWh)	Reprocessing MOX (mill/kWh)	Reprocessing Last MOX (mill/kWh)	Disposal (mill/kWh)	Min (mill/kWh)
$p_M{}^0$=	-100,800	2.63	2.05	2.05	2.05	2.05
$p_M{}^1$=	-100,394	2.63	2.05	2.05	2.05	2.05
0.33	-70,000	2.45	1.99	2.02	2.05	1.99
0.33	0	2.02	1.83	1.94	2.05	1.83
0.33	70,000	1.59	1.67	1.86	2.05	1.59
	Expectation	2.02	1.83	1.94	2.05	1.80

Figure D.8 – *Path* **A**

SFME		Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
	Interim Storage UOX (3T)	200	$/kgHM	0.12	-5	15	11
	Interim Storage UOX (T)	100	$/kgHM	0.88	-5	56	44
	SFME Fee	-1,161	$/kgHM	1	-5	-731	-573
	Interim Storage UOX (2T)	200	$/kgHM	0.12	-16.5	15	7
	Interim Storage UOX (T)	100	$/kgHM	0.88	-16.5	56	25
	SFME Fee	-1,161	$/kgHM	1	-16.5	-731	-327
	Reprocessing of SF	1600	$/kgHM	0.88	-16.5	891	399
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-17.5	-64	-27
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-17.5	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-18	175	73
	Sale of MOX	-2428	$/kgHM	0.12	-18.5	-177	-72
	Repository for UOX	540	$/kgHM	2	-23	680	221
	Repository for MOX	3,598	$/kgHM	0.23	-23	524	171
	Repository for UOX-HLW	216	$/kgiHM	1.77	-23	241	78
	Interim Storage UOX/MOX (2T)	200	$/kgHM	1.00	-28	126	32
	SFME Fee	-1,161	$/kgHM	1	-28	-731	-187
	Reprocessing of SF	1600	$/kgHM	0.88	-28	891	227
	Sale of Reprocessed Uranium	-122	$/kgHM	0.83	-29	-64	-15
	Purchase of Depleted Uranium	10	$/kgHM	0.11	-29	1	0
	Fabrication of MOX fuel	2400	$/kgHM	0.12	-29.5	175	41
	Sale of MOX	-2428	$/kgHM	0.12	-30	-177	-41
	Interim Storage UOX/MOX (2T)	200	$/kgHM	1	-39.5	126	18
	SFME Fee	-1,161	$/kgHM	1	-39.5	-731	-106
						Total	0

SFME fee	2.05 mill/kWh

Figure D.9 – *Path* **B**

SFME		Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
	Interim Storage UOX (3T)	200	$/kgHM	1	-5	126	99
	SFME Fee	-669	$/kgHM	1	-5	-421	-330
	Interim Storage UOX (2T)	200	$/kgHM	1	-16.5	126	56
	SFME Fee	-669	$/kgHM	1	-16.5	-421	-188
	Repository for UOX-HLW	216	$/kgiHM	4.00	-23	544	177
	Interim Storage UOX (1T)	100	$/kgHM	1	-28	63	16
	SFME Fee	-669	$/kgHM	1	-28	-421	-107
	Interim Storage UOX (0T)	0	$/kgHM	1	-39.5	0	0
	SFME Fee	-669	$/kgHM	1	-39.5	-421	-61
	Reprocessing of SF	1600	$/kgHM	4	-39.5	4,032	587
	Sale of Reprocessed Uranium	-122.3	$/kgHM	3.7	-40.5	-288	-40
	Sale of Reprocessed TRU	-46,302	$/kgHM	0.051	-40.5	-1,500	-208
						Total	0
	Interim Storage UOX (3T)	200	$/kgHM	1	-5	126	99
	SFME Fee	-633	$/kgHM	1	-5	-399	-313
	Interim Storage UOX (2T)	200	$/kgHM	1	-16.5	126	56
	SFME Fee	-633	$/kgHM	1	-16.5	-399	-178
	Repository for UOX-HLW	216	$/kgiHM	2.00	-23	272	89
	Repository for UOX	540	$/kgiHM	2.00	-23	680	221
	Interim Storage UOX (1T)	100	$/kgHM	1	-28	63	16
	SFME Fee	-633	$/kgHM	1	-28	-399	-102
	Interim Storage UOX (0T)	0	$/kgHM	1	-39.5	0	0
	SFME Fee	-633	$/kgHM	1	-39.5	-399	-58
	Reprocessing of SF	1600	$/kgHM	2	-39.5	2,016	293
	Sale of Reprocessed Uranium	-122.3	$/kgHM	1.87	-40.5	-144	-20
	Sale of Reprocessed TRU	-46,302	$/kgHM	0.026	-40.5	-750	-104
						Total	0
	Interim Storage UOX (3T)	200	$/kgHM	1	-5	126	99
	SFME Fee	-631	$/kgHM	1	-5	-397	-311
	Interim Storage UOX (2T)	200	$/kgHM	1	-16.5	126	56
	SFME Fee	-631	$/kgHM	1	-16.5	-397	-178
	Repository for UOX-HLW	216	$/kgiHM	1.00	-23	136	44
	Repository for UOX	540	$/kgiHM	3.00	-23	1,020	332
	Interim Storage UOX (2T)	200	$/kgHM	1	-28	126	32
	SFME Fee	-631	$/kgHM	1	-28	-397	-101
	Interim Storage UOX (0T)	0	$/kgHM	1	-39.5	0	0
	SFME Fee	-631	$/kgHM	1	-39.5	-397	-58
	Reprocessing of SF	1600	$/kgHM	1	-39.5	1,008	147
	Sale of Reprocessed Uranium	-122.3	$/kgHM	0.93	-40.5	-72	-10
	Sale of Reprocessed TRU	-46,302	$/kgHM	0.013	-40.5	-375	-52
						Total	0

Probability	TRU Price ($/kgHM)	Reprocessing All (mill/kWh)	Reprocessing 2 UOX (mill/kWh)	Reprocessing Last UOX (mill/kWh)	Disposal (mill/kWh)	Min (mill/kWh)
p_U^0=	46,302	1.18	1.12	1.12	1.12	1.12
p_U^1=	48,323	1.17	1.11	1.11	1.12	1.11
p_U^2=	62,639	1.06	1.06	1.08	1.12	1.06
0.33	-70,000	2.08	1.57	1.34	1.12	1.12
0.33	0	1.54	1.30	1.21	1.12	1.12
0.33	70,000	1.00	1.03	1.07	1.12	1.00
	Expectation	1.54	1.30	1.21	1.12	1.08

Figure D.10 – *Path* **C**

SFME		Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
	Interim Storage UOX (3T)	200	$/kgHM	1	-5	126	99
	SFME Fee	-631	$/kgHM	1	-5	-397	-311
	Interim Storage UOX (2T)	200	$/kgHM	1	-16.5	126	56
	SFME Fee	-631	$/kgHM	1	-16.5	-397	-178
	Repository for UOX	540	$/kgHM	4.00	-23	1,360	443
	Interim Storage UOX (2T)	200	$/kgHM	1	-28	126	32
	SFME Fee	-631	$/kgHM	1	-28	-397	-101
	Interim Storage UOX (2T)	200	$/kgHM	1	-39.5	126	18
	SFME Fee	-631	$/kgHM	1	-39.5	-397	-58
						Total	0

SFME fee	1.12	mill/kWh

Figure D.11 – *Path* **D**

SFME		Unit Cost		Number of Units	Time before milestone	After Tax Cost	NPV
	Interim Storage UOX (2T)	200	$/kgHM	1	-5	126	99
	SFME Fee	-955	$/kgHM	1	-5	-602	-472
	Repository for UOX	540	$/kgHM	4.00	-11.5	1,360	776
	Interim Storage UOX (2T)	200	$/kgHM	1	-16.5	126	56
	SFME Fee	-955	$/kgHM	1	-16.5	-602	-269
	Interim Storage UOX (2T)	200	$/kgHM	1	-28	126	32
	SFME Fee	-955	$/kgHM	1	-28	-602	-154
	Interim Storage UOX (2T)	200	$/kgHM	1	-39.5	126	18
	SFME Fee	-955	$/kgHM	1	-39.5	-602	-88
						Total	0

SFME fee	1.69	mill/kWh

Figure D.12 – *Path* **E**