Comparison of different nuclear fuel cycles for LWR applications

Tobias Winblad von Walter
Abstract

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Nuclear power is considered a vital energy source, without greenhouse gas emissions, regarding the commitment towards sustainable energy systems. This is especially on the topic of the present climate debate. A central aspect of nuclear power is nuclear fuel. Presently Uranium dioxide (UOX) is the most common nuclear fuel in the world. However, an increased uranium price, waste and proliferation issues are some of the aspects that have resulted in a growing interest for other nuclear fuels. Mixed Oxide (MOX) and thorium are additional nuclear fuels that might be of interest for Light Water Reactor (LWR) applications. The present work is an attempt to make a comparison of these nuclear fuels, in order to understand the potential of each fuel and which fuel that is the best option under certain boundary conditions.

Delimitations were to only consider nuclear fuels for the present reactor technology, i.e., LWR, and the front-end, i.e., from mining to fuel fabrication. Operation and back-end is not covered in this thesis.

The result of this work shows that the present dominance of UOX is likely to withstand for at least the near future. MOX will only represent a few percent of the nuclear fuel market and thorium even less. Uranium is presently the most cost-efficient alternative, even if the price for uranium continues to increase to the double of the present price (~90 USD/lb U3O8). Furthermore, the infrastructure is particularly established for uranium-based nuclear power and other nuclear fuels will meet resistance when trying to enter this market. However, there are other factors, like political, that might change this picture in favor for other nuclear fuels in certain countries in the future.
**Populärvetenskaplig sammanfattning**


Syftet med detta arbete har varit att ge en övergripande bild av vilka kärnbränslen som i dagsläget finns tillgängliga för lättvattenreakteror, samt att göra en uppskattning av under vilka förutsättningar som MOX eller torium skulle kunna bli attraktiva substtitut till det etablerade kärnbränslet uran.

Avgränsningarna på arbetet var att enbart undersöka möjliga kärnbränslen för dagens reaktorteknologi, d.v.s. kokar- eller tryckvattenreaktorer. Denna avgränsning sattes upp eftersom tidperspektivet var från dagens datum och 10-20 år framåt i tiden. Den fjärde generationens reaktorer förväntas ta längre tid än så innan kommersialisering. En annan avgränsning var att undersöka bränslecyclens första del, front-end, d.v.s. från brytning till bränsletillverkning. De kärnbränslen som således jämfördes var uran, MOX och torium.

Resultatet av denna undersökning visar att uran, även i fortsättningen, kommer att vara det dominerande kärnbränslet och även det mest ekonomiska alternativet. MOX kommer med stor sannolikhet bara stå för ett fåtal procent av den totala kärnbränsleknadnen och torium förmodligen en ännu mindre del av densamma. Den totala bränsleknadnen för MOX och torium är alloverat till bränsletillverkningen medan för uran är uranpriset i dagsläget den största delen. MOX skulle kunna bli ekonomiskt attraktivt om uranpriset skulle stiga ytterligare eller om tekniken för MOX bränsleframställning förbättras väsentligt. Dessa båda scenarios anses dock osannolika.

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABWR</td>
<td>Advanced Boiling Water Reactor</td>
</tr>
<tr>
<td>AGR</td>
<td>Advanced Gas-cooled Reactor</td>
</tr>
<tr>
<td>BNFL</td>
<td>British Nuclear Fuel Ltd</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>CANDU</td>
<td>CANada Deuterium Uranium, Reactor</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy (the US)</td>
</tr>
<tr>
<td>EDF</td>
<td>Electricité de France</td>
</tr>
<tr>
<td>EFR</td>
<td>European Fast Reactor</td>
</tr>
<tr>
<td>EPR</td>
<td>European Pressurized Reactor</td>
</tr>
<tr>
<td>FBR</td>
<td>Fast Breeder Reactor</td>
</tr>
<tr>
<td>HM</td>
<td>Heavy Metal</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>LWR</td>
<td>Light Water Reactor</td>
</tr>
<tr>
<td>MOX</td>
<td>Mixed Oxide Fuel (U, Pu) O2</td>
</tr>
<tr>
<td>NEA</td>
<td>Nuclear Energy Agency</td>
</tr>
<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
</tr>
<tr>
<td>NRC</td>
<td>(the US) Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>PHWR</td>
<td>Pressurized Heavy Water Reactor</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
</tr>
<tr>
<td>RBMK</td>
<td>Reaktor Bolshoy Moshchnosti Kanalniy, which means “reactor of high power of the channel type”. A graphite-moderated reactor, built only in the Soviet Union</td>
</tr>
<tr>
<td>SKI</td>
<td>Swedish Nuclear Inspectorate</td>
</tr>
<tr>
<td>SWU</td>
<td>Separative Work Unit</td>
</tr>
<tr>
<td>t</td>
<td>1000 kg</td>
</tr>
<tr>
<td>THORP</td>
<td>Thermal Oxide Reprocessing Plant</td>
</tr>
<tr>
<td>UOX</td>
<td>Uranium Oxide</td>
</tr>
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</table>
1 Introduction

Nuclear fuel is an important aspect of nuclear power. It is therefore essential for the owners of nuclear power plants to understand the consequences of implementing different nuclear fuels in order to optimize the process. This diploma thesis will give the reader an idea of the advantages and drawbacks of different nuclear fuels through several different criterions. The delimitations of this work are the following:

- nuclear fuels applicable in the present reactor technology systems, i.e., LWRs
- front-end, i.e., from mining to fuel fabrication

The different nuclear fuels considered in this thesis are aimed at LWRs, reflecting the present dominance of LWRs and the likelihood that it will persist as the most common reactor type in the near future. Which of these options that are eventually adopted by nuclear utilities will depend on a large number of factors, such as: political, strategic, logistic, environmental, sustainability, economic etc. and is not discussed in this thesis.

The front end of the fuel cycle refers to the initial process of nuclear power and is interconnected to the back-end via reactor operation. The master thesis covers the front-end but the operation and back-end processes are not considered due to the limited time for the work. Further studying these aspects will be necessary in order to get a complete picture. Furthermore, only to consider the present technology is a consequence of the timeframe for the application, which is about ten to twenty years from present date.

1.1 Purpose

The main purpose of this thesis is to give the reader a comprehensive and general idea of the front end of different nuclear fuel cycles applicable in LWRs. Furthermore, a general overview for the different aspects related to the fuels is presented and valuated. Operation and back-end is not considered in this thesis.
1.2 Disposition

Chapter 1 gives a brief introduction to the subject and also a summary of different trends in the nuclear industry.

Chapter 2 describes issues of the uranium nuclear fuel cycle and the costs associated with each activity.

Chapter 3 explains the concept of recycling uranium in LWRs as MOX.

Chapter 4 describes the front end of the thorium fuel cycle and the costs associated with the activities

Chapter 5 gives a comparison of the front end of the different fuel cycles. Highlighting the major drawbacks and advantages with each activity.

Chapter 6 gives estimates of economic consequences of each nuclear fuel

Chapter 7 conclusions

Chapter 8 states the necessary further studies that need to be examined in order to get a complete picture of the different fuel cycles
1.4 A general nuclear overview

The world population of 6.5 billions is gradually increasing and the electricity consumption at an even higher rate – 2 %/year, which equals to almost 1000 TWh/year. To meet the increasing demand, Sweden, among other countries, has stressed the importance of “sustainable development”. This implies an energy system with emphasis on energy sources that is part of the nature’s circulation and hence is “inexhaustible”. Nuclear power is not renewable but fulfils the criterion for sustainable development because there are practically no emissions of carbon dioxide throughout the whole fuel cycle [1].

Nuclear fuel has a high energy density, and the emissions throughout the whole fuel cycle are very limited. The power production, fuel fabrication and the mining part of the cycle are almost emission free. If the electricity required to enrich nuclear fuel only comes from coal power plants, nuclear power would still only emit one thousandth of the carbon dioxide that a coal power plant with an equivalent electricity production would [1].

In Europe, about 30 % of generated electricity comes from nuclear power [2]. The need for electricity will, according to the minister council yearly meeting in March 2007, increase by 32 % within EU25 during the period 2000 – 2030. This number excludes the increasing electricity demand of the transport sector due to stricter environmental constraints [3].

The expansion of nuclear power during the last 20 years have been concentrated to Southeast Asia, in particular China, Taiwan, Japan, South Korea and India. Today, on the other hand, totally different signals are received from the western countries. Finland is building a large nuclear power plant (NPP) and France is currently constructing an identical NPP. The US government has taken several strategic actions to facilitate a nuclear power expansion. A similar development is present in the UK and other European countries [4]. In other words new “emission free” (CO₂) nuclear power is considered indispensable when it comes to the commitment towards a sustainable development among more and more countries in the world. The expansion of renewable energy sources into the energy systems is considered too expensive and too slow as opposed to nuclear energy [4].

Nuclear fuel is not a renewable energy source like solar-, wind- or waterpower, but fulfils the criterion for sustainable development in contrast to coal, oil and natural gas. Nuclear energy is sustainable because the uranium supply is much larger than the demand. In addition basically no emissions of carbon dioxide to the environment during the electricity production is released [1]. Drastically increasing gas prices in combination with greenhouse gas emission restrictions implies that nuclear power will be an important part of the future energy system, in Europe as well as in the US.

Most of the reactors that will be constructed in the near future are of pressurized water model, either with normal or heavy water as moderator, i.e. PWR or PHWR. This is a reflection of the historic dominance of this reactor. All reactors that currently are operating are presented in Figure 1, including number and installed power capacity.
The dominance of Light Water Reactors (LWR), which includes both Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR), is illustrated in Figure 1. Presently LWRs provide more than 90% of the total installed nuclear power in the world.

When nuclear power first got commercialised, the nuclear industry believed that uranium was relatively scarce and that the number of reactors would grow rapidly, leading to rapidly rising uranium prices. The nuclear industry projected from these assumptions that there would be a relatively fast transition from LWRs that relies on energy from the fissioning of $^{235}\text{U}$ to Fast Reactors (FR) that more efficiently transforms $^{238}\text{U}$ into plutonium, which is fissioned in-situ or recycled through reprocessing. Recycling in LWRs was considered a temporary solution until the FRs were fully commercialised. The transition to FRs has however taken much longer than expected, due to the following:

1. Uranium has turned out to be abundant and inexpensive
2. Nuclear industry has grown much slower than anticipated
3. FRs turned out to be more expensive and problematic than once expected

Recently FRs have received increased attention as a long-term option due to its efficient usage of uranium resources. The different nuclear reactors through history, present time and expected future are presented in Figure 2.
1.5 The nuclear fuel cycle

Large-scale electricity production almost always involves a controlled process to boil water, except for Waterpower. Nuclear power is no different and the nuclear energy comes from the binding energy of the atoms, which is released when they split (fission).

\[
235\text{U} + n \rightarrow X + Y + 200 \text{ MeV} \\
C + O_2 \rightarrow \text{CO}_2 + 4 \text{ eV}
\]  

(1)

As indicated above, the energy released when splitting a uranium atom is about 50 millions higher compared to complete combustion of coal. This energy can be transformed into heat and subsequently electric energy in a steam turbine power plant. Nuclear reactors differs from each other in terms of three fundamental components of the system:

1) **fuel**: e.g. uranium, thorium or MOX in different fissile concentrations and compositions  
2) **moderator**: can be water, heavy water, graphite etc. The material has the property of slowing down the speed (decreasing the energy) of the neutrons  
3) **coolant**: can be water, pressurized gas or liquid metal and extracts the heat in order to produce steam and subsequently electricity through a steam turbine

There are presently several compositions of these components generating electricity to the grid. Presently the most common commercial reactor type is however the Light Water Reactor (LWR). This reactor type provides more than 90 % [2] of the electricity generated from nuclear reactors and involves uranium oxide enriched to 3-5 % as fuel and water is used for both moderation and cooling. The LWR design enables the reactor to control a chain reaction in order to generate electricity. Obligation for a civil nuclear reactor is to sustain a criticality of exactly 1. Power in the reactor is highly related to the neutron flux, but criticality is however not related to the output power. Criticality is a term that represents how many neutrons that yields per fission neutron. The speed of this process depends on the lifetime of the neutrons. Some neutrons are not released directly when an atom is split, thereby the name: delayed neutrons. These neutrons are very important in terms of regulation since they provide favorable operating conditions.
The delayed neutron fraction is lower for plutonium than uranium and that is why a reactor needs to be adapted when substituting uranium fuel with some composition of plutonium in a reactor. In a reprocessing plant the plutonium and the uranium are separated from each other. These materials can subsequently be remixed in a fuel fabrication plant to form a Mixed Oxide Fuel, or MOX. The production of such a fuel requires remote handling, due to the presence of plutonium, and is more complex and expensive in comparison with pure uranium fuel production. The Swedish nuclear policy was historically reprocessing, i.e. recycling uranium in the form of MOX in LWRs. This policy was however abandoned due to the costs related to this process and the hazard that it would bring. Vattenfall AB (VAB) sold all their reprocessing contracts and the only Swedish reactor that is currently obliged to insert MOX is Oskarshamn 3, owned by Oskarshams KraftGrupp (OKG), from the historical reprocessing contracts.

Thorium can be used as a nuclear fuel in equivalence to uranium and MOX. Research has been conducted on thorium for several years, especially in the beginning of the commercialisation of nuclear power (1960s) when the uranium deposits were considered scarce. There has occurred a renewed interest for thorium due to reasons covered later on in this thesis.

The investigation of these fuels is therefore essential to provide knowledge of the diverse possibilities. The major advantages and drawbacks in implementing these fuels is a fundamental question that is stressed in this work.
2 UOX fuel cycle

The nuclear fuel cycle refers to all activities involved in the process of making electricity from the energy of an element. For uranium these events are: mining & milling, conversion, enrichment, fuel fabrication, operation, reprocessing and disposal or recycling and is illustrated in Figure 3.

![UOX fuel cycle diagram](image)

**Figure 2 – The UOX fuel cycle. Mining to fuel fabrication is called the front end of the fuel cycle and interim storage to geological disposal is called back end of the fuel cycle [5]**

*Mining* is the process where the uranium ore is extracted from the ground by various methods depending on the character of the soil and the depth of the deposits. The *milling* process increases the concentration of the uranium. After *conversion* the material is *enriched* to achieve criticality in LWR and thereafter transformed at a *fuel fabrication* plant into a fuel assembly.

The nuclear fuel, in the oxide form, is now ready for *operation* and normally remains in the reactor for 5 years before it is removed for either *reprocessing* or *disposal*. In case the nuclear fuel is removed for disposal, the whole fuel cycle is commonly called “once through fuel cycle”, i.e. the nuclear fuel is only used once in the reactor.

During operation different isotopes of plutonium are formed, and later on consumed. As a matter of fact the fission of plutonium contributes to approximately one third of the energy released from the nuclear fuel, in the reactor. Plutonium is present in the fuel after removal from the reactor. This is one of the incentives to recycle the fuel, i.e. utilize more of the energy present in the fuel rods.

The activities of the uranium fuel cycle are represented in Figure 3. All the activities of the front end, i.e., from mining to fuel fabrication, are subject to competition. The proprietor of the nuclear power plant, e.g., a power company, is responsible for all these activities. They decide from which mine the uranium is to be extracted, to which conversion facility it will
later on be sent, which enrichment facility to use and finally which fuel fabrication factory will manufacture the fuel assemblies. The uranium fuel cycle is by far the most commonly applied civil nuclear power program in the world.

Long before a reactor is in need of new fuel, the power company counts backwards from the reactor to the mine in order to guarantee that the fuel will arrive in time to meet the demand. They take into consideration the bottlenecks and the possibility that some of the facilities might not function. After the uranium is converted into UF₆ it is stored, because the conversion cost is a small part of the mining costs and that the conversion facility might not function (old facilities) when the supply is urgent.

2.1 Supply

To operate all of Sweden’s nuclear reactors require about 2000 t U/year (2007), and to provide the world’s nuclear reactors in total it takes about 65 000 t U/year (2007) [6]. The world leading countries when it comes to production of uranium for power production purposes are Canada, Australia and Kazakhstan, and these are the countries that possess the largest deposits in the world as well, see Table 1.

Table 1– Currently known recoverable resources of uranium. Identified Resources at an extraction cost of USD130/kgU [7, 45]

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserves [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1 143 000</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>816 000</td>
</tr>
<tr>
<td>Canada</td>
<td>444 000</td>
</tr>
<tr>
<td>USA</td>
<td>342 000</td>
</tr>
<tr>
<td>South Africa</td>
<td>341 000</td>
</tr>
<tr>
<td>Namibia</td>
<td>282 000</td>
</tr>
<tr>
<td>Brazil</td>
<td>279 000</td>
</tr>
<tr>
<td>Niger</td>
<td>225 000</td>
</tr>
<tr>
<td>Russian Fed.</td>
<td>172 000</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>116 000</td>
</tr>
<tr>
<td>Ukraine</td>
<td>90 000</td>
</tr>
<tr>
<td>Jordan</td>
<td>79 000</td>
</tr>
<tr>
<td>India</td>
<td>67 000</td>
</tr>
<tr>
<td>China</td>
<td>60 000</td>
</tr>
<tr>
<td>Other countries</td>
<td>287 000</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>4 743 000</strong></td>
</tr>
</tbody>
</table>

The location, extent and grade of deposit are determined by airborne, surface and drill hole methods based on the radioactive character of the material. Presently (2007), a 0.1 % concentration, or more, of uranium in the ground is economically defendable to extract. The known recoverable resources in the world of uranium are represented in Table 1 and different uranium ore concentrations in Table 2.
Table 2 – Concentration of uranium in different ores.

| Ore                          | Uranium Concentration (ppm) |
|------------------------------|----------------------------|---|
| High-grade ore               | 20,000                      |
| Low-grade ore                | 1,000                       |
| Granite                      | 4                           |
| Sedimentary rock             | 2                           |
| Earth’s continental crust (average) | 2.8                    |
| Seawater                     | 0.003                       |

### 2.1.1 Technology

The technology for mining uranium is by open-pit mining, underground mining or in situ leach (ISL) mining. From a general point of view open pit mining is used where the deposits are close to the surface and for deep deposits underground mining is applicable. Open pit mining has higher productivity, higher recovery, easier dewatering, safer working conditions and usually lower costs than underground mining. However, the environmental disturbance is less for the underground mines in comparison with open pit mines. Another method to extract uranium is by in situ leaching, ISL, where a chemical solution (acid or alkali) is circulated through a very porous ore in order to dissolve the uranium and bring it to the surface. This method saves the excavation costs and is normally performed where the uranium ore exist in saturated sandstone. Mainly used in Kazakhstan, Australia, the US and Russia. Which method to be used is decided through a compromise between ore body, safety and economical aspects. In 2006 the production of uranium from mines is presented in Table 3.

Table 3 – 2006 uranium production from different mining methods [8]

<table>
<thead>
<tr>
<th>Mining Method</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground</td>
<td>41%</td>
</tr>
<tr>
<td>Open pit</td>
<td>24%</td>
</tr>
<tr>
<td>In situ leach (ISL)</td>
<td>26%</td>
</tr>
<tr>
<td>By-product</td>
<td>9%</td>
</tr>
</tbody>
</table>

After uranium is mined it is extracted from the crushed ore by chemical methods, called milling. The uranium is dissolved either by a strong acid (hydrochloric acid) or a strong alkaline (sodium carbonate) solution depending on the ore body and the product is known as “yellowcake” (U₃O₈). Uranium mills are often located near the mines in order to limit transportation. The yellowcake is thereafter packed and shipped in casks to the conversion facility. About 200 t of “yellowcake” is required to keep a large nuclear power plant (around 1000 MWe) generating electricity for one year [2].
The remainder of the ore is a waste product (tailing), containing long-lived radioactive materials, low-level waste (see Chapter 2.4 Waste management), heavy metals etc and is illustrated in Figure 4 above. The tailings needs to be taken care of and isolated from the environment.

Uranium needs to be in gaseous state before it can be enriched and this necessitates conversion of the yellowcake, U3O8, into uranium hexafluoride (UF6) at a conversion plant. At the conversion facility, uranium is refined to uranium dioxide, UO2. This product can be used as a nuclear fuel in reactors that does not need enriched uranium, e.g. CANDU reactors. However, most of the UO2 is converted into UF6, which is the product sent to the enrichment plant [10].

The transport of yellowcake is not a large cost compared to the conversion process. Several conversion facilities exist at the open competitive market around the world. The yellowcake can be sent to whichever conversion facility the power company decides, regardless of location [11]. Conversion plants with their capacity and location is presented in Table 4.

Table 4 – The capacity of uranium hexafluoride conversion in the world [12]

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Capacity [t U/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>Minatom</td>
<td>24 000</td>
</tr>
<tr>
<td>France</td>
<td>Comurhex</td>
<td>14 350</td>
</tr>
<tr>
<td>USA</td>
<td>ConverDyn</td>
<td>14 000</td>
</tr>
<tr>
<td>Canada</td>
<td>Cameco</td>
<td>10 500</td>
</tr>
<tr>
<td>U.K.</td>
<td>BNFL</td>
<td>6 000</td>
</tr>
<tr>
<td>China</td>
<td>CNNC</td>
<td>400</td>
</tr>
<tr>
<td>Iran</td>
<td>-</td>
<td>193</td>
</tr>
<tr>
<td>Brazil</td>
<td>IPEN</td>
<td>90</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>69 533</strong></td>
</tr>
</tbody>
</table>
2.1.2 Safety

Mining has environmental impacts, regardless of which mineral that is mined. The environmental effects and hazards of uranium mining are comparable to that of other minerals. Hazards of noise, dust, vibration, rock falls, chemicals and explosives are common to all mining operations. In addition, uranium-mining material is more radioactive than other types of mining, i.e., the waste rock needs to be taken care of. The biggest difference for uranium is radiation, which results in special measures for radon and radium in air, water and solid waste and direct radiation exposure. Uranium mining results in large amounts of waste rock, called tailings, which contains radioactive material. In particular they contain all the radium present in the original ore. When radium undergoes natural radioactive decay one of the products is radon gas. Because radon and its decay products are radioactive and the tailings are now on the surface, measures are taken to minimise the emission of radon gas. If radon gas is inhaled it can in time cause lung cancer if frequently exposed. The proprietor of the mine must guarantee that large amounts of water does not flow through and carry radioactive materials to watercourse or groundwater. A way of doing so is to build a pile of waste rock, cover it with low permeability material, e.g., clay, and introduce erosion protection. These measures prevent water and the problem is avoided. It is also worth mentioning that uranium mining does not increase the radioactivity of the soil. On the contrary, the material is less radioactive than before the mining. On the other hand radioactive materials can more easily be transported away from the mining site [13]. Uranium minerals always contain other radioactive elements such as radium and radon. Therefore, even though uranium itself is not very radioactive, the ore that is mined, especially if it is very high-grade, should be handled with care, for occupational health and safety reasons.

Miners must wear dust-filter masks and a radiation-recording device to ensure that the limits of exposure, set by the International Committee for Radiological Protection (ICRP), are not exceeded. The risk of internal exposure comes mainly from radon, which can be inhaled and settle in the lungs where it decays and emits alpha particles, which is hazardous to humans. Alpha particles cannot penetrate a sheet of paper or the outer layer of human skin and is a health hazard only if it gets inside the body by inhalation, ingestion or through a cut. Different shielding requirements for different radiations are illustrated in Figure 5.

Swedish power industry purchase uranium directly from several mines. The power company must certify all mines before it can be considered a supplier [1]. The main hazard in the conversion facility is the use of hydrogen fluoride. A report from 1998 that investigated the long-term population dose due to radon from uranium mining concludes that the dose is insignificant [14].

![Figure 4 – Illustration of the shielding of different kinds of radiation](image-url)
A common misconception is that the transport of uranium and other radioactive substances is associated with large risks. This is however not the case, because the radioactivity is very low as long as the uranium has not been irradiated. In addition all uranium transported is safely loaded in containers that guarantee safety in all predictable situations [15].

### 2.2 Enrichment

Natural uranium consists of approximately 99.3 % of $^{238}\text{U}$ and 0.7 % $^{235}\text{U}$. $^{235}\text{U}$ is the only nuclide that exists in nature that is fissile by thermal neutrons. In LWRs the uranium fuel needs to be enriched in order to make the reactor go critical. Enrichment means that the ratio of $^{235}\text{U}$ to $^{238}\text{U}$ is increased. In LWR the concentration of $^{235}\text{U}$ is approximately 3-5 %. The by-product of this enrichment operation is called depleted uranium (DU) that contains less $^{235}\text{U}$ than natural uranium and is normally stored at the enrichment plants. Uranium is classified according to the amount of fissile material present, i.e., the percentage of $^{235}\text{U}$. The classifications of uranium are presented in Table 5.

<table>
<thead>
<tr>
<th>Classification</th>
<th>$^{235}\text{U}$ [% of total]</th>
<th>$^{238}\text{U}$ [% of total]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Uranium (NU)</td>
<td>0.7</td>
<td>99.3</td>
</tr>
<tr>
<td>Depleted Uranium (DU)</td>
<td>0.2 – 0.4</td>
<td>99.6 – 99.8</td>
</tr>
<tr>
<td>Slightly Enriched Uranium (SEU)</td>
<td>0.9 – 2</td>
<td>98 – 99.1</td>
</tr>
<tr>
<td>Low Enriched Uranium (LEU)</td>
<td>2 – 20</td>
<td>80 – 98</td>
</tr>
<tr>
<td>High Enriched Uranium (HEU)</td>
<td>&gt; 20</td>
<td>&lt; 80</td>
</tr>
</tbody>
</table>

Enrichment is an activity subject to competition like all other front-end activities. The major companies, their location and capacities are presented in Table 6. The capacity of enrichment in the world is presently much larger than the demand.
Table 6 - Capacity of enrichment facilities in the world [11]

<table>
<thead>
<tr>
<th>Country</th>
<th>Company</th>
<th>Process</th>
<th>Capacity [SWU$^{*}10^6$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>USEC</td>
<td>Diffusion</td>
<td>18.8</td>
</tr>
<tr>
<td>Russia</td>
<td>MINATOM</td>
<td>Centrifuge</td>
<td>20</td>
</tr>
<tr>
<td>France</td>
<td>EURODIF</td>
<td>Diffusion</td>
<td>10.8</td>
</tr>
<tr>
<td>Germany</td>
<td>URENCO</td>
<td>Centrifuge</td>
<td>4.5</td>
</tr>
<tr>
<td>Netherlands U.K.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>JNFL/PNC</td>
<td>Centrifuge</td>
<td>1</td>
</tr>
<tr>
<td>China</td>
<td>CNNC</td>
<td>Diffusion/centrifuge</td>
<td>0.8+0.4</td>
</tr>
<tr>
<td>Argentina</td>
<td>Others</td>
<td>Diffusion/centrifuge</td>
<td>0.035</td>
</tr>
<tr>
<td>Pakistan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>56.335</strong></td>
</tr>
</tbody>
</table>

2.2.1 Technology

Enrichment is, as previously mentioned, performed to increase the $^{235}$U to $^{238}$U ratio in uranium. Presently two methods are most commonly applicable: *diffusion* and *centrifugation*.

Figure 4 – The figure to the left is an illustration of the principles of a Zippe-type gas *centrifuge* with $^{238}$U represented in dark blue and $^{235}$U in light blue (left picture) [17] and the figure to the right illustrates the Gaseous diffusion process with membrane and two separate fractions of uranium[18]

---

$^*$ SWU = Separative Work Unit, is described in Chapter 2.2.1.1
These methods use the physical properties of molecules in order to separate isotopes, i.e., the mass difference is of main importance. The methods employ identical steps that produce successively higher concentrations of $^{235}$U. Each step concentrates the uranium before it is sent to the next step and the tailings are sent back to the beginning of the enrichment cycle for further processing. The gaseous diffusion method separates the gaseous uranium hexafluoride into two streams by utilising a ceramic membrane. $^{235}$U, which is lighter, passes through the membrane easier than $^{238}$U. This procedure creates a stream of enriched uranium to the required level (3-5%), i.e., Low Enriched Uranium (LEU), the other stream consists of tails, i.e., depleted uranium (DU), see Figure 4. This method demands a large amount of electricity and has been replaced by more efficient methods, e.g. gas centrifugation. A gas centrifuge employs a large number of rotating cylinders in series and the rotation creates a centrifugal force. $^{238}$U, which is heavier isotope, will end up at a higher concentration at the outside of the cylinder and $^{235}$U at the centre due to this force. Gas centrifuges needs less electricity to enrich uranium in comparison to gaseous diffusion, and this is why diffusion plants are being replaced in favour of the centrifuge method. An improved version of the gas centrifuge concept also exists on the market, called zippe centrifuge. The main difference is that it uses heat in the bottom of the cylinder in order to produce convection current that moves the $^{235}$U upwards in the cylinder, see Figure 4.

### 2.2.1.1 Separative work unit

Separative work unit, or SWU, is a unit that measures the quantity of energy used in the enrichment process. The unit considers the quantities of the natural uranium feed, the tails consisting of depleted uranium and the product, which is uranium enriched to a specified level. Modern gaseous diffusion typically require about 2500 kWh of electricity per SWU in comparison to the more efficient gas centrifuge process that uses about 50 kWh of electricity per SWU [19].

For light water reactors the product, i.e. the enriched uranium, has typically 3.6 % $^{235}$U and the tails consist of about 0.2 – 0.3 % $^{235}$U. Depending on the uranium price and price of electricity the enrichment process can be optimized, so called “tails optimization”. This is best explained with an example: “When producing 1 kg of uranium enriched to 3.6 % $^{235}$U, 8 kg of natural uranium (NU) and 4.5 SWU are needed if the tails contains 0.3 % $^{235}$U. If process is changed so that the tails instead contain 0.2 % $^{235}$U, only 6.7 kg of NU but 5.7 SWU is required” [17]. This means that if uranium is considered expensive then more work is put into the plant and vice versa. See Chapter 2.6.2. for further explanations.

### 2.2.2 Safety

To enrich uranium for a Swedish NPP, the enrichment plant needs to be certified [1]. The major safety concern at the enrichment plant is associated to chemical hazards. The chemical hazards involve mainly handling of uranium hexafluoride (UF$_6$). This material forms hydrogen fluoride and uranyl fluoride when it reacts with moisture in the air. Occupational health is a concern if the material is inhaled and it is thereby essential to minimise dust particles at the site. This type of hazard is controlled and surveyed by automatic instruments that alert if there is any danger for the workers [20].
Radiation is not a problem as long as the fuel has not been irradiated and natural, enriched or depleted uranium can be handled without any additional shielding. The transport of these materials is about the same as transporting corrosive materials in terms of safety requirements [20].

### 2.3 Fuel fabrication

Vattenfall AB’s (VAB) nuclear fuel assemblies are produced at fuel fabrication plants all over the world. The choice of fuel fabrication plant depends on several factors, e.g., price, safety and technology. General Electrics (GE), AREVA and Westinghouse provide fuel fabrication services for BWRs and for PWRs only AREVA and Westinghouse [21]. The fuel arrives as enriched uranium hexafluoride ($\text{UF}_6$), and departs as a complete fuel assembly with uranium dioxide ($\text{UO}_2$). The fuel purchaser, i.e., the power-producing company, owns the uranium and buys a transformation service from the fuel fabricant, i.e. the fuel fabrication factory never owns the uranium. This is in order to avoid ownership and liability issues [13].

Several companies provide fuel fabrication services all over the world and the fuel fabricating company normally collects the enriched uranium from the enrichment facility. The present capacity of producing $\text{UO}_2$ LWR fuel is presented in Table 7.

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity [t U/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>3 900</td>
</tr>
<tr>
<td>Russia</td>
<td>2 020</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>2 000</td>
</tr>
<tr>
<td>Japan</td>
<td>1 674</td>
</tr>
<tr>
<td>France</td>
<td>820</td>
</tr>
<tr>
<td>Belgium</td>
<td>750</td>
</tr>
<tr>
<td>Germany</td>
<td>650</td>
</tr>
<tr>
<td>Sweden</td>
<td>600</td>
</tr>
<tr>
<td>Korea</td>
<td>400</td>
</tr>
<tr>
<td>U.K.</td>
<td>330</td>
</tr>
<tr>
<td>Spain</td>
<td>300</td>
</tr>
<tr>
<td>Brazil</td>
<td>100</td>
</tr>
<tr>
<td>China</td>
<td>100</td>
</tr>
<tr>
<td>India</td>
<td>25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>13 669</strong></td>
</tr>
</tbody>
</table>

A normal LWR with output power of about 1000 MWe requires some 25 t of fresh fuel each year, which is about one fifth of the total fuel. The fuel remains in the reactor for about 5 years.
2.3.1 Technology

The process described below is according to the nuclear fabrication factory of Westinghouse, in Västerås, Sweden. This process is however representative to for LWR fuel fabrication in general. The variations from this process are mainly concerning how the conversion of the uranium hexafluoride into uranium dioxide is accomplished.

LEU, with less than 5 \(^\text{\textsuperscript{5}}\text{\textit{\%}}}\) of the uranium isotope \(^{235}\text{\textit{\textit{U}}}\), arrives to the fuel fabrication factory from the enrichment facility in cylinders. It arrives as UF\(_6\), which is solid at room temperature.

First the cylinders are heated to over 60\(^\circ\text{C}\), transforming the UF\(_6\) into a gaseous state. The gaseous uranium hexafluoride reacts with carbon dioxide, CO\(_2\), and ammonia, NH\(_3\), in a wet process (with H\(_2\)O) to form ammonium uranyl carbonate (AUC), UO\(_2\)CO\(_3\)\(\cdot\)(NH\(_4\))\(_2\)CO\(_3\). This wet-method produces AUC as an intermediate product in order to facilitate the elimination of the fluorine due to the larger particles that is formed. In the next step the AUC is reduced with hydrogen gas, H\(_2\), to uranium dioxide, UO\(_2\). The ammonia and the carbon dioxide is recycled and reused at the first step of the process, see Figure 5.

![Figure 5 – Conversion of UF\(_6\) to UO\(_2\). After this process the uranium is prepared for pelletizing, see Figure 7.](image)

The uranium dioxide is now a powder and subsequently pressed into small pellets, about 0.8 cm in diameter and about 1 cm high. These uranium pellets are then sintered in an oven at high temperature (about 1700\(^\circ\text{C}\)) to form a ceramic material, see Figure 7. Some of the fuel pellets are blended with gadolinium, which is a so-called burnable absorber. This material has high neutron absorption cross-section, i.e., the probability of absorbing neutrons is high for this material. The main purpose of adding this material is to make the power distribution more even for fresh and irradiated fuel and this also means avoiding using the control rods at the
beginning of the irradiation cycle. Gadolinium is consumed during the fuel cycle, hence the name: burnable absorber.

Figure 6 – Illustration of the process where uranium pellets are manufactured. Some of the uranium pellets are blended with the burnable absorber material gadolinium.

The pellets are thereafter put in pipes of zirkaloy, which is an alloy mainly of the metal zirconium. This metal is used thanks to its positive properties in the reactor. The metal absorbs very few neutrons in a nuclear reactor and thereby does not hamper the nuclear reaction. The pipes are thereafter filled with helium, welded shut and inspected for leaks, see Figure 7.

Figure 7 – The final steps of the fuel fabrication process
The pipes are manufactured at Sandvik Steel and the pipes are subsequently put together into fuel assemblies, with a base plate and a top nozzle. The fuel assemblies contain about 100 fuel rods for BWR and about 200 for PWR [22]. In a PWR, depending on size, there are about 121 – 193 fuel assemblies. In a BWR there are between 368 assemblies for the smallest and 800 assemblies for larger reactor, depending on output power.

2.3.2 Safety

All activities during fuel fabrication are performed under strict criticality and safety limits. This means that controls are performed throughout the process to ensure that a critical mass cannot be assembled unintentionally. These procedures aim to verify the fissile mass, the geometry and the moderating properties in the vicinity of fuel. Neutron detector systems are utilised to monitor and warn for the occurrence of criticality.

The uranium hexafluoride is transported in steel cylinders with exterior packing that according to international standards are required to withstand a nine-meter drop and a fire at 800°C during 30 minutes. The cylinders containing the uranium is shipped from the enrichment facility to a Swedish harbour and transported by truck to the fuel factory.

The fabrication of the nuclear fuel needs to be of high quality since the fuel assemblies must function at high temperature and high radiation levels during five years in a reactor and at least forty years of storage in a water pool. Safety checks are continuously performed throughout the whole process of fabrication; see Figure 5 – 7.

2.4 Waste management

Wastes from the UOX fuel cycle are categorized as low-, medium- or high-level waste according to the amount of radiation they emit. These categories are:

- **Low-Level Waste (LLW)** produced at all stages of the fuel cycle
- **Intermediate-Level Waste (ILW)** produced during operation and by reprocessing
- **High-Level Waste (HLW)** is spent nuclear fuel and other materials containing fission products (e.g., strontium, cesium, plutonium, etc.)

Low- and intermediate waste can be stored in Sweden near Forsmark NPP at “Slutförvar för radioaktivt driftavfall (SFR)” while High-Level waste results in more complex handling. When the concentration of fissile nuclei, i.e., $^{235}$U, in the fuel is low, the spent fuel is removed from the reactor. The spent fuel will be emitting both radiation and heat. The fuel is therefore unloaded into a storage pond adjacent to the reactor, to allow the radiation levels to decrease. The used fuel is stored in the ponds for several months up to years, the water shielding the radiation and absorbing the heat [10]. After the radiation and heat from the fuel has decreased to a satisfactory level, the fuel is either sent to a central storage facility (CLAB in Sweden) or for reprocessing (e.g. Sellafield in the UK or La Hague in France), see Chapter 3.
2.5 Non-proliferation

Natural uranium consists of two isotopes, \(^{235}\text{U}\) and \(^{238}\text{U}\) with a 0.7 enrichment of fissile \(^{235}\text{U}\), which is the only naturally occurring fissile nucleus. To manufacture a nuclear explosive from uranium the \(^{235}\text{U}\) content must be 80 – 90 %, i.e., Highly Enriched Uranium (HEU). If HEU is procured it is not complicated to manufacture a nuclear explosive because the technology to make the device explode is simple. However for LWRs the enrichment never exceeds 5 %, i.e., LEU. The enrichment facility, which provides the fuel fabrication facility with enriched uranium, can in a short period of time change their process so that HEU can be produced. When having 5 % enriched uranium the major work to obtain 90 % enrichment is already done [23]. All activities of the uranium fuel cycle is however subject to domestic and international safeguards. An enrichment facility cannot produce HEU without any attention from the IAEA. This is why the once-through uranium fuel cycle is considered to be proliferation resistant.

The risk that weapon-useable nuclear material may end up in the wrong hands is one of the major public concerns, when it comes to nuclear power. Proliferation issues may be one of the major obstacles to worldwide expansion of nuclear power. However all uranium traded is sold for electricity production only, and two layers of international safeguards guarantee that this really is the case. All western countries have ratified the Non Proliferation Treaty (NPT). NPT is an international agreement that aims to reduce the proliferation of nuclear weapons. A country that has ratified the agreement guarantees to use nuclear material only for civil purposes, contribute to the disarmament and will not to spread technology, knowledge or material to countries outside NPT. The only countries with nuclear capability that have not ratified the NPT are India, Pakistan, Israel and North Korea. By accepting NPT the country also admits the International Atomic Energy Agency (IAEA) to perform regular and unprepared controls in order to secure that the country in question follows their nuclear program as intended [15].

2.6 Costs

All the front-end activities of the UOX fuel cycle are subject to competition. Companies providing these services are government, private or have a mixed ownership. The power company, which normally is the proprietor of the nuclear reactor in need of fuel, decides which activity that will be performed by which company. For the mining and milling process there are about eight major companies located in Canada, Australia, Africa and Kazakhstan that represents about 85 % of the market [8]. The conversion costs are approximately 6-7 % of the mining and milling costs and is therefore often included in the price for mining. There are companies present in Canada, USA, France, U.K. and Russia, which perform this service. The mining and milling company is normally responsible for the transportation of uranium to the conversion plant. The conversion company thereafter delivers the converted uranium to the enrichment facility. It is however normal procedure that the fuel fabrication company collect the uranium from the enrichment facility. As previously mentioned GE, AREVA and Westinghouse are the major companies that provides LWR fabrication services. However there are other companies that provide fuel fabrications services but mainly for domestic usage. It is not unlikely that these companies e.g., TVEL (Russia) or Mitsubishi (Japan) will provide Europe and the US with nuclear fuel in the future. Before a fuel vendor can sell their services to Vattenfall AB (VAB) they must be certified, and for Swedish reactors the Swedish
Nuclear Inspectorate (SKI) must give authorization [21]. VAB tries to always have 4-5 independent suppliers in order to get a more diversified fuel chain [21].

The production price of a kWh from a Swedish nuclear power plant is somewhere around 0.20 SEK [1]. Included in this figure are capital costs, improvement costs, operation and maintenance, fuel- and waste costs together with taxes and charges. Nuclear power is capital intense like water- and wind power, which implies low variable costs.

The total fuel costs are divided between the price for uranium, conversion, enrichment and fuel fabrication cost. According to reasons stated in Chapter 2.6.1 the only cost that fluctuates significantly is the uranium costs. There is an uncertainty on the uranium price in short- to medium-term. How this will influence the total fuel cost is illustrated in the Figure 8.

![Figure 8 – The fuel cost dependence on the price of uranium](image)

Figure 9 illustrates how the uranium cost affects the total fuel cost for a price from 20 – 140 USD/lb U₃O₈. The following assumptions were made:

- **Burnup = 45 MWd/kgU**
- **Conversion cost = 6 % of uranium price**
- **Enrichment cost = 145 USD/SWU and 5 SWU/kgU with 3.6 % enrichment level**
- **Fuel fabrication cost = 275 USD/kgU**

The price of uranium corresponds to about 50 % of the total fuel costs at the present price, 90 USD/lb U₃O₈. The long-term uranium price is however expected to be about 40 – 50 USD/lb U₃O₈ [21]. The assumption that the enrichment cost is constant is not accurate because it is depending on the uranium price. This is however discussed in Chapter 2.6.2 and the consequence of this assumption is not significant to the total fuel cost. The enrichment cost would have a slightly higher part of the fuel cost as the uranium price is increasing.

Burn-up is another aspect that affects the fuel cost. Burn-up has increased historically for LWR due to technological improvements. It is unclear whether this trend will continue in the future or if there’s any technological limit to LWR burn-up. Increasing the burn-up much
beyond 60 MWd/kgU will imply that the enrichment limit of 5 weight-percent must be exceeded. This is a costly procedure and if any incentives exist for doing so is unclear, because the fuel cost might not decrease if the facilities are obliged to make large investments. The fuel cost dependence on burn-up is illustrated in Figure 9 and the same assumptions as for Figure 8 were made.

![Figure 9](image-url)

**Figure 9 – The fuel cost dependence on burn-up with variable uranium price**

It is obvious from Figure 9 that the higher the burn-up the lower the fuel cost. However other factors like the cost for enrichment, validation costs, etc are not included in this estimate.

### 2.6.1 Extraction cost

The extraction costs is difficult to estimate since it is not publicly available information. A mine that has been operating for several years has an extraction cost of about 13 – 14 USD/lb U₃O₈, which is equivalent to about 30 – 40 USD/kgU [21]. On the other hand, a mine that recently been put into operation, has an extraction cost of about 25 – 26 USD/lb U₃O₈, which is equivalent to about 60 – 70 USD/kgU [21]. About 80 % of the uranium presently produced comes from old mines.

There is no formal exchange for uranium as there is for other supplies such as gold or oil. The uranium spot price is published by two private business organizations that independently survey uranium market activities, such as offers, bids and transactions. These organizations are the Ux consulting company (UxC) and TradeTech [11]. They analyze the market developments, including precedent and present transactions, demand and supply issues and events that affect the market. According to experience only a small number of transactions goes through these organizations [11, 21]. If a buyer purchases a volume of uranium for a certain price, this action fundamentally affect the spot price, since transactions are not a daily activity and all activities regardless of volume affects the price. Operators on the market can
manipulate the spot price for their own gain [11]. Formerly uranium trade involved large volumes and the spot price was thereby more reliable [21]. The spot price and the actual price the fuel buyers pay is illustrated in Figure 10.

During much of the 1990s the uranium production was well below the consumption due to the reduction of inventories and the prices decreased to the degree where it was not economically feasible to continue extracting uranium. In addition, excess weapons-grade uranium from nuclear warheads, which has been down-blended to civil grade, has been liberated to the market. There has recently been concern whether the mine production could increase fast enough to meet the demand when the supply from the inventories runs out. This is one of the reasons why the spot price has increased. When all relevant mines are under operation the long-term price for uranium, U₃O₈, is expected to be about 40-50 USD/lb [21]. According to a report by Bunn et al. [26] it is unlikely that the price will rise above this level for any longer periods of time, but some short-term fluctuations before all of these mines are operating are probable.

Uranium spot prices have increased from 10 USD/lbU₃O₈ in 2002, to more than 50 USD/lbU₃O₈ in 2006 and peaked at 135 USD/lbU₃O₈ in June 2007. The uranium price is anticipated to fluctuate until new mines are opened and can guarantee a long-term supply. The impact on the total generation cost is however small, about 5 – 10 %, from this uranium price increase.

The spot price has however not yet affected the uranium market price; since the price of uranium is subject to long-term agreements, see Figure 11. These agreements are of different time span but most commonly of 5-year contracts. Historically the uranium price has been subject to a minimum and maximum threshold price. The minimum price is a guarantee for the uranium mining company to uphold their production and the maximum price is an assurance for the power company to avoid massive price fluctuations. If the price of uranium lies between the threshold prices the power company pays the market price. These threshold prices are stated after an agreement between the two parties. The supplier of uranium is presently not willing to uphold the same conditions. They want the contracts to constitute of

Figure 10 - Spot- and market prices of Europe and the US [24, 25]
larger portion of market price and do not want to have a maximum price limit [11]. This could be an indication that mining companies suspect the uranium price will increase. The price limits are not published because it is negotiation between the two parties and no standard exists.

2.6.2 Enrichment cost

Enrichment cost corresponds to about one third of the fuel cost and is charged according to the number of separative work units (SWU) needed. The cost for the enrichment process is normally quoted in USD/SWU. The Nuclear Energy Agency (NEA) has estimated that enrichment prices in short and medium term will be in the range of 80 to 120 USD/SWU [26]. Presently the price is 145 USD/SWU [25]. It is possible that enrichment costs decrease in the future due to more efficient operating conditions [27]. Advance enrichment processes might reduce the cost to about 50 USD/SWU [26].

If natural uranium is considered expensive the operator at the enrichment facility can change the process so that the amount of \( \text{U}^{235} \) in the depleted uranium tails is reduced and less feed material is needed for the same product. Thereby an increase of the total work at the facility is necessary, i.e. the SWU increases. If on the other hand the natural uranium is considered inexpensive the operator can change the process in order to increase the amount of \( \text{U}^{235} \) in the tails and thereby the SWU decreases, hence the enrichment costs decreases. These different processes are illustrated in Figure 11.

![Figure 11 – Different enrichment procedures depending on the price of uranium](image)

The enrichment process is an electricity consuming process. The gaseous centrifuge process is more efficient than the gaseous diffusion process. For the centrifuge process it takes about 50 kWh/SWU and for the diffusion process it takes about 2500 kWh/SWU [19]. How much electricity that is consumed in the enrichment process in comparison to electricity yield by the fuel is presented in the calculation below. Assuming a burn-up of 50 MWd/kgU and a coefficient of efficiency (\( \eta \)) of 0.37 yields the following:

\[
\begin{align*}
50 \text{MWd/kgU} & = 24 \times 50 \times 1000 \quad \text{kWh/kgU} = 1200000 \quad \text{kWh/kgU} \\
\eta \times 1200000 \quad \text{kWh/kgU} & = 0.37 \times 1200000 \quad \text{kWhel/kgU} = 444000 \quad \text{kWhel/kgU}
\end{align*}
\]
It takes about 5 SWU to enrich natural uranium from 0.71% to 1 kg 3.6% $^{235}$U, with an assumed tail of 0.25% $^{235}$U [28]

\[
\text{centrifuge: } 50 \frac{kWh}{SWU} \times 5 \text{SWU} = 250 \text{kWh} \\
\text{diffusion: } 2500 \frac{kWh}{SWU} \times 5 \text{SWU} = 12500 \text{kWh}
\]

The conclusion from this calculation is that about 250 kWh/444 000 kWh = 0.056% of the electricity yield from the uranium fuel is required in the centrifuge enrichment process, while the same number for the diffusion process is 12 500 kWh/444 000 kWh = 2.8%. The reason for substituting diffusion plants in favour of centrifuge plants is obvious.

### 2.6.3 Fuel fabrication cost

In similarity to the enrichment and uranium costs, presently fuel fabrication cost corresponds to about one third of the total fuel cost. The NEA states in a report by Bunn et al. [26] that the LEU fabrication price will vary between 200 and 300 USD/kgHM in short to medium term. The technology for fabrication is mature and the impacts to the environment insignificant, so the price is not expected to change substantially in the future [26].

However, as previously mentioned, companies that presently is not operating on the market can provide fuel fabrication services in the future. This could change the fabrication prices, because the market is subject to competition.

### 2.6.4 Future trends

If the price of uranium ore would increase by 50%, in Sweden from 0.01 to 0.02 SEK/kWh, the production price would only be affected by 5%, i.e. increase from 0.18 to 0.19 SEK/kWh. If the corresponding fuel increase would take place for gas, the production price would increase 60%. For coal and oil the production price would not be as highly affected, but it would be much larger compared to the nuclear alternative.

The once-through UOX fuel cycle necessitates direct disposal storage rooms to be built. The entire back-end of the fuel cycle involves country-specific solutions concerning as opposed to the reprocessing option, which is commercially available on the world market. The final disposal is also associated with cost and for the case of Sweden it is assumed that the costs is about USD410/kgU [29]. The direct disposal costs are costs for interim storage of the spent fuel and transport to a repository site and disposal of the spent fuel.

The cost of conversion constitutes only a few percent of the total fuel cost. Fluctuations of conversion costs would thereby not significantly affect the future cost of the fuel cycle. There has always been high competition among fuel fabrication services due to the well-established market, which presently is over-supplied. There is a large difference in manufacturing costs depending on the country where the fuel is produced due to different salaries and fluctuations of currency exchange rates [29].

The worlds currently published accumulated uranium reserves, see Table 7, is 4.743 Mt and the uranium requirements for 2007 were 66 529 t [6]. Dividing the uranium reserves with the
demand indicates that uranium will suffice for more than 70 years with present rate of consumption. The amount of uranium deposits is directly dependent on the actual price of uranium per kg at the market. The market price of uranium also gives an indicator on what extraction cost is economically defendable. Hence, if the uranium price increase this leads to larger volumes of uranium being extracted. Due to the low prospecting during the last 20 years the figures presented in Table 8 have high uncertainties.

Table 8 – Uranium resources (millions t U) [2, 30]

<table>
<thead>
<tr>
<th>Cost of recovery [USD/kgU]</th>
<th>Identified</th>
<th>Conventional</th>
<th>Speculative</th>
<th>Phosphates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RAR</td>
<td>Prognosticated</td>
<td>Speculative</td>
<td>22</td>
</tr>
<tr>
<td>&lt; 40</td>
<td>1.947</td>
<td>1.700</td>
<td>4.557</td>
<td></td>
</tr>
<tr>
<td>40 - 80</td>
<td>0.696</td>
<td>0.362</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 - 130</td>
<td>0.654</td>
<td>0.285</td>
<td>0.819</td>
<td></td>
</tr>
<tr>
<td>&gt; 130</td>
<td></td>
<td>?</td>
<td>2.979</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.743</td>
<td>10.055</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The figures from Table 7 are from the so-called Red book, see the report by OECD and IAEA [30]. It is the result from reported uranium resources by 44 countries and are classified according to the level of confidence in the estimates and different recover cost categories. This book is updated and released each year. The Identified uranium resources are divided into two categories: Reasonably Assured Resources (RAR) and Inferred resources. A uranium deposit is classified as Identified resource when uranium mineral occurs in such size, grade and configuration that it could be recovered at a given cost range with proven mining technology. The estimated amount of uranium in the deposit is based on specific sample data and direct measurements. However, the Prognosticated and Speculative Resources are classified as Undiscovered Resources. Prognosticated resources are expected to occur in or near known deposits and Speculative are thought to exist in geologically favourable but yet unexplored areas. The Identified resources have increased from 2003 while the Undiscovered Resources have remained unchanged.

In addition to the conventional resources considerable amount of uranium deposits occur in so-called unconventional resources. These deposits require new technologies for their exploitation and the ore concentration is often low. Unconventional uranium resources include uranium concentrations in phosphates and uranium contained in seawater. Roughly 22 MtU of uranium is extractable at low concentrations from phosphate deposits at an extraction cost of approximately 100 USD/kgU [1]. A significant fraction of this uranium could be recovered as the world’s demand for fertilizer is rising [26]. Furthermore, large uranium deposits are contained in seawater, approximately 4 Gt uranium at an extraction costs of about 300 USD/kgU but at very low concentrations. This extraction cost is however subject to large uncertainties because technology is not yet developed [1].
2.6.5 Conclusions

The facts stated earlier in this chapter indicate that the supply of uranium is sustainable. The price of uranium and the extraction cost determines how large the uranium deposits actually are. The increase of uranium price would create incentives for further prospecting of earlier non-investigated areas with ore deposits. The conclusion is that under these constraints uranium will suffice in production purposes for several hundreds of years. In the case of utilising the uranium deposits in seawater the deposits will last for about 60,000 years with 2007 rate of consumption. The future uranium price is however subject to some uncertainties. The current fluctuations in price are anticipated to continue until all necessary mines are opened to guarantee supply of an increasing demand. However, the long-term uranium price is expected to be about 40 –50 USD/lb U₃O₈. The conversion cost is a small part of the fuel cost and is not likely to significantly affect the fuel cost. Enrichment processes becomes more and more efficient leading to lower costs and is not either expected to influence the fuel cost significantly in the future. Fuel fabrication costs is currently lower than the enrichment costs and will remain stable in the short to medium term. The cost that is subject to the largest uncertainties at the front end is associated with the uranium price.
3 MOX fuel cycle (U-Pu fuel cycle)

Nuclear power first got commercialised in Sweden in the 1960s, and the only answer to waste management at that time was reprocessing. In the mid 1980s both the government and the industry changed their point of view. They promoted instead the once-through fuel cycle as a method to manage the used nuclear fuel. The reprocessing alternative was thereby abandoned because it was considered too large a risk and too expensive. Oskarshams Kraftgrupp (OKG) signed an agreement with a reprocessing plant in England, Sellafield, in 1969. OKG shipped over 140 t spent nuclear fuel to Sellafield during 1969 – 1984, that they have paid around 650 MSEK to get reprocessed [31]. The government examined the possibilities to bring the spent fuel back to Sweden instead of making MOX, but the conclusion was that this would be too dangerous and, above all, too expensive. The reprocessed fuel from Sellafield will be enough to manufacture about 80 fuel assemblies. These assemblies will be loaded in the reactor from 2010 in two batches with 40 assemblies in each batch [32]. The OKG reactor O3 that will be loaded with MOX is of BWR type and has 700 fuel assemblies in total, which means that approximately 11 % of the total reactor load will be MOX fuel. Presently OKG has no intention of increasing the utilisation of MOX after these batch loadings [33]. However most LWRs use MOX as about 30 – 50 % of their core and the new Advanced LWRs, such as EPR and AP-1000, can accept 100 % MOX fuel loadings [34].

Utilising MOX fuel is a way to manage the radioactive waste from spent fuel. The spent fuel is presently not recycled more than once in LWRs as MOX. A final disposal is thereby still required to manage the spent MOX fuel. In order to utilise the uranium resources more efficiently a FR would be necessary to implement. This is however not covered in this study. The reprocessing facilities that is mandatory for the MOX fuel cycle is also a requirement to supply the FRs with fuel. The MOX fuel cycle for LWRs is illustrated in Figure 12.

![Figure 12 – Illustration of the MOX fuel cycle](image)

There are currently about 25 years experience in producing MOX fuel and the first large-scale plant, Melox, started operating in France 1995 [2]. MOX fuel already provides about 2 % of
the new fuel used today, this figure is nevertheless expected to rise above 5% by 2010. MOX is used in Europe, where currently 32 reactors are using the fuel (in Belgium, Switzerland, Germany and France) and there are also future plans for usage in Japan [34]. The majority of these reactors are PWRs, which implies that the experience of MOX usage in BWRs is less, with only two large BWRs in Germany currently using MOX fuel [35]. Across Europe about 40 reactors are licensed to load 20-50% of their cores with MOX fuel and Japan plans to have one third of its 54 reactors using MOX by 2010.

3.1 Supply

The MOX-fuel cycle is much different from the uranium fuel cycle, since it consists of spent nuclear fuel to some degree. The MOX-fuel cycle starts where the UOX once through fuel cycle ends. Plutonium is produced during reactor operation and can be extracted when the irradiated uranium-based nuclear fuel is reprocessed. Only a few commercial reprocessing plants are available for LWRs and they are situated in Europe and Russia, see Table 9.

Table 9 - World commercial reprocessing capacity for LWR fuel [2]

<table>
<thead>
<tr>
<th>Plant</th>
<th>Location</th>
<th>Capacity [tHM***/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Hague</td>
<td>France</td>
<td>1700</td>
</tr>
<tr>
<td>THORP</td>
<td>UK</td>
<td>900</td>
</tr>
<tr>
<td>Mayak</td>
<td>Russia</td>
<td>400</td>
</tr>
<tr>
<td>-</td>
<td>Japan</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3014</td>
</tr>
</tbody>
</table>

Presently the output of reprocessing plants exceeds the rate of plutonium usage in MOX and this causes stocks of civil plutonium in numerous countries. These stocks are expected to exceed 250 t before they start to decline after 2010 when MOX usage is anticipated to increase as noted earlier [34].

3.1.1 Safety

The plutonium from reprocessed fuel is normally fabricated into MOX as quickly as possible to avoid problems with short-lived radioactive isotopes. $^{241}$Pu decays into $^{241}$Am, which is a strong gamma emitter, this gives rise to severe problems for the MOX plant. The level of $^{241}$Am increases by 0.5% each year, with corresponding decrease of fissile isotopes of the plutonium [34].

3.2 Reprocessing

Spent UOX fuel consist of about 95% $^{238}$U, 1% $^{235}$U, 1% Pu and 3% fission products*, which are highly radioactive. Reprocessing means separating the spent UOX fuel into uranium, plutonium and waste products, containing fission products, i.e., high-level waste. This type of reprocessing plants is commercially present for an international market in France (La Hague), UK (THORP) and Russia (Mayak), see Table 8.

** HM = Heavy Metal
* Uranium fuel with initial enrichment of 3.7% $^{235}$U and average thermal burnup = 41.2 GWd/tHM
Spent fuel assemblies removed from a reactor are very radioactive and produce heat. They are therefore put into large tanks or "ponds" of water in order to cool and shield the radiation. Here they remain for a number of years and the level of radioactivity decreases considerably. For most types of fuel, reprocessing occurs anywhere from 5 to 25 years after reactor discharge.

### 3.2.1 Technology

PUREX, Plutonium and Uranium Recovery by EXtraction, is an aqueous method commonly applied for the process of reprocessing irradiated uranium fuel, see Figure 13. The method involves dissolving the spent nuclear fuel in warm concentrated nitric acid and all insoluble solids are subsequently removed. 30 % tributyl phosphate (TBP) in kerosene is an organic solvent used to recover the uranium and plutonium. The fission products remain in the aqueous nitric phase. Uranium and plutonium is extracted by liquid-liquid extraction, which is a process where the tributyl phosphate forms complexes with the extracted actinides. The result of this extraction is separate fractions of uranium, plutonium and high-level waste, containing fission-products and transuranic elements.

![Figure 13 – Flowsheet of the PUREX process](image)

### 3.2.2 Safety

Commercial PuO$_2$ powder is primarily an alpha emitter, it also emits neutrons, X-rays, gamma rays and beta particles, i.e., a hazardous radioactive material. It is the alpha and beta emissions along with the toxicity of plutonium that necessitates remote handling in gas tight glove boxes with large windows and suitable gloves. The gamma activity is mainly from the decay of $^{241}$Pu into $^{241}$Am. This radiation is however easy to shield due to the low energy. A major problem when it comes to reprocessing is radiation originating from dust deposition on equipment and inside the glove boxes. The isotopic composition of the plutonium determines the neutron activity, which increases with time. The fabrication of MOX fuel becomes more difficult with time because alpha activity and heat generation increase during storage,
especially from $^{238}$Pu. The gamma and neutron activity along with the heat generation increase with burn-up requiring heavier shielding and more remote handling in the fabrication facility to minimize the radiation dose to the plant operators. Further, if the PuO$_2$ powder is stored for too long time, an extra processing step may be required, namely separation of $^{241}$Am. Proper shielding must be considered throughout all activities involved in the MOX fuel cycle. The present reprocessing plants use glass to encapsulate and immobilise the high-level waste [27].

![Aerial photograph over the reprocessing facility La Hague, France [37]](image)

Figure 14 – Aerial photograph over the reprocessing facility La Hague, France [37]

The reprocessing facilities are extensive and complex chemical factories, see Figure 14. An accident would have significant environmental impact. During the reprocessing step extensive controls, e.g., from IAEA, are frequently performed because this is where weapons material is most likely diverted.

### 3.3 Fuel fabrication

MOX fuel fabrication started in Belgium and the USA in the 1950s, in France, Germany, Japan, the Russian Federation and the UK during the 1960s and in India during the 1970s. In Japan and the Russian Federation the MOX fuel was mainly produced for FBRs, and several plants have been taken out of operation. Currently there are only a few MOX fuel fabrication facilities for LWRs in operation in the world, see Table 10. There are currently three plants in the world that produces a commercial quantity of MOX for LWRs. Two are situated in France and one in the UK [38]. In 2005 200 t of MOX was produced, including 12-14 t of plutonium. MOX production is presently around 295 t/year using 15-18 t of plutonium, however Japan plans to build a 130 t/year MOX production plant by 2012. The Sellafield MOX plant in UK was recently downgraded from 128 ton 40 tHM/year.
Table 10 - World Mixed Oxide Fuel Fabrication Capacities for LWRs [34]

<table>
<thead>
<tr>
<th>Country</th>
<th>Capacity [t HM/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>195</td>
</tr>
<tr>
<td>UK</td>
<td>40</td>
</tr>
<tr>
<td>India</td>
<td>50</td>
</tr>
<tr>
<td>Japan</td>
<td>10</td>
</tr>
<tr>
<td>Total for LWR</td>
<td>295</td>
</tr>
</tbody>
</table>

3.3.1 Technology

The technology for fuel fabrication of MOX fuel is very similar to the fabrication of UOX fuel, except that all manufacturing steps are operated by remote control. The necessity of remote control is due to the presence of plutonium, which emits radiation. The blending of fertile material (depleted uranium, DU) with fissile material (plutonium, Pu) is the biggest difference between producing MOX fuel and the production of UOX fuel. In enriched uranium the fissile material is already present in the nuclear fuel and consequently blending is not necessary.

The plutonium that arrives to the MOX fuel fabrication facility varies in terms of isotopic composition. This is mainly due to:

- the type of reactor the plutonium origin
- the level of burn-up reached, by the spent fuel
- time since the end of irradiation, since reprocessing and purification
- flux characteristics in the reactor

The fissile quality of the plutonium is generally expressed as the ratio of Pu$^{239}$ and Pu$^{241}$ to the total plutonium according to:

$$\text{Fissile fraction} = \frac{\text{Pu}^{239} + \text{Pu}^{241}}{\text{Pu}_{\text{total}}}$$

The concentration of initial plutonium content in MOX is related to the fissile quality of the plutonium. If the fissile plutonium quality is poor, i.e., low fissile fraction, then the plutonium concentration must be increased. However increasing the plutonium concentration in order to maintain the initial fissile loading is not sufficient to maintain reactivity. In order to maintain the reactivity a further increase of plutonium concentration is necessary to compensate the increased absorption of neutrons in the even isotopes of plutonium. Hence, plutonium of poor fissile quality poses problems for the fuel fabrication. As the isotopic quality of plutonium degrades with each irradiation cycle, the initial plutonium concentration must be increased to achieve the same burn-up. Normally the concentration of plutonium is about 8 weight percent (w/o) [27] achieving a burn-up of about 45 MWD/kgU, i.e., the equivalent of uranium enriched to 3.6 %$^{235}$U. There is a general tendency toward increased burn-up levels. This is advantageous for the competitiveness of MOX fuel [27].

The quality control of UO$_2$/PuO$_2$ pellets is in principle the same as for the UO$_2$. Two special characteristics of the MOX fuel needs to be controlled separately: the homogeneity of
plutonium and the *dissolution* of plutonium during reprocessing. Until 1981 MOX fabrication, for LWRs, started from sinterable UO2 powder with good flowability and the PuO2 powder was delivered from precipitated oxalate or from plutonium nitrate solutions. These powders were subsequently mechanically blended and resulted in a powder of great homogeneity and “hot spots” were avoided. This fuel exhibited excellent irradiation behaviour and fulfilled all operating requirements [39]. However this fuel was found to be insolvable in pure nitric acid, as in PUREX. A new powder preparation technique was developed to meet the reprocessing requirements.

The most common process to fabricate MOX fuel, since 1981, is by Micronized MASter-blend (MIMAS) developed by Belgonucleaire (BN) in the early 1980s. In Sellafield, England, the Short Binderless Route (SBR) is used to fabricate MOX.

![Figure 15 – Flowsheet of the MOX fuel fabrication process](image)

The reference method, see Figure 15, was developed by BN and put into operation from 1973 until 1985. In this process the MOX fuel is produced by direct blending of PuO2 and free flowing UO2 powder resulting in dispersion of Pu-particles of various sizes in a UO2 matrix. The MIMAS process was created to meet the reprocessors requirements for high solubility. The PuO2 powder is micronized with UO2 powder to form a master blend of plutonium content of about 20-30 % in order to achieve this. The primary blend is subsequently mechanically diluted and mixed with UO2 powder to obtain the specified plutonium content. Since MIMAS was introduced the differences between MOX and UOX fuel have been significantly reduced, notably the heterogeneous character of the plutonium distribution [39].

The MIMAS process guarantees that all the fuel assemblies manufactured gives the same output power. This is due to the homogenization of the isotopic composition of plutonium over the whole process, achieved by computerized selection and cross blending of different bathes of plutonium to feed the process [40].
After the preparation of the powder mix, all the subsequent steps in order to manufacture a MOX fuel assembly are similar with some insignificant variations. The *pelletizing* is almost exclusively done by hydraulic presses, *sintering* is commonly conducted in continuous furnaces and the centreless *grinding* is performed dry. The fuel pellets are sealed in metal (normally zirconium) tubes, which are assembled into fuel elements. Tungsten inert gas (TIG) welding is commonly used to weld the fuel elements and they are thereafter pressurized. The fuel rods, for LWR, are thereafter put together into a fuel assembly where the rods are drawn from a magazine through the fuel assembly skeleton [38].

### 3.3.2 Safety

To ensure that the fabrication of MOX fuel functions without hazard, a number of safety checks are performed throughout the process. The fabrication of MOX fuel is performed under criticality limits where the maximum fissile fraction is determined. The limit is according to present documentation 12 weight percent (w/o) on the total plutonium content [27].

Plutonium is radioactive and mainly an alpha emitter, the exception being $^{241}$Pu, which is a beta emitter. Alpha radiation cannot penetrate a sheet of paper or the outer layer of human skin. Plutonium therefore presents a health hazard only if it gets inside the body by inhalation, ingestion or through a cut.

Since the concentration of Am$^{241}$ increases with time plutonium is mixed with uranium as soon after reprocessing as possible to avoid handling issues. According to gathered experience the MIMAS blend sometimes results in inhomogeneous distributed fissile atoms in the pellets on a microscopic scale. This implies high local burn-up and the structural strength of the fuel assembly must be designed to withstand this phenomenon [27].

### 3.5 Waste management

CLAB (Central Mellanlager för Använd Bränsle) already stores about 24 t MOX fuel, since 1988 due to an agreement with France. France received in return 55 t spent nuclear fuel. Hence, Sweden has already knowledge in how to handle used MOX fuel and this fuel will be stored in the same way as the ordinary UOX nuclear fuel [31]. According to a report by NEA [29], recycling uranium through MOX in LWRs does not reduce the amount of repository space needed per unit of electricity generated. The required repository is determined by the heat output of the wastes and the total waste heat per unit of electricity generated for MOX is substantially larger than for the direct disposal alternative. Hence more repository space is required for MOX fuel assemblies than for UOX fuel assemblies.
3.6 Non-proliferation

In terms of making nuclear weapons plutonium, in particular the isotope $^{239}$Pu is the most desirable element. $^{239}$Pu is produced in uranium fuel during operation. At normal reactor operation conditions a LWR produces about 200 kg plutonium per year (mainly from the absorption of a neutron in $^{238}$U). The plutonium that is produced in a LWR fuel is mixed with other radioactive materials and can be extracted at a reprocessing facility. Plutonium has significant potential as an energy source, and provides about one third of the total energy in a uranium-fuelled reactor. To manufacture a nuclear explosive 5-10 kg of plutonium is necessary [41]. The requirement of 5-10 kg of plutonium is of weapons grade and the plutonium produced in a civil reactor is reactor grade, which means that the above figures are not comparable. These two categories of plutonium have very different isotopic compositions.

Weapon-grade plutonium consists of almost pure $^{239}$Pu. Weapons-grade plutonium is produced in a specific plutonium production reactor, where the output power is low with fuel changes several times per year. As previously mentioned, it takes about 10 kg pure Pu$^{239}$ to make a bomb, and producing this takes 30 MWyears of reactor operation. The burn-up* in a reactor that produces weapon grade Pu is typically 100 MWd/t as opposed to civilian energy production with 45 000 MWd/t. Reactor-grade plutonium, that is used for MOX-fuel production, consists typically of less then 60 % $^{239}$Pu, and a large portion of other plutonium isotopes which creates serious technical problems for weapons use, e.g. Pu-240. Pu-240 emits spontaneously free neutrons that would disturb and make the initiation of a nuclear bomb difficult [23].

The only Swedish reactor that currently plans to use MOX is O3 in Oskarshamn due to an agreement with a reprocessing plant in England, Sellafield, since 1969. The plutonium content of this MOX-fuel is typically about 5 %, as for most LWRs. Therefore MOX cannot be used in nuclear weapons or nuclear explosives without separating the materials. IAEA safeguards measures would directly indicate if any attempts to separate the plutonium from the uranium were made [34, 42].

In a report by SKB [47], it was concluded that the BWR MOX reactors were 10 % more efficient than PWR MOX reactors in terms of burning plutonium in the form of MOX fuel. The use of MOX fuel reduces inventories of separated plutonium, and this will probably affect the importance of degrading weapons-grade plutonium released by disarmament. The Euroatom Supply Agency estimates that the use of a single MOX fuel element consumes 9 kg plutonium, and also avoids the production of a further 5 kg, in comparison with low enriched uranium fuel [34].

* Burn-up is a measure of the neutron irradiation of the fuel and gives a rough estimate on how many fissions that have taken place within the fuel
3.7 Costs

Spent nuclear fuel from commercial LWRs roughly consists of about 95 % $^{238}$U, 1 % $^{235}$U, 1 % Pu and 3 % fission products $^*$ [27]. About two thirds of this plutonium is fissile [34] but the fissile quality of plutonium is depending on burn-up. Recovering the plutonium and recycling it as MOX in LWRs would reduce the requirement for natural uranium ore by about 17 – 30 % depending on which source referred to [43, 44]. The large stockpiles of spent fuel, potentially available for recycling, could run the US reactor fleet of about 100 GWe for almost 30 years without introducing supplementary uranium [44]. Saving uranium resources is of course environmental- and moneysaving but the compulsory operations to obtain a MOX fuel, i.e. reprocessing and fuel fabrication, are expensive processes. Presently there is a general perception that the total power production cost for a NPP with MOX fuel is higher compared to UOX [26, 43, 44, 45]. A MOX producer does not buy or own the plutonium or the uranium, this in order to avoid ownership and liability issues. The fuel purchaser pays the MOX fabrication facility for providing them a service, namely transforming the uranium and plutonium powders into MOX fuel. The $\text{PuO}_2$ is however selected by the MOX fabricant, within its available stocks [40].

The markets for the front end of the UOX fuel cycle publish prices for the different activities and are widely available, see chapter 2.6. However the prices associated with recycling is considered proprietary information. The estimated figures in this paper are therefore based on the limited information that is provided from the reprocessors, other studies, press reports and private communication. MOX and UOX front end costs are presented in Table 11.

<table>
<thead>
<tr>
<th>Fuel cost</th>
<th>MOX</th>
<th>UOX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining &amp; milling</td>
<td>-</td>
<td>30 USD/kgHM</td>
</tr>
<tr>
<td>Conversion</td>
<td>-</td>
<td>5 USD/kgHM</td>
</tr>
<tr>
<td>Enrichment</td>
<td>-</td>
<td>90 USD/SWU</td>
</tr>
<tr>
<td>Fuel fabrication</td>
<td>1,100 USD/kgHM</td>
<td>250 USD/kgHM</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>800 USD/kgHM</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 11 – UOX and MOX fabrication costs (USD 2001) [46]

3.7.1 Reprocessing costs

There are only two companies outside Russia that are presently operating large reprocessing plants: COGEMA (part of the Areva group), which operates two plants in France and BNFL, which operates THORP in the UK. The costs are better known for THORP because of the precedent debate of the facility. THORP has cost about 5,900 million USD to build [26] and has a capacity of about 800 tHM/year. BNFL has not publicly presented THORP’s operating costs but states that a similar plant would cost about 560 million USD per year to run. The cost of reprocessing is strongly dependent on the way they are financed. A commercial reprocessing plant would have to charge 3,100 USD/kgHM. In France and UK the facilities are subsidized and the price can thereby be lower to cover their costs. In the report by BUNN et al. a price of approximately 1 350 USD/kgHM is assumed for a governmental facility to cover their cost [26].

$^*$ Uranium fuel with initial enrichment of 3.7 % $^{235}$U and average thermal burnup $= 41.2$ GWD/tHM

35
The most recently built large-scale reprocessing plant is in Japan, Rokkasho-mura, and the costs is roughly about 18 000 million USD with operational costs of about 1 400 million USD per year [26]. This is about three times the cost for THORP. One big difference is that the reprocessing process at Rokkasho-mura, developed in Japan, does not yield pure plutonium but produces MOX powder. This means that the proliferation risk is significantly reduced and the blending step is to some degree avoided.

The PUREX process has been improved for more than five decades, so any dramatic cost reductions of this or similar technologies are unlikely. Reprocessing is thereby not likely to be competitive with the once through UOX fuel cycle for most of this century [26].

### 3.7.2 Fuel fabrication costs

In similarity to reprocessing, fuel fabrication of MOX is expensive because it requires large capital-intensive facilities and highly trained personnel. The industry is dominated by a small number of firms, namely BNFL and COGEMA. There is no official information on costs for fuel fabrication either but there is some information available from Sellafield Mox Plant (SMP) due to the public attention.

SMP has approximately cost 750 million USD [26] with a capacity of about 120 tHM/year. No operating costs have been published for any existing MOX plant but a group has estimated the operational costs for SMP to be about 50 million USD/year [26]. A plant with about the same capital cost as SMP with a capacity of 100 tHM/year and life-time of 30 years would have different fabrication costs depending on the financial arrangements in similarity to the reprocessing plants. A commercial MOX fuel vendor would have to charge about 2100 USD/kgHM. However the MOX fuel fabrication facilities in France and the UK has been subsidized by the government and would only have to charge about 1 000 USD/kgHM to cover their cost [26]. The transport of MOX fuel is not added in this figure and will bring an extra cost to the fuel.

The Rokkasho MOX plant, in Japan, that will be taken into operation in 2012 is the only MOX plant currently under construction. It will have a capacity of 130 tHM/year and is expected to cost about 1000 million USD [26].

MOX fuel fabrication is about three to four times more expensive than UOX fuel fabrication. This is partly due to the remote handling of fuel during manufacturing, safety requirements and increased safeguards as a result of handling with weapon usable material, i.e., plutonium. However, the small size of the plants and the relatively early stage of development of the recycling industry are also reasons for the high cost of MOX fuel fabrication [29]. MOX fuel fabrication costs are higher than those of enriched uranium oxide fuels because of its higher investment cost and the substantially lower throughput of fuel assemblies. As the use of MOX fuel increases and MOX fabrication plants reach higher commercial throughputs, the present MOX fabrication prices are likely to decrease [29]. In a report by EDF it is also stated that the fuel fabrication cost for MOX is more expensive than for UOX fuel [2]. It is however claimed that the higher fabrication cost is approximately compensated by the economy of uranium.

MOX fuel fabrication is a costly activity that is compulsory in the recycling process. This method is however less mature than the PUREX reprocessing process, which could lead to technical improvements and cost reductions in the future.
3.7.3 Future trends

According to a report by Lester the fuel cycle costs will increase about 300 % if utilising MOX instead of UOX [43]. Since fuel costs corresponds to about 10 % of the total cost of nuclear electricity from NPPs the total production cost would increase by about 20 %. Several parameters that affect the price are not included in this estimate, which means that the increase would probably be higher than 20 %. In the report by Azar, he conclude that the MOX alternative would be about 90 % more expensive than the ordinary once through UOX fuel cycle [43]. These results where however achieved under a number of simplifying assumptions. If, for example, the burnup level would increase from the presumed 40 GWd/tHM to 60 GWd/tHM the MOX alternative would be more attractive from an economic point of view.

In order for the MOX alternative to become competitive with the UOX direct disposal option, the uranium price must increase or the MOX fuel cycle costs must decrease. As previously stated, the higher fuel fabrication costs is approximately compensated by the reduction of uranium usage according to ref [2]. This is however a statement that many experts and reports are questioning [21, 26, 32, 33, 43, 45]. A more reliable estimate on how much the uranium price needs to increase before recycling becomes competitive the equation in Figure 16 can be utilised to give a rough estimate of break-even* price.

\[
\frac{\text{cost of interim disposal}}{\text{disposal of spent fuel}} + \frac{\text{cost of reprocessing}}{\text{disposal of wastes}} = \frac{\text{cost of producing LWR MOX fuel using reprocessed U and Pu}}{\text{cost of equivalent LEU fuel}}
\]

* Break-even price = the price of uranium at which the cost of electricity would be the same for both options

For the uranium once through option the reactor operator suffers costs for interim storage of spent fuel, transport to a repository site and disposal of the spent fuel. The MOX alternative has costs for transportation of the spent fuel to the reprocessing plant, reprocessing costs and cost for disposal of the reprocessing wastes. There are many other factors to take into account to get a complete calculation, such as charges on the costs of material during its processing and use, fuel burnup, the quality of reprocessed material etc. This is however fully documented in the report by Bunn et al. [26] and a rough estimate based on this reference is sufficient. The cost of disposal of MOX is not included in this estimate. As previously mentioned MOX fuel is presently recycled once and it must be stressed that final disposal of spent MOX fuel is associated with larger cost than the UOX alternative. Thereby an additional cost should be included in the MOX alternative if the fuel only is recycled once. Some utilities are however storing their spent fuel in order to supply the future FRs, which presently are under development.

For a reprocessing price of 1000 USD/kg, which was assumed to be a realistic assumption, the breakeven uranium price is about 380 USD/kg, see Figure 17. This is about 150 USD/lb U₃O₈ and corresponds to about 65 % increase of the present uranium price, which currently is about 90 USD/lb U₃O₈ [24]. The reason why the uranium price must increase so much is that the cost of uranium is a small part of the total production costs. The parameters that have the largest effect on breakeven uranium price are reprocessing price, difference between the disposal cost for spent fuel and HLW, MOX fuel fabrication price and the cost of interim storage of spent fuel [26].
As previously mentioned, the break-even price for reprocessing occurs when the uranium price is about 150 USD/lb $\text{U}_3\text{O}_8$. With the present price of uranium, which is about 90 USD/lb $\text{U}_3\text{O}_8$, the cost for reprocessing must decrease to about 700 USD/kgHM. Both of these scenarios are however considered unlikely in short- to medium term. However, the cost for MOX fuel fabrication could decrease and make MOX more competitive. Assumptions made for Figure 17 is attached in the appendix.

The burn-up of MOX fuel is another important factor that affects the total costs. It is likely that MOX fuel will be able to achieve the same burn-up as UOX fuel in a near future, which yields a better economy for MOX. An increase in burn-up could be accomplished by increasing the fissile material in the fuel, i.e., increasing the enrichment. Adding more fissile plutonium, as opposed to enriching uranium to higher levels of $^{235}\text{U}$, which is relatively expensive, can easily increase the fissile concentration of the MOX fuel assembly [34].

Plutonium is normally blended with Depleted Uranium (DU) to form MOX. Currently the price of uranium is driven by LWRs. Also DU from past enrichment operation has a small range of utilisation and therefore the price will be low. According to the report by Bunn et al. the price of DU is assumed to be in the order of 6 USD/kgU [26].

Utilising MOX fuel is a way of decreasing the amount of plutonium in the stockpiles all over the world, see Chapter 3.6. The storage cost of plutonium is estimated to 1 to 2 USD per gram and year [45]. However attitudes towards plutonium management vary from country to country and from utility to utility: some regard plutonium as a liability and others as a valuable source of energy for future use, e.g., in FRs, despite the large storage costs. Long-term storage of plutonium result in costs but might also result in another step in the reprocessing process, which is separation of $^{241}\text{Am}$.
3.7.4 Conclusions

The fuel cost associated to MOX utilization is to a great deal depending on the financial arrangements of the facilities needed to provide fuel, i.e. a reprocessing plant and a MOX fuel fabrication plant. The initial purpose of the reprocessing plants was to supply fuel to the FRs. These reactors have failed the commercialization so the present best economic option for the reprocessors is to continue supplying feed material to the MOX fabrication plant.

The reprocessing is an important parameter of the MOX fuel cycle and has impact on the overall costs. The PUREX process has been improved for more than five decades, so any dramatic cost reductions of this or similar technologies are unlikely. Reprocessing is thereby not expected to be competitive with the once through UOX fuel cycle for most of this century.

The fuel fabrication costs could on the other hand decrease in the future as a consequence of improved technology and higher throughput due to an increased demand. In this case the MOX alternative would be a more attractive option from an economical point of view.

The major advantages of reprocessing are that it reduces the amount of high-level radioactive waste and the energy extracted from natural uranium is increased. Spent uranium fuel is however presently only recycled once. The final storage of spent MOX fuel is associated with significantly larger cost than the UOX direct disposal alternative.
4 Thorium fuel cycle

Thorium can, as well as uranium, be used as a nuclear fuel. The thorium-based fuel cycle has been studied for more than 30 years, but not to the same degree as uranium or uranium/plutonium fuel cycles. Nuclear research and development, concerning thorium, has been made all over the world, in particular Germany, India, Japan, Russia, the UK and the US. One of the reasons why thorium was considered a potential nuclear fuel during the 1950 – 1970s was because of its abundance (about 3-4 times more abundant than uranium) when the shortage of uranium was considered a problem.

Another incentive to consider the thorium fuel cycle is that $^{233}$U can be bred in a thermal-neutron spectrum, i.e., low-energetic neutrons, see Figure 18, as opposed to plutonium that only can be bred through $^{238}$U in a fast-neutron spectrum, i.e. high energetic neutrons. During 1970-1980 the US made significant efforts into developing a Light Water Breeder Reactor (LWBR) of a commercial scale. The incentive was to provide the US nuclear industry with a large-scale thorium fuel cycle. The idea was to examine the possibilities of breeding $^{233}$U from a “Thorium mixed with $^{233}$U” fuel. The program was run at Shippingport and was successful. More fissile material was present at the end of the fuel cycle than at the beginning, which is a proof of successful breeding. PWR designs were developed, which were capable of breeding [47]. The historic interest for thorium fuel cycles was however not for long as a result of new discoveries of uranium deposits and their approved availability [48].

Thorium itself is not fissile and this leads to an initial need of neutrons provided from another fissile material. This material is referred to as “driver” material, e.g. enriched uranium (20%), $^{233}$U or reactor grade plutonium. At present time renewed interest in thorium-based fuel cycles in the developing countries has occurred due, in particular, to the need for the following:

- low production of Pu and minor actinides
- breeding of fissile material ($^{233}$U) in LWRs
- fuel with proliferation-resistance
- longer fuel-cycles
- higher burnup
- reduction of plutonium inventories by in-situ burning

However, the thorium fuel cycle has a number of challenges that must be addressed, for example:

![Thorium Fuel Cycle](image)
• the daughter products of $^{232}$U is short lived and associated with strong gamma radiation, which implies difficulties in reprocessing and fuel fabrication
• the database and experience of using thorium as a nuclear fuel are very limited
• spent ThO$_2$ is inert making it difficult to dissolve, which implies difficulties in reprocessing

Presently India has an interest in thorium because they have large national deposits of the material and almost no uranium. Since India has still not ratified the NPT, sanctions of uranium-trade has been present for several years, which means that uranium is not easily accessed by India. This fact has created incentives for a reliance on thorium in their nuclear program [48]. The major goal for the Indians in terms of their nuclear power programme is to utilise thorium in a three-stage programme with a closed fuel cycle. It starts with natural uranium fuelled PHWRs, continues with FBRs utilising plutonium and depleted uranium from the first step and ends with a self-sustaining ABWR that utilise thorium.

Norway is also currently interested in utilising thorium in large-scale NPPs in the future. The interest for thorium is due to the following:

• There is a demand for Norway to increase their domestic power production
• CO2-neutral alternative
• Cheap and domestic fuel
• Decrease Pu inventories
• Uranium based nuclear power is not politically accepted in Norway

Furthermore, a company called Thorium Power sees great potential in the thorium fuel cycle. Thorium Power chose to highlight the following advantageous of the thorium fuel cycle over the conventional uranium fuel cycle: proliferation resistant fuel cycle, reduced amount of nuclear waste and improved industry operating conditions. They call themselves a “leading developer of thorium-based nuclear fuels” and are considering a “seed-and-blanket” concept. This concept involves a special fuel design first invented by Dr. Alvin Radkowsky [49] and the fuel design is therefore more known as the Radkowsky-concept. Thorium power has developed and improved the original fuel design to a more reactor-compatible product and testing is currently being performed in test-reactor in Moscow. The idea is to demonstrate the fuel in full-size commercial reactor in a near future. They claim that the introduction of this fuel in present LWRs would not oblige any significant changes.

Thorium Power has patented this fuel design, which consist of two sections: one section of fuel rods is placed in the centre, called the seed, is surrounded by another section of fuel rods in the outer region, called the blanket. The blanket consists mainly of thorium, blended with uranium, and the seed rods consist of a zirconium alloy with uranium, reactor-grade plutonium or weapons-grade plutonium. The idea is that the blanket section will breed fissile $^{233}$U, which will fission in-situ and in time provide energy. The seed fuel rods will have a higher power and must be refuelled more often than the blanket fuel. A major advantage with this heterogeneous design is that the blanket rods can be recycled without chemical reprocessing. The blanket remains in the reactor for a longer period of time compared to the seed fuel that must be replace more often. A drawback is that it involves, in two thirds of the scenarios, handling with pure plutonium oxide, which is a major proliferation issue.
4.1 Supply

Thorium is widely distributed all over the world, with an average concentration of 10 ppm in the earth’s crust in phosphates, silicates, carbonates and oxide materials. Thorium is not exploited commercially so far but is approximately 3-4 times more abundant than uranium, and occurs mainly as the fertile isotope $^{232}$Th in nature. There exists large thorium inventories from mining of Rare Earth (RE) extraction of monazite. The largest known thorium deposits are located in the beach and inland deposits of monazite, a mixed phosphate mineral with the chemical formula: $(\text{RE/Th/U})\, \text{PO}_4$. The ore concentration of $^{232}$Th varies between minerals, e.g., the thorium concentration is about 10 % in Indian monazite [50]. The ore deposits of thorium in the world are presented in Table 12. This data is based on assumptions, because there are no incentives for prospecting, due to a very low demand for thorium [51].

Table 12 – Thorium deposits in the world [52]

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserves [t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>452 000</td>
</tr>
<tr>
<td>USA</td>
<td>400 000</td>
</tr>
<tr>
<td>Turkey</td>
<td>344 000</td>
</tr>
<tr>
<td>India</td>
<td>319 000</td>
</tr>
<tr>
<td>Venezuela</td>
<td>300 000</td>
</tr>
<tr>
<td>Brazil</td>
<td>221 000</td>
</tr>
<tr>
<td>Norway</td>
<td>132 000</td>
</tr>
<tr>
<td>Egypt</td>
<td>100 000</td>
</tr>
<tr>
<td>Russia</td>
<td>75 000</td>
</tr>
<tr>
<td>Greenland</td>
<td>54 000</td>
</tr>
<tr>
<td>Canada</td>
<td>44 000</td>
</tr>
<tr>
<td>South Africa</td>
<td>18 000</td>
</tr>
<tr>
<td>Other countries</td>
<td>33 000</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td><strong>2 492 000</strong></td>
</tr>
</tbody>
</table>

The low demand and small range of application for thorium are the reason why the element has not been exploited so far. Some applications for thorium are:

- airplane jet engines, improves the heat resistance
- gas mantle
- alloys, e.g., with magnesium and wolfram
- glass production, gives a high refractive index and low scattering, in camera lenses
- as catalyst when producing nitric or sulphuric acid [53]

As previously mentioned, the low range of application for thorium has resulted in large inventories from mining of rare earth elements and other minerals. Approximately 25 000 t ThO$_2$ is currently stored from old residues of mining [48]. With about 100 t required for a normal reactor load and one fifth of the fuel replaced each year, the current inventories of thorium would be sufficient for approximately 1250 reactoryears. This thorium is accessible
at low cost, which creates no incentives to prospect thorium immediately. The availability of these inventories is subject to many uncertainties such as:

- *Technical*, if the ThO2 has been stored in a retrievable way (in drums for example)
- *Political*, concerning safeguard, constitutional, strategic etc issues
- *Economic*, the cost associated to extract thorium from these inventories

In order to cover the supply of the thorium fuel cycle the market and supply of the different driver materials needs to be investigated. The difficulties and possibilities with procuring these driver materials have been investigated by the author of this thesis, and attached in the appendix.

### 4.1.1 Technology

Thorium mining, due to its low demand, is typically associated with the mining of uranium and rare-earth minerals. If thorium-based NPPs would be commercialized in the future it would lead to a completely different situation. Thorium mining is almost entirely performed in open-pit mines. Open-pit mining has higher productivity, higher recovery, easier dewatering, safer working conditions and usually lower costs than underground mining. However, the environmental disturbance is less for underground mines in comparison to open-pit mines. The mining and extraction of thorium from monazite is relatively easy and significantly different from that of uranium. Most of the commercially exploited sources of monazite are from the beach or river sands along with heavy minerals. The present production of thorium is almost completely as a by-product of rare earth extraction from monazite sands. Monazite is the most interesting deposit since it is widely spread and contains high concentrations of thorium, 5 – 10 %. Nuclear grade ThO2 is produced from monazite by the following procedure:

1) Extraction and pre-concentration of beach sands
2) Conversion of ore to monazite
3) Conversion of monazite into thorium concentrate, uranium concentrate and rare earth
4) Conversion of thorium concentrate into nuclear grade thorium

In step 1 the mined beach sands has to be pre-concentrated by gravity separation in order to increase the amount of heavy minerals from 3 – 40 % to more than 90 %. Although monazite, from beach sands, contains relatively large amounts of thorium the monazite itself is always at low concentration in the ore, about 0.5 – 5%. This is why the ore is separated into its constituents in step 2 using the difference in physical properties. This results in 99 % monazite, which is then separated into thorium concentrate and rare earths by an acid or alkali attack in step 3. 50-70 % sodium hydroxide is most commonly used and leads to a solid cake. The cake is then subject to hydrochloric acid and the rare earths are leached out as chlorides and thorium remains in the hydroxide form, (Th (OH)₄ x H₂O). The hydroxide cake, which is thorium concentrate, is finally purified for nuclear use by solvent extraction, ion exchange or direct chemical precipitation in step 4.

The processing to procure nuclear grade thorium involves smaller amount of raw material but affects a larger area of disturbed land in case of low-grade thorium ore, in comparison with the uranium case.
4.1.2. Safety

The mining and extraction of thorium from monazite sand is very different from extracting uranium from its ore. The environmental impacts are much smaller and the total radioactive waste production, from mining, is about 2 orders of magnitude less [48]. Thorium mining results in simpler tailings management in comparison with uranium due to the short lifetime of thoron (220Rn), which is the radon counterpart of thorium. The high percentage of Th232 in the Indian ore leads to a relatively small amount of mining waste. There is no need to control ventilation since the extraction of monazite is performed in open-pit mines. The inhalation and ingestion dose factors are however high for thorium and thoron.

If thorium becomes commercially extracted the safety procedures in the mining would be similar to the procedure to mine uranium with minor exceptions, see Chapter 2.1.2. Mattias Sköld, press-contact spokesman for SSI, states that the risks concerning mining of thorium is substantially less compared to the mining of uranium. Thorium is less mobile and is not transported as easily as uranium by water. When it comes to contamination of water the risks are thereby less with thorium [54].

According to the ICRP-72 (International Committee for Radiological Protection) the inhalation and ingestion dose restrictions are 5 respectively 2 times higher for pure thorium compared to uranium. This necessitates more thorough environmental monitoring for workers as well as for the public when considering thorium cycles [53].

4.2 Enrichment/conversion

There is no enrichment process for thorium because almost all naturally occurring thorium consists of a single isotope (232Th), which is not fissile, but fertile. A fertile isotope has the potential of becoming fissile when absorbing a neutron. Following the absorption of a neutron natural thorium decays into 233U according to Figure 19.

The conversion of 232Th to 233U is to a great extent more efficient than 238U to 239Pu in the thermal neutron spectrum. As a matter of fact, 232Th (7.4 barns) has about 3 times larger absorption cross-section compared with 238U (2.7 barns). Consequently, 232Th is a better fertile material in comparison with 238U in the thermal neutron spectrum [48].

However, the conversion is also one of the biggest obstacles to overcome in order to close the thorium fuel cycle. In order to reprocess nuclear fuel based on thorium, the problem with handling of 232U and its daughters, which are strong gamma emitters, needs to be solved.

\[
\begin{align*}
232\text{Th} + n &\rightarrow 233\text{Th} \\
&\rightarrow 233\text{Pa} &\rightarrow 233\text{U} \\
&\beta (22.3 \text{ min}) &\beta (27.0 \text{ days})
\end{align*}
\]

\[
\begin{align*}
238\text{U} + n &\rightarrow 239\text{U} \\
&\rightarrow 239\text{Np} &\rightarrow 239\text{Pu} \\
&\beta (23.5 \text{ min}) &\beta (2.335 \text{ days})
\end{align*}
\]

Figure 19 – Illustration of the breeding of 233U and 239Pu from their fertile counterparts
In order to initiate the thorium fuel cycle an initial starter material that provides excess neutron is necessary. Thorium, which is fertile, needs to be blended with a fissile material, e.g., 20 % enriched uranium, reactor-grade plutonium or $^{233}$U. The blending process is the equivalent of the enrichment process for uranium. In order to achieve a successful breeding the only driver material possible is $^{233}$U. The breeding can be achieved according to ref. [55] in a thermal spectrum, which is a big advantage.

### 4.3 Fuel fabrication

The fabrication of thorium-based fuels has been conducted in several countries in the past. The processes used are similar because the research has been performed under close cooperation.

Most of the fabrication facilities, designed to manufacture thorium-based fuels for water-cooled reactors, are based on the “powder-pellet” method. Fine powders are however not free-flowing and pose problems in remote and automated fabrication. Further the mechanical blending of fissile and fertile material in mixed oxide cannot provide a completely microhomogeneity. There are several technologies developed for manufacturing thorium-based mixed oxide fuels:

- **Powder-pellet route**: this process has extensively been used to manufacture ThO$_2$ based fuels, e.g. (Th,Pu)O$_2$. The essential steps of the manufacturing process are: milling, granulation and binder addition, cold pelletization and sintering. The fuel pellets are subsequently encapsulated in cladding tubes.
- **Vibro-sol route**: uses nitrate solutions of uranium, plutonium and thorium and adapting some kind of ammonia “gelation” to create hydrated gel microspheres. The microspheres are subsequently sintered and vibro packed in cladding tubes followed by encapsulation.
- **Sol-gel microspheres pelletization**: uses dust free and free-flowing sol gel derived oxide fuel microspheres for direct pelletization and sintering.
- **Impregnation technique**: partially sintered ThO$_2$ pellets of relatively low density and porous ThO$_2$ microspheres are vacuum impregnated in uranyl or plutonium nitrate solution followed by calcination and sintering to form thorium-based mixed oxide pellets. The fuel pellets are subsequently encapsulated in cladding tubes [48].

The Indian Bhabha Atomic Research Centre (BARC) has manufactured thorium-plutonium MOX pellets of controlled density and microstructure. This fuel was manufactured for the development of water-cooled thermal reactors based on thorium. ThO$_2$ and PuO$_2$ powder was used as starting materials and these powders were subject to co-milling, cold-pelletization and sintering, i.e., followed the powder-pellet route. The fuels contained 4 and 6.75 % PuO$_2$ and achieved an 18.4 MWd/t burn-up without failure. However two clusters, one of each fuel composition, was test irradiated to a burnup of 18 000 MWd/t without any failure [48]. Thorium-based fuel can be of heterogeneous or homogenous design. The heterogeneous design can be inside the pellet, separate pellets, separate fuel rods or even separate fuel assemblies (which is the Radkowsky-koncept). The following chapters aims however to explain the homogenous blending of thorium-based nuclear fuel.
4.3.1 Thorium-plutonium MOX

The MOX fuel factories of today produce a mixed oxide fuel containing PuO$_2$ and UO$_2$ powder, containing 5-9% fissile plutonium and the remainder is normally depleted uranium from the enrichment tails. In order to produce thorium-based oxide fuel instead implies that thorium substitutes the depleted uranium. Manufacturing of such a fuel necessitates restructuring of the MOX fabrication plant to some degree or building a new facility, due to the different properties of the materials.

ThO$_2$ has similar crystal structure as UO$_2$ and PuO$_2$ and it forms complete solid solution at all percentages with UO$_2$ and PuO$_2$ [56]. Hence, fabrication of thorium-plutonium MOX fuels is similar to that of uranium-plutonium MOX fuel. The flow sheet to be followed for (Th, Pu) MOX is similar to the (U, Pu) MOX. The flow sheet of fabrication of (Th, Pu) MOX is illustrated in Figure 15.

ThO$_2$ powder has higher melting point (~3350°C) compared to the UO$_2$ powder (~2800°C), this implies a higher sintering temperature in order to obtain high density-pellets. The sintering temperature for UO$_2$ powder is about 1700°C compared to > 2000°C for ThO$_2$ powder. This means that the furnaces need to be modified to ensure that the sintering process works. However this high sintering temperature can be avoided with small additions of “sintering aids” like Nb$_2$O$_5$, CaO, MgO or U$_3$O$_8$. Adding about 2% of U$_3$O$_8$ lowered the sintering temperature to about 1100°C. This process helps manufacturing of high-density pellets without the additions of sintering aids and without the high temperature in the ovens [48].

Further investigations of the pressability of the ThO$_2$ powder is necessary to make approved pellets. The need of analytical methods to determine the metal/oxide and the Pu/Th ratio is obvious. Approximately 2 years is needed to apply and obtain a license from safety authorities [40]. Finally, LWRs of today are not qualified for the thorium fuel cycle. It is however been proven that it is possible to implement thorium-based fuel in these kind of reactor systems. Qualification process of such a fuel in the reactor would need 10 years, both because of the neutronic properties of thorium and reactivity control of the reactor in a thorium cycle [40].

(Th, Pu)-MOX is the most promising fuel to start the Thorium-fuel cycle in Norway [57].

4.3.2 Thorium-enriched uranium (20 % $^{235}$U)

The use of thorium-uranium dioxide fuels has mainly been proposed in order to increase the proliferation resistance of all uranium fuel. Further, (Th,U)-MOX has a higher resistance to oxidation compared to UOX fuel, which is an encouraging property primarily when it comes to final disposal. The costs associated with manufacturing a thorium-uranium dioxide fuel for LWRs has been examined and published in a report ordered by Westinghouse [50]. The purpose was to determine the feasibility for US manufacturers to economically manufacture a (Th, 20 % $^{235}$U)-MOX fuel in plants that previously only manufactured UO$_2$ fuel with less than 5% $^{235}$U enrichment. They examined five options for the conversion of uranium and thorium feed to dioxide powders. The costs differ depending on which of these processes that is chosen.
In the report it was determined that there were no fundamental obstacles in order to change the process so that a thorium-uranium oxide fuel can be manufactured. However the necessity of a change and additions to the process is obvious and this requires changes in existing, and generation of new, permits and licenses. It is possible to use the existing plant, but with the exception that new shipping, receiving and storage areas must be built. The estimated cost for this area is 2.4 million USD [50] and is applicable to all processes. The equipment cost ranges from 11.6 to 28 million USD [50] depending on which option that is applied. The personnel at the Columbia facility [50] estimated that the start-up time would be about 24 months, including 3 months for process start-up, 3 months for shakedown, 6 months at one-half capacity and 12 months at three-quarters to full capacity.

Thorium-uranium dioxide fuels can be manufactured into several different pellet configurations. The main categories are however homogenous, where the thorium and uranium are mixed in the final fuel pellet, and heterogeneous, where the thorium and uranium are formed into separate regions without mixing. According to the personnel at the Colombia facility there would not be a significant increase in cost for the heterogeneous option [50]. Regardless if the fuel design is homogenous or heterogeneous it can be manufactured in a LWR fuel factory with enrichment limit of 5 % $^{235}$U if 20 % uranium is the driver material chosen. In all cases a thorium-uranium mixed oxide costs more that the comparable UOX fuel and the percentage increase of costs would be at least 25 % but it could be up to 38 % and even higher. If the thorium oxide to uranium oxide ratio changes from the proposed 75/25 to 70/30 the cost increases up to 64 % [50].

The work required to obtain 1 kg 5 % enriched $^{235}$U from natural uranium is about 5.4 SWU, with tails assumed 0.25 % $^{235}$U. To obtain a 20 % $^{235}$U enrichment, with the same assumptions as above, requires about 28.1 SWU [28]. The ratio of 20 % enriched uranium to the total fuel is however small, about 25-30 %, but corresponds to a large cost. The production of 20 % $^{235}$U would cost about 24,500 USD/kg in comparison with 5 % $^{235}$U that costs about 19,500 USD/kg [50].

### 4.3.3 Thorium-$^{233}$U

The technological challenge in manufacturing a (Th, $^{233}$U) MOX is mainly associated with the presence of $^{233}$U. This uranium isotope is always present in a thorium-based fuel together with its immediate decay product $^{229}$Th. The amount of $^{232}$U present in the fuel is related to:

- the isotopic composition of uranium in the initial thorium fuel
- the burn-up
- neutron spectrum in the reactor

The average concentration of $^{232}$U the uranium driver material is about 1250 ppm [56]. The challenge lies in the strong gamma radiation that is associated with the daughter products of $^{232}$U, i.e., $^{212}$Bi and $^{208}$Tl. The decay of these daughter products emit 0.7 – 1.6 MeV and 2.6 MeV gamma respectively. This radiation is highly energetic and the fuel fabrication facility must be constructed with heavy shielding and remote handling is mandatory for transportation, fuel fabrication and reprocessing of the thorium fuel.

Manufacturing of a (Th, $^{233}$U)-MOX fuel requires a remote-controlled fabrication line inside a heavily shielded hot cell facility. This requirement is valid even though the concentration of
U\textsuperscript{232} could be lowered to 5-10 ppm. Operation of this kind of facility is about 30 times slower than the operation in glove boxes with human intervention as in the (Th, Pu) MOX case.

Dust is a problem in the fuel fabrication process, because cleaning of powder containing \textsuperscript{233}U is very time consuming. This cleaning must be done utilizing remote handling tools. To avoid problems with dust several alternative routes for fabrication (instead of the powder-pellet route) are being investigated to render the process more efficient. It is to be kept in mind that the basic problem in fabrication of (Th,\textsuperscript{233}U) MOX through conventional route centres on powder generation [56].

In order to get a larger time span to manufacture a (Th, \textsuperscript{233}U) fuel the contamination of \textsuperscript{232}U must be lowered considerably, preferably to about 5 ppm. It is the concentration of \textsuperscript{232}U that determines the rate of gamma activity in the fuel.

### 4.3.4 Safety

The fabrication conditions of thorium-plutonium fuel compared with MOX are similar in terms of radiation exposure. This was concluded in a report by the European commission [53]. It was concluded that the same radioprotection that is used in the existing MOX plant, e.g. SMP or MELOX, could be used without exceeding the safety limits for exposure if the starting material is fresh thorium, uranium and plutonium. If however the thorium-based fuel is manufactured from recycled fuel the radioprotection needs to be reinforced [53].

\textsuperscript{233}U possesses significant radiological hazards, which make "hands on" contact handling and inspection of the material difficult. The storage facilities must provide safety concerning radiation, criticality and proliferation. \textsuperscript{233}U has a much smaller critical mass than HEU but is just as usable for making a nuclear device. The strong gamma radiation associated with this material is a major hazard for people in the event of exposure. In addition the primary hazard from \textsuperscript{233}U-based fuel is alpha radiation and the alpha activity of \textsuperscript{233}U is three orders of magnitude higher than that of HEU and about one order magnitude less than that of weapons grade plutonium [56].

As concluded earlier in this chapter the timeframe available for transportation, reprocessing and fabrication of \textsuperscript{233}U-based fuel is inversely proportional to the concentration of \textsuperscript{232}U in the fuel. The concentration of \textsuperscript{232}U must be kept below a certain level, which is accomplished by special remote handling equipment. This technology is advanced and very expensive. If the concentration of U\textsuperscript{232} could be held around 5 ppm, then (Th, \textsuperscript{233}U)-MOX fuel handling would only require normally glove boxes that dramatically would reduce the costs.

Reducing the amount of \textsuperscript{232}U in the fuel is a complex and difficult task but could be accomplished by an advanced version of the Atomic Vapour Laser Isotope Separation process. This process is being developed and attempted at BARC, India, for the first time in the world [56].
4.5 Reprocessing

Thorium-based nuclear fuels cannot easily be dissolved as opposed to its uranium counterpart. Hence the PUREX process cannot be utilised, because pure nitric acid is not capable of dissolving thorium-based nuclear fuels. The process to treat and reprocess thorium-based fuels is called THOREX, see Figure 20, and this process has some similarities with PUREX, but also some significant differences. This process has never been industrially practised outside India and it needs considerable research and development in order to extract the three metals (Pu, U and Th) that would result if reactor-grade plutonium were to be used as initial fissile material [48].

4.5.1 Technology

THOREX is a reagent consisting of: 13 M HNO₃ + 0.05 M HF + 0.1 M Al(NO₃)₃ and was developed during the 1950s by the Oak Ridge National Laboratory (ORNL). The ThO₂ powder mixed fuel is dissolved under agitation in boiling THOREX solution at around 393K and under atmospheric pressure. However if the THOREX solution is used during other conditions, 473 K and 9 atmospheres of inert gas pressure, the dissolution is greatly increased. Irradiated fuel has also proven to dissolve easier compared with fresh fuel. This process is however in need of development to achieve a three-way material separation, in order to obtain separate uranium, plutonium and thorium fractions [48].

Figure 20 – Reprocessing of Thorium-based fuels according to the THOREX process

4.5.2 Safety

Irrespectively of the driver used for thorium fuels $^{233}$Pa is built up during operation. This material could be diverted somewhere during the operation or reprocessing part of the fuel cycle. If this material is stored for approximately 1 year all the $^{233}$Pa will have decayed into $^{233}$U. This material is an excellent bomb-material, and remote manufacturing of this kind of bomb, due to the presence of $^{232}$U, is not a major cost in a nuclear-weapon program [58].
4.6 Non-proliferation

\( ^{233}\text{U} \) could be used as a nuclear explosive similarly to plutonium. These two elements have about the same critical mass. \( ^{232}\text{U} \) is however always present together with \( ^{233}\text{U} \) and its daughter products are associated with strong gamma radiation. This radiological hazard makes "hands on" contact handling and inspection of the material difficult. Manufacturing a nuclear explosive with \( ^{233}\text{U} \) would necessitate remote handling in all steps. This fact implies that a country that plans to manufacture a nuclear explosive would probably chose another material (such as HEU or Pu), which is less difficult to handle. Diverting \( ^{233}\text{Pa} \) and leaving it to decay for about 1 year would lead to almost pure \( ^{233}\text{U} \), and this yields proliferation issues. An intrinsic barrier could inhibit this proliferation risk, for example by blending it with depleted uranium.

It is not true to say that a nuclear explosive is impossible to construct from the thorium fuel cycle. The process of manufacturing a nuclear bomb from \( ^{233}\text{U} \) is more difficult than from Pu, but it can be done. It is however unlikely that a country, willing to procure nuclear weapons material, choose \( ^{233}\text{U} \) as their first atomic bomb material according to the IAEA.

Another important non-proliferation issue for the thorium fuel cycle is associated to plutonium consumption. Both weapons- and reactor-grade plutonium could be mixed with thorium to form a (Th,Pu) MOX fuel. Plutonium is not bred in this fuel configuration as opposed to the conventional (U,Pu) MOX fuel. In addition \( ^{232}\text{U} \) that is formed during operation ensures that the spent fuel is proliferation resistant, due to the strong gamma radiation associated to its daughters [48]. If the policy is to reduce the plutonium inventories thorium is a much better material in terms of burning plutonium in comparison to uranium.
4.7 Costs

The cost associated with manufacturing a thorium-based nuclear fuel is subject to great uncertainties. This is because thorium-based NPPs have not yet been manufactured in a commercial scale. India is the only country that has been trying to develop a thorium-based nuclear program for the last couple of years. India has not ratified the Non-Proliferation Treaty (NPT), which means that information about their nuclear program is not accessible to foreigners. The purpose for India to consider thorium is because of the large thorium deposits and basically no uranium. In addition, India suffers from sanctions of uranium-trade because of not signing the NPT, which was previously stated.

This chapter aims to give rough estimates of the costs associated to the thorium-fuel cycle based on assumptions, since data is not available. The front-end fuel cost for different homogenous fuel design with different driver materials is estimated in Figure 21 based on assumptions from private communication and limited reports [50, 57]. It should be stressed that the uncertainties is illustrated by the diffuse limits in Figure 21.

![Figure 21 – Illustration of rough fuel cost estimates for the different thorium fuel configurations and UOX fabrication as a reference](image)

4.7.1 Extraction cost

Thorium is not commercially exploited to the same degree as uranium and it is thereby difficult to predict the future eventual large-scale extraction costs. Without further prospecting the mining costs cannot be stated for thorium. However, presently known relatively large thorium deposits will probably result in low extraction costs. It must be stressed that thorium is almost entirely mined in open-pit mines, which are more effective and less costly compared to other types of mining. A conclusion is that the costs for thorium mining would not hinder a large-scale commercialization of thorium-based NPPs. This cost would, in similarity to uranium, be a relative small part of the total fuel cycle cost [13]. The low range of application for thorium has resulted in large inventories from mining of rare earth elements.
Approximately 25,000 t ThO$_2$ is currently stored from old residues of mining. As previously mentioned the present thorium inventories would be sufficient for approximately 1250 reactor years with a requirement of about 100 t for a normal reactor load. This thorium is also accessible at a low cost, which creates no incentives for prospecting thorium. The availability of these inventories is subject to many uncertainties such as:

- **Technical**, if the ThO$_2$ has been stored in a retrievable way (in drums for example)
- **Political**, concerning safeguard, constitutional, strategic etc issues
- **Economical**

The extraction costs for thorium can be shared with the extraction of zirconium (Zr) and titanium (Ti) and rare earth elements, which is normally not the case for uranium. The ore concentrations differ for uranium and thorium when it comes to the extraction. The ore concentration of thorium is normally significantly higher. This fact implies lower costs and a smaller overburden during mining for thorium.

### 4.7.2 Fuel fabrication cost

There is no enrichment process for the thorium cycle since thorium is fertile. The equivalent of the enrichment process of uranium is the blending process for thorium. Depending on which driver material that is chosen to initiate the thorium fuel cycle different cost are involved. The fuel configuration that would result in the least costs is when uranium enriched to 20 % $^{235}$U is chosen as driver material. This fuel could be manufactured at a fuel fabrication facility that formerly produced LWR fuel with an enrichment limit of 5 % $^{235}$U, with some modifications of the plant [50].

Manufacturing a Th-Pu MOX would necessitate a different kind of facility, the equivalent of a MOX facility. It has been concluded that (Th,Pu) MOX could be manufactured in an existing MOX facility but whether the proprietor of the facility is willing to make the compulsory and irreversible changes or not is uncertain. This means that either building a new plant or significantly rearranging an existing plant is compulsory in order to supply this kind of fuel and gives thereby rise to higher costs.

The fuel configuration that would cause the highest costs is when $^{233}$U is utilised as driver material. This is due to the strong gamma radiation that is associated with the daughter products of $^{232}$U and is always present together with $^{233}$U. The plant must be built to efficiently shield this radiation and the remote control must be extended in comparison to the MOX case.

The costs associated with procuring the driver materials must also be added to the fabrication price of thorium. The cost of these materials is not publicly published and depends on the bilateral arrangements between the vendor and its customer. There can never be an open market for the driver materials, because they are all weapons-usable to some degree.

Thorium Power claims that their heterogeneous fuel design would cost about 10-15 % less than uranium fuel, but they stress that this statement is based on preliminary estimates and not quoted data.
4.7.3 Conclusions

The cost for thorium mining would no inhibit the commercialisation of a large-scale thorium-based nuclear power programme. The major material cost is not to thorium but the driver materials. Futhermore, the technology for manufacturing a thorium-based fuel is not commercially developed, which implies difficulties in estimating the cost. The different fuel configurations cause diverse costs. (Th, 20\%^{235}\text{U}) is likely to result in the least cost since it could be produced in an existing LWR fuel fabrication facility and the experience of operation is high. The next fuel in terms of fuel costs is (Th, Pu) MOX, which could be manufactured at an existing MOX plant or similar. The most expensive fuel configuration is probably (Th, \text{\underline{233}}\text{U}) due to the presence of \text{\underline{232}}\text{U} whose daughter products are associated with strong gamma radiation and implies difficulties in the fabrication process. This fuel fabrication is a reprocessing option since \text{\underline{233}}\text{U} is produced during operation.

The fuel cost for the heterogeneous design would probably result in higher cost than uranium, despite the statement from thorium power. Uranium is very well established and thorium fuel will find it difficult to compete in terms of economy at least at the beginning of the commercialisation.

In order to close the thorium fuel cycle the issues related to the reprocessing and handling of \text{\underline{233}}\text{U} must be solved. To fully profit from the advantages of the thorium fuel cycle reprocessing is mandatory. Thorium provides the possibility of breeding in a thermal spectrum and this could be competitive with the commercialisation of the FBR, which requires a more complex, and not yet commercialised, reactor technology.
5 Comparison nuclear fuels

Several aspects need to be considered when comparing different nuclear fuels. Only considering the front end can give a misleading picture. An advantageous characteristic of a nuclear fuel at the front-end could result in difficulties or drawbacks when considering the entire fuel cycle. The front-end of thorium and uranium is from mining to fuel fabrication, while the MOX fuel cycle begins when the uranium fuel is removed from the reactor. It is assumed in this work, in order to compare the three fuel cycles, that the front-end of the MOX fuel cycle involves reprocessing and fuel fabrication.

5.1 Supply

The supply is an important aspect of the nuclear fuel cycle. The supply of material must be sufficient in order to meet the demand. Depending on the demand the price of the material can be determined and also which extraction costs that is economically defendable. The supply for MOX fuel is related to the amount of spent fuel accessible and how much fuel that already been reprocessed.

5.1.1 Reserves

Uranium mining is well established on the international competitive market. The supply of uranium can meet the demand for power production purposes for many years to come. The deposits of thorium exceed uranium by a factor 3-4 according to geological calculations. Because the current demand for thorium is low no dedicated mining is conducted. Technology for large-scale mining is not established compared to uranium. Thorium is mainly procured as a by-product from mining of other minerals, such as Rare Earth Elements (REE). The technology for large-scale uranium and thorium mining are very different. Nevertheless, there are no obstacles in terms of technology to overcome before large-scale mining for thorium can be realised. The only thing missing is a large demand. Thorium mining is most commonly done in open pit in contrast to uranium where underground mining is most applicable.

The availability of feed materials, plutonium and depleted uranium, is essential for producing MOX fuel. Enormous amounts of spent fuel are presently in storage around the world. Numerous tons of spent fuel is also removed from reactors each year. The output of reprocessing plants exceeds the rate of plutonium usage in MOX at present date and this causes stock of civil plutonium in many countries. Large amounts of depleted uranium are in stock at the enrichment facilities. There are, in other words, presently no shortages of these materials on the market. The technology for supplying the market with these materials is well established and commercial reprocessing plants are presently available in France, the UK and Russia.

5.1.2 Safety

Mining should be performed under strict safety limits to ensure that the environmental and human impacts are limited. Thorium is less mobile, i.e., it does not propagate in the same way as uranium. Thereby, it should be stressed that the hazard is less for thorium mining when it comes to contamination of (ground) water. Thorium mining results in simpler tailings management in comparison with uranium due to the short lifetime of thoron, which is the
equivalent of radon in uranium mining. The environmental impacts are much smaller and the total radioactive waste production, from mining, is about 2 orders of magnitude less. There is no need to control ventilation since the extraction of monazite is performed in open-pit mines. The inhalation and ingestion dose factors are however high for thorium and thoron. According to the ICRP-72 (International Committee for Radiological Protection) the inhalation and ingestion dose restrictions are 5 respectively 2 times higher for pure thorium compared with uranium. This necessitates more thorough environmental monitoring for workers as well as for the public.

Reprocessing of irradiated UOX fuel is compulsory in order to create a supply for MOX fuel usage. The environmental and human impacts of this activity are related to the radio toxicity and emissions from the irradiated fuel. Commercial PuO₂ powder is essentially an alpha emitter, although it is also a producer of neutrons, X-rays, gamma rays and beta particles, i.e., a hazardous radioactive material. However, for plutonium to cause any injuries it must be inhaled or digested since alpha radiation cannot penetrate the outer layer of the human skin.

5.1.3 Costs

The cost of uranium mining corresponds presently to more than one third of the total fuel cost; but the uranium price has not a large effect on the production price. This fact would also apply to the thorium fuel cycle, since presently known, relatively large, thorium deposits will result in low extraction costs. A conclusion is that the costs for thorium mining would not prevent a large-scale thorium commercialization in terms of power production. Large inventories exist, about 25 000 t from old residues of mining rare earth elements containing ThO₂. Presently no immediate need for mining thorium exists and the demand can be covered from these inventories, at least in short to medium term.

The mining methods are normally open pit for thorium and underground for uranium. Open pit mining has generally lower costs. Thorium mining is thereby less costly since it is easier to extract. The extraction costs for thorium can be shared with the extraction of zirconium (Zr), Titanium (Ti), rare earth elements, etc. which is not the case for uranium. Uranium mining cost could however be shared with mining of for example copper and gold. The ore concentrations differ for uranium and thorium when it comes to the cost of recovery, which is related to the extraction. Thorium, when mined, has normally a higher ore concentration than uranium. This fact gives for example rise to a smaller overburden during mining for thorium.

The reprocessing is an important parameter of the MOX fuel cycle and has an impact on the overall costs of fabrication. This service-cost is however not expected to decrease, since the process has been developed and improved under the last five decades and can be considered a mature technology. The major advantages of recycling are that it reduces the amount of high activity radioactive waste and the energy extracted from natural uranium is increased. Recycling is the only way of getting something back, in terms of energy, from the plutonium.
5.1.4 Conclusions

The fact that thorium deposits are more abundant than those of uranium is presently not an incentive to substitute uranium because its deposits would guarantee a power production for several hundred years. The best way to utilize the large plutonium inventories in the world is currently being investigated, but from a sustainable energy point of view power production would be the best option. This can be done in LWRs as a mixture with either uranium or thorium. However, storing plutonium for future generation IV reactors is presently also an alternative. The current attention to the increasing spot price of uranium has led to some uncertainty when it comes to the future competitiveness of uranium-based nuclear power. This paper indicates however that no shortage of uranium is present but fluctuation of uranium price in short to medium term is probable. The uranium price is anticipated to stabilise after all necessary mines, to provide a sufficient supply, are operating. For all three fuel cycles the supply of material is presently more than sufficient, which is also concluded in Table 12.

<table>
<thead>
<tr>
<th></th>
<th>Uranium</th>
<th>MOX</th>
<th>Thorium</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reserves</strong></td>
<td>+ Large uranium reserves</td>
<td>+ Large quantities of spent fuel</td>
<td>+ Large thorium reserves (e.g in Norway)</td>
<td>+ Large quantities of Uranium, Thorium and spent fuel</td>
</tr>
<tr>
<td></td>
<td>- Relatively low ore concentration</td>
<td>- Complex conversion process</td>
<td>+ About 25 000 t in stockpile</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ Relatively high ore concentration</td>
<td></td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>+ Minor safety issues (appr. equivalent to other mining)</td>
<td>- Involves handling highly radioactive materials</td>
<td>+ Less mining waste</td>
<td>- MOX (and Thorium) involves handling highly radioactive material</td>
</tr>
<tr>
<td></td>
<td>• Radon is a health aspect</td>
<td></td>
<td>- Inhalation and ingestion dose restrictions are higher</td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>+ Uranium quoted on global market</td>
<td>- Expensive process</td>
<td>+ Inexpensive to extract thorium</td>
<td>- Future costs for Uranium uncertain but same for Thorium and MOX</td>
</tr>
<tr>
<td></td>
<td>- In recent years large price increase and fluctuations</td>
<td></td>
<td>- Probably higher due to procurement cost of the drivers materials (uranium, plutonium)</td>
<td></td>
</tr>
</tbody>
</table>

Table 13 – Comparison of the supply of the nuclear fuels
5.2 Enrichment

Enrichment means increasing the content of fissile material. The thorium fuel cycle has no enrichment in the same meaning as uranium because almost all naturally occurring thorium consists of a single isotope \(^{232}\text{Th}\), which is not fissile, but fertile. For MOX and Thorium based fuels the equivalent of enrichment is when fissile material is blended with fertile. UOX fuel has the fissile material already present in the material and consequently blending is not necessary. Blending is however compulsory for MOX and Thorium fuel in order to achieve criticality in LWRs. This blending step is performed at the fuel fabrication facility and results in different costs depending on the process applied.

5.2.1 Technology/Safety

The technology for uranium enrichment is gradually improving and becomes more and more efficient. The modern gas centrifuge process utilizes significantly less energy per SWU compared to the gas diffusion process. This is also why several diffusion plants have been replaced, in favour of centrifuge plants. The enrichment process is continuously improving and other technologies are also under development, e.g. laser enrichment, which could advance the technology further.

As previously mentioned, the equivalent of the enrichment step for MOX and thorium is when fissile material is blended with the fertile material. The MIMAS process is well established and commonly performed to manufacture a good homogeneity of plutonium and uranium oxide powders. The process is improving and other processes could be proven more efficient in the future. In contrast to uranium it is relatively easy to increase the fissile concentration for MOX fuel. Adding more plutonium to the mix, where as for uranium it is more complex, increases the fissile concentration. There are several technologies under development for the thorium-based fuels and still uncertain which process that will be applied if a facility were to be constructed. If however thorium fuel design is heterogeneous no blending is performed. The need of excess neutrons is still present and is provided from a so-called seed fuel, e.g., plutonium or uranium.

The principal hazards at an enrichment plant are chemical hazards and not radiation. These chemical hazards are associated with the handling of UF\(_6\). The major consequence occurs if the material is inhaled. This type of hazard is controlled and surveyed by automatic instruments that alerts if there is any danger for the workers. Thorium in itself is not a hazardous material, it is mainly the driver material that implies the risk. 20\% \(^{235}\text{U}\) has about the same properties as 5 \% \(^{235}\text{U}\) when it comes to radiation, but 20 \% \(^{235}\text{U}\) has a slightly lower critical mass. Plutonium is a hazardous material harmful for human and environmental exposure and \(^{233}\text{U}\) is the most hazardous. Plutonium and \(^{233}\text{U}\) has about the same critical mass and can be utilised in nuclear explosives, which results in stricter safeguards for MOX and Thorium-based fuels than for UOX.

5.2.2 Costs

Enrichment cost corresponds to about one third of the fuel cost for uranium and are charged according to the number of separative work units, SWUs. The cost for the enrichment process is normally quoted in USD/SWU. There is, however, a trend that enrichment unit costs will decrease in the future due to more efficient processing. There is a tendency of increasing the
enrichment in order to increase the burn-up of nuclear fuels. Adding more plutonium, as opposed to enriching uranium to higher levels of $^{235}$U, which is relatively expensive, can easily increase the fissile concentration of the MOX fuel assembly.

Depending on which kind of design for thorium that is chosen, implies different costs. The starter material gives rise to the majority of the cost and the cost is sensitive to the ratio driver material to thorium. $20\% \ 235$U would probably be the least, and $233$U the most, expensive of the driver materials. Despite that the enrichment process of uranium is electricity consuming the blending process of the other fuels are likely to result in higher costs. The heterogeneous thorium fuel fabrication cost is higher than that of uranium.

5.2.3 Conclusions

Enrichment corresponds to about one third of the fuel costs for uranium. Blending is compulsory for thorium-based nuclear fuel and MOX. This blending process is equivalent to the enrichment process of uranium, since this is the part where fissile material is added. The enrichment cost for uranium is likely to decrease in the future as a consequence of more efficient technology. The enrichment technology for uranium is more mature than the blending step of the other fuels. The blending cost for thorium and MOX is included in the fabrication costs, since the blending is performed at the fabrication facility. The reprocessing facility in Japan is producing a MOX powder instead of separating the uranium and plutonium. Blending is avoided, which saves the costs for this process, and reduces the proliferation risk. Handling is more difficult for thorium and MOX because uranium is not associated with any radiation as long as the fuel has not been irradiated. The fissile nucleus in the thorium fuel cycle, $^{233}$U, is associated with strong gamma radiation which results in proliferation resistance. A comparison of the enrichment processes is presented in Table 13.

<table>
<thead>
<tr>
<th>Technology/ Safety</th>
<th>Uranium</th>
<th>MOX</th>
<th>Thorium</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology/ Safety</strong></td>
<td>+ No radiological hazard as long as not irradiated + Expected to be more efficient in the future - Main hazard is chemical UF$_6$</td>
<td>- Proliferation issues - Problems with radiation and dust - Complex process</td>
<td>+ Non-Proliferation issues • Safety requirements depends on driver material and design</td>
<td>+ Enrichment costs for uranium relatively low and perhaps decreasing</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>+Enrichment cost likely to decrease + Price is set at a open competitive market -Electricity consuming</td>
<td>+ Easy to increase fissile concentration leading to higher burnup - Blending is costly because of remote handling</td>
<td>- Enrichment cost likely to be higher than uranium due to driver materials</td>
<td>+ MOX could more easily than uranium increase fissile concentration - Due to higher radioactivity, enrichment of MOX and thorium more expensive</td>
</tr>
</tbody>
</table>
5.3 Fuel fabrication

Fuel fabrication is where the feed materials are blended and subsequently formed into fuel pellets, put in metal tubes and finally gathered into fuel assemblies. This process is well established for uranium, which is not the case for the other two fuels. It should be stressed that thorium fuel fabrication is not developed and the estimations done in this chapter are based on assumptions and subject to great uncertainties.

5.3.1 Technology/Safety

The technology for producing a uranium dioxide fuel assembly is validated since several decades for power production purposes in LWRs. The handling of uranium is not a major problem and necessitates no remote handling as opposed to the production of MOX fuel.

Depending on which driver material that is chosen to initiate the thorium fuel cycle different procedures are applied. The driver material that would result in the least difficult process is uranium enriched to 20 % $^{235}$U. This fuel could be manufactured at a fuel fabrication facility that formerly produced LWR fuel with an enrichment limit of 5 % $^{235}$U, with some modifications of the plant. Manufacturing a (Th,Pu) MOX would necessitate a different kind of facility, the equivalent of a MOX facility. The fuel that would result in the most complex process is when $^{233}$U is utilised as driver material. This is due to the strong gamma radiation that is associated to the daughter products of $^{232}$U. The facility must be designed to efficiently shield this radiation and the remote control must be extended in comparison to the MOX case.

UOX fuel fabrication is performed without any major radiation protection devices, because the fuel can be inspected “hands on” as long as the fuel has not been irradiated. The UOX process is thereby less time consuming and the throughput of material in the plant is generally higher than for MOX or thorium-based fuels. This is one of the reasons why MOX fuel fabrication is more expensive and also why thorium-based are expected to be more expensive than UOX. In addition, the different parts of the fuel fabrication process are easier repaired, in case of malfunctioning, for UOX compared with the other fuels. This is because of the remote process that is required due to the radioactive character of the fissile materials.

Fabrication of UOX fuel could be performed without remote control and radiation protection. The radioactivity is built up during operation, which means that the UOX fuel is not hazardous as long as the fuel is not irradiated. MOX fuel production is performed under remote operation, since it consists of spent fuel. Plutonium is an alpha emitter, which means that it cannot penetrate the outer layer of human skin and causes injuries to humans only if digested or inhaled. The fabrication of (Th,Pu) MOX fuels is comparable with (U,Pu) MOX fabrication methods provided that fresh thorium (i.e. not recycled) is used and similar radiological containment and shielding arrangements are then required.

Fabrication of (Th,20 % $^{235}$U) is comparable with the fabrication of UOX in terms of safety. However (Th,$^{233}$U) results in the most difficult and hazardous fuel and the fabrication facility must be designed accordingly.
5.3.2 Costs

The uranium manufacturing process is more established and developed than for MOX fuel. Thorium-based fuel fabrication is under development, which results in uncertainties of the process and the associated costs.

The economic consequences of the fabrication of UOX fuel are well documented, because the technology has been validated since several decades. However the prices associated with recycling, i.e. MOX, is considered proprietary information. Cost estimations are based on the limited information provided by the fuel fabrication companies, reports, official documents and private communication. All sources however conclude that the fabrication of MOX fuel is more expensive than UOX fuel. The fuel fabrication cost for MOX is approximately four times greater than the fabrication of UOX fuel. This is partly due to the remote handling of MOX fuel during manufacturing, the safety requirements and increased safeguards as a result of handling with weapon-usable material, i.e. plutonium. However, the small size of the plants and the relatively early stage of development of the recycling industry are also reasons for the high cost of MOX fuel fabrication.

Thorium-based nuclear fuels have not yet reached the commercial stage of manufacturing and the costs are thereby based on assumptions. In a report by Lahoda it is concluded that thorium-20 % 235U fuel can be manufactured at a UOX fuel fabrication facility with 5 % enrichment limit [50]. The costs will according to this reference be about 25 % higher than the for the normal LWR UOX fuel.

(Th,Pu) MOX fuel can be manufactured at the equivalent of a MOX fuel fabrication facility. It has been concluded that (Th,Pu) MOX could be manufactured at an existing MOX facility but whether the proprietor of the facility is willing to make the compulsory and irreversible changes is uncertain. Another option is to construct a new fabrication facility and the cost would be in the same order of magnitude as a conventional MOX plant. The fuel cost would thereby probably be approximately the same as for a conventional MOX fuel. A (Th,233U) MOX fuel would require an extended remote controlled facility in comparison to the MOX fuel plant. This is because of the nature of the material and result in a higher cost than the other two alternatives.

5.3.3 Conclusions

The economic consequences for fuel fabrication of different nuclear fuels depend to some degree of the technology and the safety requirements associated with the fabrication. The LWR UOX fuel fabrication is a mature technology with a small number of companies that currently is providing this service. A small number of companies are providing MOX fabrication services for LWRs as well but the technology is not as mature as the UOX alternative. Technology could improve and result in a less costly process. The cost of a thorium-based fuel is difficult to estimate because the type of design and driver material is not yet decided. Even if a decision were made on which kind of thorium fuel to manufacture the cost is still uncertain. This is because the mandatory plants have not been constructed and the cost is depending on the arrangement between the vendor and his customer. One conclusion is that regardless of the driver material and process that is chosen, the fuel fabrication cost for thorium is anticipated to be higher than that or uranium. A comparison of the different fuel fabrication processes and their consequences is presented in Table 14.
### Table 15 – Comparison of the fuel fabrication process for the nuclear fuels

<table>
<thead>
<tr>
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<th>Uranium</th>
<th>MOX</th>
<th>Thorium</th>
<th>Conclusions</th>
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<tbody>
<tr>
<td><strong>Technology/Safety</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ No radiation</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+ Fuel fabrication costs for uranium relatively stable and perhaps increasing competition</td>
</tr>
<tr>
<td>associated with the</td>
<td>Alpha radiation</td>
<td></td>
<td></td>
<td>- MOX fabrication four times more expensive than uranium</td>
</tr>
<tr>
<td>fuel</td>
<td>is easily shielded</td>
<td></td>
<td></td>
<td>- Thorium probably more expensive than uranium</td>
</tr>
<tr>
<td>+ Mature technology</td>
<td>+</td>
<td>+</td>
<td>- Driver materials give rise to radiation and criticality concerns</td>
<td></td>
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<tr>
<td>+ Easy to repair</td>
<td>Could improve in the future</td>
<td></td>
<td></td>
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<tr>
<td>- Not likely to</td>
<td>- Performed under remote control</td>
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<td></td>
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<tr>
<td>improve</td>
<td>- Difficult to repair</td>
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<td><strong>Costs</strong></td>
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<td>+ Not expected to</td>
<td>- About 4 times more expensive than UOX</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>change significantly</td>
<td></td>
<td></td>
<td></td>
<td>- Probably more expensive than uranium and depends on driver material</td>
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<td>in the future</td>
<td></td>
<td></td>
<td></td>
<td>- Heterogeneous design could be less expensive</td>
</tr>
<tr>
<td>+ New companies</td>
<td></td>
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<tr>
<td>could enter market in future</td>
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</table>
5.4 Non-proliferation

Certain nuclear materials are more attractive than others in terms of constructing nuclear weapons. Highly Enriched Uranium (HEU) is not as attractive as plutonium and that is why some HEU has been liberated to the market after the US – Russian agreement of disarmament. The amount HEU needed to construct a nuclear explosive is however much larger than for plutonium. HEU could be procured from an enrichment facility if the process continues over the 5 % \(^{235}\text{U}\) enrichment limit. HEU is thereby the sought bomb material in the uranium fuel cycle. The radiation associated with the HEU is small as long as it has not been irradiated, which simplifies the transport of this material.

Plutonium could be diverted from the reprocessing plant or from the MOX fuel fabrication plant. This material is mainly emitting alpha particles but also some beta radiation. The radiological hazard results in more difficult handling compared to HEU. Reprocessing, which is a compulsory part of the MOX fuel cycle and results in inventories of plutonium. Plutonium from spent nuclear fuel has very different fissile concentration \((^{239}\text{Pu} + ^{241}\text{Pu})\). The fissile concentration is depending on burn-up and a uranium fuel assembly with normal burn-up has relatively low fissile concentration. This implies that plutonium from civil reactors is difficult to utilise in nuclear explosives.

The material of interest in terms of nuclear bomb material in the thorium-fuel cycle is \(^{233}\text{U}\), which is bred from natural thorium. \(^{233}\text{U}\) is however always associated with \(^{232}\text{U}\), which daughter products emits high-energetic gamma radiation. Manufacturing a \(^{233}\text{U}\) explosive requires remote operation in heavy shielded hot cells. According to IAEA the gamma radiation associated to this bomb material implies proliferation resistance to the thorium-fuel cycle [48]. However if \(^{233}\text{Pa}\) could be diverted and stored for about 1 year, almost pure \(^{233}\text{U}\) cold be obtained and this material has about the same properties as \(^{239}\text{Pu}\) in terms of bomb material. A comparison of the weapons material associated to the different fuel cycles is presented in Table 15.

<table>
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<tr>
<th>Nuclear fuel</th>
<th>Potential bomb material</th>
<th>Place of production</th>
<th>Radiation associated to the material</th>
<th>Most likely place of diverting</th>
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<td>Uranium and MOX-based reactors with low burn-up</td>
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<td>(^{233}\text{U})</td>
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6 Economic estimation

This chapter aims at providing some insights on economic trends and to give some estimates for different fuel cycles rather than to state exact figures. The reader will get an idea of the costs related to different activities in the fuel cycles that are considered in this thesis. The results that are presented in this analysis are subject to some uncertainties due to technological progress, research, financial agreements, political and social environments etc.

A comparison of the UOX fuel cycle with the MOX fuel cycle as two independent fuel cycles gives a misleading picture. The MOX fuel cycle does not exist without the UOX fuel cycle since plutonium does not exist freely in nature. The comparison should instead be once-through UOX or UOX with reprocessing, i.e. using MOX. The once-through UOX fuel cycle is not sustainable indefinitely regardless the amount of uranium supply, because new waste repositories are needed to complete the fuel cycle. The only way of receiving something from the waste in terms of energy, i.e., money, is to reuse it as fuel in a reactor, since energy is still obtainable. Manufacturing MOX and implementing it in LWRs is one way to accomplish this. However, utilising MOX in FBRs is a more attractive alternative because all transuranic isotopes are fissionable in a fast neutron spectrum [34]. Multiple recycling cannot be accomplished in LWRs, leading to storage of spent MOX fuel waiting for the commercialisation of FBRs. The FBR is however not covered in this thesis.

The uranium price will probably remain below the price for reprocessing and recycling in LWRs for at least the next two decades, except for dramatic reduction in price for reprocessing or manufacturing of MOX fuel, which is considered unlikely [26].

The cost for the front end of the uranium fuel cycle is estimated from quoted data, see chapter 2.6. Uranium fuel cost is most probable to lie in the range of 0.03 – 0.05 SEK/kWhel. Uranium price is the factor that is anticipated to have the largest impact on the total fuel cost in short to medium term. MOX and thorium fuel cost are anticipated to be greater than for uranium. The uncertainties associated to the fuel cost are greatest for thorium and depending on the fuel design and the future arrangements. MOX fuel cost is also subject to some uncertainties and the cost for fuel fabrication, that is anticipated to decrease, will affect the fuel cost. The reprocessing cost is not likely to decrease in the future due to the mature technology. It should be stressed that cost for disposal of MOX fuel results in larger costs as opposed to uranium. However, at present the general policy is not to reprocess or dispose spent MOX fuel as previously mentioned, but to store it and await the introduction of the FBRs.
Figure 22 – The front-end fuel cost for uranium oxide (UOX), MOX and thorium. UOX cost estimates are based on data, MOX on limited information and thorium on assumptions.

The uncertainty in the future fuel cost for uranium lays mainly in the future uranium price. For MOX and thorium the feed material cost are relatively low and the total fuel costs is mainly depending on the fuel fabrication costs. The cost estimations for the front-end of the fuel cycles are illustrated in Figure 22. Uranium cost is based on quoted data, which is illustrated by the sharp edges in the figure and for MOX and thorium the fuel cost range is more uncertain and illustrated by the more diffuse limit range.
7 Conclusions

The present dominance of LWRs and uranium fuel is likely to continue over the next 10 – 20 years at least. Uranium gives rise to the lowest fuel costs of the three nuclear fuels examined in this thesis. The uranium market is well established and mature. Uranium fuel purchase is complex and all activities throughout the front-end are subject to competition. The owner of the NPP has different contracts for each activity at the front-end. Several companies are providing different services and the present production capacity is much greater than the demand. Presently uranium price gives rise to some uncertainty in terms of the future fuel cost. The increase of uranium price over the last couple of years has resulted in an increase of the total fuel cost. Uranium fuel cost has previously been divided equally between uranium, enrichment and fuel fabrication cost, but uranium is currently the cost unit responsible for the majority of the fuel cost. The total production cost for nuclear power is however relatively insensitive to increased fuel cost as opposed to other power sources, e.g., gas. It is difficult to estimate when thorium becomes economically competitive with uranium because thorium fuel is not commercially available. The driving factor of the total fuel cost is allocated to fuel fabrication as oppose to uranium where uranium cost is the main unit cost. It is however likely that uranium fuel will be less expensive than thorium fuel over the next decades. This statement is of course sensitive to other factors than economy, which might provide advantages for thorium, such as political, waste, proliferation etc. Thorium power claims that their heterogeneous design will be 10-15 % less expensive than uranium, but stresses that this statement is based on preliminary estimates rather than real data.

According to estimates MOX will be competitive if the uranium price exceeds approximately 175 USD/lb U₃O₈. Another possibility is that the reprocessing price will decrease to about 700 USD/kgHM. Both of these scenarios are considered unlikely. Furthermore, the cost for disposal of MOX fuel is not included in this estimate. Disposal of MOX fuel gives rise to higher costs than the disposal of uranium fuel leading to an even higher break-even price. However, MOX fuel is presently stored waiting for the arrival of FBRs, which enables multiple recycling of plutonium, and the energy still present in the fuel can be recovered. Therefore the cost for final disposal of MOX fuel is not included in the estimate. MOX is not anticipated to provide more than a few percent of the new nuclear fuel over the next two decades and thorium is expected to represent even less of the nuclear fuel market for the same period if time.

8 Further Studies

This thesis only considers the front end of the fuel cycle, which implies the necessity to investigate operation and back-end aspects in order to get a complete picture. The reason why these, very important features, are not included is because of the time limit of the master thesis.
Acknowledgements

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References

http://www.analys.se/publicerBakgrund.htm, Nyköping, Sweden, 2005

[2] Claire LECOINTE, David LECARPENTIER, Vincent MAUPU; EDF, NEEDS Project -
Technology report nuclear power plants A 2050 technology roadmap, EDF R&D, Paris, France,
2007


(2007-11-05)


(2007-09-17)

nuclear.org/info/inf23.html (2007-09-17)


nuclear.org/info/inf03.html (2007-09-18)


[13] Roland ROBERTS, Department of Geosciences, Uppsala University, “private communication,”
September 2007,

due to Radon from Uranium Mill” Tailings, http://www.world-

nuclear.org/info/inf50.html (2007-09-10)

[16] Commissariat à l'Énergie Atomique (CEA), Direction de la communication Documentation,
“L’information sur l’énergie edition 2005,” e-mail : patrice.renault@cea.fr, Paris, France, 2005


http://www.nrc.gov/materials/fuel-cycle-fac/faq.html#2, 2007-12-17
[23] Christian AZAR, “Produktion av uran och plutonium för kärnvapen och kärnkraft,”
http://www.foi.se/FOI/templates/Page____485.aspx, 2004
[26] Mathew BUNN, John P. HOLDREN, Steve PETTER, Bob VAN DER ZWAAN, “The
economics of reprocessing versus direct disposal of spent nuclear fuel,” Nuclear technology vol.
150, June, 2005
[27] Nuclear Energy Agency (NEA) report, Organization for Economic Co-operation and
[29] Nuclear Energy Agency (NEA) report, Organization for Economic Co-operation and
Development, “The Economics of the Nuclear Fuel Cycle,”
“Uranium 2005: Resources, Production and Demand,” 2005
[31] Swedish Nuclear Power Inspectorate (SKI), “MOX-bränsle,”
www.ski.se/dynamaster/file_archive/050621/bc52ca3181a7ed2ab695269ecc131c19/mox.pdf
(2007-09-12)
[33] Reidar LÖFSTRÖM, Oskarshams Kraftgrupp (OKG), "Private communication", November 2007
[34] World Nuclear Association, “Mixed Oxide Fuel (MOX),” http://www.world-
nuclear.org/info/inf29.html (2007-09-13)
[35] Nuclear Energy Agency (NEA), Organization for Economic Co-operation and Development,
“Plutonium Management in the Medium Term,” 2003, Paris, France
[37] Svensk Kärnbränslehantering AB (SKB), “Separation och transmutation - Belysning av
[38] International Atomic Energy Agency (IAEA), “Status and Advances in MOX Fuel Technology,
[39] Eduard PELCKMANS, Yvon VANDERBORCK, Marc DE VLEESCHHAUWER,
Carlo VERHEYEN, Léon MERTENS, “BELGONUCLEAIRE MOX fuel : a quality minded
product,” 2005, Tsukuba, Japan
(2007-11-12)
[40] Sammy SHIHAB, Belgonucleaire, “private communication,” October-December 2007
Appendix

BUNN Mathew, HOLDREN John P., PETTER Steve, VAN DER ZWAAN Bob, “The economics of reprocessing versus direct disposal of spent nuclear fuel,” Nuclear technology vol. 150, June, 2005

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# World Nuclear Power Reactors 2006-08 and Uranium Requirements

14 January 2008

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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WORLD**</td>
<td>2658</td>
<td>16</td>
<td>439</td>
<td>372,059</td>
<td>34</td>
<td>27,798</td>
</tr>
</tbody>
</table>

Sources:

Reactor data: WNA to 14/01/08.
IAEA- for nuclear electricity production & percentage of electricity (% e) 5/07.
WNA: Global Nuclear Fuel Market (reference scenario) - for U.

Operating = Connected to the grid;
Building/Construction = first concrete for reactor poured, or major refurbishment under way;
Planned = Approvals, funding or major commitment in place, mostly expected in operation within 8 years, or construction well advanced but suspended indefinitely;
Proposed = clear intention or proposal but still without firm commitment. Planned and Proposed are generally gross MWe;

TWh = Terawatt-hours (billion kilowatt-hours), MWe = Megawatt net (electrical as distinct from thermal), kWh = kilowatt-hour.

64,615 tU = 76,200 t U3O8

* In Canada, ‘construction’ figure is 2 laid-up Bruce A reactors.
** The world total includes 6 reactors operating on Taiwan with a combined capacity of 4884 MWe, which generated a total of 38.3 billion kWh in 2006 (accounting for 20% of Taiwan’s total electricity generation). Taiwan has two reactors under construction with a combined capacity of 2600 MWe.