Master Thesis

Transmutation Strategies - a Swedish Perspective

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ABSTRACT

This study focuses on developing economically and environmentally sustainable scenarios to achieve a net zero or less production of minor actinides (MA) in all nuclear reactors in Sweden after the year 2035. These scenarios are compared to a reference scenario of 10 light water reactors (LWR) in Sweden after 2035.

Two scenarios to achieve a net zero production of MA are analysed, one with 8 LWRs and 2 sodium-cooled fast neutron reactors (FR), and one with 9 LWRs and one accelerator-driven system (ADS). One scenario to reduce the MA inventory in Sweden by nearly half of the predicted 2035 amount is considered, with 8 LWRs, 1 FR and 1 ADS. Transmuting all MA in Sweden is found to be unsustainable due to lack of availability of MA fuel. It is found that the utilisation of an ADS in Sweden is only fully sustainable if electrometallurgical pyroprocessing technology for reprocessing of spent nuclear fuel is developed into an industrial scale process.

The total cost of all nuclear reactors in Sweden is found to decrease with the introduction of a FR or ADS. However, the cost of electricity generation per MW_e increases by around 5% for a scenario with approximate net zero MA production, and 8% with approximate 50% MA reduction, due to the lower power of these reactors.

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CHAPTER 1

INTRODUCTION

The world needs more and more energy. At the same time, there is a growing concern about climate change, caused mainly by CO_2 emissions from the burning of fossil fuels. Reviving nuclear energy is one answer to this dual problem. However, the management of nuclear waste, safety and proliferation concerns limit the acceptability of nuclear power. To resolve the nuclear waste question, and to ensure the long-term sustainability of nuclear power, the introduction of safe and economic new designs of reactors to transmute highly radiotoxic, long-lived nuclear waste is required.

Concerning the structure of this report, this chapter describes an introduction to the topic of transmutation of nuclear waste and the current process of disposal of spent nuclear fuel in Sweden. Chapter 2 presents a theoretical background on the designs and concepts of nuclear reactors that will be considered in this study. There is also a section describing the economics of nuclear power. The final two sections in chapter 2 give information on the transmutation scenarios to be considered and a description of the calculations that were required. Chapter 3 presents the results for this study. A discussion of the results is given in chapter 4, while the final chapter presents the conclusions of this study and recommendations for further work.

1.1 Aims and Objectives

This study will focus on developing a strategy for Sweden to introduce reactors capable of transmuting highly radiotoxic long-lived nuclear waste. The aim of the study is to determine a sustainable strategy that results in the net zero production, or destruction of high level nuclear waste over all reactors in Sweden at an appropriate economic cost. The amount of waste transmuted and total cost of all reactors to be built will be analysed to determine whether such strategy is sustainable and can be implemented. This study will focus on three different methods:

- Transmutation of nuclear waste in a sodium-cooled fast neutron reactor.
- Transmutation of nuclear waste in an accelerator-driven system (ADS).
- Transmutation of nuclear waste in boiling water reactors using mixed oxide (MOX) fuel with a special hafnium cladding.

1.2 Nuclear Reactors in Sweden

Sweden has 10 nuclear reactors providing around 45% of its electricity. Of these 10 reactors, all are light water reactors (LWR), among which 7 are boiling water reactors (BWR) and 3 are pressurized water reactors (PWR). Hydro electric plants generate a further 45% (depending on precipitation) of Sweden's electricity with a further 9% imported from foreign fossil fuel plants, and 1% from wind energy. Table 1.1 shows the nuclear reactors in Sweden along with their operating power and the year in which commercial operation commenced.

Table 1.1: Nuclear reactors in Sweden with their net power output and initial year of operation, [1].

Operator	Reactor	Type	MW_e Net	Commercial Operation
OKG	Oskarshamn 1	BWR	467 MW_e	1972
OKG	Oskarshamn 2	BWR	605 MW_e	1974
OKG	Oskarshamn 3	BWR	1450 MW_e	1985
Vattenfall	Ringhalls 1	BWR	859 MW_e	1976
Vattenfall	Ringhalls 2	PWR	866 MW_e	1975
Vattenfall	Ringhalls 3	PWR	1045 MW_e	1981
Vattenfall	Ringhalls 4	PWR	950 MW_e	1983
Vattenfall	Forsmark 1	BWR	987 MW_e	1980
Vattenfall	Forsmark 2	BWR	1000 MW_e	1981
Vattenfall	Forsmark 3	BWR	1170 MW_e	1985
		Total	**9399 MW_e**	

Lifetimes of these reactors are scheduled for between 40 to 60 years, meaning that all the nuclear reactors must be replaced between 2012 and 2045 or before in order to meet Sweden's energy demands. Until February 2009 nuclear reactors were to be phased out in Sweden, and no new construction was allowed. The coalition government then reversed its decision allowing new reactors to be built, although only to replace current reactors [1].

1.3 Radiotoxicity of Spent Nuclear Fuel

Spent nuclear fuel discharged from light water reactors (LWR) constitutes the main contribution to nuclear waste. Figure 1.1 shows the composition of spent nuclear fuel from a standard PWR with UO_2 fuel irradiated with a burnup of 33 gigawatt days per tonne (GWd/t) UO_2. Extended burnups or use of MOX fuel in the reactor increases the quantities of minor actinides (neptunium, americium and curium) produced.

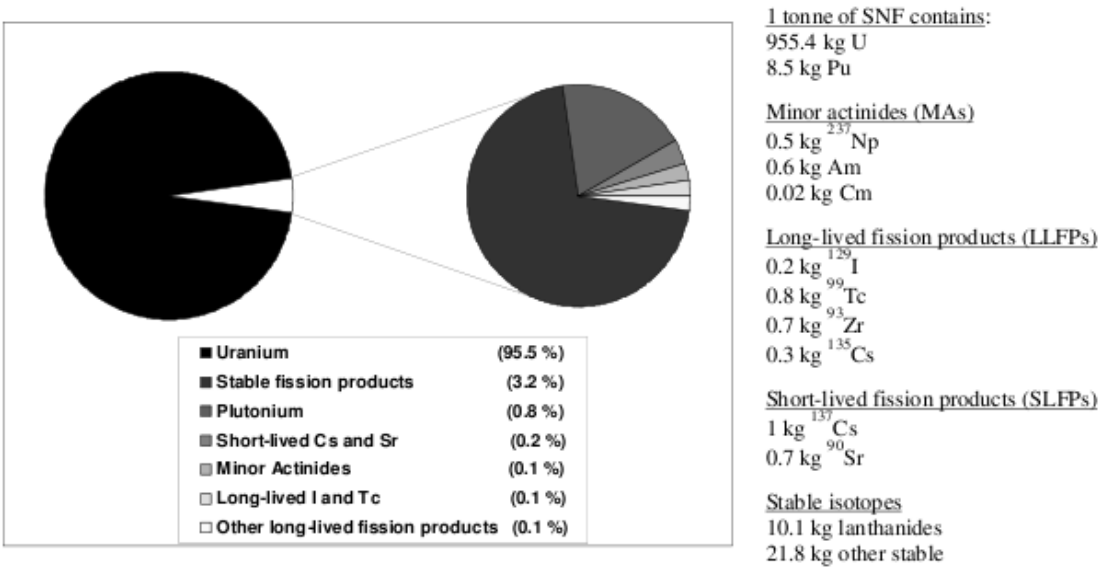

Figure 1.1: Composition of spent nuclear fuel from a standard PWR with UO_2 fuel irradiated to a burnup of 33 GWd/t, 10 with year cooling, [2]

Although these radioactive by-products in the spent fuel are present at low concentrations, they are a hazard to life forms when released into the environment. It is therefore necessary that they be isolated from the biosphere in deep geological formations for long periods of time. A reference point for a safe level of radiotoxicity is the level of radiotoxicity associated with the raw material required to fabricate 1 tonne of uranium. The radiotoxicity level of the spent fuel will only be at a safe level after at least 100,000 years. Figure 1.2 shows the contributions of different transuranium isotopes of spent nuclear fuel to their total

radiotoxicity over the long term. Figure 1.3 shows the evolution of radiotoxicity over time of fission products and transuranium elements from spent nuclear fuel [3].

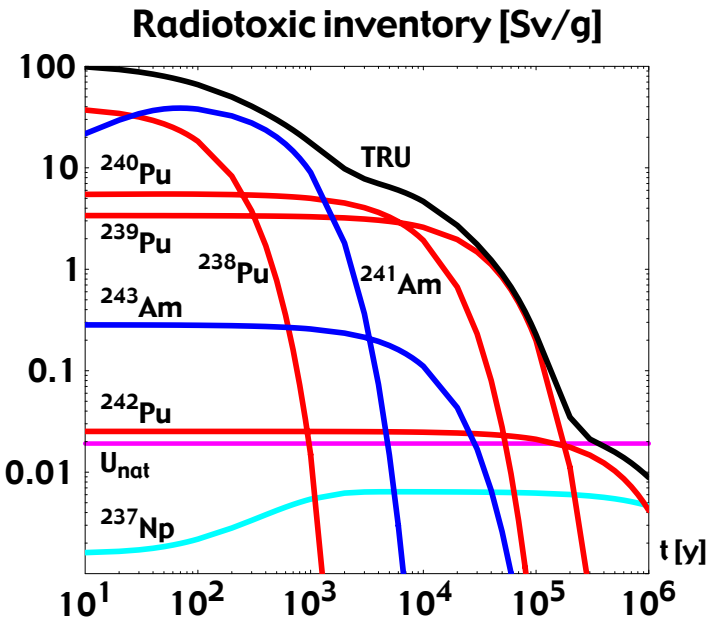

Figure 1.2: Evolution of radiotoxicity over time of individual transuranium isotopes from spent nuclear fuel. The purple line is the radiotoxicity level of raw material to create 1 tonne of uranium, and is the accepted safe level of radiotoxicity. It can be observed that the radiotoxicity level of neptunium-237 is below the reference level and hence gives a negligible contribution to the total radiotoxicity of spent nuclear fuel [3].

During the first 100 years the radiotoxicity from the fission products is the dominant source. However after 300 years the fission products reach the reference radiotoxicity level. Long term radiotoxicity is dominated by the trans uranium elements (TRU), which consist of plutonium plus the minor actinides. If these nuclides were removed from spent nuclear fuel, radiotoxicity inventory reduction factors of higher than 100 can be obtained.

Radiotoxicity reduction will also allow a reduction in the volume of radiotoxic waste to be stored, the associated decay heat of the deposited waste and the cost of a repository. The risk of proliferation (related to the mass of plutonium in the fuel cycle) is also greatly reduced in some partition and transmutation strategies where the TRU are not separated from each other.

Radioactivity and radiotoxicity of TRUs and fission products present in spent nuclear fuel are shown in table 1.2. The radiotoxicity of TRUs is several orders of magnitude higher than the fission products in most cases, further highlighting the requirement to reduce the amount of TRU in spent nuclear fuel.

1.4 Transmutation of Nuclear Waste

Partitioning and transmutation of TRU presents an alternative to the strategy of long term geological disposal of all these materials. Removing these nuclides from the waste (partitioning) and their consequent fission (transmutation) in a reactor is a method to achieve this. If all plutonium from spent nuclear fuel is fissioned a reduction of radiotoxicity inventory of factor 10 can be achieved. If all MAs are also fissioned the reduction factor increases to over 100 [2].

Transmutation of nuclear waste is the full recycling and eventual fissioning of plutonium and minor actinides in nuclear reactors. The original idea, suggested by Clairborne in 1972, [5], was to use existing pressurised water reactor (PWR) designs to achieve this. However, in due course other such methods, more efficient at transmuting nuclear waste have been developed, and will be discussed in the following chapter.

Commercial fuel for LWRs consists of uranium. The fissile isotope ^{235}U is enriched to a concentration typically from 3 - 5%, of which the remaining is ^{238}U. The energy production from LWR fuel comes mostly

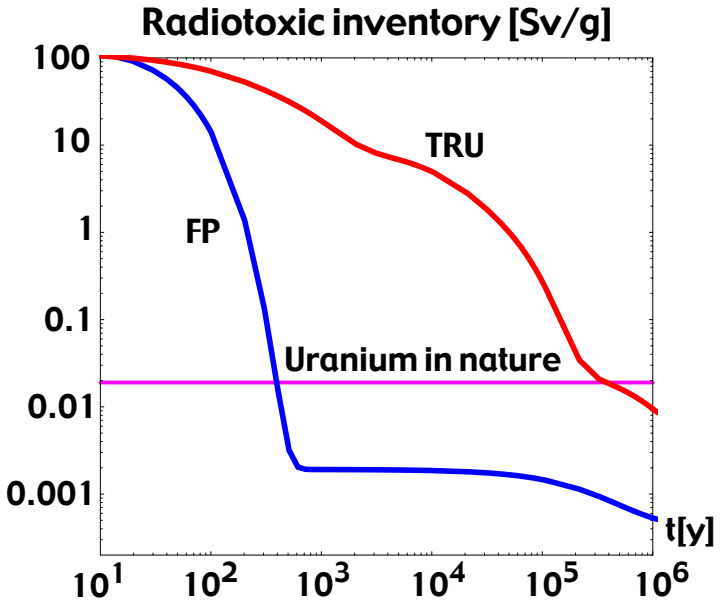

Figure 1.3: Evolution of radiotoxicity over time of spent nuclear fuel and its components.The purple line is the radiotoxicity level of raw material to create 1 tonne of uranium, and is the accepted safe level of radiotoxicity. It can be seen in the graph that if the transuranium elements were removed from the spent nuclear it fuel would reach the safe level in around 1000 years, compared to 100,000 [3].

from the fission of ^{235}U following the absorption of a thermal neutron, by the following reaction:

$$n +^{235} U \rightarrow^{236} U^* \rightarrow FP + 2.4n + \beta + \gamma + \nu \tag{1.1}$$

Each one of these fission reactions releases an average of 2.4 neutrons. There are normally two fission products (FP) per reaction, one with atomic mass number ranging from around 60 to 100, e.g. ^{93}Zr, and the other around 120 to 170, e.g. ^{127}Cs. Most of the FPs are initially unstable and decay via beta, gamma or neutron emission to stable nuclides. However there are some which have longer half-lives ranging from days to years, which are the main source of short term radiotoxicity of spent nuclear fuel [3].

In addition to the nuclear fission reactions taking place within the reactor, ^{238}U captures a neutron, creating ^{239}U. This reaction does not lead to fission, and is known as neutron capture. In a LWR various plutonium, americium and curium isotopes are produced by a chain of neutron captures and beta decays originating from the neutron capture of ^{238}U. For example, ^{239}Pu is produced by the following chain of neutron capture followed by two consecutive beta decays:

$$n +^{238} U \rightarrow^{239} U^* \rightarrow^{239} Np + \beta \rightarrow^{239} Pu + \beta \tag{1.2}$$

Heavier plutonium isotopes are produced from further consecutive neutron captures of ^{239}Pu. Americium isotopes are produced by consecutive captures of ^{239}Pu followed by a beta decay:

$$^{239}Pu + n \rightarrow^{240} Pu + n \rightarrow^{241} Pu + n + \beta \rightarrow^{241} Am \tag{1.3}$$

$$^{241}Pu + n \rightarrow^{242} Pu + n \rightarrow^{243} Pu + n + \beta \rightarrow^{243} Am \tag{1.4}$$

Curium is produced from neutron capture of americium. Figure 1.4 shows the transmutation chain from neutron capture of ^{238}U to ^{252}Cf.

Californium is the most intensive known emitter of neutrons, which results from spontaneous fissions of the nuclei. These neutrons will cause the majority of the neutron dose during reprocessing of spent nuclear fuel, complicating the process and giving rise to higher handling costs.

Table 1.3 shows the isotopic composition of PWR fuel with an initial enrichment of 4.2 weight percent after a burnup of 50 GWd/t and 4 years of cooling.

The following points can be noted:

Table 1.2: Table showing the radioactivity and radiotoxicity of different isotopes of spent nuclear fuel [4]. It can be observed that the radiotoxicity of the transuranium elements is much higher than that of the fission products in most cases.

Isotope	**Half-life (years)**	**Dose Factor (SV/Bq)**	**Radioactivity (Bq/kg)**	**Radiotoxicity (ingested) (Sv/kg)**
		Fission Products		
^{99}Tc	$2.11\ 10^{5}$	$7.8\ 10^{-10}$	$6.3\ 10^{11}$	$4.9\ 10^{2}$
^{129}I	$1.57\ 10^{7}$	$1.1\ 10^{-7}$	$6.5\ 10^{9}$	$7.0\ 10^{2}$
^{135}Cs	$2.30\ 10^{7}$	$2.0\ 10^{-9}$	$4.2\ 10^{10}$	$8.0\ 10^{1}$
^{93}Zr	$1.53\ 10^{6}$	$1.1\ 10^{-9}$	$9.3\ 10^{10}$	$1.0\ 10^{2}$
		Transuranium Elements		
^{233}U	$1.59\ 10^{6}$	$2.5\ 10^{-7}$	$3.6\ 10^{11}$	$9.0\ 10^{4}$
^{238}Pu	$8.77\ 10^{2}$	$2.3\ 10^{-7}$	$6.3\ 10^{14}$	$1.4\ 10^{8}$
^{239}Pu	$2.41\ 10^{5}$	$2.5\ 10^{-7}$	$2.3\ 10^{12}$	$6.0\ 10^{5}$
^{240}Pu	$6.56\ 10^{3}$	$2.5\ 10^{-7}$	$8.3\ 10^{12}$	$2.1\ 10^{6}$
^{241}Pu	$1.43\ 10^{1}$	$4.7\ 10^{-9}$	$3.8\ 10^{15}$	$1.8\ 10^{7}$
^{242}Pu	$3.73\ 10^{5}$	$2.4\ 10^{-7}$	$1.5\ 10^{11}$	$4.0\ 10^{4}$
^{237}Np	$2.14\ 10^{6}$	$1.1\ 10^{-7}$	$2.6\ 10^{10}$	$3.0\ 10^{5}$
^{241}Am	$4.33\ 10^{2}$	$2.0\ 10^{-7}$	$1.3\ 10^{14}$	$3.0\ 10^{7}$
^{243}Am	$7.37\ 10^{3}$	$2.0\ 10^{-7}$	$7.4\ 10^{12}$	$1.5\ 10^{6}$
^{243}Cm	$2.91\ 10^{1}$	$2.0\ 10^{-7}$	$1.9\ 10^{15}$	$4.0\ 10^{8}$
^{244}Cm	$1.81\ 10^{1}$	$1.6\ 10^{-7}$	$3.0\ 10^{15}$	$0.5\ 10^{9}$
^{245}Cm	$8.50\ 10^{3}$	$3.0\ 10^{-7}$	$6.3\ 10^{12}$	$1.9\ 10^{6}$

- 1/6 of the initial ^{235}U inventory has been transmuted to ^{236}U and ^{237}Np by neutron capture.
- 3.8% of the initial ^{238}U inventory has been transmuted. In an LWR neutron spectrum the fission probability is 8%, meaning that around 0.3% of the ^{238}U was fissioned, and the remaining 3.5% transmuted to plutonium through neutron capture.
- Plutonium constitutes 1.2% of the spent fuel, meaning that around 60% of the plutonium produced through the lifetime of the fuel must have been fissioned.
- Plutonium fission contributes to around 40% of the energy produced in a LWR.

Due to the half-life of ^{241}Pu (14 years), the inventory of ^{241}Pu and ^{241}Am in the spent fuel will be dependant on the cooling time. If the burnup of the fuel is increased, the relative fraction of fissionable plutonium would decrease, leading to an increase of curium. This is due to the transmutation of ^{242}Pu and americium into curium is completed almost only by neutron capture [3].

The probability of fission of a nucleus depends on the energy of the incident neutron that it absorbs. In LWRs the neutron spectrum has an average energy of approximately 1 eV, whilst a fast neutron reactor or accelerator-driven system has fast neutrons (approximately 0.1 to 1 MeV). Figures 1.5 and 1.6 show the probability of fission of transuranium nuclei in a PWR and a sodium-cooled reactor neutron spectrum respectively.

One can see that in a fast neutron spectrum the fission probabilities of many transuranic nuclei increases to a sufficient level that production of these elements and californium will be greatly reduced compared to a thermal spectrum. It is for this reason that fast neutron reactors and accelerator-driven systems should be utilised for a transmutation strategy, and these will be described in chapter 2.

1.5 Current Process in Sweden

The current process in dealing with spent nuclear fuel in Sweden is to deposit it long term in a final repository facility, developed by Svensk Kärnbränslehantering AB (SKB). SKB's task is to manage spent nuclear fuel

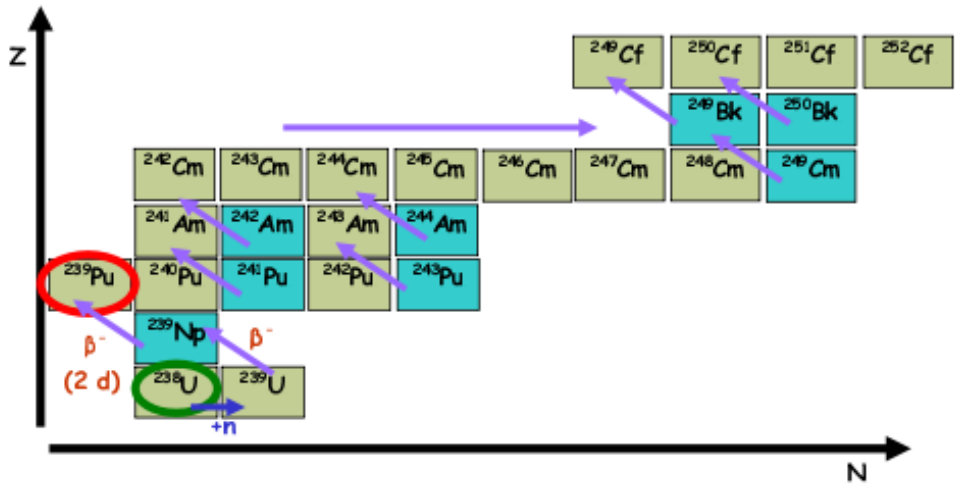

Figure 1.4: Transmutation chain from neutron capture of ^{238}U in a LWR. Throughout consecutive neutron captures and beta decays plutonium, americium, curium and californium will all be produced [2].

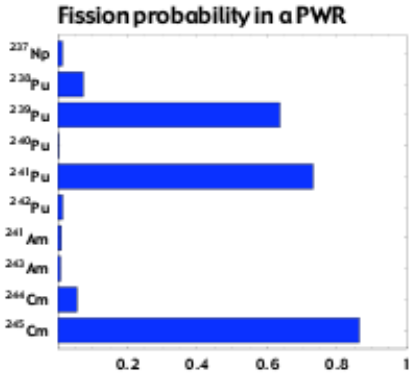

Figure 1.5: Fission probabilities of transuranic nuclides in a PWR neutron spectrum [3].

and radioactive waste from the Swedish nuclear power plants in such a way that man and the environment are protected in the short and long term [7].

Spent fuel from all Swedish nuclear reactors is initially stored in pools at the reactor site for at least 9 months before being transported in casks using a specially designed ship, m/s Sigyn, to the Central Interim Storage Facility for Spent Nuclear Fuel (CLAB). This facility is located adjacent to the Oskarshamn Nuclear Power Plant and is operated by SKB. It consists of eight storage pools, located 40 meters underground, with capacity to store 8000 tonnes of spent fuel between them [8]. At the end of 2008, 4900 tonnes of spent nuclear fuel was present at the facility [9]. CLAB consists of an above-ground part for receiving the spent nuclear fuel, and an underground part with the storage pools. A schematic of the Clab facility is shown in figure 1.7.

After all spent nuclear fuel and other waste is removed from CLAB, the above-ground facilities and parts of the storage pools that have become radioactive will be dismantled. The parts that have become radioactive during the operation of the facility will be sent to a final repository for long lived, low and intermediate level waste (SFL) [9].

1.5.1 KBS-3 Method of Final Disposal of Spent Nuclear Fuel

The process of final disposal of spent nuclear fuel in Sweden is known as the KBS-3 method.

After interim storage, the spent nuclear fuel is prepared for final disposal. The spent fuel is transferred to an encapsulation plant, located next to CLAB, where it will be encapsulated in watertight and load-bearing copper canisters. Each canister will hold up to 12 BWR assemblies, or 4 PWR assemblies. A schematic showing the design of the canisters is shown in figure 1.8.

Encapsulation is due to begin in 2023 with a trial operation involving 20 canisters. Routine operation will

Table 1.3: Table showing the isotopic composition of PWR fuel with an initial enrichment of 4.2 weight percent after a burnup of 50 GWd/t and 4 years of cooling [6].

Isotopic percentage after 4 years cooling from a PWR with burnup 50 GWd/t		
Isotope	**With Fission Products**	**Without Fission Products**
^{235}U	0.767	0.809
^{236}U	0.552	0.582
^{238}U	92.186	97.186
^{237}Np	0.072	0.076
^{238}Pu	0.042	0.044
^{239}Pu	0.623	0.657
^{240}Pu	0.286	0.302
^{241}Pu	0.155	0.163
^{242}Pu	0.095	0.100
^{241}Am	0.038	0.040
^{243}Am	0.028	0.030
^{244}Cm	0.010	0.011
^{245}Cm	0.001	0.001
Fission Products	5.145	-
TOTAL	**100**	**100**

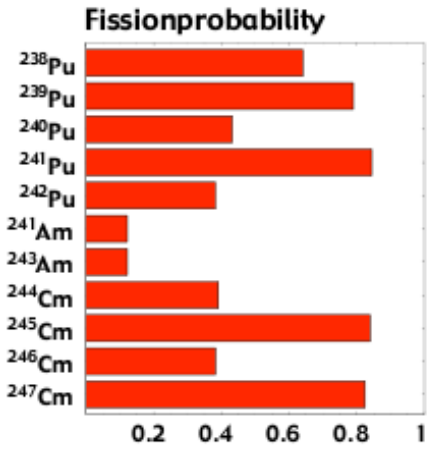

Figure 1.6: Fission probabilities of transuranic nuclides in a sodium-cooled reactor neutron spectrum [3].

commence the following year, and it is expected that the plant will produce around 6000 canisters in total, with 150 being produced each year, reducing to 100 per year towards the end of the operation [9].

The canisters are then transported to a final repository facility. This is to be located in Forsmark, in the municipality of Östhammar, Sweden. Applications for permits to build the repository facility will be submitted by SKB in 2010 [10]. At the repository, the canisters will be deposited in cavities at 400 - 700 meters depth in crystalline rock. A protective buffer consisting of bentonite clay will surround the canisters in the cavities, in order to prevent water flow [7]. Figure 1.9 shows a schematic of the final repository facility.

1.6 Reprocessing of Spent Nuclear Fuel

In order for plutonium and minor actinides to be transmuted in nuclear reactors they must first be separated from spent nuclear fuel by reprocessing. Currently spent nuclear fuel is reprocessed in France, UK, Japan and Russia into MOX fuel, thereby using a significant amount of plutonium that would otherwise go to waste. The plutonium in the MOX fuel is then fissioned mostly in LWRs. As depleted uranium is also recovered through reprocessing, the amount of natural uranium required for fuel fabrication is also reduced [11].

There are two disadvantages with the current reprocessing situation that have become apparent:

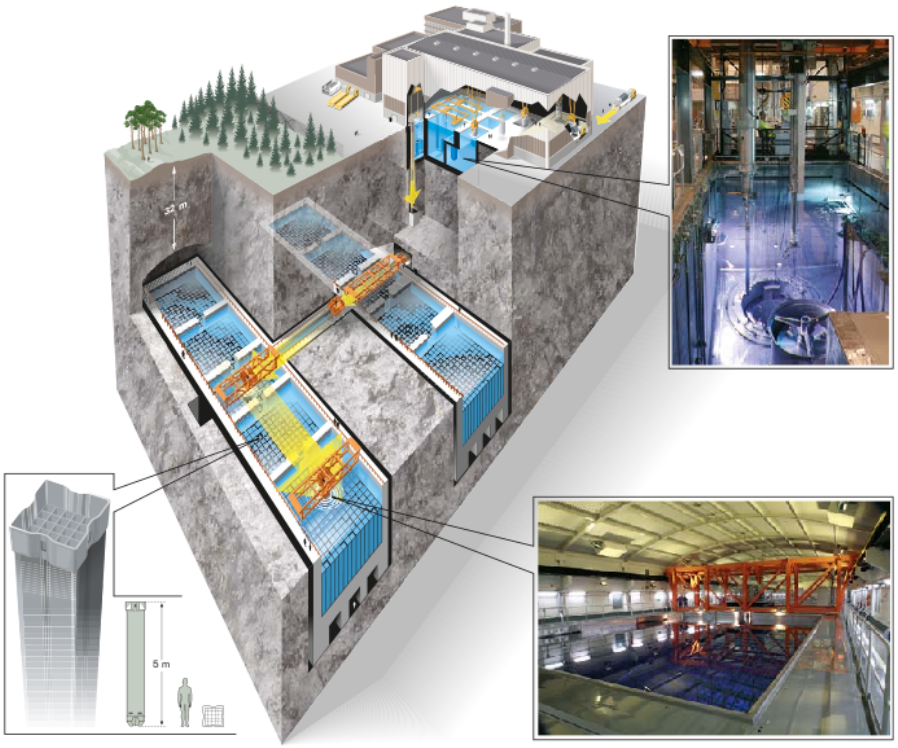

Figure 1.7: Central Interim Storage Facility for Spent Nuclear Fuel (CLAB), [8]

- The separated plutonium is a proliferation risk.
- Minor actinides remain in the separated waste.

As there is no recycling of minor actinides, the reprocessing of spent nuclear fuel and subsequent recycling through LWRs does not completely meet the potential of actinide waste management.

Due to the high radiotoxicity of spent nuclear fuel, special techniques have been developed for reprocessing. There are two methods for reprocessing; PUREX, which is currently operational and electrometallurgical pyroprocessing, which is under development.

1.6.1 PUREX Reprocessing

Plutonium uranium extraction (PUREX) reprocessing is an industrial technique to separate plutonium and uranium from spent nuclear fuel, and has been in place since the mid-1950s. PUREX is a solvent extraction process which takes advantage of the multi-valent nature of the actinides [12]. The spent fuel elements are dissolved in a concentrated nitric acid. Chemical separation of plutonium and uranium is then undertaken by solvent extraction steps. The plutonium can then be used to fabricate MOX fuel, whilst the uranium can be sent to a conversion plant for re-enrichment. A current PUREX reprocessing plant can reprocess around 800 tonnes of spent fuel per year. Table 1.4 shows the current world commercial reprocessing capacity. [11]. The minor actinides americium, curium and neptunium are not extracted and remain in the aqueous solution. These are treated as waste and go through a vitrification process following PUREX reprocessing [12].

Fast reactor MOX fuel requires an increase of up to 4 times the plutonium content (15 - 30 %) compared to that used in a LWR (7 - 9%) [3]. Due to the low solubility of plutonium this may make aqueous reprocessing harder to achieve. With the introduction of advanced technologies aqueous reprocessing can be considered as valid for fast reactor and future ADS fuel if the decay heat can be reduced by longer cooling periods or by dilution with LWR fuel [12].

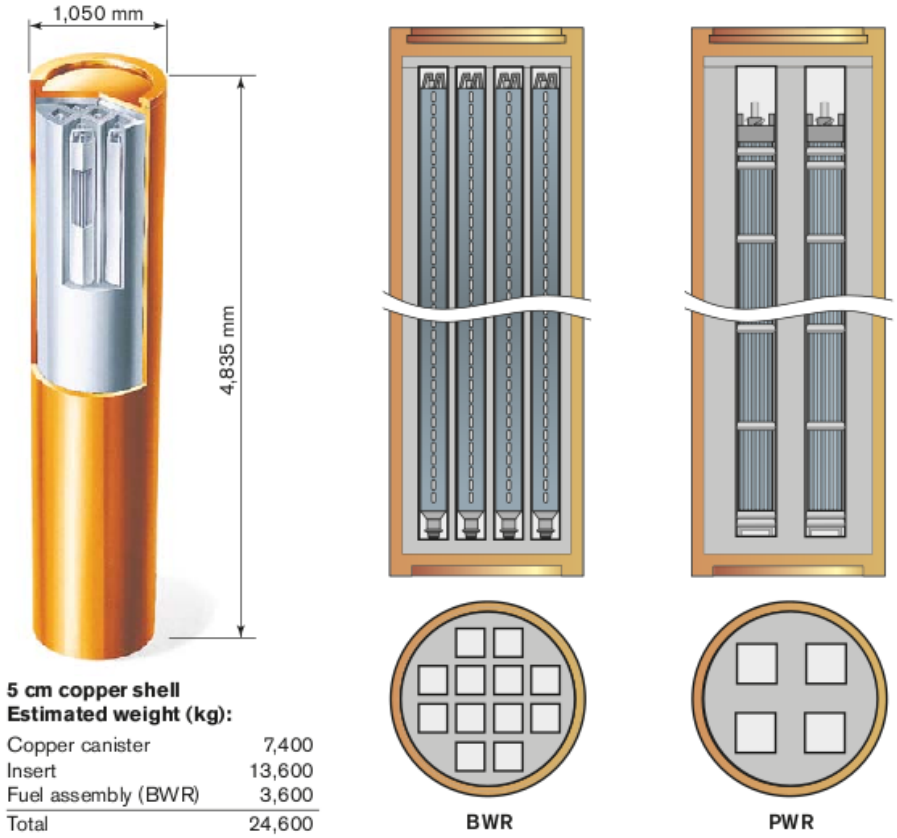

Figure 1.8: Copper canisters encapsulating spent nuclear fuel, [9]

1.6.2 Electrometallurgical Pyroprocessing

Electrometallurgical processing techniques (pyroprocessing) involves separation of TRU by electrochemical techniques. The process is typically operated at very high temperatures and is hence ideally suited to spent nuclear fuel that has been cooled for a short time and that generates considerable decay heat. A fuel cooling time of two years is of adequate length before initiation of pyroprocessing [12].

Pyroprocessing is a process that involves several stages including: volatisation, liquid-liquid extraction using immiscible metal-metal phases or metal-salt phases, electrolytic separation in molten salt, and fractional crystallisation. It is based on the use of fused salts such as chlorides and fluorides, or fused metals such as cadmium, bismuth or aluminium. It is designed to be applied mainly to metallic fuels rather than oxide fuels and is envisaged for fuel for Generation IV reactors [11].

An advantage of electrometallurgical pyroprocessing is that it can be readily applied to a high burnup fuel and fuel which has had little cooling time (2 years), as the operating temperatures are high. However this process is still at an early stage of development and does not yet exist on an industrial scale, whereas PUREX processing is already operational [11].

1.6.3 Fuel losses in Reprocessing

The actinides cannot be completely recovered from spent nuclear fuel during reprocessing and it is inevitable that some amounts will go to waste. For an effective actinide transmutation system a target recovery value of 99.9% is acceptable [12].

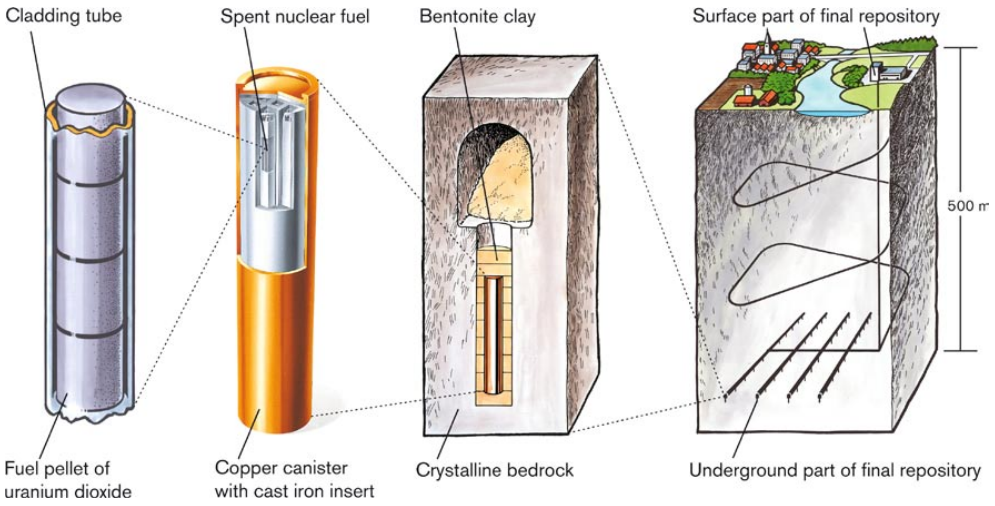

Figure 1.9: Final repository facility for spent nuclear fuel of KBS-3 method, [7]

Table 1.4: Table showing the current world reprocessing capacity in 2010 per country per fuel type in tonnes per year [11].

	Location	**Reprocessing Capacity, Tonnes per Year**
LWR Fuel	France, La Hague	1700
	UK, Sellafield (THORP)	900
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)	800
	Total (approx)	3800
Other Nuclear Fuels	UK, Sellafield (Magnox)	1500
	India	275
	Total (approx)	1750
Total Civil Capacity		**5550**

CHAPTER 2

METHODOLOGY

This chapter describes the theory of the reactor designs and concepts to be considered in calculations, the transmutation scenarios to be studied, and the methodology of the calculations.

2.1 Transmutation in Sodium-Cooled Fast Reactors

Fast neutron reactors (FR) have existed as long as thermal neutron reactors. The first FR was in Los Alamos in 1946 and the first nuclear reactor in the world to produce electricity, in the United States in 1951, was a FR, the EBR-1. Since then, 21 fast reactors of various sizes have operated at criticality, and of these most FRs that have been in existence used sodium as a coolant. However due to the technical difficulties of using a sodium coolant and the economic problems of a non-expanding nuclear energy market, the BN-600 (600 MW_e) in Russia, and the Superphenix (1240MW_e) in France (which was shut down in 1998) have remained the only industrial scale FRs to operate. Therefore there is much less operating experience of FRs than thermal neutron reactors [12]. As the BN-600 remains the only operational FR at current time, the section of this project on transmutation of transuranium elements (TRU) in sodium-cooled fast neutron reactors will have a strong focus on the BN-600 design.

The motivation for building fast reactors has changed over time. Initially, the main purpose was to breed plutonium in order to conserve uranium resources, where a shortage and price increase in uranium was predicted in the 1970s. However uranium remained sufficiently abundant and relatively cheap, as growth rate of nuclear energy had been slower than originally expected. Nowdays, the use of a FR operating as a plutonium burner to recycle the excess plutonium and minor actinides produced in light water reactors has become of importance and is now a particular focus of fast reactor research and development activities [12].

Fuel for Fast Neutron Reactors

Many types of fuel have been tested since the start of development of fast neutron reactors. These included enriched uranium or plutonium in metallic, nitride, oxide or carbide form, or a mixture of plutonium and uranium oxides. Due to the change in performance demands and priorities, the popularity of various fuel types has changed throughout the time of development.

Nowdays fuel pellets are composed of ceramics, produced by sintering. The most commonly used fuels are a mixture of plutonium and uranium oxides $(U,Pu)_2$ (MOX), with up to 30% plutonium content. The uranium content in the fuel is natural or depleted uranium oxide. If the reactor is designed to breed plutonium, more natural or depleted uranium will be located in axial or radial blankets surrounding the core. The cladding of the fuel usually consists of stainless steel, as it is chemically and physically compatible with the fuel and the coolant (molten sodium in the case of the BN-600). It also strong enough to guarantee the high mechanical strength required throughout the life of the fuel pin [12].

Fast Reactor Fuel Reprocessing

Reprocessing of fast reactor fuel is completed through the same process (PUREX) as that of fuel from LWRs. However extra factors must be taken into account due to the presence of sodium from the coolant, high residual power, high plutonium content and the use of stainless steel cladding and structural components. The United Kingdom and France have experience in reprocessing FR MOX fuels, although this is little in comparison to that from a LWR [12].

For a sustainable transmutation strategy involving fast reactors it will be essential that MOX fuel from these reactors is reprocessed multiple times.

Reactor Coolant Choice

Liquid metals are selected as a coolant for fast reactors, mainly due to their low moderating power, as well as high thermal conductivity. This enables the reactor to be operated at low pressure and hence reduces the risk of a loss of coolant accident. Initially mercury was chosen as the coolant to use on the first prototype reactors, but this was replaced with sodium. Sodium has a density similar to water at reactor operating temperatures, therefore well-known pumping technology can be used. However there are certain drawbacks to using sodium; at operating temperatures sodium can spontaneously ignite in air and reacts violently when in the presence of water. This means that sodium-water reactions must be accounted for when designing the steam generator of the reactor. The technology for solving these problems is now available today.

The isotope ^{23}Na in the coolant becomes activated to radioactive ^{24}Na in the reactor core. This means a secondary inactive sodium coolant circuit must be constructed to separate the sodium in the core from the steam generator. Although there is technology available to easily overcome this problem, it does present a cost disadvantage [12].

2.1.1 Plutonium and Minor Actinide Recycling in Fast Neutron Reactors

There are two methods to recycle plutonium and minor actinides (MA) in fast neutron reactors. The following sections give an introduction to the process of each and the expected destruction rates of plutonium and MA.

Homogeneous Recycling

The homogeneous recycling mode in a fast reactor is to recycle plutonium and minor actinides that have not been separated from each other during reprocessing. This aims to stabilise plutonium and MA mass flows so that the only radiotoxic isotopes sent to waste are those lost through reprocessing, typically around 0.1% [2].

The main advantages of the homogeneous recycling mode are:

- The concept is designed to produce energy and makes an optimised use of the fuel cycle process.
- There is no separation of plutonium and MA from each other. This makes the fuel cycle in this mode more efficient (in heterogeneous mode plutonium and MA are separated from each other), and also reduces the risk of plutonium proliferation.
- Several options regarding reactor size, fuel and coolant can be chosen if required.

The main reference case for fast neutron reactors for this study will be on the BN-600. The BN-600 is a sodium-cooled fast neutron reactor which has been operating in Beloyarsk, Russia since 1980, in a semi-commercial mode, with a power of 600 MW_e/1500 MW_{th}. A recent study, [13], has simulated destruction rates of plutonium and MA in a BN-600 using MOX fuel with 20 weight percent plutonium and varying amounts of americium ranging from zero to 10%. The isotopic compositions of the plutonium and americium were obtained from spent fuel from a LWR with a burnup of 50MWd/kgHM (mega-watt days per kilogram of heavy metal) after 5 years of cooling. The plutonium isotopic vector is ^{238}Pu (3.50 atomic %), ^{239}Pu (52.88 at%), ^{240}Pu (23.82 at%), ^{241}Pu (12.9 at%) and ^{242}Pu (7.90 at%). The americium isotopic vector consists of ^{241}Am (57.58 at%) and ^{243}Am (42.42 at%). It should be noted that the other minor actinides, neptunium and curium were not included in the fuel. Neptunium has a radiotoxic contribution of far less than that of natural uranium, and therefore the burning of neptunium may not be such of a priority task for Generation-IV reactors and this study.

Curium has a negligible effect on safety parameters comparing to those of americium. To properly assess the impact on safety by introducing americium to the fuel, and the upper limit for the amount of americium that can be safely permitted, curium was not added to the fuel in these simulations.

The results of the study were obtained from using the simulation code SERPENT, which is a continuous energy Monte Carlo burnup code, developed by VTT Technical Research Centre in Finland [14]. The simulations of Pu and Am destruction are run at a burnup of 100 MWd/kgHM.

In the original design of the reactor axial and radial blankets of depleted uranium dioxide were installed in the reactor core for the purpose of breeding plutonium, with a ratio of 1.3. In order for a net burning of plutonium the blankets would need to be removed. In the SERPENT code of the study of [13], the axial blanket was substituted with stainless steel as additional reflectors and the radial blanket assemblies were substituted with steel-shielding sub-assemblies.

Heterogeneous Recycling

Heterogeneous recycling mode is the transmutation of MA in specific targets in areas in the reactor. The targets are usually fuel pins in the reactor core containing larger amounts of MA, or radial or axial blankets around the core containing MA. This mode will require plutonium and MAs to be separated during reprocessing prior to fuel fabrication, hence requiring further complication than for the homogeneous mode. The dedicated MA targets can be uranium-free if an inert matrix support, such as when magnesium oxide is used. This material is favourable for fabrication and reprocessing purposes. Uranium can also be present if required [2].

Adding MA in blankets surrounding the core will increase consumption, although the rate of plutonium consumption will decrease due to the presence of blanket. In some configurations there may be a net plutonium production, rather than destruction.

2.2 Transmutation in Accelerator-Driven Systems

An accelerator-driven system (ADS) is a concept that consists of an accelerator and a sub-critical core. The majority of proposals include proton accelerators, with a proton energy of around 1 GeV. The accelerator can be either a linear (LINAC) or of a circular shape (cyclotron). Figure 2.1 shows a schematic of an ADS power plant.

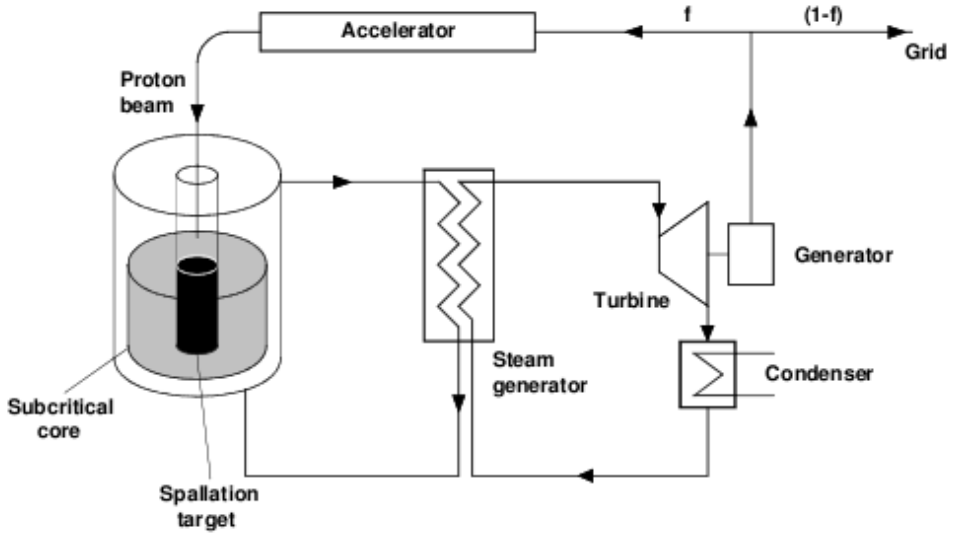

Figure 2.1: Schematic of an accelerator-driven system for electricity production. The beam of protons hits the spallation target located in the centre of the core. Neutrons from the spallation target travel outwards to the fuel to induce nuclear reactions [12].

The protons from the accelerator are injected on to a spallation target to produce neutrons, which act as a source for driving the sub-critical core. The target is made of a heavy metal and can be in either a solid or

liquid state. In the target spallation reactions emit a few tens of neutrons per incident proton. The source neutrons travel into the sub-critical core where they induce further nuclear reactions. The core is very similar to that of a normal reactor, the sub-critical state being the exception. It can be designed to operate with either a thermal or fast neutron spectrum [12]. In an ADS system, part of the electrical energy generated by the plant is recycled to power the accelerator, reducing the net electrical efficiency of the system. For an ADS with a neutron multiplication factor of 0.95, there is a reduction of electrical efficiency of around 12%.

Tables 2.1 and 2.2 summarise the principle advantages and disadvantages of an ADS system from a design and safety perspective respectively, compared with corresponding critical reactor systems such as LWRs and FRs. This comparison does not only cover transmutation objectives and applications, but also breeding of fissile material and the development of a thorium-^{233}U fuel cycle.

In a transmutation context, the main advantage of the ADS is the increased flexibility of core design and fuel management which results from the removal of the criticality condition. Therefore transmutation rates in an ADS can be higher than those in critical reactors as more MA can be used in the fuel. However this comes at a price of technical and operational disadvantages. For example the benefit of extending the length of the fuel cycle must be balanced against the requirement of a more powerful accelerator for coping with a lower neutron multiplication factor at the end of the cycle.

Table 2.1: Table summarising the principle advantages and disadvantages of an accelerator-driven system in a design perspective [12].

Advantages of Accelerator-Driven Systems	**Disadvantages of Accelerator-Driven Systems**
Design Characteristics	
• The possibility to operate a reactor core with a *neutron multiplication factor below 1.* This opens new opportunities for reactor concepts which would have otherwise been ruled out by an insufficient neutron economy. • Transmuters can be designed as *pure plutonium or minor actinide burners.* Therefore the fraction of specialised transmuters in a reactor park can be minimised. Hence a higher *burnup rate of plutonium and MA* can be achieved. • Control of the reactor is simplified by the proportionality of the reactor power to the accelerator current.	• *Accelerator:* Very high reliability and therefore high power capacity factor is required to protect the structure from thermal shocks. • *Beam window and target* are subjected to unusual conditions of stress, corrosion and irradiation. • *Sub-critical core:* Increased power peaking effects can happen due to the external neutron source (spallation target). • Compromises between neutron multiplication factor and accelerator power are required. • Increased complexity of the overall power plant design. • Reduction in net electrical efficiency of the power plant due to power consumption of accelerator.

There are important design and material problems that arise from the installation of the spallation target in the centre of the reactor core; the design of the containment must be appropriate due to the fact that the accelerator is separate from the reactor core, the spallation target and surrounding structural materials are subjected to complex degradation phenomena due to a combination of high energy particle irradiation, thermo-mechanical loads and corrosion effects from being in contact with heavy metals, which are much more significant than those in current LWRs. This applies especially to the beam window which may require frequent replacement, although there are now designs envisaged that do not use them [12].

High power accelerators will need to be improved to reduce the frequency of beam trips, and beam losses which can cause radiation damage and activation of components in the accelerator. Beam trips can cause mechanical and stress transients like those of fast control rod insertions (scrams) in critical reactors.

From a safety perspective, the main feature of an ADS is that it is has a reduced potential for reactivity-induced accidents. This is particularly relevant if it was designed as a plutonium and MA burner, where it

Table 2.2: Table summarising the principle advantages and disadvantages of an accelerator-driven system in a safety perspective [12].

Advantages of Accelerator-Driven Systems	**Disadvantages of Accelerator-Driven Systems**
Safety Characteristics	
• The reactivity margin to prompt criticality can be increased by an extra margin that *does not depend on delayed neutrons.* • This enables *safe operation of cores designed to be minor actinide burners* which would otherwise have degraded safety characteristics. • There is a *reduced potential for reactivity-induced accidents* as excess reactivity can be eliminated.	• The external neutron source can vary rapidly and reactivity feedbacks for plutonium and minor actinide dominated cores are weak. Therefore *new types of reactivity and source transients* will need to be accounted for in the design.

would suffer from significant degradations in safety parameters in the core.

From a transmutation viewpoint a general conclusion from tables 2.1 and 2.2 is that an ADS has great potential for interesting designs and safety advantages. However, these are weighed against technical and operational disadvantages which could give rise to higher costs.

2.2.1 The EUROTRANS Research Program

The main reference design of ADS for this study will be a recent design from the European Research Programme for the Transmutation of High Level Nuclear Waste in Accelerator-Driven Systems (EUROTRANS). This is funded by the European Commission and involves 31 partners across research agencies and nuclear industries, and a contribution from 16 universities. The main objective of EUROTRANS is to work towards a European demonstrator facility in two steps; first an advanced design of all components of a demonstration facility with 50-100 MW_{th} power, known as the XT-ADS machine; second a generic conceptual design of the European Facility for Industrial Transmutation (EFIT). The EFIT design [15] will be the reference design of ADS for this study. Table 2.3 shows the basic characteristics of the XT-ADS and EFIT systems [16].

The XT-ADS machine is to be built within the next decade and and will run on conventional MOX fuel, and aims to demonstrate three main objectives:

1. Demonstrate the ADS concept of the coupling of the proton accelerator, spallation target and subassembly at significantly high power levels (50-100 MW_{th}).
2. Validate MA transmutation by providing dedicated positions in the core for special fuel assemblies.
3. Serve as a multi-purpose neutron irradiation facility.

The EFIT facility will be an industrial scale transmutation demonstrator system. One of the goals of the demonstration is that it can be achieved economically. The characteristics of EFIT are an optimisation of:

1. Transmutation efficiency.
2. Ease of operation and maintenance.
3. To achieve high level availability.

The EFIT is a lead-cooled sub-critical reactor. It will use innovative uranium-free fuel with a high content of minor actinides present. The fuel will be a mixture of plutonium and MA oxides and a magnesium oxide inert matrix. The fuel type is known as: **Cer-Cer (Pu, MA)O_{2-x} + MgO**. The reactor will operate at a power of 384 MW_{th}. The conceptual design of the EFIT core is based on the '42-0' principle. This is characterised

Table 2.3: Baseline characteristics of the accelerator-driven system designs of XT-ADS and EFIT. K_{eff} is the effective neutron multiplication factor, with criticality being 1, subcriticality below 1 [16].

	XT-ADS (ADS Prototype)	**EFIT (Industrial Transmuter)**
GOALS	Demonstrate the concept. Demonstrate transmutation. Provide an irradiation facility.	Maximise the transmutation efficiency. Easiness of operation and maintenance. High level of availability.
MAIN FEATURES	50-100 MW_{th} power. K_{eff} around 0.95. 600 MeV, 2.5 mA proton beam (back-up: 350 MeV, 5 mA). Conventional MOX fuel. Lead-bismuth eutectic coolant and target.	Several 100 MW_{th} power. K_{eff} around 0.97. 800 MeV, 20 mA proton beam. Minor actinide fuel. Lead coolant and target (back-up: gas).

by a net zero plutonium balance throughout the fuel cycle, and a destruction rate of 42 kg/TWh_{th} of minor actinides. This rate will be used in performance and economic calculations.

Some considerations have been taken into account in the core design; the plutonium breeding gain is avoided by using uranium-free fuel. Plutonium burning is also to be avoided as it would be consumed quicker than in critical reactors. Therefore a zero net balance is an optimal design choice. Each fission has to be devoted, directly or indirectly to the MA. As the final fission balance is to be 42 kg/TWh_{th} (the intended sum of the plutonium and MA balance) the aim of the design is to achieve approximately 42 kg/TWh_{th} for MA and zero kg/TWh_{th} for plutonium.

2.3 Transmutation using a fast neutron spectrum in Boiling Water Reactors

Recent studies ([17], [18], [19], [20]) have demonstrated a possibility to transmute transuranic elements within a fast neutron spectrum in boiling water reactors (BWR). Currently the BWR is the most common type of reactor in Sweden and therefore this approach, although different and less studied than fast reactors or ADS for transmutation, should be included in this study. There is also an economic initiative to this method; the main component of the cost of nuclear electricity is the capital cost, therefore it is interesting to investigate whether current reactors can be modified to transmute TRU in a fast neutron spectrum as well as new reactors.

In boiling water reactors there is a large coolant void fraction towards the top of the core, meaning there is less water available to moderate the neutrons to thermal energies. At this area in the core there may be a double peak neutron spectrum with average energy of a few keV. These energies will more favour transmutation of minor actinides than a pure thermal spectrum. Therefore it has been suggested that locating transmutation fuel at the top of cores in BWRs could improve performance in transmutation of minor actinides [19].

The average energy of neutrons in the bottom of the core is around 1 keV, the top being 3 keV. This hardening of the spectrum is not sufficient enough to increase the fission probability of the even number nuclides. To achieve a true fast spectrum in a BWR two design changes of the reactor were suggested [19]:

- Use metallic alloy fuel in order to reduce the number of light nuclides in the fuel which cause neutron moderation.
- Use a hafnium-based clad. This will shield slow neutrons from being absorbed by the actinides present.

Hafnium was chosen to be used as a cladding material due to the fact that it has very similar properties to zirconium, which is a cladding material on uranium oxide fuel for BWRs, and also that it has a very high capture cross section for thermal and epithermal neutrons [20].

The compatability of metallic alloy fuel was later questioned over dissolution of fuel in lead. Therefore it was decided to experiment with two different fuels; uranium-free inert matrix nitride fuel and low fertile MOX fuel. It was shown [18] that by using these fuels with hafnium clad that a net destruction in TRU elements

could be achieved, comparing to a production of TRU with ordinary uranium oxide fuel. It can be noted that with uranium-free inert matrix nitride fuel TRU inventories could be stabilised with the use of 47% of BWRs of this type at the reactor park [18]. However it was required to further investigate safety parameters before assuming complete feasibility of this method.

A further study [20] tried using parts of fuel pins with normal uranium oxide fuel with zirconium cladding, and part (1/3) consisting of MOX or inert matrix nitride (IMN) fuel at the top of the fuel pins in the core with hafnium cladding. Also a core full of entire pins with MOX and IMN fuels were tested with hafnium cladding. It was found that for using entire fuel pins of IMN fuel achieved much higher rates of actinide burning than 1/3 IMN fuel as there is no presence of uranium in IMN fuel, but neutron absorbtion by hafnium also reduces the neutron multiplication factor. Also improved safety parameters would arise if there were more thermal neutrons present in the core. This lead to the most recent study [17] to use 16% IMN at the top of the fuel pins in the core with 5% of the clad consisting of hafnium. Although destruction rates of TRU are lower, appropriate safety parameters were said to be reached.

It has been suggested by [21] that a burnup of 10 kg/MWh$_{th}$ of minor actinides in a BWR using these methods could be achieved by 2035 if further research on this topic is carried out between now and then. This value will be used in calculations to analyse transmutation performance of a BWR with hafnium cladding.

2.4 Economics of Nuclear Power

There are a number of special factors affecting investment in new nuclear power plants (NPP) in a different way to building other types of large infrastructure. These special features make financing nuclear energy particularly challenging. These include [22]:

- High capital cost and technical complexity of NPPs. There are relatively high risks during construction (delays and cost overruns), and during operation (equipment failures and unplanned outages).
- The long period that is required to repay loans or recoup investments for construction, which can increase the risk from uncertainties in the electricity market.
- The controversies surrounding nuclear-related projects give rise to additional political and regulatory risks.
- The requirement for financing schemes and clear solutions for management of nuclear waste and decommissioning, which only governments can decide upon.
- The need for NPPs to operate at high capacity factors.

Tables 2.4 and 2.5 give an approximate breakdown comparing electricity generating costs for nuclear, coal and natural gas with discount rates of 5 and 10 % respectively.

Table 2.4: Table showing approximate breakdown in electricity generating costs for nuclear, coal and natural gas, with a 5 % discount rate [22].

Discount Rate 5%	**Nuclear**	**Coal**	**Natural Gas**
Investment Costs	50	35	14
O & M Costs	30	20	9
Fuel Costs	20	45	77

Table 2.5: Table showing approximate breakdown in electricity generating costs for nuclear, coal and natural gas, with a 10 % discount rate [22].

Discount Rate 10%	**Nuclear**	**Coal**	**Natural Gas**
Investment Costs	70	50	20
O & M Costs	20	15	7
Fuel Costs	10	35	73

As can be seen, the majority of costs of generating electricity from nuclear energy arise in capital costs. Fuel costs however have the smallest contribution and therefore when a NPP is built the risk of fluctuating fuel prices that occur with coal and gas will not be so prevalent in the nuclear case. The higher capital costs for a NPP mean that its overall economics are more dependant on capital costs and discount rates. The capital costs may comprise several parameters; the bare plant costs (the engineering to procurement to construction costs), the owner's costs (land, cooling, infrastructure), administration, licences, cost escalation and inflation [23].

The construction phase of a nuclear project is considered the most risky for investors. This will be especially true for 'first of a kind' plants and for new nuclear programmes in countries that have not yet had nuclear power. Therefore in the case of this study some assumptions may have to be made when calculating economic costs of fast reactors and accelerator-driven systems. Large amounts of capital must be invested early on in the project, and returns on the initial investment will not begin until years later when the operation of the plant commences. Traditionally, the construction risk was passed onto electricity consumers through regulated prices, however this is no longer possible in liberalised markets. Construction risk can be shared with vendors and contractors who build the plant, although contractors may only have a limited capacity for such risk taking. The risk of delays and overruns will sit mainly with equity investors, as loan guarantees may not cover delays, and debt investors may not usually accept such risks. To reduce these risks equity investors can chose standardised NPP designs that are currently in operation elsewhere which have been built by experienced contractors. Targeted government support (if available) can also reduce risk for investors to acceptable levels [22].

2.4.1 Cost Estimates for New Nuclear Power Plants

In recent years there have been very few nuclear power plants built. Therefore it can be difficult to estimate the cost of a new plant to be built. The first NPP currently being constructed in Western Europe for over 18 years is the Olkiluoto-3 plant in Finland. This reactor, with power 1600MW$_e$ is the new European Pressurised Reactor (EPR), of French and German design. It is a light water reactor, and the first reactor of the third generation design to be built. In the early stages of licensing, the Finnish Power Company Teollisuuden Voima Oyj (TVO) predicted the project to take four years to build with a cost of €2.5 billion. Subsequently a higher capacity reactor was ordered, and a fixed contracted price of €3.2 billion with a 4.5 years construction time was agreed. In mid-2008 construction delays along with an increase in price of raw materials led to a cost overrun estimated around €1.5 billion, putting the total investment cost of the reactor up to €5 billion. After 2.5 years of construction it was estimated the construction might now take up to 7 years [24].

Another EPR is currently being constructed in France, and the construction cost estimate is €3.4 billion [24]. This is lower than the plant in Finland as it does not foresee the increased costs associated with the problems described above. This figure will be used as a reference for the investment cost in calculations for costs for new LWRs. The associated cost estimates for operation and maintenance, fuel, waste and decommissioning will be in the form of €/MWh from existing experience of LWR operation [25]. Table 2.6 shows prices in Euros for a new LWR that will be used as a reference in calculations.

Table 2.6: Costs for a new light water reactor. Note the investment cost is in Euros from [24], and other costs are in €/MW$_h$ from [25].

Cost Estimates for a new Light Water Reactor	**€**
Investment Costs	3.40E+09
	€/MW$_h$
Operation and Maintenance Costs	5
Fuel Costs	4
Waste, Decommissioning Costs	2
Other Costs	1
TOTAL	**12**

Table 2.7 shows investment costs [26], fuel fabrication and fuel reprocessing cost estimates [12] for fast reactors, and fuel reprocessing costs for accelerator-driven systems. The investment cost is expressed in G€. The fuel fabrication and reprocessing costs are expressed in 2000 US Dollars. These will be used as the

reference costs in the calculations. In addition, cost estimates for operation and maintenance, waste and decommissioning will be added, shown in table 2.8. These costs will be based on an assumption of twice the costs for a FR compared to a LWR, and three times the cost for an ADS to a LWR. Table 2.9 shows the itemised investment cost estimates for the EUROTRANS EFIT design of ADS from [27]. This will be used as the reference value for investment cost for ADS in the calculations.

Table 2.7: Cost estimates for investment [26], fuel fabrication and fuel reprocessing for a fast reactor, and fuel reprocessing costs for an accelerator-driven system [12]. The costs are expressed in 2000 US Dollars.

Cost Estimate FR 2000$	**Low**	**Nominal**	**High**	**Unit**
Investment	-	2.5	-	G€
Fuel Fabrication	1400	2600	5000	$/kgHM
Fuel Reprocessing	1000	2000	2500	$/kgHM
Cost Estimate ADS 2000$				
Fuel Reprocessing	5000	7000	18000	$/kgHM

Table 2.8: Cost estimates for operation and maintenance, waste and decommissioning for fast reactors and accelerator-driven systems. The costs are in Euros per MW_h.

Cost Estimates, €/MW_h	**FR**	**ADS**
Operation and Maintenance	10	15
Waste and Decommissioning	2	2
Other	1	1
TOTAL	**13**	**18**

Table 2.9: Table showing itemised investment costs for the EUROTRANS EFIT design of ADS from [27].

Items	**Best Estimate (M€)**	**Low Price (M€)**	**High Price (M€)**
Buildings and civil structures	309	216	402
Accelerator (including accelerator buildings, utilities and management)	664	525	804
Primary circuit and emergency systems	158	126	190
Spallation target	15	12	19
Nuclear fuel (1 core)	33	25	40
Secondary System	224	179	267
Management	112	90	134
Auxiliaries	155	124	186
Engineering and procurement	89	71	106
Remote handling system	49	39	59
Power supply	43	34	52
Licensing	38	30	46
Total	**1889**	**1472**	**2305**

The cost of a BWR using fuel with a hafnium cladding described in section 2.3 will be assumed to be the same as that of a normal LWR.

2.5 Transmutation Scenarios in Sweden

For Sweden to have a sustainable transmutation strategy the building of new reactors described in the previous sections must take place. The question is what the target of a strategy would be; how much plutonium and minor actinides should be transmuted and how much extra it should cost economically, rather than continuing with the current strategy of long-term geological disposal. Certain scenarios could include:

- Stabilise plutonium and minor actinide production rates in Sweden so that there is a net zero increase/decrease of the current inventory.
- Half the current inventory of plutonium and minor actinides by implementing at strategy that slowly consumes these materials to half the current amount by a certain date.
- Aim for a transmutation of 100% minor actinides and plutonium by a certain date. This would likely to be a long-term phase out of nuclear power.

The start date of the scenario must be considered first. In this study all scenarios considered will start in the year 2035. 2035 has been selected as a date because it appears a realistic end of life date for the current reactors operating, if their lifetimes were to be of approximately 60 years each. It is also assumed that due to the lengthy process of building a new nuclear reactor, especially one of a new design such as an ADS, it is unlikely that one would be operating before 2035. The following assumptions are made with regards to each scenario:

- All 10 reactors currently operating in Sweden will continue until 2035. In 2035 each of these reactors will be replaced with new ones.
- The number of reactors in Sweden will remain at 10. Currently legislation only provides for new reactors to replace old ones and no extra reactors being built. Therefore each current reactor will be replaced by one new reactor at the end of its life.
- The amount of plutonium and minor actinides will be calculated based on assumptions described in the next section for the year 2035. Every scenario considered will start with the aforementioned calculated amount of plutonium and MA available for use in transmutation reactors in Sweden.
- Each reactor will have an assumed lifetime of 60 years. It will therefore be possible to calculate estimated amounts of plutonium and MA present in Sweden at the year 2095 at the end of life of the new reactors to be built.

Apart from selecting a transmutation goal for plutonium and MA there are other factors that must be considered before initiating a strategy:

- Is there enough plutonium and minor actinides available to fuel the reactors? A certain amount of plutonium and MA will be required depending on the type and number transmutation reactors to be built. This must be checked for the initial length of the first fuel cycle and the lifetime of the reactor.
- Reprocessing of spent nuclear fuel. The time between spent fuel leaving the reactor and when it is to be reprocessed (cooling time) will influence how much fuel is available throughout the life of the new reactors, and also the amount of time it will take to reach a transmutation goal for transmuting pre-determined quantities of plutonium and MA. For conventional PUREX reprocessing technology a 10 year cooling time is required, whereas if pyroprocessing were to be successfully developed and implemented the cooling time would be reduced to just 2 years. In a study by [4] it was found that the time required to transmute 99% of TRU in Sweden using ADS would be 200 years with PUREX processing, and 50 years with pyroprocessing.
- The need for a reprocessing plant. A typical reprocessing plant can reprocess 800 tonnes of heavy metal per year [11]. Results from calculations will show whether a reprocessing plant should be built and operated at full capacity in Sweden, or whether one could be shared with other countries should Sweden only require a reprocessing plant to operate at partial capacity.

The main scope of this study will focus on developing a strategy to achieve a net zero production of minor actinides from all nuclear reactors in Sweden. Scenarios to transmute half of the MA inventory, and the complete elimination of MA in Sweden will also be investigated. Calculations will be made to approximate the amount of MA produced or destroyed per reactor design. This will determine the number of LWRs and transmutation reactors required to achieve this goal. All transmutation scenarios will be compared to a reference scenario where 10 LWRs and no transmutation reactors are used. The total cost of all nuclear reactors in the scenario along with the cost of electricity generation per MW will be presented to analyse the economic effect of introducing transmutation reactors to Sweden. The power penalty due to the lower power of transmutation reactors, over the all nuclear reactors in Sweden will also be presented. The amount of heavy metal required in each scenario for reprocessing will determine whether a reprocessing plant would need to be built in Sweden. Scenarios for the reduction, and complete elimination of MA in Sweden will also be analysed for practical and economic sustainability.

2.6 Calculations for Transmutation Scenarios

In this section the calculations to obtain results for the scenarios described in section 2.5 will be described.

2.6.1 Inventory of Plutonium and Minor Actinides in Sweden in 2035

The first step is to calculate how much spent fuel would be present in Sweden in 2035. A study by [4] has calculated that in 2025 there will be 9826 tonnes of heavy metal from spent nuclear fuel in Sweden. In order to calculate for 2035, it is assumed the 10 reactors in Sweden would be operating as at 2010 levels, and would be discharging the same amount of spent fuel per year between 2025 and 2035 as they are in 2010. A PWR in Sweden discharges approximately 24.2 tonnes of spent fuel every 14 months [28], a BWR in Sweden discharges approximately 17.4 tonnes every 12 months [29]. Table 2.10 shows the amount of spent nuclear fuel calculated to be discharged between 2025 and 2035.

Table 2.10: Table showing the amount of spent nuclear fuel to be discharged in Sweden in 10 years, from 2025 to 2035. The values for spent fuel discharged per year were received from [28] for a PWR and [29] for a BWR.

	PWR	**BWR**	**TOTAL**
Number of reactors in Sweden	3	7	10
Refuelling time in months	14	12	-
Refuelling cycles in 10 years	9	10	-
Spent nuclear fuel discharged per fuel cycle (tonnes)	24.2	17.4	41.6
Total spent nuclear fuel discharged in 10 years (tonnes)	**654**	**1218**	**1872**

It is therefore calculated that the amount of spent nuclear fuel present in Sweden at 2035 is 9826 + 1872 = 11698 Tonnes.

To calculate the isotopic quantities and hence the amount of plutonium and minor actinides contained in the spent fuel the total amount of spent fuel must be multiplied by a vector, containing individual isotopic quantities of transmutation elements from the spent fuel. The fuel vector used in this study is shown in table 1.3 and is for spent fuel from a PWR with uranium enrichment to 4.2 weight percent with a burnup of 50 GWd/t after 4 years of cooling [6]. The spent fuel quantity up to 2025 (9826 tonnes) was multiplied by the vector minus fission products, as this number was quoted as just containing heavy metals [4]. The spent fuel estimated from 2025 to 2035 is multiplied by a vector including fission products. The total amount of uranium, transuranic elements and fission products estimated to result from all spent fuel in Sweden in 2035 is shown in table 2.11.

2.6.2 Spent Nuclear Fuel from Light Water Reactors in Sweden after 2035

In order to determine the net amount of plutonium and minor actinides which are transmuted through any transmutation scenario, the amount of plutonium and MA produced from light water reactor spent fuel must be calculated. It is not yet known which type(s) of LWR would be built in Sweden to replace the existing fleet after 2035. As different designs of LWR use differing amounts of fuel, an assumption must be made regarding the amount of spent fuel from LWRs per year. It has been assumed that 20 tonnes per year per reactor will be an appropriate value. This is approximately the median value of current rates for spent fuel production from LWRs in Sweden. The individual isotopic quantities of the spent fuel are calculated as described above. Estimates of isotopic quantities of heavy metals and fission products produced per year after 2035 are shown in table 2.11

Quantities of plutonium and MA from spent fuel from transmutation reactors are assumed to be the total quantity that entered the reactor as fuel throughout the lifetime minus the quantity transmuted.

2.6.3 Transmutation Rates

To calculate the quantity of plutonium and minor actinides transmuted in a reactor, plutonium and MA transmutation rates for the reference reactor designs are required. Table 2.12 shows transmutation rates for plutonium, americium and curium in kg/TWh$_{th}$ for a BN-600 reactor described previously, received from

Table 2.11: Table showing estimated quantities of uranium, transuranic isotopes, and fission products from all spent nuclear fuel in Sweden by 2035 (in the central column), and per year from spent nuclear fuel from a LWR after 2035 in the right-hand column.

Isotope	**Amount, Tonnes, in Sweden in 2035**	**Tonnes per year per LWR after 2035**
^{235}U	93.8	0.153
^{236}U	67.5	0.110
^{238}U	11275.2	18.437
^{237}Np	8.8	0.014
^{238}Pu	5.1	0.008
^{239}Pu	76.2	0.125
^{240}Pu	35.0	0.057
^{241}Pu	19.0	0.031
^{242}Pu	11.6	0.019
^{241}Am	4.6	0.008
^{243}Am	3.4	0.006
^{244}Cm	1.2	0.002
^{245}Cm	0.1	0.000
Fission Products	96.3	1.029
TOTAL	**11698.0**	**20.000**
Total Pu	**146.89**	**0.240**
Total Am	**8.07**	**0.013**
Total Cm	**1.35**	**0.002**
Total TRU	**156.31**	**0.256**

[13]. The rates are shown for the reactor with differing amounts of americium present in the fuel, ranging from 0 to 5%. It can be observed that curium rates are negative as it is produced in the reactor.

Table 2.12: Table showing transmutation rates of plutonium, americium and curium in kg/TWh$_{th}$ for a BN-600 reactor [13]. If the transmutation rate is negative for a certain material it experiences a net production in the reactor.

BN-600 Reactor	**Percentage of Americium in Fuel**					
	0% Am	1% Am	2% Am	3% Am	4% Am	5% Am
Transmutation Pu kg/TWh	+4.9	+4.5	+4.2	+4.0	+3.8	+2.7
Transmutation Am kg/TWh	-1.5	0.0	+1.7	+3.4	+5.4	+8.4
Transmutation Cm kg/TWh	-0.3	-0.8	-1.3	-1.8	-2.3	-2.8

Table 2.13 shows transmutation rates of minor actinides, expressed per year per reactor and also in kg/TWh for the EUROTRANS EFIT design of ADS [15]; the reference design used in the calculations for ADS. Transmutation rates per year shall be used in the calculations.

Table 2.13: Table showing destruction rates of minor actinides in the EUROTRANS EFIT design of ADS [15]. Destruction rates per year shall be used in the calculations.

Total MA Destruction (kg)		
Per Year	Per Cycle (3 years)	In TWh$_{th}$
120	360	42

It can be noted that transmutation rates of plutonium and MA in the reactors mentioned above are expressed in different units by each author. Therefore, calculations for each reactor design will be adjusted to allow for these different units.

To calculate the transmutation performace over the duration of each scenario it is necessary first to calculate the amount of plutonium and minor actinides transmuted during the lifetime of a new reactor to be built

from 2035, which is assumed to be 60 years. This is achieved by multiplying the lifetime of the reactor by the transmutation (or production) rate per year and by a power capacity factor for the particular reactor concerned. In cases where the transmutation rate is expressed in kg/TWh_{th}, the power generated in TWh_{th} per reactor lifetime is calculated and then multiplied by the transmutation rate and power capacity factor.

The next step in assessing transmutation performance of each scenario is to calculate the amount of plutonium and MA that will be present at the end of the scenario. This is simply the amount in 2035 plus the amount produced in LWRs minus the amount transmuted in transmutation reactors. A net change in mass of plutonium and MA can then be calculated by subtracting the mass at the end of the scenario from the mass at 2035.

An additional constraint in running a transmutation strategy is whether there will be enough material initially present to fuel the transmutation reactors. Therefore the required amount of plutonium and MA for the first fuel cycle of all transmutation reactors for the particular scenario is considered. Due to cooling times required for reprocessing of spent fuel described in section 2.5, there must be enough fuel for transmutation reactors to run for at least one fuel cycle plus cooling time. The amount required for plutonium and MA for the fuel cycle length plus associated reprocessing cooling time will be compared against the amount at the start of the scenario in 2035.

To determine if there will be enough spent fuel throughout the scenario to require a reprocessing plant to be built in Sweden, or if it is more appropriate to share one between two or more countries, the total amount of spent fuel per year from all reactors in the scenario is calculated. The amount of spent fuel per year per reactor design is calculated and summed up per number of reactors of each type according to the particular scenario.

With these calculations it can be determined if the scenario in question is a realistic prospect.

2.6.4 Cost Estimate of Transmutation Strategy

The cost for each transmutation scenario is calculated for its total duration. The cost estimates for the different reactor types shown in tables 2.6, 2.7, and 2.8 are multiplied by their relevant parameter for the duration of the lifetime of the reactor. All costs are converted to Euros for the current time.

It will then be possible to make an analysis of the costs for each transmutation scenario.

2.6.5 Summary of Assumptions

A number of assumptions have had to be made in the calculations to obtain the results. These are summarised in table 2.14.

Table 2.14: Table showing assumptions made during the calculations for a LWR, BN-600 and EUROTRANS EFIT ADS reactor.

LWR Assumptions	
Cycle length, years	5
Reactor lifetime, years	60
Mass heavy metal, kg, reactor load	100000
Mass heavy metal, kg, over reactor lifetime	1200000
Mass heavy metal, kg, per year	20000
Power Capacity Factor	0.9
Power of reactor, MW Thermal	3500
Power of reactor, MW Electric	1400
Investment Cost LWR	€3,400,000,000
BN-600 Assumptions	
Power of reactor, MW Thermal	1280
Power of reactor, MW Electric	512
Power Capacity Factor	0.9
Cycle length, years	4
Reactor lifetime, years	60
Investment Cost BN-600	€2,500,000,000
EFIT ADS Assumptions	
Reactor lifetime, years	60
Power of reactor, MW Electric	153.6
Power Capacity Factor	0.9

CHAPTER 3

RESULTS

In this chapter the results from the calculations will be presented. The transmutation scenarios presented are all compared to a reference scenario using 10 LWRs and no transmutation reactors. The power penalty over all reactors in Sweden, that occurs when a transmutation reactor is added due to its lower power than a LWR is shown for all scenarios in section 3.1. Section 3.2 presents cost estimates for each reactor, and the total cost of all reactors over all scenarios. The performance of each reactor and scenario in the transmutation of Pu and MA is shown in section 3.3, along with the requirements for reprocessing of spent nuclear fuel for each scenario. Section 3.3.1 presents MA transmutation results for a scenario including a BWR using MOX fuel with a hafnium cladding with a hypothetical MA burnup rate of 10 kg/TWh$_{th}$.

3.1 Power Penalty

The power penalty over all reactors in Sweden associated with the introduction of transmutation reactors per scenario compared to a reference scenario (10 LWRs in Sweden) is shown in table 3.1. The power of each scenario is also compared to the current power available in 2010 from all nuclear reactors in Sweden. It can be observed that the introduction of transmutation reactors in place of LWRs in Sweden will result in less total power over all reactors than in the reference scenario. However, all scenarios give an increase in total power to that currently available in 2010 from nuclear power in Sweden.

Table 3.1: Power penalty in MW$_e$ and percent over all reactors in Sweden for each transmutation scenario compared to the reference scenario. The power of each scenario is also compared with the total power currently available in 2010 from nuclear reactors in Sweden.

	Reference Scenario	**Transmutation Scenarios**					
Number of LWR in Scenario	10	9	9	8	8	8	7
Number of BN-600 in Scenario	0	1	0	2	0	1	2
Number of ADS EFIT in Scenario	0	0	1	0	2	1	1
Total Power MW$_e$ for Scenario	14000	13112	12754	12224	11507	11866	10978
Power Penalty MW$_e$ for Scenario	N/A	-888	-1246	-1776	-2493	-2134	-3022
Power Penalty (%) Electric for Scenario	N/A	6.3%	8.9%	12.7%	17.8%	15.2%	21.6%
Increase in power (%) compared to total current power in Sweden (9399MW$_e$)	49.0%	39.5%	35.7%	30.1%	22.4%	26.2%	16.8%

3.2 Cost Estimates

Table 3.2 shows the cost estimate of a new LWR, BN-600 and ADS EFIT to be built in Sweden. The total cost of the reactor and cost per MW_e is shown. It can be observed that although the total cost of the BN-600 and ADS EFIT is lower than that of an LWR, the costs per MW_e are much higher.

Table 3.2: Cost estimates for a LWR, BN-600 and ADS EFIT over one lifetime and per MW_e.

	Total cost, G€			**Cost per MW_e, M€**		
	Low	Nominal	High	Low	Nominal	High
Cost estimate LWR	-	11.3	-	-	8.1	-
Cost estimate BN-600	6.0	6.3	6.8	11.7	12.4	13.3
Cost estimate ADS EFIT	3.7	4.5	6.1	24.3	29.2	39.7

Table 3.3 shows the cost estimates per scenario in terms of total cost of all reactors and cost per MW_e.

Table 3.3: Cost estimates per transmutation scenario. The total cost of all reactors in each scenario is shown, along with the cost per MW_e of each scenario.

	Reference Scenario	**Transmutation Scenarios**					
Number of LWR in Scenario	10	9	9	8	8	8	7
Number of BN-600 in Scenario	0	1	0	2	0	1	2
Number of ADS EFIT in Scenario	0	0	1	0	2	1	1
Total cost for scenario, G€	113.5	108.9	108.2	104.3	103.0	103.7	99.1
Cost per MW_e, M€	8.11	8.31	8.49	8.54	8.95	8.74	9.03

3.3 Transmutation of Plutonium and Minor Actinides per Scenario

The esimtated inventory of MA in Sweden in 2035 is 9.42 tonnes. The estimated inventory of Pu in Sweden in 2035 is 147 tonnes.

Table 3.4 shows the estimated transmutation or production rates of plutonium and americium per reactor lifetime for a LWR, BN-600 FR and EFIT ADS. It can be observed that a FR transmutes around 4 times as much MA as a LWR produces, and an ADS around 9 times as much.

Table 3.4: Estimated rates of production/destruction of plutonium and minor actinides per reactor lifetime for a LWR, BN-600 and EFIT ADS.

	Tonnes per reactor lifetime	
	Plutonium	**Minor Actinides**
LWR	+13.0	+0.8
BN-600	-1.6	-3.4
EFIT ADS	0.0	-7.2

The projected minor actinide inventory in Sweden at the end of each scenario in 2095 along with the net change in MA from the scenario start in 2035 is shown in table 3.5. Two scenarios; one with 8 LWRs and 2 FRs, or one with 9 LWRs and 1 ADS will lead to an approximate net zero production of MA over all reactors. Using 8 LWRs with 1 FR and 1 ADS will transmute approximately half of all MA in Sweden. Two scenarios indicating a reduction of around 90% of MA from Sweden use 8 LWRs and 2 ADSs, or 7 LWRs, 2 FRs and 1 ADS.

Table 3.6 shows the projected plutonium inventory in Sweden at the end of each scenario in 2095 along with the net change in plutonium from the scenario start in 2035. All scenarios experience a net production of plutonium. However, the addition of an FR or ADS will make this production rate lower.

Table 3.5: Minor actinide inventory in Sweden and at the scenario end (2095) in tonnes. The net change in minor actinides throughout the scenario in tonnes is also shown.

	Reference Scenario	**Transmutation Scenarios**					
Number of LWR in Scenario	10	9	9	8	8	8	7
Number of BN-600 in Scenario	0	1	0	2	0	1	2
Number of ADS EFIT in Scenario	0	0	1	0	2	1	1
MA at scenario end, 2095, tonnes	17.7	13.5	9.7	9.3	1.7	5.5	1.3
Net change in MA, tonnes	+8.3	+4.1	+0.3	-0.1	-7.7	-3.9	-8.1

Table 3.6: Plutonium inventory in Sweden at the scenario end (2095) in tonnes. The net change in plutonium throughout the scenario in tonnes is also shown.

	Reference Scenario	**Transmutation Scenarios**					
Number of LWR in Scenario	10	9	9	8	8	8	7
Number of BN-600 in Scenario	0	1	0	2	0	1	2
Number of ADS EFIT in Scenario	0	0	1	0	2	1	1
Plutonium at scenario end, 2095, tonnes	277	262	264	247	251	249	234
Net change in plutonium, tonnes	+130	+115	+117	+100	+104	+102	+88

Table 3.7 shows the amount of plutonium and minor actinides that are required to start all reactors per scenario. The table also shows the amount of MA required to fuel a reactor for the initial core load plus the cooling time for reprocessing of spent fuel using the PUREX and pyroprocessing methods. The total amount of spent fuel discharged per year from all reactors in the scenario is also shown. It can be noted that the amount of MA required to fuel an ADS for its initial core load plus the PUREX reprocessing cooling time is more than the inventory of MA in 2035. This is discussed in section 4.3.

3.3.1 Hypothetical Study of Transmutation of Minor Acinides in a BWR

The results for MA transmutation rates in a BWR using MOX fuel with a hafnium cladding for the study described in section 2.3 are presented in this separate section due to its hypothetical nature. As this reactor is assumed to be identical to that of a normal LWR all parameters are assumed to be the same excluding the minor actinide transmutation rates. There is therefore no cost or power penalty associated with a scenario of using such reactors. Transmutation rates of plutonium were not considered for this study. Table 3.8 shows the projected MA inventory in Sweden at the end of that scenario in which such a BWR is used, of that along with the net change in MA from the scenario start in 2035.

Table 3.7: Table showing the amount of plutonium and minor actinides required to start all reactors per scenario in tonnes. The amount of MA to start all reactors for one fuel cycle plus the waiting time for reprocessing of spent fuel using the PUREX and pyroprocessing methods are shown. The total amount of spent fuel discharged from all reactors per year per scenario is shown in the bottom row.

	Reference Scenario	**Transmutation Scenarios**					
Number of LWR in Scenario	10	9	9	8	8	8	7
Number of BN-600 in Scenario	0	1	0	2	0	1	2
Number of ADS EFIT in Scenario	0	0	1	0	2	1	1
Plutonium required to start all reactors, tonnes	0	2.3	2.4	4.6	4.8	4.7	7.0
MA required to start all reactors, tonnes	0	0.6	3.0	1.1	6.0	3.6	4.1
MA required to start all reactors plus 10 years for PUREX reprocessing, tonnes	0	2.0	13.0	4.0	26.0	15.0	17.0
MA required to start all reactors plus 2 years for Pyroprocessing reprocessing, tonnes	0	0.9	5.0	1.7	10.0	5.9	6.7
Spent fuel discharged from all reactors per year, tonnes	200	183	182	166	164	165	148

Table 3.8: Minor actinide inventory in Sweden and at the scenario end (2095) in tonnes. The net change in minor actinides throughout the scenario in tonnes is also shown.

	Reference Scenario	**Transmutation Scenarios**
Number of LWR in Scenario	10	9
Number of Special BWR in Scenario	0	1
MA at scenario end, 2095, tonnes	17.7	0.3
Net change in MA, tonnes	+8.3	-9.1

CHAPTER 4

DISCUSSION OF RESULTS

This chapter contains an overall discussion of the results from a transmutation, economic and sustainable perspective.

4.1 Performance of Transmutation of Minor Actinides

Table 3.5 shows that with the addition of a BN-600 fast neutron reactor or EFIT ADS reactor into the Swedish nuclear reactor fleet in 2035 there will be a reduction of minor actinide production compared to that of a scenario of running only LWRs. To achieve an approximate net zero production rate of minor actinides from 2035 to 2095 it is observed that 2 FRs or 1 ADS is required. Using 1 FR and 1 ADS will result in a net destruction of minor actinides of 3.9 tonnes, reducing the inventory to nearly half in 2095 of the projected 2035 value. To achieve a complete destruction of MA inventory in Sweden using 2 ADS reactors will result in a net destruction of 7.7 tonnes, leaving just 1.7 tonnes in 2095.

Although one might want to reduce or completely eliminate minor actinides to achieve a zero inventory in Sweden, there will be practical implications that must be considered:

- An EFIT ADS design requires 5.4 tonnes of nuclear fuel to run, of which 3 tonnes consist of MA. Therefore unless the reactor is run at a reduced burnup and efficiency with more plutonium used as fuel in place of MA there will always have to be at least 3 tonnes of MA present in Sweden if an ADS was chosen to be used.
- Running an ADS on less MA fuel than designed for will also lead to economic concerns due to the reactor not running at its full potential.
- The amount of MA required to start 2 ADS will not be enough due to the fact that 1 ton per year per reactor must be reprocessed and then fabricated into new fuel, the ADS would have to stop running as the amount of MA fuel would run out quicker than it can be reprocessed.

It could also be possible to use a FR operating in heterogeneous recycling mode as described in section 2.1.1. Destruction rates of plutonium and MA in homogeneous and two heterogeneous recycling modes in a 600MW$_e$ SFR are compared in a study by [30]. The comparison is also repeated for a lead-cooled fast reactor. Three different reactor configurations are compared:

1. Homogeneous recycling of plutonium and MA in the core. No MA in the axial and radial blankets.
2. No MA in fuel in the core, but MA in blankets at a fraction of 10%.
3. MA present in fuel in the core, and also present in blankets at a fraction of 10%.

Whilst heterogeneous recycling modes have not been considered in this study it can be suggested that further research on including this concept in a transmutation scenario is undertaken.

4.2 Performance of Transmutation of Plutonium

Table 3.6 shows that there will be a net production of plutonium over all scenarios where FRs and ADS are utilised in Sweden. It can be noted that the production rate does decrease with their presence compared to the reference scenario of 10 LWRs and no transmutation reactors. As shown in table 2.12 the BN-600 does transmute plutonium, however due to the higher rate of production in an LWR transmutation of plutonium does not appear feasible using the scenarios considered for this study. If a fuel containing less americium than the 5% used in this case for the BN-600 then the transmutation rate of plutonium could be nearly twice as high at a rate of 4.9kg/TWh$_{th}$ compared to 2.7 kg/TWh$_{th}$, although there would be less MA transmuted with the sacrifice of MA in the fuel. As the MA are more radiotoxic than plutonium, ableit a shorter half-life, they should therefore be prioritised in this study for transmutation over plutonium in the event that only one of the two can be chosen. This excess plutonium could perhaps be utilised as MOX fuel in LWRs.

4.3 Reprocessing Requirements

Table 3.7 shows that there will be between 148 and 200 tonnes of spent fuel per year from the nuclear reactor fleet in Sweden for the different scenarios considered in this study. As a current reprocessing plant can reprocess 800 tonnes of heavy metal per year (section 1.6.1), it would be uneconomical for one to be built in Sweden alone. It would therefore be wise to share capacity between different countries if they too were to adopt transmutation scenarios similar to that in Sweden, rather than Sweden build a smaller-scale reprocessing plant as this would likely drive costs up. The most efficient situation would be for a group of countries in Europe to have a central reprocessing plant at 1 location with each country involved using its share of capacity for its own requirements.

It is possible that the cooling time required from when spent fuel is discharged from a reactor to when it can be reprocessed will pose a constraint on a transmutation scenario. It can be observed in table 3.7 that using the existing PUREX method (section 1.6.1) of reprocessing will not be possible if an ADS is utilised in Sweden. The amount of MA required to run the ADS until the first batch of spent fuel can be reprocessed is 13 tonnes, more than the inventory of MA in 2035 (9.42 tonnes). If the Pyroprocessing method (section 1.6.2) could be developed for industrial-scale use by 2035, the MA amount required drops to 6 tonnes, due to the two year cooling time. However even using two ADS reactors in Sweden the requirement with pyroprocessing is 10 tonnes meaning both ADS would not be able to run constantly if this scenario was adopted in Sweden.

It is clear that pyroprocessing technology for reprocessing of spent nuclear fuel must be developed for industrial use in order to gain full usage from the transmutation reactors. There is only one possible scenario (2 FRs) to achieve a net zero production of MA by only using the PUREX method for reprocessing of spent nuclear fuel. If ADS is to be utilised in Sweden, pyroprocessing must be developed.

Reprocessing of spent nuclear fuel may increase the volume of nuclear waste due to additional chemicals used in the process. However, as the highly radiotoxic long-lived Pu and MA will be used to fabricate new fuel, this waste will decay to a safe radiotoxicity level 3 orders of magnitude quicker than Pu and MA. Therefore the amount of long-lived waste will remain almost unaffected by reprocessing.

4.4 Power and Cost Penalty of the Introduction of Transmutation Reactors into Sweden

Table 3.2 shows that the total cost for a LWR is nearly twice that of a BN-600 and three times that of an EFIT ADS. Therefore it can be observed in table 3.3 that the reference scenario of 10 LWRs and no transmutation reactors is in fact the most expensive to invest in. Therefore the addition of transmutation reactors will lower the total cost of all reactors in Sweden. Whilst this result could be marketed to investors it does not result in the fact that utilising transmutation reactors is cheaper than LWRs.

The introduction of transmutation reactors incurs a power penalty of the total amount of MW$_e$ that will be produced from nuclear power in Sweden, as the transmutation reactors produce less power than that of a LWR (FR produces 512MW$_e$, ADS produces 154 MW$_e$, compared to 1400 MW$_e$ for a LWR). Table 3.1 shows that for a scenario to achieve an approximate net zero production of MA over all reactors in Sweden a power penalty of 8.9% or 12.7% will result for the introduction of 1 ADS or 2 FRs respectively. Using 1 FR and 1 ADS to reduce the MA inventory to nearly half of the 2035 value will incur a power penalty of

15.7%. If the cost of electricity production from nuclear power is analysed in cost per MW_e, table 3.3 shows an increase in this value from the reference scenario when transmutation reactors are utilised. For scenarios involving a net zero production of MA, the cost increase is around 5%, for scenarios with a 50% reduction in MA the cost increase is around 8%. This is caused by the higher cost of electricity generation per MW_e for a FR and ADS as shown in table 3.2. Although the uncertainty of these costs are large, the magnitude of the cost increase of power generation per scenario is small. Hence the uncertainty would be unlikely to have a large effect on the magnitude of these values. As the revenue made from a nuclear reactor will strongly correlate to its power generation available in MW_e, it appears more sensible to judge the cost of introducing transmutation reactors into Sweden on the cost per MW_e over the entire fleet, rather than just the total cost to construct and operate them for their entire lifetime.

It is interesting to note that regardless of the power penalty incurred by the addition of transmutation reactors there will be more power available from the nuclear reactor fleet in Sweden after 2035 than there is in 2010, as shown in table 3.1. There will most likely be an increasing demand for energy from nuclear reactors in Sweden. Even with introducing 2 FRs or 1 ADS for a zero net MA production, there will still be an increase of 30.1% or 35.7% of the power in MW_e available from the reactor fleet, than what is currently available in 2010.

It is clear that due to less power a FR or an ADS will generate significantly less revenue for an investor than a LWR, despite the lower total cost. Therefore FRs and ADS must be made more attractive to investors as the sensible option from a purely business point of view would be to invest only in LWRs. LWRs will also prove more attractive to investors as they have already proven to operate successfully with many years of operation experience, unlike transmutation reactors where there is little operating experience for FRs and none for an ADS. The risk factor for an investor to build a LWR is hence lower. Government legislation encouraging the build of transmutation reactors, perhaps in the form of a tax relief or government subsidy would make this a more attractive investment, and a more likely reality.

A solution to reduce the power penalty associated with the introduction of FRs would be to use a higher power design. Such designs have existed previously that are now shut down such as the $1240MW_e$ Superphenix (section 2.1). If transmutation of MA was found to be as efficient in such design as the BN-600 FR, then this could present a more economically sustainable solution and hence become more attractive to investors.

4.5 Hypothetical Burnup of Minor Actinides in a BWR

If a burnup of 10 kg/TWh_{th} is achieved in a BWR, it is shown in table 3.8 that almost all MA in Sweden could be transmuted through one 60 year lifetime after 2035. However there are practical issues that make this an unrealistic prospect:

- The amount of MA and plutonium to be used to fuel the reactor must be determined. A certain amount of MA will be required to run the reactor and there will be availability problems given that all MA will be transmuted in Sweden by the end of its life.
- The production/destruction rate of plutonium is unknown, and would need to be determined to analyse transmutation performance and fuel requirements.
- The amount of MA transmuted in one of these unique BWR transmuters is almost equal to that present in 2035 plus what is produced by 9 normal LWRs over the following 60 years. As MA from spent fuel will need to be reprocessed, the waiting time required before reprocessing can commence must be instantaneous otherwise the BWR transmuter must stop running to wait for new fuel. As described in section 2.5, this would not be possible.

Running the reactor on a MA burnup at a lower rate hence less destruction of MA will solve availability problems for fuel and ensure constant running throughout its lifetime. However the nature of this part of the study is hypothetical and yet remains uncertain to whether it can become a reality. More research will be required to be completed to enable the technology for this prospect to become possible, especially in the areas of safety. The advantage of this method, should it become possible, is the high burnup potential of an existing design of reactor, only using modified fuel. This would lead to an increased cost of fuel fabrication and reprocessing, however this would be very low compared to that of a FR or an ADS. As this reactor is assumed to be of the same design of a normal BWR, the power penalty over all reactors in Sweden associated with introducing such reactor would be negligible. These factors along with the fact that there are already existing designs and operating experience of this design of reactor would make it more attractive for investment.

4.6 Uncertainties in Results

Since many of the calculations are based on assumptions shown in table 2.14 there will be uncertainties in the results. It is not possible to avoid having to make these assumptions as they are based on predictions on what will happen in the year 2035. There is no method to estimate which designs of light water reactor will be built to replace the current fleet in Sweden. Current designs under construction are for power of around 1400MW$_e$ [31] and 1600MW$_e$ [24]. With the total nuclear power of 9399MW$_e$ (shown in table 1.1 available from all 10 reactors at current time in Sweden, even with the construction of 2 transmutation reactors in place of LWRs there will be a total power increase of around 20%, which will cater for possible additional energy needs. Hence the decision was made to assume 1400MW$_e$ for the average power of an LWR in Sweden. It can be assumed there will be more than one different design built and hence reactors with different power ratings as currently almost every nuclear power-generating nation with more than one reactor has different designs. This would be unlikely to have such an effect on the amount of MA produced as that is dependant on the burnup (dependant on power) of the reactor. It is also very likely that instead of all reactors considered for scenarios in this study commencing operation in the same year, that there will be a gradual overlap from the existing fleet to the new one over a few years. As the details of this are unknown it was decided to make the assumption that all reactors start in 2035.

As it is unknown exactly what power rating and burnup new LWRs will have in 2035 the amount of MA produced in a LWR has been assumed to relate to the amount of spent fuel produced as described in section 2.6.2, which its self is multiplied by an isotopic vector of spent fuel from a PWR with a burnup of 50GWd/t.

4.6.1 Uncertainties in Cost

There is little information currently available on costs of new nuclear reactors. As there are few reactors being constructed around the world the most recent cost estimates of current examples were used. Where an error range has been stated from low to high costs such as those for the BN-600 and EFIT ADS in tables 2.7 and 2.9 respectively, the high costs have been used in the calculations. This is due to the fact that these reactors are the first of a kind of their design to be built and from previous experience such as the problems that occurred with the building of the EPR in Finland (section 2.4 [24]) it is very likely to foresee costs rising from what they are currently quoted.

Exchange rates will also make a difference. Different countries and entities publish prices in different currencies, mainly in Euros and US Dollars. As there is constantly a fluctuating exchange rate especially at this current time during a delicate economic climate it may be difficult to accurately predict a price of a new nuclear reactor in Euros if it is published in US Dollars and visa versa. Due to Sweden's location all prices were converted to Euros using current exchange rates at the time of writing.

Costs for other factors involved in the building of new nuclear reactors such as raw materials may also fluctuate between now and the time of construction.

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

Two scenarios for achieving a net zero production of minor actinides in Sweden beyond 2035 have been proposed. One consists of 8 light water reactors (LWR) and two BN-600 sodium-cooled fast neutron reactors (FR), the other consists of 9 LWRs and one accelerator-driven system (ADS) of the EFIT design. For an ADS to be utilised in Sweden, pyroprocessing technology for reprocessing of spent nuclear must be developed for use on an industrial scale for this to become a reality. Two BN-600 reactors can be utilised with existing PUREX technology for spent fuel reprocessing. Compared to a reference scenario where 10 LWRs operate beyond 2035, the total cost of all reactors will decrease when transmutation reactors are used, although the cost of power generation per MW_e increases by around 5% due to the lower power of transmutation reactors. Hence a power penalty over all reactors occurs with the introduction of transmutation reactors.

A scenario to reduce the minor actinide inventory in Sweden by approximately half has been found to consist of 8 LWRs, 1 FR and 1 ADS. As this scenario contains an ADS, it can only be achieved with the development of pyroprocessing technology.

In all scenarios there is a net production rate of plutonium over all 10 reactors in Sweden, although this rate decreases with the addition of transmutation reactors.

Scenarios to almost eliminate minor actinides in Sweden by 2095 have been found not to be achievable due to the requirement of transmutation reactors to use a larger amount of minor actinides as fuel that is available.

5.2 Suggestions for Further Work

The high hypothetical burnup rate of 10 kg/TWh_{th} of minor actinides in a BWR using MOX fuel with a hafnium cladding suggested by [21] proposes significant advantages in terms of reduced cost and power penalty if this technology was to be developed into a reality. It is therefore a suggestion that further research into burning minor actinides in a BWR using MOX fuel with hafnium clad is carried out.

Research on developing pyroprocessing technology for reprocessing of spent nuclear fuel to an industrial scale process is essential if a transmutation scenario involving ADS is to be utilised.

A compact ADS design [32] based on the EFIT design has been proposed. Nitride fuel was used in simulations and allows a reduction in core size and total power, while keeping the specific power the same, enabling the spallation target radius to be reduced. Further work could be carried out assessing if this design would be acceptable to implement into a transmutation scenario.

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