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A Cost Benefit Analysis of an Accelerator Driven Transmutation System

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Stockholm 2001

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ABSTRACT

This paper estimates the economical costs and benefits associated with a nuclear waste transmutation strategy. An 800 MWth, fast neutron spectrum, subcritical core design has been used in the study (the so called Sing-Sing Core). Three different fuel cycle scenarios have been compared.

The main purpose of the paper has been to identify the cost drivers of a partitioning and transmutation strategy, and to estimate the cost of electricity generated in a nuclear park with operating accelerator driven systems.

It has been found that directing all transuranic discharges from spent light water reactor (LWR) uranium oxide (UOX) fuel to accelerator driven systems leads to a cost increase for nuclear power of $50\pm 15\%$, while introduction of a mixed oxide (MOX) burning step in the LWRs diminishes the cost penalty to $35\pm 10\%$.

ACKNOWLEDGMENTS

I wish to thank my colleagues at the Department of Nuclear and Reactor Physics for their support. Especially I would like to thank Kamil Tucek and Janne Wallenius for their help in finding me material and crosschecking my calculations. I thank Waclaw Gudowski for supervising my work and giving me a far better understanding of how to write scientific texts.

I send special thanks to Luc van den Durpel of the Nuclear Energy Agency (OECD/NEA) who apart from arranging for my stay in Paris gave me a lot of inspiration.

I acknowledge the financial support from the OECD/NEA and from the Swedish Nuclear Fuel and Waste Management Co. (SKB AB).

DISCLAIMER

Paragraph six of the Swedish nuclear technology law reads:

”6 § Ingen får utarbeta konstruktionsritningar, beräkna kostnader, beställa utrustning eller vidta andra sådana förberedande åtgärder i syfte att inom landet uppföra en kärnkraftsreaktor.”

”6 § No one may prepare blue prints, calculate costs, order equipment or commit other preparative actions aiming at, within the country [Sweden], constructing a nuclear reactor.”

I hereby declare that, currently I have no intentions to build a nuclear reactor in Sweden.

ABBREVIATIONS

ADS	Accelerator Driven System
Am	Americium
BOL	Beginning of Life
BWR	Boiling Water Reactor
COE	Cost of Electricity
Cm	Curium
DOE	US Department of Energy
EOL	End of Life
ENEA	Italian energy agency
EPRI	US Electric Power Research Institute
FBR	Fast Breeder Reactor
GWd/t	Gigawatt days per tonne
Gy	Gray (J/kg)
HLW	High Level Waste
HM	Heavy Metal
IAEA	International Atomic Energy Agency
kgHM	kilogram heavy metal
kWe	kilowatt electric
kWh	kilowatt hour
LHC	Large Hadron Collider
LLFP	Long Lived Fission Product
LWR	Light Water Reactor
MOX	Mixed Oxide Fuel
MA	Minor Actinides
MWth	Megawatt thermal
O&M	Operations and Maintenance
PSI	Paul Scherrer Institute (Switzerland)
Pu	Plutonium
PUREX	Plutonium and Uranium extraction process
PWR	Pressurised Water Reactor
SSC	Sing-Sing Core
TRU	Transuranic elements
U	Uranium

1 BACKGROUND

1.1 Nuclear wastes

During its over fifty years of operation nuclear installations have been producing increasing amounts of highly radioactive waste. The spent fuel of the nuclear power plants contributes to the main part of the waste. In some countries nuclear weapon programs have also produced considerable amounts of radioactive wastes, however those wastes have different form and composition compared to the commercial nuclear wastes. Also industry and health care produce non-negligible amounts of radioactive wastes from their routine use of radioactive isotopes and advanced nuclear facilities, like particle accelerators.

1.1.1 Nuclear processes

In a nuclear reactor there are two dominating processes generating radioactive isotopes; nuclear fission and neutron capture. The dominating process is the nuclear fission reaction. A heavy element, e.g. uranium or plutonium, absorbing a neutron undergoes nuclear fission and forms two or three nuclei. Fission may produce any of the isotopes lighter than the element fissioned. However the most probable is, the heavy nucleus splits into two parts, one with a mass just above half the initial mass, and another with a mass just below half the initial mass. These fission products are in most cases radioactive isotopes decaying rather fast through a chain of beta decays. Only a few of the radioactive fission products, like ^{99}Tc , ^{129}I and some others, are long-lived.

The other process is the capture of neutrons. Uranium is the most abundant element in thermal reactors. With some finite probability uranium nuclei capture neutrons and - instead of fissioning - they form heavier isotopes. These isotopes decay through beta or alpha decay and form other elements. By successive neutron captures and decays, elements such as plutonium, neptunium, americium and curium are produced. These are often referred to as transuranic elements (TRU). If plutonium is excluded the group of elements is referred to as minor actinides (MA). The probability of neutron capture varies with neutron energy. This will show to be a very important property when designing reactors dedicated to burn minor actinides. Fresh light water reactor

(LWR) fuel consists of uranium oxide - UO_2 . About 95-97 percent of the uranium composition is ^{238}U and 3-5 percent fissionable ^{235}U . As the fuel in a reactor is burned out, the composition changes. When the fuel eventually gets removed from the reactor, it still consists of over 90 weight percent uranium. Most of the ^{235}U is burnt out, so the remaining uranium is mostly ^{238}U . There is about 0,7 weight percent ^{235}U left and there is also some ^{236}U , produced by neutron capture in ^{235}U .

About one weight percent of the spent fuel is plutonium. The minor actinides comprises another 0,1 weight percent. [1]

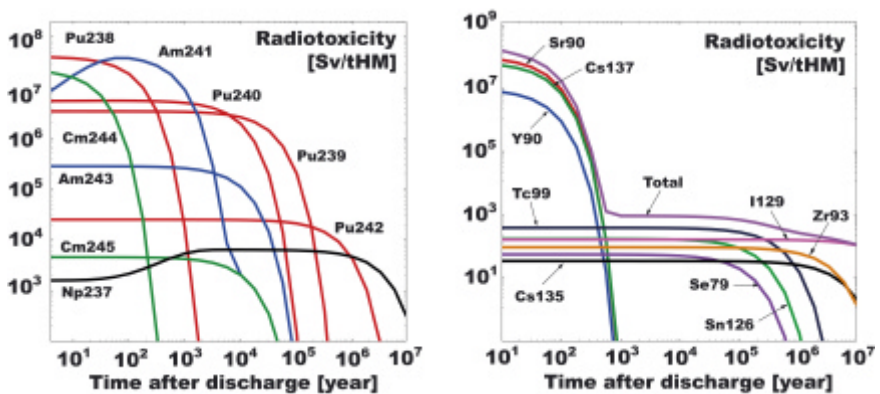


Figure 1: The radiotoxicity of spent UOX-fuel. The left graph shows the radiotoxicities of the transuranic elements. To the left the radiotoxicities of the fission products are shown. It is obvious from the graphs that the main problem in the short time scale is the fission products. The transuranic elements are the main problem on a long time scale [2].

1.1.2 Uranium and the transuranic elements

Uranium is from a radiotoxic point of view is not a major problem to the biosphere. The uranium isotopes found in nature have very long half-lives – Appendix A. Hence, they are not especially radioactive. Most of the fission products are short-lived in comparison to the transuranic elements. Typically their half-lives are less than 100 years.

¹See "The fission process", page 4

From the long-time waste management point of view, the heavy transuranic elements are the most problematic ones. They are still very radioactive, even though their half-lives are relatively long. Especially plutonium and americium are cumbersome due to their relatively high abundances. Neptunium and curium also appear in the spent fuel, but in significantly lesser amounts.

1.1.3 *Technetium*

As mentioned before, only a few fission products contribute to the long-time problems for waste management. One of them, ^{99}Tc with the half-life of 214000 years, may be a good candidate for transmutation through neutron capture. However storing ^{99}Tc geologically in Sweden does not pose a major problem. In the chemical environment of the Swedish granite bedrock, technetium does not exist in mobile forms. In the US geological storage in Yucca Mountain² though, ^{99}Tc is a problem since it is mobile in the acid chemical environment of the volcanic ashes found there.

1.1.4 *Iodine*

For most of the planned geological disposal sites ^{129}I will create problems due to its volatility and chemical reactivity. There are a few options to handle ^{129}I . Today the isotope is released into the atmosphere at reprocessing plants. This is a major radiation source to people working in the reprocessing industry. It may be possible to transmute ^{129}I if it is first formed into NaI . But it requires an isotopic separation from the stable ^{127}I -isotope in order to avoid the activation of ^{127}I . Another possibility is separating the iodine from the rest of the wastes, stabilise it as some chemical compound and finally put it into a geological disposal. Today release of the iodine into the atmosphere is considered to be a technically acceptable solution. However with increased reprocessing, ^{129}I release will at some point start becoming problematic due to the sixteen million year half-life and consequent build up of radioactive iodine in the atmosphere.

1.1.5 *Waste handling options*

Two methods are seriously considered to handle radioactive wastes. One is to isolate the wastes from the biosphere by placing them in a safe

²Yucca Mountain is the geological repository being built in the United States. <http://www.ymp.gov>

place, usually in a geological formation, and then wait for them to decay. Geological formations and a proper design of waste containers have to guarantee in practice “an eternal” isolation from the biosphere. Most nuclear countries try to adopt this strategy. Geological disposals are being planned in several places around the world. The setback of the repositories is their “eternity”. Since we have to wait for transuranic elements to decay, the time the storage has to be closed is in the order of several hundreds of thousands years.

One other possibility is to fission the minor actinides into lighter elements before storing them. Since the lighter elements have much shorter half-lives, a waste consisting of only fission products would need to stay for a considerably shorter time in the repository.

1.2 The fission process

In a fission reactor, the nuclei of heavy elements are split into lighter elements. The matter remaining after the process is somewhat less than the original mass. The difference has been transformed into energy.

The binding energies of nucleons – neutrons and protons - in different nuclei are different. Nuclei with an atomic mass of about 56 atomic mass units, thus containing about 56 nucleons, are the tightest bound. Heavier nuclei are less strongly bound. One would need to pull harder to pick out a strongly bound nucleon than a loosely bound one from a nucleus. Also one would gain more energy when merging an extra nucleon with a nucleus in the 56-nucleon area than with a heavier nucleus. Fissioning a nucleus implies going from a comparatively loosely bound structure to a more tightly bound one closer to the 56-nucleon area. The idea of a utilisation of nuclear power is to release the difference in energy between heavy and lighter nuclei, and to transform it into some useful energy like heat or electricity. The composition of the nuclei also has an impact on binding energy. An even number of both neutrons and protons (even-even) results in higher binding energy than a composition with an odd number of either neutrons or protons. Nuclei with odd numbers of both neutrons and protons (odd-odd) have low binding energies and are often very unstable.

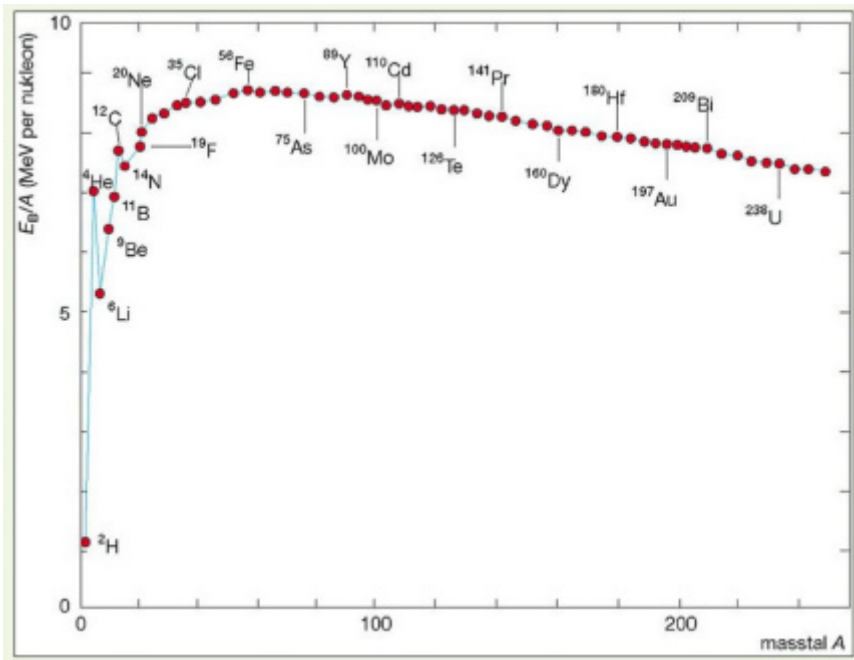


Figure 2: The binding energy per nucleon as function of mass number. The highest binding energies exist in the 56-nucleon area [3].

In principle all elements made up of more than 56 nucleons are fissionable. But in practice it is not so simple. There is a Coulomb barrier in the nucleus that has to be overcome. The nucleus simply prefers status quo. However, if the nucleus gets excited to an energy level above the Coulomb barrier, it will fission.

In a critical fission reactor, one uses a fuel of isotopes that have an even number of protons (e.g. Th, U or Pu) and an odd number of neutrons. When a neutron hits and penetrates a nucleus of such an isotope, the nucleus becomes even-even. Since even-even nuclei have higher binding energies some energy has to be released. This energy excites the nucleus and brings it over the Coulomb barrier. The nucleus fissions.

The transuranic elements in the nuclear waste are, from a waste management perspective, interesting to fission into lighter isotopes with shorter half-lives. However as discussed above not all isotopes are suitable of fissioning, particularly not using neutrons of low energy. Isotopes with even numbers of protons and odd numbers of neutrons

have the highest probability, i.e. cross-sections, for being fissioned with neutrons. Hence some isotopes have to be altered into fissionable isotopes to reach a reasonable probability of fissioning.

Proton and neutron contents changes in the reactor environment through neutron capture or alpha and beta decays. In a beta decay, the number of protons in a nucleus increases by one and the number of neutrons decreases by one. Phenomenologically it can be said that in a beta decay a neutron in a nucleus is converted into a proton, while releasing an electron and an accompanying anti-neutrino. A nucleon in a neutron environment always has a chance to capture a neutron. The probability, expressed by the nuclear cross-section, is different for different nuclei and for different neutron energies.

Moreover the neutron capture and fission rates are proportional to the density of capturing nuclei and to the neutron flux.

The neutron flux is given by

$$\Phi = \int_{v} n(v)dv \quad (1)$$

n - number of neutrons

v - neutron velocity

The reaction rate is given by

$$F = s\Phi NV = \Sigma\Phi V \quad (2)$$

s - microscopic cross section for the reaction

N - number of nuclei per volume in the target, number density

V - target volume

Σ - macroscopic cross section.

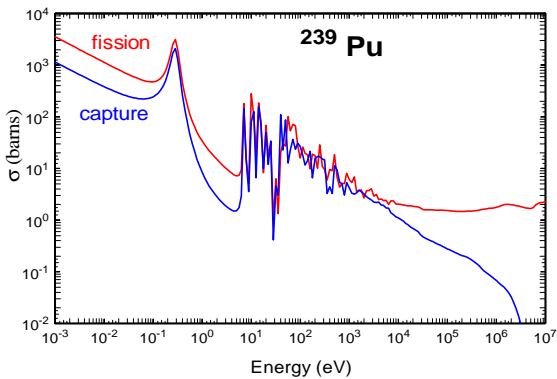
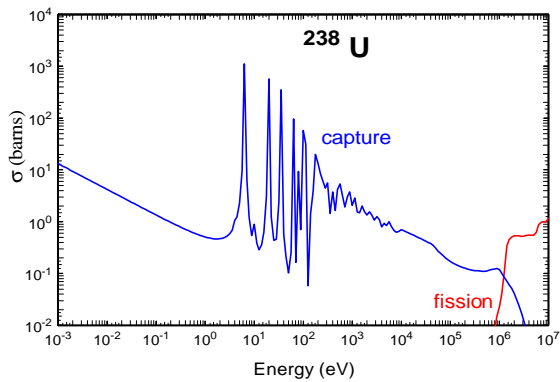


Figure 3: The neutron capture and fission cross-sections for ^{238}U and ^{239}Pu

In a critical reactor the neutron flux has to be high – in the range from 10^{13} to 10^{14} $\text{n}/\text{cm}^2\text{s}$ - in order to maintain the required power level determined by the fission rate. Fuel for critical power reactors is engineered to suit reactor operation. In a transmutation reactor the fuel must be different due to the different operational conditions. Fuel has to be designed to facilitate burn-up of a certain isotope mix as efficient as possible. The fuel designed for transmutation purposes will react differently than ordinary reactor fuel on temperature changes. The

temperature reactivity feedback is one of the main reasons why a transmutation system has got to have an external neutron source. The external neutron source ensures a subcritical operation with a required power level without a self-sustained chain reaction. Also the external source gives the possibility to counteract any undesired mode of operation or a power excursion.

Neutrons are really tricky to handle. They are not charged, so there is no simple way to accelerate them or to bend a neutron beam. The most efficient, intensive source of neutrons besides the fission process itself is spallation. Spallation is the process where neutrons are emitted out of nuclei in a powerful collision with a high-energy charged particle. For transmutation reactors proton beams hitting a target of a heavy material such as lead or tungsten are proposed as a neutron source. This is why we refer to these reactors as Accelerator Driven Systems (ADS). The spallation target would be located in the middle of the reactor core. By controlling the proton current from the accelerator, the reactor power could be altered.

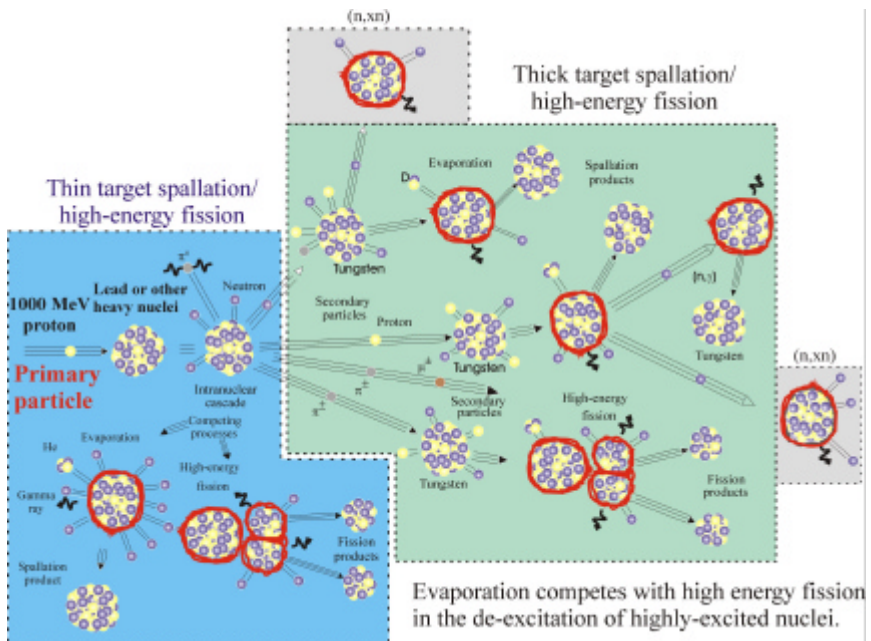


Figure 4: Spallation processes [4]

Throughout the ADS operation fuel composition constantly changes as heavy nuclei fission into lighter ones and neutrons are captured by nuclei. When the amount of heavy elements decreases, the beam power, and hence the neutron flux, has to be increased to maintain the required power level. Eventually there is not enough fissionable material left to maintain the ADS operation. The decrease of transuranic isotopes up to this point is called the burn-up of the system. When designing an ADS system, a high burn-up is very desirable because it determines the transmutation efficiency. The ultimate goal is to fission all of the transuranic atoms. A high burn-up system can achieve this faster and cheaper. Another important design parameter is the beam power. For economical reasons it is desirable to construct a system with a low beam power. For safety reasons the reactor should be sub-critical with some margin to becoming critical. It is also desirable, both for economic and safety reasons, to run the reactor with the same beam power all the time. Running an ADS with a large variation of the beam power may be risky because of the potential increase in beam power, which would immediately be followed by an increase in reactor power.

2 GOAL AND METHOD

The nuclear fuel cycle is the whole path of the reactor fuel from the mine to the final disposal. In a once through fuel cycle material is used only once. A closed fuel cycle involves recycling of reactor fuel in order to utilize fissile isotopes built up from ^{238}U . Closed fuel cycles use significantly less uranium and also produce far less waste than does the once through cycle. The somewhat misleading phrase “closed” suggests the same fuel would be used forever. This is not true of course, but the fuel does get used much more efficient than in the once through cycle. The closure of the nuclear fuel cycle is an important research topic in many countries. Several designs of ADS have been proposed to address this issue [5], [6]. Also several fuel cycles are being discussed. Some aspects of the fuel cycles are of a special interest. First, the transmutation efficiency is very important. The efficiency is strongly connected to the time needed and the cost to transmute the wastes. Radiation hazard is another important issue. Transmutation will increase safety for human generations to come. However it might increase the exposure of radiation to people living today. The risk of proliferation of nuclear weapon usable materials has to be given serious concern. In a fuel cycle with extensive reprocessing it will be easier to find highly enriched elements compared to the once through fuel cycle. However, after a few hundred years of storage, disposed wastes from light water reactors will make up a prime plutonium ore. It will be possible to mine the plutonium, as radioactivity will have become low enough for industrial handling of the material. Geological disposal means postponing the proliferation risks.

On top of these aspects, there is the question of economics. The technology for accelerator driven transmutation and for the reprocessing seems realistic today without major unresolved technical issues even if some elements of these technologies require very intensive development. Moreover there is no consensus on the costs for implementation of a transmutation strategy on a large scale.

When assessing costs of a complex technological system, there are two main strategies to choose between. One may either adopt a bottom up or a top down approach. A bottom up strategy means calculating the costs of individual components and eventually summing up to reach an overall cost estimate. The top down approach is based on unit costs estimations for flows through different parts of the system.

In this paper a top down approach has been used to calculate costs for a fuel cycle based on the Sing-Sing core design [7] considering a Swedish perspective³. A rather simple model based on unit costs, mass flows and losses have been used to calculate fuel cycle costs and costs of electricity.

All calculations have been performed assuming a steady state, where all mass flows have levelled out. In practice steady state is a very unlikely situation. It would take a very long time to reach steady state. More likely is a situation where Sweden builds ADSs that in the beginning run together with LWRs. Eventually the LWRs are closed and the transmutation of waste continues for the following century⁴ or so.

³Please read disclaimer, page iii

⁴Transmuting the last fuel would take a very long time since the amounts get so small. It would be reasonable to cooperate between countries to handle the last wastes. The “one century” mentioned is meant to give the reader an order of magnitude, not as an exact prediction.

3 PRESENT KNOWLEDGE

There is a lot of information available on the costs for running light water reactors. Costs of uranium, LWR fuel fabrication and so on are well known. There are also several estimates published concerning the short and long-term developments of these costs. Also the costs of producing, burning and reprocessing mixed oxide fuels (MOX) are fairly well known.

The EPRI report “A Review of the Economic Potential of Plutonium in Spent Nuclear Fuel” from 1996 [18] contains an Appendix C in, which the breakeven uranium ore cost for plutonium to be a competitive fuel is calculated. Several interesting cost estimations were performed in this work.

The Global ‘95 international conference on evaluation of emerging nuclear fuel cycle systems contains new estimations of fuel cycle costs. B. G. Chow wrote “Plutonium Economics and the Civilian Nuclear Future” where both MOX fabrication and reprocessing costs are presented together with estimations of fixed charge rates for nuclear power investments [17].

The OECD/NEA produced several reports on nuclear fuel cycles over the years. The most recent OECD/NEA publication containing a lot of information in this field is the not yet published “Trends in the Nuclear Fuel Cycle” [16].

Both American and European scientists published “roadmaps” for accelerator driven transmutation of nuclear wastes [5], [6]. The two reports are suggestions on how to reach a situation with a running transmutation system, starting from the present situation. This includes estimations of the associated costs of research and construction.

The advanced fuel cycles though are not as well examined. Experience originates mainly from fast reactor programs. A few estimates have been done concerning reprocessing of and fuel fabrication from really radioactive material. Two reports are the prime sources of information in this field. There is the US ATW roadmap [5] and there is the MIT-NFC-TR-019 by D. Kim et al. [22]. Both reports try to find the costs of the advanced fuel cycles. However since there is basically no industrial experience in this field, all figures originate from small scale experiments and subsequent estimations.

Fuel cycle calculations for advanced nuclear fuel cycles have been performed. R. A. Krakowski of PSI in Switzerland has been working on

this for a long time [27]. Those calculations were based on a number of unit costs and parameters. Krakowski spends a lot of effort on analysing the sensitivity of his results. The calculations performed in this work are similar to the ones performed by Krakowski, but have been tailored to fit the Sing-Sing core design.

4 TRANSMUTATION

4.1 Physical properties of ADS

The goal of an ADS is to decrease the long-lived radiotoxic inventory of finally disposed waste. The main contributors to the spent fuel radiotoxicity are - in a long time perspective - the transuranic elements - Figure 1. We are interested in transmuted those into short-lived fission products. When designing a transmuter, one has to look for a design that favours the fission reactions of the transuranic elements over the capture of neutrons in those elements. Energy dependence of neutron cross sections show - Figure 5 - that the fission to capture ratio goes up with increasing neutron energy for all the isotopes of interest. However working with a harder⁵ neutron spectrum in combination with the decrease of the uranium content of the core leads to some operational control problems.

A reactor working with neutrons in the thermal⁶ spectrum is dependent on a medium moderating the neutrons to thermal energies. A good moderator is water, which can also be used as coolant. In a water cooled, water moderated reactor, loss of coolant will lead to a decrease of reactivity and consequently to reactor shutdown. In nuclear systems with fast neutron spectrums use of water is clearly prohibited by physics since water is an efficient moderator that thermalizes the neutrons. Therefore other coolants are used such as Na, Pb, Pb/Bi or gas. Loss of coolant⁷ in such a system in most cases increases the reactivity and contributes to dangerous positive temperature reactivity feedbacks.

⁵ A hard neutron spectrum is a high-energy neutron flux.

⁶ Thermal neutrons have low energies, typically in the order of 0,25 eV.

⁷ Metal coolants are the most common.

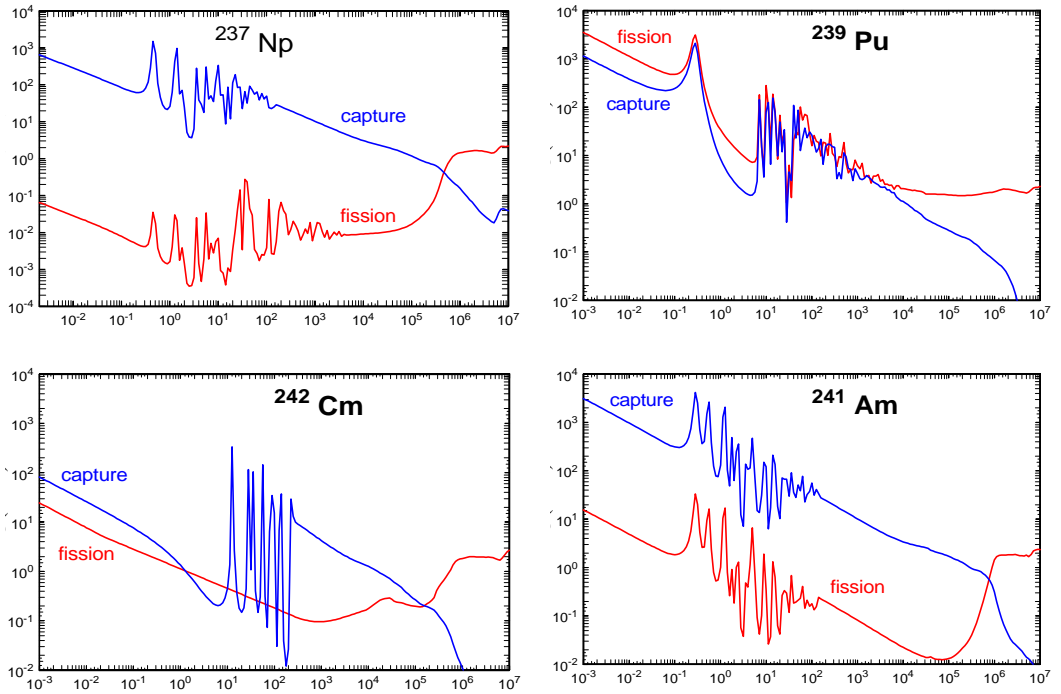


Figure 5: The neutron capture and fission cross-sections for some important transuranic elements. At high neutron energies fission dominates over capture.

The Doppler effect in uranium fuel ensures another important feedback in light water reactors. When temperature of the reactor fuel increases the nuclei in this fuel get higher thermal vibrations. This process increases the neutron capture probability due to the Doppler effect in neutron capture cross-section⁸ resonances. The Doppler effect gives a prompt negative feedback to temperature increases by increasing the capture of neutrons. This effect is especially strong for ^{238}U , having very large resonances. However, capture reactions in ^{238}U leads to increased production of transuranic isotopes. The purpose of the transmuter is to reduce the amount of transuranic material. Hence ^{238}U content in the transmuter has to be kept as low as possible. Absence of

⁸The cross-section is a measure of the interaction probabilities between particles. It is expressed as the area of a particle “seen” by another particle. The unit is “barn”. $1 \text{ barn} = 10^{-28} \text{ m}^2$.

^{238}U severely reduces the negative Doppler feedback to reactivity.

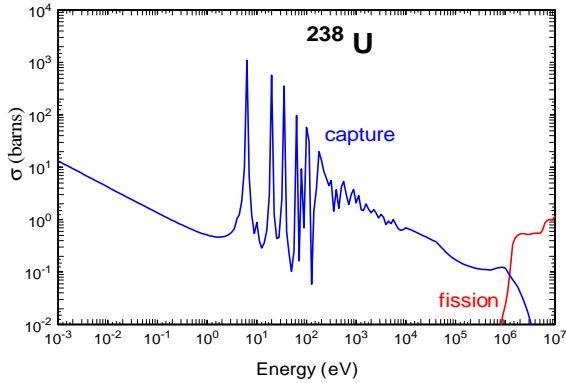


Figure 6: ^{238}U has very strong resonance peaks, which Doppler effect broadens when temperature increases.

The smooth and reliable power control of the thermal reactors fuelled with uranium is ensured by a control of the delayed neutrons. Delayed neutrons are released from fission products within seconds after the fission reaction. The neutrons released directly in the fission reactions are referred to as prompt neutrons. The life time of the prompt neutrons in a reactor core is orders of magnitude shorter than the time delay corresponding to release of delayed neutrons. Therefore, the thermal reactor is designed in such a way that prompt neutrons themselves are not sufficient to maintain the self-sustained chain reaction. The delayed neutrons constitute for those extra neutrons needed for the reactor to become self-sustained, i.e. critical. Since these neutrons are released after much longer time compared to the life-times of prompt neutrons, the reactor operation is determined by these longer time-constants. It is virtually impossible to control a reactor which runs on prompt neutrons only, the increase of power is driven by the very fast increase of neutron flux determined by the short life-time of the prompt neutrons. These changes are very rapid compared to the thermal hydraulic time constants determining efficient cooling of the reactor core. The delayed neutrons appear relatively abundantly when fissioning uranium. With plutonium or minor actinides as a fuel the fraction of delayed neutrons is reduced significantly.

In conclusion, when replacing the uranium fuel with transuranic fuel and simultaneously hardening the neutron spectrum, all three major phenomena of inherent safety of the thermal uranium reactor are lost. Something has got to be done in order to improve the safety of the transmuter.

To increase the safety of the transmuter, the best solution is not to let the fission reaction be self-sustainable. This solution requires an external neutron source, which constantly supplies the reactor with the extra neutrons needed to maintain the fission reaction rate under normal operation, and cuts the neutron source in case of unexpected events. Such a system would operate in steady state until the external neutron source was switched off.

4.2 System design

4.2.1 Accelerator

An accelerator driven transmutation system consists of four main parts; the proton accelerator, the spallation target, the reactor core and the fuel reprocessing facility.

The accelerator has one task only. It should deliver an intense and reliable current of protons. Beam stops are very undesirable, since a loss of beam shuts down the nuclear reaction. There are a few options for accelerators needed for ADS. First of all a decision has to be made whether to use a linear accelerator or a cyclotron⁹. A second choice is whether to use one or several accelerators per reactor. Using more than one accelerator decreases the probability of reactor shutdown due to beam stops. But cost may also increase. A different option is to use one (or more) very powerful accelerator and split the beam between several cores. This solution was suggested by the US ATW roadmap [5]. However there is a major safety concern to this kind of solution. If the beam would lock on one of the cores when operating at full power, the sudden power increase at this core would most probably lead to a severe accident. For such a design a single beam stop would lead to the shutting down of several transmuters simultaneously. If the transmuters are to be used for electricity production, this raises very high demands on the electrical grid, especially on reserve capacity.

⁹The characteristics of accelerators are discussed in a separate chapter.

4.2.2 Target

The spallation target is to be manufactured from heavy elements, having neutron rich nuclei with small cross-sections for neutron capture reactions. Lead, lead-bismuth eutectic alloy and tungsten have been suggested. As the spallation target is placed inside the reactor core, the temperature is rather high. Both lead and bismuth are present in their liquid states.

4.2.3 Target window

The accelerator beam pipe has to operate under vacuum. But, it still has to stay in contact with the liquid metal spallation target. A kind of “window” has to be placed in between the beam pipe and the spallation target. This spallation window has got to be thin to let through most of the particle beam. But, it will also have to be extremely radiation resistant in order to withstand the intense particle beam passing through it. In fact radiation induced material damage to the spallation window is one of the main stumbling-blocks of transmutation research. It might be necessary to replace the spallation window even more often than once per year [8]. Keeping down the lengths and number of transmuter stops is a main economic concern.

4.2.4 Core

Surrounding the spallation target is the subcritical reactor core. It consists of the fuel elements with isotopes to be transmuted. Important design parameters are burn-up and power peaking¹⁰. Power peaking is the relation between the highest and lowest unit power in the core. Since a major limitation to reactor construction is the allowed upper fuel temperature, a homogeneous temperature distribution, and thus a low power peaking, is desired.

4.2.5 Reactor criticality

The criticality of the reactor core is determined by the parameter k_{eff} . The value of one corresponds to the reactor operational conditions called shortly - “criticality”, which can be understood as the constant fission rate in a reactor, where one fission process generates only one

¹⁰The power peaking is the relation between the highest and lowest power densities in the core. Since upper temperature is a limit to construction, the power density should ultimately be kept constant all over the core.

consequent fission, i.e. only one neutron from the fission generates the next fission. Fission process in this mode is self-sustained. A subcritical reactor operates at a k_{eff} values less than one, where the nuclear fission chain is not self-sustained.

Reactor reactivity is defined through k_{eff} as:

$$\mathbf{r} = \frac{k_{eff} - 1}{k_{eff}} \quad (3)$$

\mathbf{r} - reactivity

k_{eff} – k-effective

Safety problems may arise from uncontrolled increases in reactivity. Should anything happen which causes k_{eff} to rise above one, the reactor power starts increasing. The higher the value of k_{eff} , the faster the power increase. A reactor operating with a value of k_{eff} far below one is less probable to reach a value of k_{eff} larger than one, and is thus safer than is a reactor running with k_{eff} close to one. But, the smaller we make k_{eff} , the more neutrons have to be added to maintain the chain reaction. This means more power has to be added to the accelerator generating the spallation neutrons. Of course from an economic point of view this means the amount of energy available to be sold to the grid will decrease. Choosing a proper value of k_{eff} becomes a delicate problem where the choice between safety and the benefits of the transmuter.

The value of k_{eff} is determined by many parameters of the reactor core, like geometry, enrichment of the fuel, type of the fuel and presence of neutron absorbing materials etc. The burn-up of the fuel also causes changes of k_{eff} . It is desirable to keep k_{eff} constant because changes in k_{eff} will lead to the altering of beam power. This in itself is a safety problem. The accelerator driven system has to be constructed in such a way, that a proton beam will be turned off when reactor power increases too quickly. In order to function automatically this switching off has to rely on phenomena like thermal expansion or pressure.

4.3 The Sing-Sing core design

A design for a 1200 MWth transmutation core called the “Sing-Sing Core” (SSC) was suggested by Wallenius et al [7]. The main proposal of the authors is to introduce large amounts of burnable absorbers into the core. Boron carbide ($^{10}\text{B}_4\text{C}$) effectively absorbs thermal neutrons.

Because of high capture cross-sections, thermal neutrons are undesirable in a transmuter. The absorbers leave the fast neutrons that have far more favourable capture to fission probability ratios. Hardening the neutron spectrum also decreases core power peaking. A major benefit from the introduction of the absorbers is the decrease in neutron capture in ^{241}Am . This capture reaction is a problem since americium alpha-decays and produces helium. The helium production raises the pressure within the fuel pins and eventually destroys them. In a uranium fuelled reactor, neutron economy is a very important design parameter. Introducing neutron absorbers into such a reactor may jeopardize the criticality of the reactor. However fissioning minor actinides gives a far better neutron economy. There are more neutrons released in an average fission reaction, which makes the use of absorbers possible.

The SSC uses a nitride fuel matrix. Nitride fuel was chosen because of its high actinide content compared to oxide fuels, and the possibility of reprocessing using traditional aqueous methods. Even if a primary choice for transmutation systems is pyrochemical reprocessing opening possibilities for reprocessing of highly radioactive fuel and consequently shortening fuel-recycling times, such technology is not readily available today though. This gives reason to keep the possibility of using aqueous reprocessing.

The spent LWR fuel is assumed to have cooled down in the interim storage for about thirty years before it enters the transmutation cycle.

4.3.1 Coolant

As coolant, liquid lead-bismuth eutectic has been proposed. Lead-bismuth has a very high boiling point. The loss of coolant due to temperature increases and subsequent boiling is unlikely when using lead-bismuth. The neutron capture cross-section is very low which makes the lead-bismuth almost transparent to neutrons. Lead-bismuth has got a high scattering cross-section that helps distributing neutrons evenly throughout the core. Table 1 summarizes physical properties of the main reactor coolant candidates.

	ρ g/cm ³	T_{melt} °C	T_{boil} °C	C_p kJ/kg, °C	V m/s	k W/m×°C (~400C)	h heat transfer coeff. kW/m ² ×°C
Na	0.82	98	880	1.3	6	75	132
Pb/Bi	10.73	123.5	1670	0.15	3	13	29
Pb	11.07	327.4	1737	0.15	3-4?	16	23
Hg	13.2	-38	357	0.14	6	12	32
NaK (56/34 w%)	0.78	18	826	1	6	29	20
H₂O 12MPa	0.75	-	325 (sat)	5.2	4-5	0.6	30

Table 1: Physical properties of major reactor coolant candidates

Setbacks of using lead-bismuth are several. Neutron capture in ²⁰⁹Bi produces ²¹⁰Bi, which, with a half-life of 5 days, decays to ²¹⁰Po. The ²¹⁰Po is a very mobile isotope, which alpha-decays in 138 days. It is thus very radiotoxic. Further lead-bismuth is very corrosive and may cause severe material damages. Corrosion of Pb-Bi eutectic may be controlled dynamically by creation of an oxide film on fuel cladding and reactor parts. This oxide film is destroyed if temperature is raised over 620°C or coolant flow exceeds 3 m/s. In practice this reduces coolant temperature to 550°C. An alternative to using lead-bismuth would be using sodium as coolant. Sodium has better thermo dynamical properties – see Table 1, needs less pumping effort and is less corrosive than is lead-bismuth. However sodium is very inflammable in an oxygen environment. Using sodium would mean a major risk of fires and explosions. The choice of lead-bismuth is mainly due to its high boiling temperature and to the safety concerns of sodium.

4.3.2 Core design

The SSC is divided into four fuel zones - Figure 7. The innermost zone is a so-called driver zone designed mainly for efficient neutron multiplication. Here ²³⁸U is introduced to enhance neutron production. Zone two is similar to zone one, but also contains ⁹⁹Tc to be transmuted. The outer zones, three and four, are the main transmutation regions in

the reactor. Fuel in these two zones contains mainly minor actinide nitrides. In these zones the absorber pins are also introduced. With the suggested composition, the SSC reaches a TRU burn-up of 12,4 percent in 600 days.

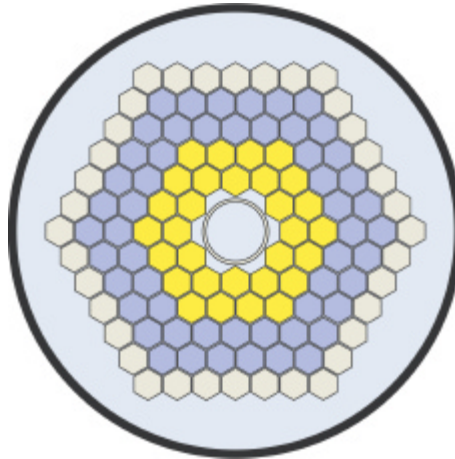


Figure 7: Sing-Sing core sketch. The spallation target is located in the centre of the core [1].

5 FUEL CYCLES

Three different fuel cycle scenarios are considered in this paper. The main idea is to examine the benefits and associated costs of using a Sing-Sing type transmuter in a closed nuclear fuel cycle.

As reference case, the once through fuel cycle is assumed. In the once through cycle, uranium ore is mined, after enrichment the uranium is sent to a fuel fabrication facility where it is turned into uranium oxide fuel bundles. The fuel stays in the reactor for five years leading to a burn-up of just above 40 GWd/t. A burn-up of 40 GWd/t is realistic for Swedish BWRs. Spent fuel is left to cool for forty years after which it is encapsulated and deposited into a geological storage.

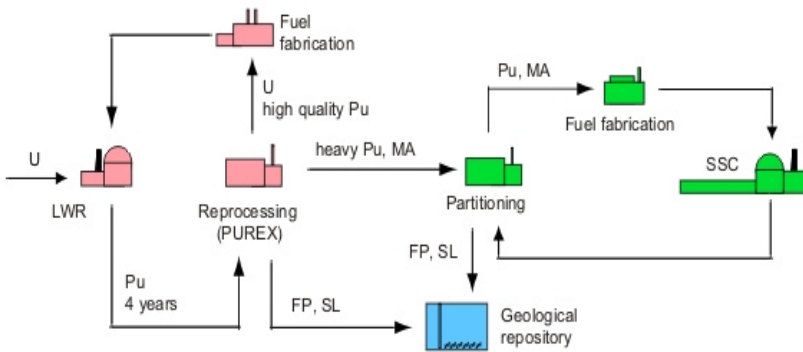


Figure 8: Sketch of a fuel cycle with recycling of Pu in LWRs and burning of transuranic elements in Sing-Sing reactor (FP-fission products, SL-separation losses, MA-minor actinides) [2].

A closed fuel cycle including an accelerator driven system would look like the once through fuel cycle up to where the fuel is removed from the light water reactor. Instead of depositing the spent fuel, it is reprocessed in an aqueous process. Plutonium and the minor actinides are extracted from the spent fuel. The losses of the process are treated as high-level waste and deposited in a geological storage. Irradiated depleted uranium is the main reprocessing product. It is not very radiotoxic and is no longer high-level waste. The transuranic elements

and long-lived fission products are fabricated into nitride ADS-fuel. Due to the high Am and Cm content the fuel is very radioactive after irradiation in the ADS. Since the burn-up in the ADS is far from complete the fuel has to be recycled and the isotopes resent to the fuel fabrication facility. Because of the radioactivity, ADS fuel should ultimately be recycled using pyrochemistry in order to keep down fuel recycle times. In the reprocessing short-lived fission products are sorted out and sent to the geological storage.

A developed alternative to the ADS fuel cycle is the introduction of a LWR-MOX step. With this strategy mixed-oxide fuel (MOX) containing plutonium is loaded into light water reactors. A great part of the plutonium is burned in the LWRs. The ADS takes care of the surplus plutonium, the rest of the transuranic elements and of the long-lived fission products.

6 ACCELERATORS

High-energy protons are produced in particle accelerators. Two main types of accelerators are suitable for spallation. Cyclotrons, in which the particles are accelerated in a loop, and linear accelerators in which the particles pass through the linear beam pipe only once. Neutron yield of the spallation is dependent on the incident proton energy, the target nuclei and on the spallation target design.

6.1 Cyclotrons

A cyclotron accelerator is a circular device consisting of areas with and without electric fields. Two half-spheres are separated by a gap. The particles start out in the middle of the cyclotron. They are accelerated over the gap by an electric field. After the acceleration they enter a metal half-sphere where the electric field is zero. Here, the particle beam is bent 180 degrees by a strong magnetic field. Then, the beam enters the acceleration gap again. The electric field is produced by alternating current, so this time the voltage has shifted and the field has been redirected.

As the energy of the particles increases they circulate further away from the centre of the cyclotron. Hence, the path travelled every turn grows longer. However, the increased speed compensates exactly for the increased distance – the frequency remains constant.

The cyclotron is a simple accelerator with one major setback. As particles reach relativistic energies, their momentum changes according to:

$$p = gmv \tag{4}$$

$$g = \left(1 - \frac{v^2}{c^2}\right)^{-1/2} \tag{5}$$

p – particle momentum

v – particle velocity

c – speed of light

The relativistic effect causes the particles to move to slowly and get out of phase due to the increased energy needed to increase particle velocity. This gives an upper limit to proton energy around 40 MeV. The problem of relativistic effects can be overcome by altering the frequency of the electric field. A cyclotron where the electric field varies with the radius is called a synchrocyclotron. Particle energy in the synchrocyclotron is limited by cost. A 500 MeV synchrocyclotron is in the order of hundreds of millions of dollars. The cost is believed to increase as the cube of the energy [3], which means a 5 GeV synchrocyclotron would cost hundreds of billions of dollars.

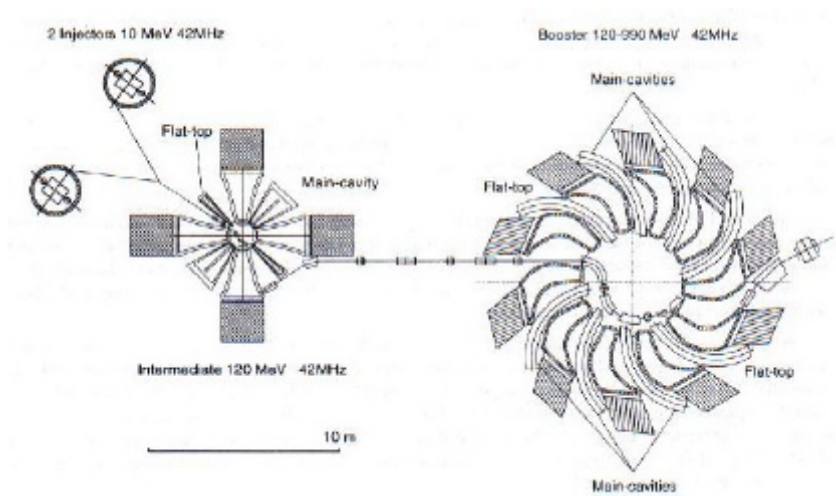


Figure 9: Sketch of a proposed ADS cyclotron [4].

If both the frequency of the electric field and the strength of the magnetic field are altered energy may be increased at a more modest cost. This kind of cyclotron is called synchrotron. In the synchrotron, the particles follow the same path during the acceleration. As particle energy increases the power to the bending magnets is increased and also the frequency of the acceleration field is increased. There are a few really big synchrotrons built. The LHC (Large Hadron Collider) currently being constructed at the European particle physics laboratory CERN in Geneva will be able to reach energies above 1 TeV. Still however, the particle current in such an accelerator is rather small. To run an ADS a current of 5 to 40 mA of 1 GeV protons may be needed. Today there is no synchrotron that can deliver a sufficient current for

the ADS, but it is believed that it will be possible to reach such currents with two or three synchrotrons working together [9].

6.2 Linear accelerators

Acceleration of particles in a linear accelerator is based on the same principle, as is the cyclotron. Particles are accelerated over evacuated gaps by an alternating current. As the voltage changes the particle travels through a field free “drift tube”. The main difference to cyclotrons is that the beam travels along a linear path. No bending magnets are needed. Loss of beam focus problems are almost eliminated.

As particle velocity increases the length of the drift tubes has to be increased. Linear accelerators tend to be very long. When energies increase linear accelerators grow expensive compared to circular accelerators. However, linear accelerators may produce larger currents than synchrotrons and one linear accelerator will be able to run the ADS alone.

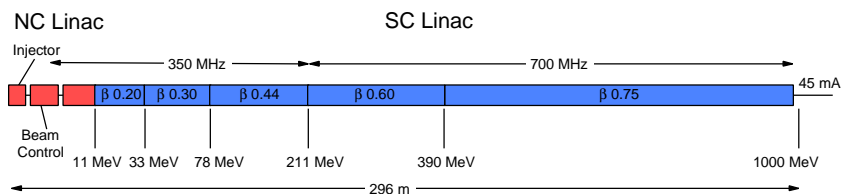


Figure 10: Linear Accelerator [10]

7 PARTITIONING TECHNIQUES

All nuclear fuel cycle strategies except from the once-through cycle require partitioning of radioactive material. In the simple case MOX fuel is manufactured from uranium and plutonium from spent fuel. More advanced strategies may involve fuel mixed with minor actinides, such as MINOX-fuel. Some strategies even involve the transmutation of fission products. These strategies all need reprocessing. The elements have to be separated to make construction of advanced fuels and transmutation targets possible.

Many methods of partitioning have been proposed, but today only the aqueous PUREX process is used industrially for commercial purposes. There are a few important aspects when discussing partitioning methods. The main limiting factors today are losses and costs. Losses have to be very small in order to reduce the amounts of secondary wastes. With transmutation, the losses together with the burn-up in the ADS decide the efficiency of the entire fuel cycle.

Safety is another important issue. An industrial scale reprocessing plant holds huge amounts of radioactive material. Both radiation hazards to workers and to the environment have to be considered. Also, the separating of plutonium, thus making it attainable for potential weapon makers, has to be given serious consideration.

7.1 Liquid – liquid aqueous partitioning

The partitioning technique that is used predominantly in industry today is called PUREX (plutonium-uranium extraction). It is a hydro metallurgical process. Variants of the process have been used for forty years to partition spent LWR fuel.

The principle of liquid-liquid aqueous partitioning is the following. The spent fuel is dissolved in an acid. In PUREX nitric acid is used. This aqueous phase is put in contact with an organic phase with some organic molecule¹¹ dissolved in a hydrophobic solvent. The molecule extracts metals from the aquatic solution. In PUREX uranium, plutonium and neptunium can be extracted. Extracting americium and curium is difficult; they are both trivalent and mix with trivalent lanthanides. As the organic molecule has picked up the metals, the

¹¹ For the PUREX process tri-butyl-phosphate (TBP) is used.

aqueous and organic phases are separated. The metals are then stripped from the organic molecule into another aqueous solution. By changing the valence of plutonium from IV to III, plutonium can be extracted from uranium. The losses in aqueous reprocessing are small, PUREX shows losses in the order of 0,01 percent.

There are some major setbacks to the PUREX technique. As discussed it cannot separate trivalent actinides from trivalent lanthanides. Several lanthanides show strong neutron capture resonance. However, if running the transmutation process with a hard neutron spectrum, the problem of neutrons getting captured in lanthanides becomes smaller compared to when running with a thermal spectrum [11]. Also, the organic molecules are sensitive to radiation. Hence hot fuel with high americium and curium contents have to cool before reprocessing, or it will destroy the organic molecules. In an advanced fuel cycle with, for example, an ADS present, the cooling would significantly lengthen the times needed to transmute the transuranic elements. However for reprocessing LWR spent fuel PUREX works fine. Even the hotter LWR-MOX fuel can be reprocessed if it is diluted with ordinary LWR fuel.

There have been a few aqueous processes suggested to deal with the minor actinides. These are all based on organic molecules that extract the transuranic isotopes from some acid solution. Much research effort is being performed around the world to improve these techniques. The efforts are concentrated on finding molecules that extract the metals without binding them to hard to strip them again. These molecules also have to be soluble in some liquid that does not mix too much with water. Today there are laboratory scale processes that can separate transuranic elements (TRU) with small losses. But still the problem remains to find extraction molecules that withstand intense radiation and which is not too expensive for industrial applications.

7.2 Chromatographic reprocessing

Chromatographic methods are similar to the liquid-liquid aqueous ones. The dissolved waste passes through a column filled with ion exchange resins. Different resins might be placed in the column, thus extracting different elements at different positions. The elements are then released from the resins using some other solution. As with aqueous partitioning the main problem is the radio sensitivity of the organic molecules. Today there are molecules that can withstand about 10^4 Gy [12]. The hot fuels will give much higher doses though.

7.3 Pyrochemical partitioning

There are some partitioning methods that do not involve any aqueous technologies but rather molten salts. These are referred to as pyrochemical partitioning methods. Pyrochemical methods were developed early before the PUREX process got into use.

There are two main methods of pyrochemical partitioning. The one primarily considered for advanced fuel cycles is electro refining. The electro refining process uses the differences in redox potentials of the actinides, fission products, cladding material and process construction materials. The fuel is released from its cladding, chopped and put in an anode basket. The anode is placed in a molten lithium-potassium salt. By altering the voltage between the cathode and the anode, one element at a time can be extracted. After some time the salt gets polluted with fission products and has to be purified. Research in this area is underway. The purification is based on a liquid salt – liquid metal process. Today, the main difficulty of electro refining is keeping away oxygen and water from the argon atmosphere that surrounds the molten salt. More than a few parts per million of those gases in the atmosphere would ruin the extraction process. Also the purification of the salt at an industrial scale is a major engineering task that has got to be managed.

The other pyrochemical partitioning method is based on chemical reactions in molten oxochlorides and oxofluorides. This second method has been used a lot by the Russians to separate uranium and plutonium from the minor actinides. However it is almost impossible to then separate the minor actinides from the lanthanides. This is because the metals gets poisoned by oxochlorides and oxofluorides. Pyrochemical reprocessing has one major advantage to aqueous reprocessing. The process is very insensitive to radiation. It is possible to partition hot material directly without cooling. Problems arise because of the radiation hazards to process personnel, but the process itself will withstand extreme radiation doses. However the need for radiation shielding when partitioning highly active material makes the process expensive. On the other hand a pyrochemical facility may be very compact and potentially generates small amount of secondary waste streams.

8 UNIT COSTS

A top down approach has been used to calculate the costs of nuclear fuel cycles. Using this approach, unit costs control total costs. The estimated unit costs are multiplied by for example material flows or installed power. Summing together gives the total cost of the entire system. This total cost can easily be transformed into for example the unit cost of produced electricity.

The alternative is to use a bottom-up strategy where explicit costs for different processes are summed together to give the total cost of the system. The top-down strategy was chosen due to the large technological uncertainties in the technologies connected to some of the unit costs. It is in some cases simply not possible to guess the explicit cost of a process. Estimations based on the costs of similar processes have to be used. A bottom-up approach does not allow for this.

8.1 Calculation models

In estimating the costs two economical models have been applied. With increased experience technology gets cheaper. Costs for design and construction decreases. This is known as the learning effect. For nuclear power a learning rate of 5.8% applies [13], meaning costs fall by this amount for every doubling of experience. Costs of operations are usually estimated to rise over time as maintenance costs are estimated to increase. Here, steady state is assumed, operation and maintenance (O&M) costs are assumed constant as installations are assumed being of different ages.

Second a model for calculating the economies of scales has been used. The idea of the model is that bigger plants are relatively cheaper than smaller ones. The following expression has been used.

$$C_n = C_o \times \left(\frac{K_n}{K_o} \right)^X \quad (6)$$

C - cost (o: reference, n: scaled cost)

K - capacity (o: reference, n: scaled capacity)

X - 0.6 for reactor systems, 0.7 for fabrication and reprocessing [14]

Further all monetary values were recalculated to 2001 dollars. In doing this recent exchange rates have been used. The inflation has been set to being three percent over all time.

Comparing costs and the value of money is problematic. Costs develop differently in different countries and in different industries. Thus, it is not so easy as to just recalculate between currencies using the exchange rate valid at the time the figure was given. The average inflation approach was chosen. It does give some errors, but those errors are assumed being rather small in comparison to the errors included in unit costs themselves.

8.2 Description of unit costs

Unit costs are summarized in Appendix B.

8.2.1 $Cost_U$ – Cost of natural Uranium (\$/kg)

Natural uranium prices are fairly easy to estimate in the short time scale. However in the longer time scale the price is not as obvious. The price today is about 40 \$/kg. The unit cost was chosen to 30 \$/kg [15]. OECD/NEA [16] suggests 20 \$/kg as lower and 80 \$/kg as upper bound for uranium price fluctuations.

8.2.2 $Cost_{Uconv}$ – Cost of Uranium conversion (\$/kg)

The cost for uranium conversion has been chosen to 5 \$/kg. A lower limit estimation is 3 \$/kg and an upper 8 \$/kg. Conversion costs are discussed in details in the Global 95' conference proceedings [17].

8.2.3 $Cost_{Uenr}$ – Cost of Uranium enrichment (\$/kg)

Different authors address the cost of enriching uranium [17], [18]. There seems to be some understanding of a price around 90 \$/kg ranging between 70 \$/kg and 120 \$/kg.

8.2.4 $Cost_{Udepl}$ – Cost of the handling of depleted Uranium (\$/kg)

The handling of depleted uranium is not performed in Sweden. Hence, the cost of it does not show in our calculations. The cost is included in the other uranium costs and was simply set to zero.

8.2.5 $Cost_{UOXfab}$ – Cost of UOX-fuel fabrication (\$/kg)

Much has been written [16], [17] on the cost of fabricating UOX-fuel. The general belief is that the cost of future manufacturing will be about 250 \$/kg ranging from 200 \$/kg to 350 \$/kg.

8.2.6 $Cost_{UOXIntstor}$ – Cost of spent UOX-fuel interim storage (\$/kg)

The unit cost of the Swedish interim storage CLAB is 59 \$/kg UOX [19]. International references [16], [17], [20] suggest somewhat higher costs, both the Global '95 conference and OECD/NEA suggests unit costs as high as around 300 \$/kg UOX. Based on this, a reasonable unit cost for spent UOX-fuel interim storage in the future is assumed to be 120 \$/kg UOX ranging from 60 \$/kg to 300 \$/kg.

8.2.7 $Cost_{UOXrepro}$ – Cost of spent UOX-fuel reprocessing (\$/kg)

Reprocessing of the spent UOX-fuel is assumed to be performed by an aqueous process such as the UREX or PUREX process. There are a few reprocessing plants, e.g. La Hauge and Sellafield, running today. These installations are rather old and are more or less paid off. Future reprocessing is assumed to be a bit more expensive than reprocessing today. Several references [16], [18], [21], [22] suggest a unit cost ranging from 500 to 1100 \$/kg heavy metal¹² (kgHM). A reasonable estimate of the unit cost in the future is 800 \$/kgHM. The Global '95 conference proceedings suggests a cost as high as 1800 \$/kgHM [17]. Since all other references suggest far lower values the lower value of 800 \$/kgHM ranging from 500 \$/kgHM to 1100 \$/kgHM was chosen.

8.2.8 $Cost_{MOXfab}$ – Cost of MOX-fuel fabrication (\$/kg)

The unit cost has been set to 1100 \$/kgHM ranging from 600 to 1750 \$/kgHM. This is based on figures from the EPRI, Global '95 and OECD/NEA references [16], [17], [18].

8.2.9 $Cost_{MOXrepro}$ – Cost of MOX-fuel reprocessing (\$/kg)

The mass flow of spent MOX-fuel is rather small in comparison to the flow of spent UOX-fuel. Hence dilution of the MOX-fuel with UOX-fuel is assumed to decrease the radiation per mass. If the fraction of MOX-fuel is kept below twenty percent of the total mass flow, the same

¹²When speaking of heavy metal (HM) both the fuel metal itself and the cladding material, which mostly consists of zirkaloy, are included.

process is assumed as for pure UOX-fuel, leading to the same costs. The unit cost for reprocessing spent MOX-fuel was set to 800 \$/kgHM, ranging from 500 to 1100 \$/kgHM.

8.2.10 $Cost_{UOXgeo}$ – Cost of spent UOX-fuel geological disposal (\$/kg)

A number of countries have announced estimations of the costs of disposing spent UOX-fuel geologically. The estimations differ a bit, mainly depending on which storage method is preferred. The value published for Sweden is 220 \$/kgHM [19]. The unit cost value was chosen to be 300 \$/kgHM ranging from 130 to 500 \$/kgHM.

8.2.11 $Cost_{HLWgeo}$ – Cost of High Level Waste geological disposal (\$/kg)

The cost of storing high level waste is about 400000 \$/m³ [23]. The unit is often expressed as cost per volume as volume is the real cost driver when constructing geological storages. One tonne of glass waste needs two cubic metres meaning the unit cost would be 800 \$/kgHLW.

8.2.12 $Cost_{ADSfab}$ – Cost of ADS-fuel fabrication (\$/kg)

Estimating unit costs for the ADS-fuel is hard. ADS fuel is very radioactive. All handling needs major radiation-shielding measures. The shielding makes handling expensive. There are rather few references that address this hot fuel. Estimates originate from the few references though. Costs were rescaled according to the mass flow of interest. Figures given in PNNL-13018 [21] and MIT-NFC-TR-019 [22] suggest the unit cost for manufacturing ADS fuel to be 11700 \$/kgHM. After scaling this value falls to 5000 \$/kgHM, This is a major scaling that ends up far away from its origin. Five thousand \$/kgHM is suggested as unit cost, however this is questionable. The unit cost is assumed ranging from 5000 to 17500 \$/kgHM. A lower boundary of 2600 \$/kgHM was suggested by MIT-NFC-TR-019 originating from the estimate for integral fast reactor fuel fabrication, however 5000 \$/kgHM is a more recent estimate. The upper boundary is 150% of the 11700 \$/kgHM value.

8.2.13 $Cost_{ADSrepro}$ – Cost of spent ADS-fuel reprocessing (\$/kg)

Spent ADS-fuel will be very hot due to high contents of mainly americium, but also curium. To shorten cooling times, and thus the fuel

cycle length, non-aqueous reprocessing methods should be used for the reprocessing. Radiation from the spent fuel is the main cost driver of the reprocessing plant. A high content of americium and curium makes the process more expensive. The PNNL-13018 [21] and MIT-NFC-TR-019 [22] reports discuss the costs for small scale reprocessing of hot fuel [21], [22]. The unit cost was estimated to 20000 \$/kgHM. However scaling the unit cost for the Swedish nuclear power park suggests a lower unit cost of 16000 \$/kgHM. More recent estimates [23] suggests 11000 \$/kgHM would be a better value. This was chosen as the unit cost in the calculations. Five thousand dollars per kgHM is proposed as lower limit. The unit cost was scaled to fit a US sized reactor park running in a transmutation scenario. This gives 10000 \$/kgHM. The figure was then halved to give some space for technological breakthroughs. Thus, the lower limit was calculated to 5000 \$/kgHM. As an upper limit for the unit cost 30000 \$/kgHM is proposed. This is simply fifty percent more than the value proposed in the references.

8.2.14 CAP_{LWR} – Investment LWR (\$/kWe)

Some LWR-reactors are being built around the world today. Finland is planning for a fifth commercial reactor. It is estimated to cost around 1590 \$/kWe installed [24]. Cost estimations for other reactors are as high as 2200 \$/kWe installed [23]. These values include interest during construction and decommissioning. In the calculations 1700 \$/kWe was chosen as unit cost. Labour costs in Sweden are rather low which together with a low expected interest during construction motivates this rather low value.

8.2.15 CAP_{ADS} – Investment ADS (\$/kWe)

To estimate the investment needed to build an ADS plant, figures from fast reactor construction have been used [17], [25], [26]. An ADS system is very similar to the fast reactor when it comes to heat transfer, cooling and electricity production. The very different component is the accelerator. The unit cost for the ADS was estimated to the cost of building a fast reactor plus the cost of an accelerator. A fast reactor is assumed to need an investment of 1950 \$/kWe ranging from 1200 to 3450 \$/kWe installed power.

8.2.16 $Cost_{beam}$ – Cost of accelerator (\$/W beam)

The beam cost is assumed to be 15 \$/W beam ranging from 5 to 20 \$/W beam. This assumption is mainly relying on the US ATW roadmap [5].

8.2.17 $O\&M_{reactor}$ – Operations and maintenance costs for reactors (% of investment / yr)

Operations and maintenance cost for LWR-reactors is known [27], [28] to be ranging from two to three percent of the original investment annually.

8.2.18 $O\&M_{ADS}$ - Operations and maintenance costs for ADS (% of investment / yr)

The O&M costs for an ADS system is assumed to be twice the LWR costs, i.e. four to six percent of the original investment annually. This is mainly due to accelerator maintenance and the frequent replacements of spallation windows.

8.2.19 FCR – Fixed charge rate (%)

The fixed charge rate is assumed to be ranging from eight to fourteen percent. This should be understood as the return on investment expected by investors.

A ten percent fixed charge rate paid during twenty years corresponds to an interest rate of 7,8 percent if paying the dept in equal amounts during the twenty years. This follows from the expression for annuity

$$a = c \cdot \frac{\left(1 + \frac{p}{100}\right)^t \cdot \frac{p}{100}}{\left(1 + \frac{p}{100}\right)^t - 1} \quad (7)$$

a – annual payment

c – original dept

p – interest rate expressed in percent

t – pay back time expressed in years

9 UNIT PARAMETERS

9.1 Description of unit parameters

Most of the unit parameters chosen for the calculations are more or less standard and need not be commented. There are a few though, which might need a comment. Unit parameters are summarized in appendix B.

Table 2. Unit parameters used in modelling

Total electric energy produced in LWR park per year	73 TWh
Thermal efficiency LWR	34 %
Thermal efficiency ADS	40 %
Load factor LWR	82 %
Load factor ADS	70 %
Own energy consumption LWR (% of thermal power)	1 %
Own energy consumption ADS (% of thermal power)	5 %
Loss factor in mining & milling	0,01
Loss factor in conversion	0,001
Loss factor in enrichment	0,001
Loss factor in UOX-fuel fabrication	0,001
Loss factor in MOX-fuel fabrication	0,001
Loss factor in UOX-fuel reprocessing	0,001
Loss factor in ADS-fuel fabrication	0,001
Loss factor in ADS-fuel reprocessing	0,001
Scaling exponent for reactors	0,6
Scaling exponent for fuel fabrication	0,7
Scaling exponent for reprocessing	0,7
ADS Accelerator beam power	40 MW

9.1.1 Thermal efficiency LWR - 34%

The modern Swedish LWRs reach 34% thermal efficiency. This value seems reasonable also for new reactors, especially if they are big ones.

9.1.2 Thermal efficiency ADS – 40%

An ADS will reach a higher thermal efficiency than does the LWRs. This is due to the much higher upper temperature in the ADS. In theory an even higher efficiency could be reached. It is just a question of how many steam over heaters you can afford to build. The upper temperature of coolant reaching the heat exchanger limits the thermal efficiency.

9.1.3 Load factor LWR – 82%

The average availability of Swedish LWRs is historically around 82%.

9.1.4 Load factor ADS - 70%

The ADS load factor depends mainly on the accelerator availability and is thus very hard to estimate with good accuracy. Some suggest 85% [2], [23], which is believed to be a bit optimistic. Here, 70% is used, which might be below the targeted load factor, but is in good agreement with proven load factors for the fast reactors BN-600 and BOR-60.

10 RESULTS

10.1 Cost of electricity

The cost of electricity from nuclear power has been calculated in three different fuel cycle scenarios. As the reference case a light water reactor scenario without reprocessing was used (Once through). The two other scenarios use dedicated subcritical systems to transmute the wastes from the light water reactor park. In one of the scenarios (LWR UOX + ADS) spent UOX fuel is sent directly to transmutation. The other scenario (ADS + LWR MOX) contains an intermediate step of plutonium recycling in the light water reactors.

The costs for producing electricity in these three scenarios range from 24,54 mills/kWh to 37,24 mills/kWh - Figure 11. Only the production costs were considered. No taxes or subsidises were taken into account. Once through is the cheapest scenario. The advanced fuel cycles show a higher cost of electricity, but are still low enough to be competitive in a future market with anticipated higher electricity prices.

The main cost driver of the three fuel cycles is the capital cost of the light water reactors. Also in the advanced fuel cycles light water reactors are still the main reactor type. Operation and maintenance costs are proportional to the installed power and follow the capital costs.

Even though mass flows are rather small, the ADS fuel cycle accounts for a main part of the total cost in the advanced fuel cycles. In the second scenario these costs are very close to half the total cost. But, recycling plutonium in light water reactors as MOX-fuel significantly reduces the amount of material to transmute and consequently reduces the cost of the transmutation. The total capacity of light water reactors have to be a bit greater which increases LWR related costs, but the total cost of the third scenario remains smaller than does the total cost of the second scenario.

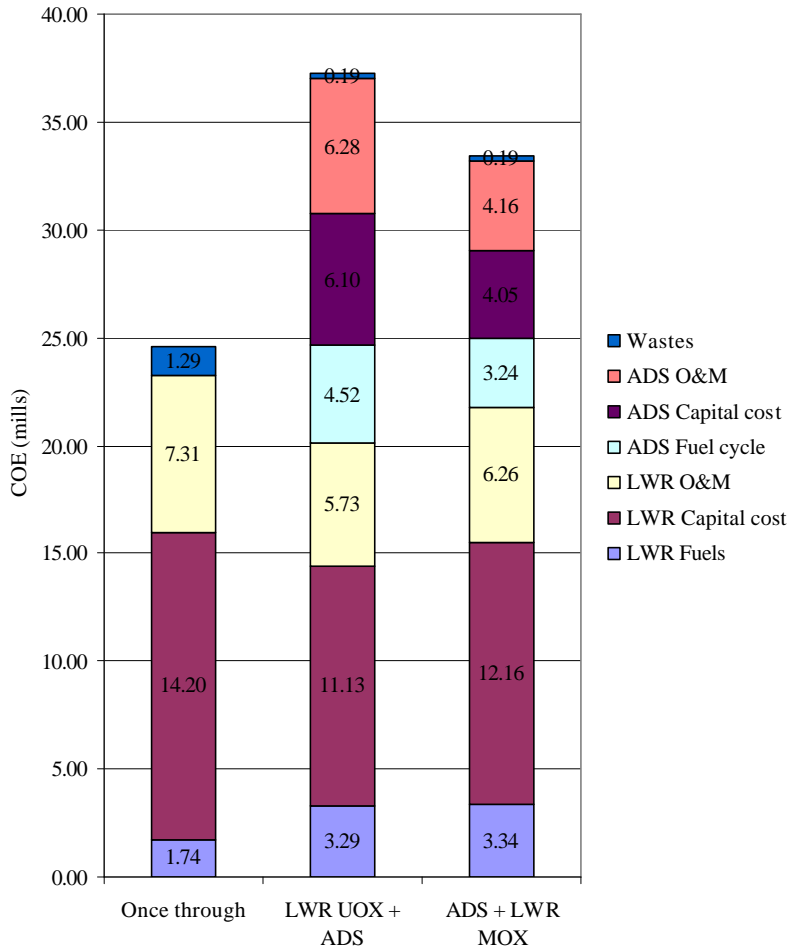


Figure 11: Overall cost distributions for the three fuel cycles considered. COE is the abbreviation for Cost of Electricity, O&M - for Operation and Maintenance.

10.2 Sensitivity analysis

A sensitivity analysis has been performed in order to understand the impact of some parameters of the final cost of electricity. The cost calculations were based on estimated unit costs and parameters -

Appendix B. The results of these sensitivity studies for some important parameters are presented in Figure 12 through Figure 23.

10.2.1 Capital costs

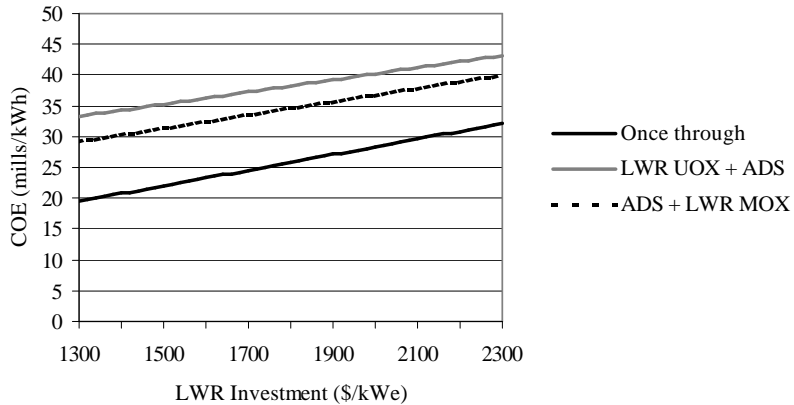


Figure 12: The cost of electricity as function of the LWR investment

The cost of constructing the light water reactors is a very important part of the total economy of all three fuel cycles - Figure 12. Even small changes in the cost may significantly change the cost of electricity. As an example a ten percent higher capital cost raises the once through cost of electricity by 8,8 percent.

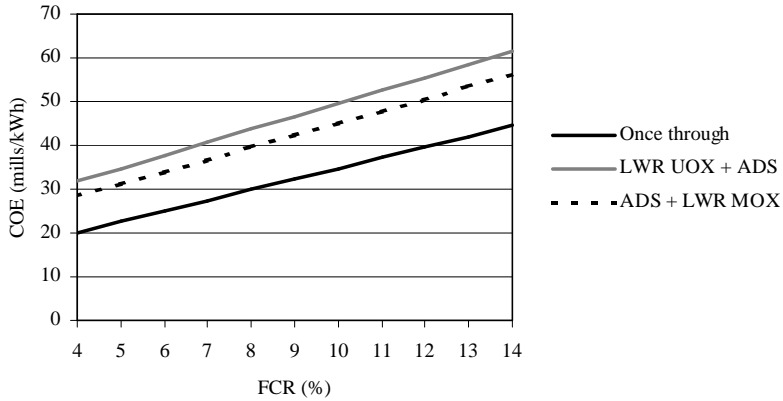


Figure 13: The cost of electricity as function of the fixed charge rate

The capital cost is very closely connected to the interest rate. Also changes in the interest rate have a great impact on the cost of electricity - Figure 13. Doubling of the interest rate increases the cost of electricity almost by fifty percent.

10.2.2 Reactor operation

Other very important aspects of the total fuel cycle economy are the parameters of the reactor operation. The thermal efficiencies, availabilities and burn-ups all affect the cost of electricity produced significantly. Figure 14 presents the effect of LWR thermal efficiency on the final cost of electricity.

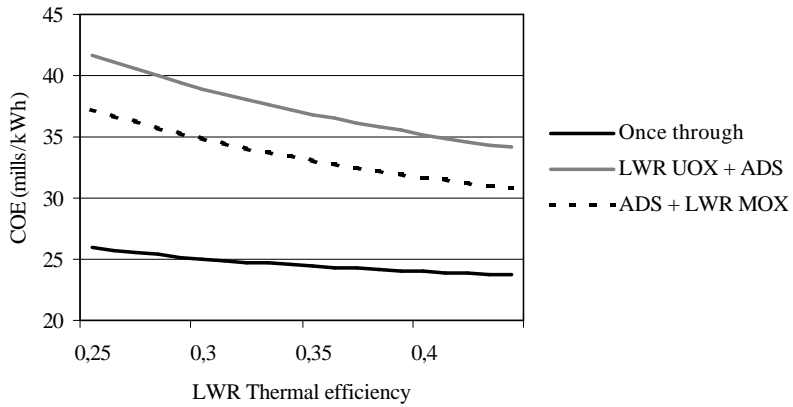


Figure 14: The cost of electricity as function of the LWR thermal efficiency.

The cost of electricity lowers as the efficiency of the turbines and generator increases. For the advanced fuel cycles the effect is stronger. This is because the need for expensive transmutation decreases as the fuel is used more efficiently in the light water reactors.

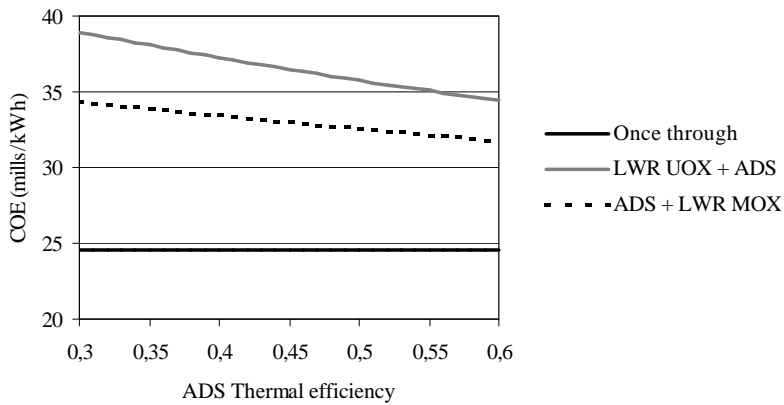


Figure 15: The cost of electricity as function of the ADS thermal efficiency

Also the ADS thermal efficiency has a rather large impact on total economy - Figure 15. The ADS thermal efficiency can be raised quite a lot by over-heating steam. However every extra steam over-heater requires an investment. That effect is not taken into account in the plot above. This means at some point the curve will start rising again. Also raising the upper temperature of reactor coolant raises the efficiency.

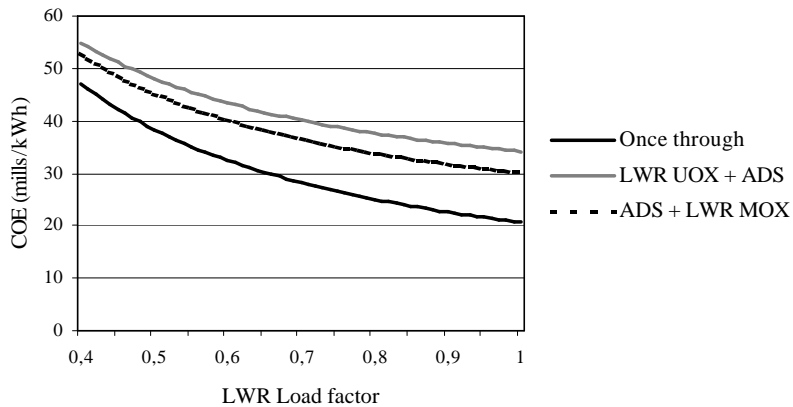


Figure 16: The cost of electricity as function of the LWR load factor

A high load factor for LWR operation is a prerequisite for an efficient reactor operation. Reactor stops are very expensive. Figure 16 shows the impact of the LWR load factor on the COE.

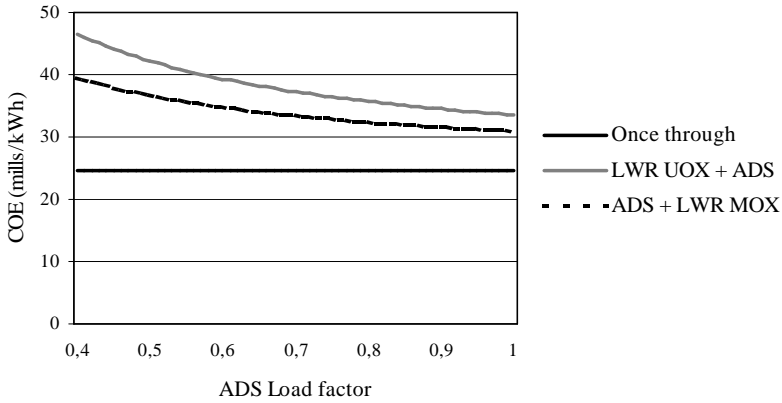


Figure 17: The cost of electricity as function of the ADS load factor

As seen in Figure 17 the effect of low load factors of ADS is smaller than in the LWR case. This is due to the much smaller power production in the ADS part of the fuel cycle.

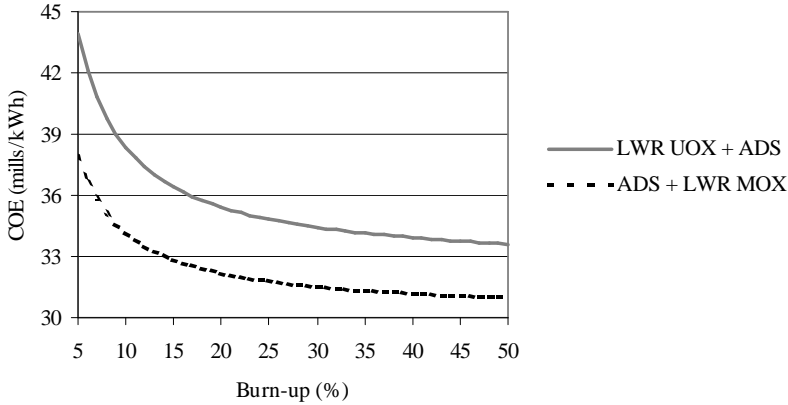


Figure 18: The cost of electricity as function of the ADS burn-up.

Together with separation losses the burn-up factor in the ADS determines the efficiency of the transmutation. The higher burn-up, the less reprocessing is needed. Since reprocessing is very expensive, this is an important aspect to the total cost. However the largest impact of

increased burn-up can be seen in the interval of 5 – 20% burn-up – Figure 18 – were the final costs can drop by almost 30%. A further increase in the burn-up over the twenty percent level has a minor impact on the final costs. The Sing-Sing reactor design has a burn-up of 12,4%, increased burn-up to 20% could give a 10% drop on the final cost of electricity.

10.2.3 Accelerator economics

The cost of particle accelerator construction for commercial use in transmutation facilities is still difficult to assess.

Figure 19, based on the data from the US ATW Roadmap [5] shows, surprisingly, that these are not driving costs. However the accelerator has a great impact on total economy since its properties are important to the ADS availability. It is important to achieve high accelerator reliability since beam stops lead to the stopping of the electricity production. Even though the ADS load factor is not the main cost driver, the prime interest apart from producing electricity is to transmute radioactive wastes. Transmutation is only possible when the accelerator is running.

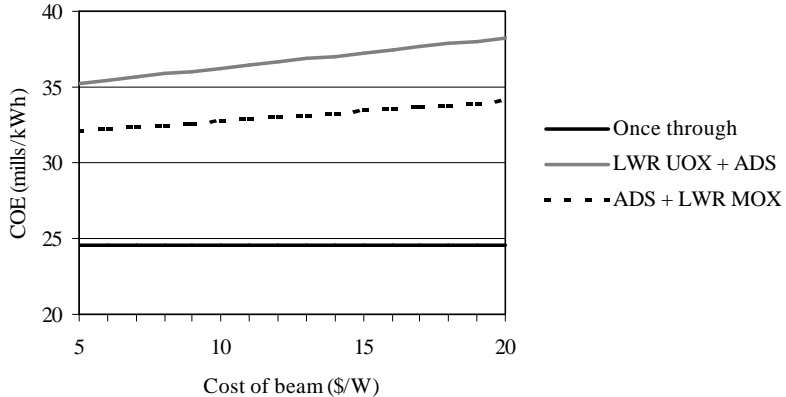


Figure 19: The cost of electricity as function of the cost of constructing the ADS accelerator

10.2.4 Fuel cycle economics

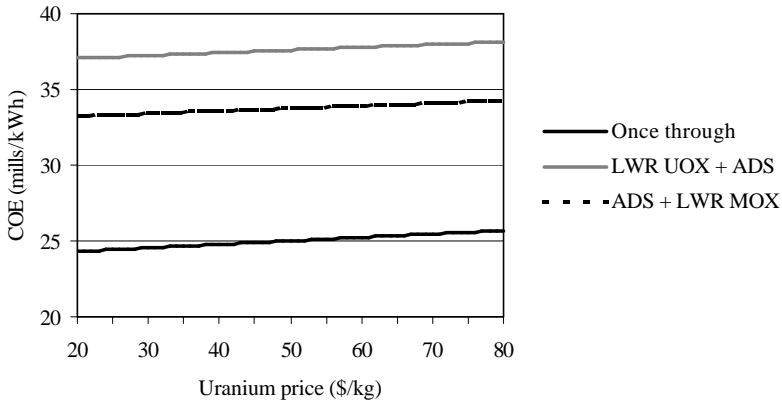


Figure 21: The cost of electricity as function of the uranium price

Figure 21 indicates that uranium price is not a very important cost driver of any of the nuclear fuel cycles studied. The once through fuel cycle uses more uranium per kWh produced than do the other scenarios. Consequently the once through fuel cycle is affected more by changes in the uranium price. However, the changes in COE are still small.

Reprocessing of spent UOX fuel is an important element in both of the advanced scenarios - Figure 22. Even though, the impact of rather large changes in the unit cost is still within a few percent on the total cost of electricity. The once through fuel cycle does not include any form of reprocessing; consequently the cost of electricity remains the same when the unit cost for reprocessing changes.

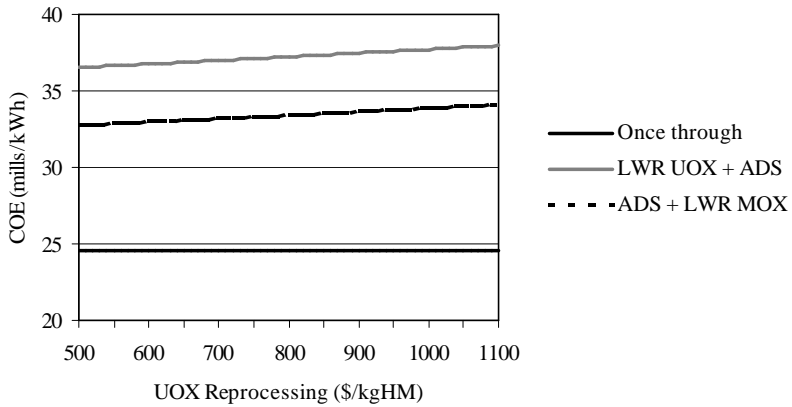


Figure 22: The cost of electricity as function of the uranium oxide (UOX) reprocessing costs

It is very difficult to estimate the cost of handling the very radioactive spent ADS fuel. It shows though - Figure 23 and Figure 23 - that neither the ADS fuel fabrication nor ADS reprocessing are very important cost drivers. An increased ADS fuel fabrication costs by a factor of two gives only a few percent (2-3%) impact on the final electricity cost. Variations of the reprocessing costs by a factor of six - from 5000 \$/kg HM to 30000 \$/kg HM - results in COE increases of only 12% and 16% respectively for the two advanced schemes.

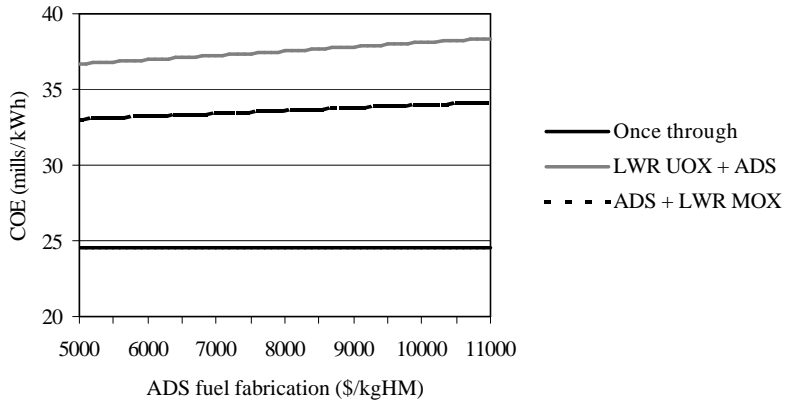


Figure 23: The cost of electricity as function of the ADS fuel fabrication cost.

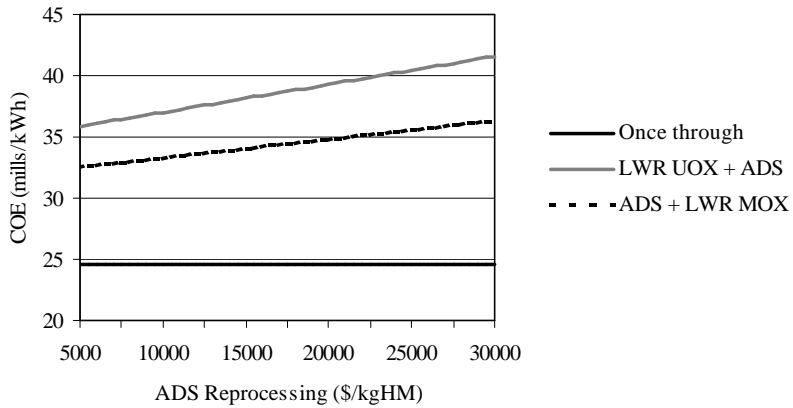


Figure 23: The cost of electricity as function of the ADS reprocessing cost

11 CONCLUSIONS

Figure 12 through Figure 23 all have one thing in common. In all of them, the three scenarios line up in the same order. “Once through” is cheaper than is “ADS + LWR MOX” which, is cheaper than is “LWR UOX + ADS”. It is obvious that an ADS strategy needs MOX recycling in light water reactors to be competitive.

The COE show a linear behaviour in most cases described here. The calculation model used contains very few feed-backs between variables. Mainly this is because of the bad knowledge in many areas. Even finding a single estimate for a unit cost is often difficult. Finding the dependency of that cost on another one is very hard.

	Once through	LWR UOX + ADS	ADS + LWR MOX
LWR Fuels	1.74	3.29	3.34
LWR Capital cost	14.20	11.13	12.16
LWR O&M	7.31	5.73	6.26
ADS Fuel cycle	0.00	4.52	3.24
ADS Capital cost	0.00	6.10	4.05
ADS O&M	0.00	6.28	4.16
Wastes	1.29	0.19	0.19
COE	24.54 100%	37.24 152%	33.40 136%

Table 3: Summary table of fuel cycle costs

Electricity from the “LWR UOX + ADS” scenario is 52% more expensive than is “once through” electricity, “ADS + LWR MOX” is 36% more expensive. Assuming an 85% ADS load factor and 20% TRU burn-up would lower the relative costs to 136% and 125% respectively for the advanced fuel cycle scenarios.

Compared to other sources of electricity nuclear shows to be a realistic alternative. The costs of electricity from many types of power plants are in the range of the costs discussed above.

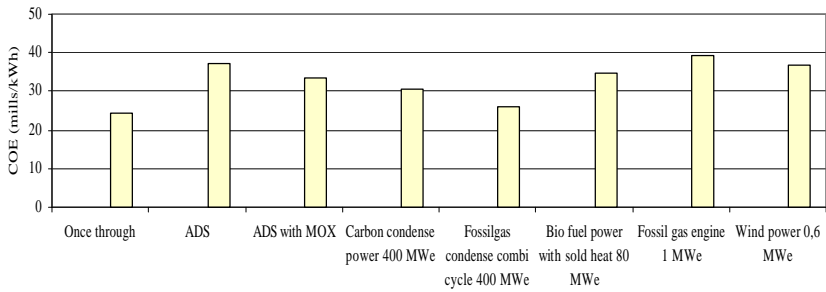


Figure 25: The cost of electricity from different power plants¹³.

As seen in Figure 25 nuclear power plants are competitive to other power plants. It is also – from an economic point of view - realistic to transmute the nuclear wastes in a transmutation fuel cycle.

¹³ The costs were calculated using a computer-based model provided by the Swedish National Energy Administration. Costs apply to the current Swedish situation.

12 FINAL REMARKS: ASPECTS OF ADVANCED NUCLEAR FUEL CYCLES

When, in the beginning of the last century, people realised it might be possible to tap matter itself of energy, optimism was enormous. At last there seemed to be a distant possibility of creating a paradise on earth. The almost free energy from the fission and fusion processes would give mankind totally new possibilities. With water from the ice at the poles Sahara would be transformed into a garden. People would travel around the planet in hours leaving no smoke, nor noise. And, poverty would be extinct.

Until today, nuclear power did not fulfil this dream. Several accidents taught us of the dangers of nuclear power. The destructive side of nuclear power got obvious, and forever connected to, the cruelty of the human race on the sixth of August 1945.

Today the dreams are all gone. Nuclear energy is part of everyday life. It will stay that way as long as our benefits from having nuclear power exceeds the cost of doing so. Discussion on the costs and benefits of nuclear power finally caught wind after the Three Mile Island accident in 1979. It boosted following the Chernobyl meltdown in 1986. The discussion is, and should be, a very important aspect of nuclear power itself.

The once through fuel cycle used in Sweden today could easily be mistaken for the ultimate clean and safe way to produce cheap electricity. People using the electricity discover no severe problems. They do not see the opencast mines where huge amounts of radon leaks into the atmosphere and living creatures are poisoned by the heavy metals leaking from slag deposits. Also these people will have been long dead when eventually material from the geological disposals starts reaching the biosphere. The only thing left for them to care about is the risk of an accident in a nuclear power plant. Considering the experience gained from running nuclear reactors combined with the culture in the nuclear industry to always work on safety this risk is probably small. Even if a severe accident would occur the amount of radiation released would most probably be small. However, people actually do care, especially people care about the geological disposal of wastes. People would rather see that there was no radioactive waste at all.

12.1 Radiation hazards

Transmutation does offer a possibility of almost deleting the storages of radioactive wastes. However, new problems arise in a transmutation fuel cycle.

In a once through fuel cycle uranium mining and geological disposal seem to be the main problems. With recycling of reactor fuel far less uranium is needed and with transmutation far less waste is left for disposal. Both of the main problems are reduced. Recycling though raises new problems. If running recycling on a big scale for many years, somewhere, someday there is going to be a malfunction of some system which is going to cause release of radioactive material into the biosphere. With less reprocessing plants the average time for this to happen is longer, but it will still happen somewhere, someday. From a radiation hazards point of view, the question of using transmutation is condensed to the question whether to expose the people living today to the radiation or to expose the generations to come.

12.2 Proliferation risks

As long as there are plants enriching uranium or reactors producing plutonium, there will be the threat of nuclear weapons. A once through fuel cycle has the advantage of not piling up plutonium anywhere. When reprocessing the spent fuel, there will be plutonium lying around to be stolen, or removed in a legal way, to produce nuclear weapons.

However in a few hundred years though, when the wastes in the geological repositories have cooled down, they will make a prime uranium ore. Anyone who needs plutonium could just start mining it from the bedrock.

The benefit of the reprocessing alternative is that we know who might want the plutonium today. We could protect ourselves from it at least in the short term. We do not know though how society looks in, say, five hundred years, and who might need the plutonium then. The choice is who to trust, the people of today, who deliberately killed 183 million people the last century [29], or our grand grand children whom we do not know.

12.3 Social aspects of transmutation

Whether to use advanced nuclear fuel cycles like transmutation is not an issue for scientists or engineers. Society has to make the choice based on the costs and the benefits of different alternatives.

A really important aspect is the stability of society. Transmutation is a major project. If started it would have to run for a long time. Society should be ready to accept nuclear power as the main power source for several hundreds of years. Of course nuclear power can only be safe, especially considering non-proliferation aspects, in a peaceful and stable society. Before making the decision to start the transmutation fuel cycle we would need to be confident that our society will stay stable for a long time.

In order to decide for transmutation in Sweden a pro transmutation opinion would be needed. Then parliament could change laws concerning planning of nuclear power. Also several paragraphs in the environmental laws would have to be changed in order to build Sing-Sing cores. Especially a clearance to use huge amounts of lead would be vital.

We have shown that advanced fuel cycles might become an economically realistic option. It seems society will have to reach the decision pretty soon, whether to use nuclear power or not.

APPENDIX A – ISOTOPE HALF-LIVES

The half-lives of some important isotopes are listed below. Data originates from Kenneth S. Krane [3].

Element	Z	A	Abundance or Half-life
<i>Uranium, Plutonium and the Minor Actinides</i>			
U	92	233	0,1592 My
		234	0,245 My
		235	0,720 %
		236	23,42 My
		237	6,75 d
		238	99,275 %
		239	23,5 m
Np	93	236	0,11 My
		237	2,14 My
		238	2,117 d
		239	2,36 d
Pu	94	237	45,3 d
		238	87,74 y
		239	24100 y
		240	6570 y
		241	14,4 y
		242	0,376 My
		243	4,96 h
Am	95	240	50,9 h
		241	433 y
		242	16,0 h
		243	7370 y
		244	10,1 h
Cm	96	246	4700 y
		247	16 My
		248	0,34 My
		249	64 m

Some important Fission Products

Se	34	79	0,065 My
Kr	36	85	10,7 y
Sr	38	90	28,8 y
Zr	40	93	1,5 My
Tc	43	99	0,214 My
Pd	46	107	6,5 My
Sn	50	126	0.1 My
I	53	129	16,0 My
Cs	55	137	30,2 y

APPENDIX B – UNIT COSTS AND PARAMETERS

Unit costs

Unit cost of natural uranium	30	\$/kgU
Unit cost of conversion	5	\$/kgU
Unit cost of enrichment	90	\$/kgU
Unit cost of storing depleted uranium	0	\$/kgU
Unit cost of UOX-fuel fabrication	250	\$/kgUOX
Unit cost of UOX-fuel interim storage	120	\$/kgUOX
Unit cost of UOX-fuel reprocessing	800	\$/kgHM
Unit cost of MOX-fuel fabrication	800	\$/kgMOX
Unit cost of MOX-fuel reprocessing (by dilution with UOX-fuel and when MOX/UOX < 20%)	800	\$/kgMOX
Unit cost of UOX-fuel geological disposal	300	\$/kgUOX
Unit cost of HLW geologic disposal	800	\$/kgHM
Unit cost of ADS-fuel fabrication	7000	\$/kgHM
Unit cost of ADS-fuel reprocessing	11000	\$/kgTRU
Unit cost of installed power LWR (including D&D)	1700	\$/kWe
Unit cost of installed power FR (including D&D)	1950	\$/kWe
Unit cost of installed power ADS (including D&D), excl. Beam	1950	\$/kWe
Cost of accelerator beam power (ATW/ADS)	15	\$/Wbeam
Annual O&M costs as fraction of capital costs for reactors	3	%/year
Annual O&M costs as fraction of capital costs for ADS/ATW	6	%/year
Annual O&M costs as fraction of capital costs for fuel cycle installations (excl. reactor)	10	%/year
Fixed charge rate	6	%/year

Unit parameters

Total electric energy produced in LWR park per year	73	TWhe
Thermal efficiency LWR	34	%
Thermal efficiency ADS	40	%
Load factor LWR	82	%
Load factor ADS	70	%
Own energy consumption LWR (% of thermal power)	1	%
Own energy consumption ADS (% of thermal power)	5	%
Loss factor in mining & milling	0,01	
Loss factor in conversion	0,001	
Loss factor in enrichment	0,001	
Loss factor in UOX-fuel fabrication	0,001	
Loss factor in MOX-fuel fabrication	0,001	
Loss factor in UOX-fuel reprocessing	0,001	
Loss factor in ADS-fuel fabrication	0,001	
Loss factor in ADS-fuel reprocessing	0,001	
Scaling exponent for reactors	0,6	
Scaling exponent for fuel fabrication	0,7	
Scaling exponent for reprocessing	0,7	
ADS Accelerator beam power	40	MW

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