EURATOM SIXTH FRAMEWORK PROGRAMME

Partitioning and Transmutation and Other Concepts to Produce Less Waste in Nuclear Energy Generation

LWR-DEPUTY

Light Water Reactor fuels for Deep Burning of Pu in Thermal Systems

DELIVERABLE 08

Feasibility of burning plutonium in LWRs with innovative fuels

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Feasibility of burning plutonium in LWRs with innovative fuels

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Summary

This report treats prospects for introduction of innovative plutonium burning fuels into the LWR nuclear fuel cycle. At present, plutonium is partly re-used in LWRs in the form of uranium-plutonium mixed oxide (MOX). The current plutonium consumption rate by use of MOX is, however, not sufficient to stabilize the plutonium stockpiles. Therefore, alternative routes for plutonium management are studied. It is, specifically, a scenario with a continuation of the light water reactor era, where enhanced plutonium use is needed to stabilize or decrease plutonium stockpiles, that calls for a plutonium management strategy towards achieving a reduction of existing stockpiles with innovative plutonium fuels. Such fuels should burn plutonium at increased rates compared to MOX fuel. This can be achieved by using a carrier or matrix that does not contain uranium, such as thorium-based and inert matrix fuels, so that no new plutonium is formed while burning the existing plutonium stock. Within the LWR-Deputy project, the matrix materials ThO_2, ZrO_2, Mo (molybdenum) and FeCr (iron-chromium alloy) have been evaluated for use in this manner. Of these, the thorium plutonium mixed oxide (i.e., $(Th,Pu)O_2$) most closely resembles existing MOX fuel, while the two novel cermet fuels offer the possibility of higher linear heat rates and therefore even higher plutonium burning rates.

In this study, the position of a number of stakeholders has been studied in order to assess the feasibility of introducing plutonium burning fuels; these stakeholders are governments, fuel vendors & developers, reactor utilities, and waste disposal organisations. Given the long time still needed to develop innovative fuels such as thorium-based plutonium fuel and inert matrix fuels, it is not straightforward to identify the most important stake-holders. It has been concluded in this study that the most active and crucial stakeholders are the fuel vendors and developers, who invest in the long-term R&D of innovative fuels and who have the capability of introducing new fuels and new fuel cycles. In the study we therefore describe how thorium-based and inert matrix (IMF) fuels for plutonium burning are viewed by some fuel vendors & developers.

Issues of long-term supply of natural uranium are of concern to vendors. The concomitance of the renewal of the existing reactors and projected growth of the nuclear park between 2030 and 2050 may lead to an important increase of demand for natural uranium. Within this scenario, it is beneficial to be able to supply fuel that requires less natural uranium.

An option that is specifically advocated by the Norwegian company ThorEnergy, is to use plutonium as a start-up material for bringing thorium into the nuclear fuel cycle. In this strategy plutonium is burnt while

U-233 is created as a new fissile component to generate energy for the future. This strategy brings into play thorium as a valuable mining product, since it is then used as a component in innovative nuclear fuels.

In view of these developments, there is a clear focus on thorium, based on the fact that the abundance of thorium is around 3-4 times that of uranium. Another, not insignificant factor is the past interest in thorium-based fuel, which has produced significant irradiation experience with generally positive results. This has positioned the state of development of thorium-based fuel ahead of that of IMFs.

In conclusion, one sees that the current long-term developments into innovative fuels are focused on uranium resource preservation, by either reducing future demands on natural uranium, or by bringing into the nuclear fuel cycle the vast amounts of thorium in the earth as a resource for nuclear energy generation.

Nevertheless, it should be stressed, that the development of innovative nuclear fuels requires a significant R&D effort that takes decades. Before any innovative fuel can make its introduction into the nuclear fuel cycle, a clear long-term fuel cycle strategy should be maintained. Both for thorium-based fuels and for IMF, the development efforts and initiatives in Europe are still rather small. As a consequence, the conclusions from this study should be treated with prudence, as the actual introduction of innovative, plutonium-burning fuels is still a long path with many uncertainties.

Introduction

The plutonium that is produced by light water reactors world-wide is currently re-used to a limited extent only. Historically, it was intended to introduce plutonium into the nuclear fuel cycle by evolving from light water reactor (LWR) parks to parks where plutonium would be bred and used in fast reactors (FR). However, the introduction of a fast reactor fleet was not accomplished in the 20th century and within the Generation IV programme is expected to become fully deployed only in the second half of this century. This leads to the question what to do with the plutonium stockpiles arising from reprocessing of uranium oxide used in LWRs. The world-wide generation of reactor-grade plutonium in spent fuel is about 70-75 tons per year. By the end of 2010 the total amount of civil plutonium, either separated or in spent nuclear fuel is estimated to be about 2100 tons [1]. Plutonium is the dominant contributor to the radiotoxicity of spent nuclear fuel for storage times from ~ $10^2 – 10^5$ years.

At present, plutonium is partly re-used in the form of uranium-plutonium mixed oxide (MOX). About 10% of the reactors world-wide have a license to use MOX, mainly for a 1/3 loading with MOX and 2/3 with UO_2 (UOX). The current plutonium consumption rate by use of MOX is not sufficient to stabilize the plutonium stockpiles. Therefore, alternative routes for plutonium management are studied. This is very well outlined in the OECD report on plutonium management [2]. Starting from the current light water reactor era with an increasing surplus of plutonium, one could distinguish different types of plutonium management strategies:

- stop reprocessing of UO_2 fuel and accept the risks involved with underground storage of plutonium
- a strategy towards a fast reactor era, where plutonium is used to fuel future fast reactor parks;
- a continuation of the light water reactor era, where enhanced plutonium use is needed to stabilize or decrease plutonium stockpiles;
- a phase out of nuclear energy, where there is no option to burn plutonium in nuclear reactors, such that plutonium needs to be immobilized.

It is, specifically, the third scenario that calls for a plutonium management strategy towards achieving a reduction of existing stockpiles with innovative plutonium fuels. Such fuels should burn plutonium at increased rates. This can be achieved by using a carrier or matrix that does not contain uranium, such as thorium-based and inert matrix fuels, so that no new plutonium is formed while burning the existing plutonium stock.

Within the LWR-Deputy project, the matrix materials ThO_2, ZrO_2, Mo (molybdenum) and FeCr (iron-chromium alloy) have been evaluated for use in this manner. Of these, the thorium plutonium mixed oxide (i.e., $(Th,Pu)O_2$) most closely resembles existing MOX fuel, while the two novel cermet fuels offer the possibility of higher linear heat rates and therefore even higher plutonium burning rates.

This report treats prospects for introduction of innovative plutonium burning fuels into the nuclear fuel cycle. First, in Chapter 1 the existing plutonium stockpiles in the world are estimated and current Pu management policies in Europe are described. Chapter 2 zooms in on Pu burning in the current LWR fleet and covers the available options. This is followed in Chapters 3 and 4 by an exploration of the acceptability of enhanced plutonium burning routes to the stakeholders (notably vendors, utilities and governments); the results of this survey are given in Chapter 4. Conclusions are given in Chapter 5.

1 Existing plutonium stocks in Europe

1.1 Current plutonium stock-piles

To obtain an accurate estimate of the currently existing civil plutonium stock-piles is not straightforward. The main reason for this is that not all countries report the amounts of plutonium in an open and uniform manner. In addition, various countries follow different fuel cycle strategies, either with or without reprocessing and with or without the use of MOX fuel in their nuclear power plants. Nevertheless, the most important countries, i.e. those having most nuclear power plants and those with reprocessing capabilities and a reprocessing strategy, report their plutonium amounts yearly to the IAEA. This is communicated through information circulars (so-called 'INFCIRC-549'), with indication of the amount of separated plutonium and the plutonium contained in spent or fresh fuel [3]. The information circulars INFCIRC-549 account for about 75% of the total world's plutonium inventory. In addition, the information circulars give a good and representative picture about global (separated) plutonium stocks, as well as about fuel cycle trends in various countries.

In Table 1 and Table 2, an overview is given about the INFCIRC-549, stating plutonium stock-piles at the end of the year 2003 and at the end of 2009. From Table 1 and Table 2, a clear overview can be obtained about current stock-piles, but also about the fuel cycle strategies and recent developments with respect to plutonium management. As an example, the United Kingdom's separated plutonium stock is increasing, whereas France's separated plutonium inventory stays roughly constant, due to the extensive use of MOX fuel in nuclear power plants in France. Also the discontinuation of reprocessing spent fuel in Germany is reflected in decreasing amounts of separated plutonium. The closure of the MOX fabrication plant of Belgo-Nucleaire in Belgium in 2006 is also seen in the numbers. Note, that the separated plutonium in the USA is former military plutonium that has been declared excess to national security needs, and therefore moved to the civil sector. From this plutonium, 34 tons will be burnt as MOX fuel, as agreed in the plutonium disposition programme with the Russian Federation.

	Belgium	Switzerland	Germany	France	Japan	Russia	UK	USA	Total
Unirradiated separated Pu									
1 at reprocessing plants	0.0	0.0	0.0	48.6	0.7	37.0	92.7	0.0	**179.0**
2 in course manufacturing	2.1	0.0	0.0	13.3	3.2	0.0	1.0	0.1	**19.7**
3 in unirradiated MOX	1.4	0.0	10.8	13.2	1.1	0.2	1.9	4.6	**33.2**
4 other	n.a.	< 0.05	1.7	3.5	0.4	1.0	0.6	40.4	**47.6**
Total separated Pu	**3.5**	**0.0**	**12.5**	**78.6**	**5.4**	**38.2**	**96.2**	**45.1**	**279.5**
Pu in spent fuel									
1 at reactor sites	23.0	14.0	49.3	94.1	98.0	56.0	7.0	383.0	**724.4**
2 at reprocessing plants	0.0	0.0	0.0	96.5	7.0	3.0	30.0	0.0	**136.5**
3 held elsewhere	0.0	1.0	6.4	0.5	< 0.5	29.0	< 0.5	12.0	**48.9**
Total Pu in spent fuel	**23.0**	**15.0**	**55.7**	**191.1**	**105.0**	**88.0**	**37.0**	**395.0**	**909.8**

Table 1. Reported plutonium stockpiles according to INFCIRC549, as of 31-12-2003

	Belgium	Switzerland	Germany	France	Japan	Russia	UK	USA	Total
Unirradiated separated Pu									
1 at reprocessing plants	0.0	0.0	0.0	47.1	4.4	46.3	107.7	0.0	**205.5**
2 in course manufacturing	< 0.05	0.0	0.0	6.8	3.3	0.0	1.3	0.1	**11.5**
3 in unirradiated MOX	< 0.05	0.0	5.4	27.2	1.9	0.3	2.1	4.6	**41.5**
4 other	< 0.05	< 0.05	0.0	0.7	0.4	1.1	0.9	49.3	**52.4**
Total separated Pu	**0.0**	**0.0**	**5.4**	**81.8**	**10.0**	**47.7**	**112.0**	**54.0**	**310.9**
Pu in spent fuel									
1 at reactor sites	33.0	13.0	86.9	100.3	120.0	71.0	8.0	520.0	**952.2**
2 at reprocessing plants	0.0	0.0	0.0	129.6	24.0	4.0	26.0	0.0	**183.6**
3 held elsewhere	< 0.05	3.0	5.9	6.6	< 0.5	47.0	< 0.5	12.0	**74.5**
Total Pu in spent fuel	**33.0**	**16.0**	**92.8**	**236.5**	**144.0**	**122.0**	**34.0**	**532.0**	**1210.3**

Table 2. Reported plutonium stockpiles according to INFCIRC549, as of 31-12-2009

Unreported Pu exists in addition to the stockpiles communicated through INFCIRC-549. This is almost exclusively contained in spent fuel of countries without reprocessing strategy. In Europe, this is about 215 tons, half of which in spent fuel in Sweden and Spain, and the remaining half in spent fuel in Bulgaria, Finland, Czech Republic, and others. In Table 3, an overview is given of the estimated plutonium stocks of European countries not reporting to the IAEA through INFCIRC-549, as of beginning of 2010. With the exception of the Netherlands, these countries have no strategy to reprocess their spent nuclear fuel. Numbers are estimated and therefore rounded to whole tons (Table 3).

Note that from the Netherlands, spent fuel is reprocessed in France. The separated plutonium is currently not used in Borssele NPP, the only Dutch Nuclear Power Plant, although Borssele NPP is preparing a license renewal to allow for the use of MOX fuel. In the past, Borssele NPP has had a strategy to have its separated plutonium used as MOX fuels in foreign NPPs. However, detailed information about how much plutonium has been used as MOX fuel is not available publicly.

Table 3. Estimated amounts of plutonium in European countries, not reporting to the IAEA through INFCIRC 549, beginning 2010

Country	Total estimated Pu	Country	Total estimated Pu
Bulgaria	19	Netherlands *	5
Czech Republic	15	Romania	10
Finland	18	Slovenia	4
Hungary	12	Slovakia	6
Italy	6	Spain	45
Lithuania	11	Sweden	65

* Plutonium from the Netherlands is (partially) separated and possibly (partially) transferred and used as MOX fuel in foreign NPPs

1.2 Summary: plutonium stocks in Europe

From Tables 1-3, the following summary of plutonium stocks can be given for the situation in Europe (EU-27 plus Switzerland), as plotted in Figure 1. Most separated plutonium is located in the United Kingdom and France. The total separated plutonium in Europe amounts to some 200 tons, whereas the amount of plutonium in spent nuclear fuel is around 635 tons. Note that for some countries, that use or have used MOX fuel in the past, such as France, Germany, Belgium and Switzerland, some of the plutonium is contained in spent MOX fuel. The total plutonium in Europe accounts for roughly 40% of the world's total civil amounts.

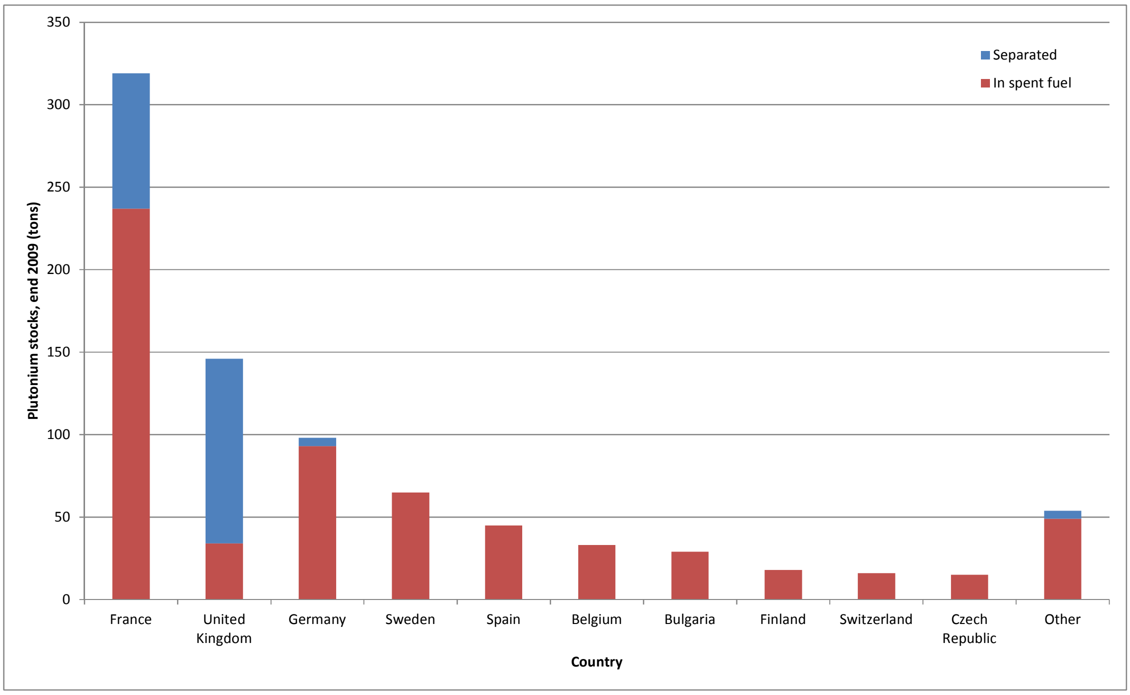

Figure 1. Estimated stocks of plutonium, both separated and in spent fuel, for European countries (EU-27 plus Switzerland), as of beginning 2010

1.3 Fuel cycle strategies

Within various European countries, a number of fuel cycle strategies exist. Roughly, they can be divided into two main strategies:

1. open fuel cycle without reprocessing
2. partially closed fuel cycle with reprocessing

In the open fuel cycle, spent fuel is kept directly without further treatment and without taking out plutonium. In the (partially) closed fuel cycle, spent nuclear fuel is reprocessed in order to separate plutonium, which is then used as MOX fuel. In the following sections, nuclear fuel cycle policies are sketched for the countries in the LWR-Deputy programme and in France, the latter being the most important producer of nuclear energy in Europe. Most information has been taken from the country overview from the World Nuclear Association [4]. European countries not involved in LWR-Deputy and therefore not treated in this section, all follow an open fuel cycle strategy, i.e. without reprocessing. Therefore separated plutonium stocks are (almost) non-existent in these countries.

1.3.1 France

France operates 58 nuclear power plants (NPPs), which are all Pressurised Water Reactors (PWR). The total installed capacity is 63 GWe, which supplies (in 2010) 410 TWh of electricity.

The fuel cycle strategy in France has always been that of a closed cycle, both to increase energy production per kg U, by an estimated 17%, and to reduce the waste volume to be disposed. 70-90% of the spent fuel is reprocessed in the La Hague plant, and 99.9% of the U and Pu is recovered. Total reprocessing throughput was 929 tons in 2009, with the aim to increase throughput to 1500 ton/yr by 2015. Associated MOX fuel production capacity in the MELOX plant near Marcoule is around 150 ton/yr, with a license for up to 195 ton/yr. The resulting fuel cycle costs are stated to be 'comparable to direct disposal'. France reprocesses foreign material in addition to domestic spent fuel.

The MOX fuel itself is currently not reprocessed. 100% of the spent MOX fuel and 10-30% overall of generated spent fuel is currently being stored with the aim to reprocess later for use in fast-spectrum reactors. Ultimate waste destined for geological disposal consists of fission products and minor actinides; The clay formation at Bure has been identified as the best site.

Long term strategy is based on a combination of Fast Reactors and advanced reprocessing techniques. Fast Reactors should be capable of burning not only Pu and U from spent MOX fuel, but also the minor actinides that currently are scheduled for disposal. By 2040, when the La Hague plant is scheduled to be replaced, co-extraction of U and Pu as well as separate or joint extraction of minor actinides will need to be validated for industrial use. However, according to a 2010 government report [4], transmutation of minor actinides adds around 10% to power costs.

1.3.2 United Kingdom

The UK has 18 NPPs, normally generating about 18% of its electricity. All but one of these will be retired by 2023, but the UK has implemented a very thorough assessment process for new reactor designs and their siting, and the first of some 19 GWe of new-generation plants are expected to be online about 2018. Current total installed capacity is 11 GWe, which produced 56.48 TWh net in 2010. The country has full fuel cycle facilities in place, including major reprocessing plants.

Fabrication of UO_2 fuel for the AGR and PWR plants is performed at Springfield, while additional PWR fuel is bought internationally. A 1500 t/yr Magnox fuel reprocessing plant in Sellafield is due to close around 2016; a second reprocessing plant at the same location (THORP) and operating until 2020 faces technical problems. The Sizewell B reactor is the only domestic unit using reprocessed enriched (UO_2) fuel. MOX fuel fabrication for export purposes took place at Sellafield until recently, but the fabrication plant has recently been shut down.

A report on the UK's plutonium management strategy was issued in 2011 [4]. Overall conclusion of the report was that fabrication of MOX fuel from the existing stockpile of >100 tons separated Pu and around 35 tons more in spent fuel (see section 1.1) would be favorable although not profitable. The government has recently announced in response that it preferred the MOX option over indefinite storage or disposal for as much of the plutonium as possible. A new MOX production plant is therefore currently considered. However, the current default position of the UK is still 'to store the material until 2070 at Dounreay and until 2120 at Sellafield'.

GE-Hitachi is preparing a proposal to reuse the UK's significant Pu stockpile in two 311 MWe units of their PRISM fast reactor concept at Sellafield.

1.3.3 Germany

Until March 2011, Germany's 17 operating nuclear power reactors supplied about 28% of the electricity (133 TWh net in 2010). 6 of these units are boiling water reactors (BWR), 11 are pressurised water reactors (PWR). All were built by Siemens-KWU.

Until 1994, utilities were obliged to reprocess spent fuel for reuse of U and Pu. 13 out of the 17 operating reactors were licensed to use Mixed Oxide (MOX) fuel produced from recycled plutonium; the necessary reprocessing step were foreseen to be performed in France in the period up to 2022. However, starting from 1998, policy has been to directly dispose spent fuel. Main repository criteria as re-established in 2009, are proven ability to store high-level waste for a million years, and retrievability during the period of storage.

In 2000, nuclear phase-out was enforced by government, and a maximum production of 2.6 TWh per unit (32-year average plant life) was negotiated with the utilities. Another result of this agreement is that almost all of the German plutonium is currently stored in on-site spent fuel pools. In 2010 the utilities succeeded in negotiating extensions in return for heavy taxation on consumed fuel and produced electricity, as well as additional subsidies on renewable energy. However, after the Fukushima accident in 2011, phase-out was reintroduced while keeping the tax on nuclear fuel. 8 reactor units built before 1980 remain shutdown, while the remaining 9 will operate until 2022.

1.3.4 Belgium

Belgium has seven nuclear reactors, providing 54% of the country's domestically-generated electricity (about 43 TWh/yr net). Most Belgian electricity is produced by Electrabel, which also operates all the nuclear plants.

The fuel cycle is managed by Synatom, owned by Electrabel. Belgium operated a (partially) closed fuel cycle until 1993. Reprocessing was performed in Dessel (Eurochemic) and in La Hague in France, but reprocessing activities in Dessel were suspended in 1993. Since 1993, spent fuel is stored on-site, which has led to a situation similar to that of Germany. Wit respect to refabrication, a 200 ton/yr MOX fuel line is still included in Areva's 700 t/yr FBFC plant in Dessel, but a 35 ton/yr MOX plant at the same site (Belgonucleaire) closed in 2006. MOX fuel has been used in LWRs since 1995 and the policy is to use all plutonium previously recovered from reprocessing for MOX fuel fabrication as quickly as possible. Utilities pay a levy on each kWh of electricity sold, which goes into a decommissioning and waste management fund, managed by Synatom. Research on deep geological disposal of long-lived intermediate-level and high-level wastes is underway and focused on the clays at Mol.

In 1999, the Belgian government banned further reprocessing, while in 2003 the political decision was made to prohibit the building of new nuclear power plants and to limit the operating lives of existing reactors to 40 years (shutdowns in the period 2014-2025). This policy is still in place, but can be overridden if Belgium's security of supply is threatened or prices rise unduly. A commissioned 2009 report has recommended plant life extensions [4].

1.3.5 Switzerland

Switzerland has 5 nuclear reactors generating 40% of its electricity. In 2007 nuclear power contributed 26.5 TWh net, 43% of Swiss demand.

There is no national policy regarding reprocessing or direct disposal of used fuel. However, utilities have been sending about 1000 tons of spent fuel for reprocessing until 2006, for recovery and refabrication of U and Pu into MOX fuel. Reprocessing has been performed at La Hague in France and by BNFL at Sellafield in UK under contract to individual power plant operators. Switzerland remains responsible for the returned separated high-level wastes. Since the 2005 Nuclear Energy Act halted reprocessing for ten years from mid-2006, used fuel is now stored on-site or sent to Zwilag ZZL for interim above-ground storage.

1.3.6 Netherlands

The Netherlands has one nuclear reactor, Borssele NPP; A second one has operated at Dodewaard in the period 1969-1997. Borssele is a 480 MWe PWR, which generates about 4 TWh of electricity yearly, covering 4% of Dutch electricity.

Used nuclear fuel from Dodewaard was recycled at the UK's Thorp facility at Sellafield, and that from Borssele at France's La Hague. Areva NC, operator of La Hague, holds a contract to recycle Borssele used fuel until 2015. Some recycled uranium has been used in the plant for several years, and an unknown fraction of produced Pu was re-used in foreign NPPs. EPZ is currently seeking approval to use MOX fuel (with 5.4% fissile Pu content) as 40% of the fuel load.

Management of spent fuel and other radioactive waste forms is performed by the Central Organization for Radioactive Waste (COVRA), based at Borssele, close to the nuclear power station. The COVRA operates a high-level waste facility (HABOG) for long-term (100 year) interim storage, where all HL waste from Dodewaard and Borssele is kept. In 2001 a government-sponsored committee concluded that retrievable geological disposal is technically feasible in a safe manner, on several sites in the Netherlands. Before 2016 a decision should be taken by government to choose between the preferred treatment of partitioning and transmutation, recycling as carried out today, or direct disposal. For new plants, a similar decision should be taken before 2025.

Electricity production in the Netherlands has been liberalised. Several market parties have indicated their interest in building a new nuclear reactor in the country. In 2006, the Dutch government concluded a contract with the Borssele operators and shareholders. The reactor would be allowed to operate until 2034 on condition that it would be maintained to the highest safety standards, and the stakeholders, Delta and Essent, agreed to invest EUR 250 million towards sustainable energy projects. Any new reactor must be a Generation III model with levels of safety being equivalent to those of Areva's EPR.

1.3.7 Slovakia

Slovakia has 4 nuclear reactors, which generate about 50% of its electricity. All units are VVER-440 (PWR). Total installed net capacity is 1816 MWe. 2 reactors of the same type are under construction, and expected to become connected to the grid by 2012 and 2013. One more is planned to start operation after 2020.

At the beginning of 1996, a subsidiary of Slovak Electric (SE) was established for decommissioning nuclear facilities, radioactive waste and used fuel management, with a levy of 10% of the wholesale price of electricity being paid into it by SE. In the past, some used fuel was exported to Russia for reprocessing (with Russia keeping the products). However, until 2008 government policy was direct disposal of spent fuel without reprocessing. This has changed to domestic recycling, but full facilities are not in place. An interim wet storage facility for used fuel at Bohunice supplements reactor storage ponds, and has a capacity of 1680 tons. A near-surface repository (the National Radioactive Waste Repository) at Mochovce began operation in 2001. Site selection for an underground high-level waste repository has commenced, although the country is also considering the option of participating in a shared international repository project.

2 Potential of innovative fuel types

Over the last decades new concepts and initiatives for a more sustainable nuclear fuel cycle with emphasis on the management of radioactive waste have been launched. Storage of conditioned spent fuel, or high-level waste arising from reprocessing of spent fuel, in underground repositories equipped with engineered barriers is one of the scenarios envisaged for future radioactive waste management. In several countries underground research facilities have become available (e.g. Belgium) or are currently under construction (e.g. Sweden).

Partitioning and Transmutation (P&T) is another scenario under consideration. This scenario envisages reduction of the long-term environmental impact of radioactive waste by separation (partitioning) of the most radiotoxic or most long-lived components from the waste and re-irradiating them with neutrons, thereby converting the long-lived isotopes into more short-lived or stable isotopes. P&T scenarios indicate that the reduction in radiotoxicity equivalent to a period of 150,000 year of natural decay can be reached after 500 - 3000 years [5].

It is important to realize that the two scenarios do not only differ from a technical point of view. In the case of final disposal, the fuel is utilized once and then discarded as waste. The P&T route, in contrast, acknowledges the energy potential of irradiated fuel and processes are developed to exploit this potential: a closed cycle. The ‘life cycle’ of plutonium is a good example of the latter route.

The bulk of the radiotoxic inventory of the spent fuel, 90%, consists of plutonium isotopes. The present global inventory of plutonium is over 1,400 metric tons next to about 250 metric tons of weapon-grade plutonium [6]. Plutonium is therefore an obvious candidate for P&T studies. Part of the reprocessed, fissile plutonium is currently mixed with uranium oxide and used as MOX fuel in commercial nuclear power plants. During irradiation in existing light water reactors a maximum of about 50% MOX is applicable. Plutonium is fissioned (burnt) but at the same time new plutonium is generated by neutron capture in the non-fissile U-238. As a consequence, a net reduction of the worldwide plutonium stockpiles along this line is not feasible.

New reactor designs would be needed in order to increase the maximum loading of MOX. The European Pressurized Reactor (EPR) which is constructed by AREVA, is an example of an innovative reactor that can be operated with a 100% MOX core. However, the use of alternative, U-free, fuel types in the current reactor fleet may present an alternative. The feasibility and the Pu burning potential of such innovative fuel types are discussed in the following sections.

2.1 New fuel types

2.1.1 Ceramic-Ceramic Inert Matrix fuels

Effective reduction of the plutonium stockpiles may be achieved by using Pu-bearing fuels that do not produce new fissile material and little overall waste. Over the last decade research has focussed on the incineration of plutonium (and other actinides) in inert matrix fuels (IMF). IMFs are composed of a fissile-bearing phase, containing plutonium and/or minor actinides like americium, embedded in an inert matrix, i.e. a matrix which does not interact with incident neutrons. The matrix may have a ceramic (e.g. [7], [8]) or a metallic (e.g. [9]) composition. Results of recent irradiation experiments have demonstrated the potential of the concept of IMF (minor) actinide incineration ([10], [8]).

Important parameters in studies into IMF fabrication are the chemical composition of the matrix and the distribution of the fissile phase in the matrix. The composition of the matrix is confined to elements that do not show significant interaction with neutrons during irradiation, as activation of the matrix leads to generation of radioactive waste and simultaneously disturbs the neutron balance required to generate a sustainable fission reaction. Examples of inert elements are silicon, aluminium, magnesium and zirconium. The inert matrix material should also be resistant to the different types of radiation that are present in-core, and be able to accommodate fission products, amongst which krypton and xenon, and, in some cases, large amounts of helium gas. Finally, the material should have a sufficiently high melting point and thermal conductivity, and suitable mechanical properties to provide mechanical stability of the IMF pellets. Selected ceramic matrix materials that have been studied reasonably well up till recently are MgO, spinel ($MgAl_2O_4$), Al_2O_3 and ZrO_2 ([11], [12], [7], [8]).

An important issue concerns the dispersion of the fissile material in the matrix material. A distinction can be made between composite and homogeneous types of IMF. The homogeneous type is a solid solution of the matrix and the fissile phase. A prominent example is the zirconia-based (ZrO_2) fuel which forms a solid solution with PuO_{2-x}: $(Zr,Pu)O_{2-x}$. Composite IMFs on the other hand consist of an inert matrix which contains a dispersion of either micro- (up to several tenths of a micrometer) or macro-sized (several hundred micrometers) particles of the fissile phase (usually the dioxide). The size of the particles exerts a significant influence on the behaviour of the fuel during, and after, irradiation. This is mostly due to the fact that the production of fission products, alpha particles, recoil atoms and neutrons has a profound impact on the periphery of the individual particles. In micro-dispersive systems the damage will be more homogeneously distributed over the fuel (Fig. 1). On the other hand, damaged zones will overlap and result in more swelling than in a macro-dispersive IMF as recently observed [8]. Clearly, excessive swelling is an important safety-related issue.

Several routes for the fabrication of the fissile-bearing phase and the IMF are available. As is true for the thorium oxide based fuels discussed in the next section, an important issue is the amount of radioactive waste and dust generated during the fabrication process, especially from a radiological point of view. Dioxide production by sol-gel techniques and impregnation of porous yttria-stabilized zirconia sol-gel beads with an actinide (Ac)-bearing nitrate solution are favoured routes, since the amount of radioactive waste and dust is minimized [13]. Impregnated beads are calcined, during which the Ac-bearing nitrate is converted into an oxide, forming a $(Ac,Zr,Y)_{2-x}$ solid solution.

Homogeneous zirconia-based IMF pellets can be fabricated by crushing the sol-gel beads and pressing pellets from the resulting powder. In the case of composites however, the fissile-bearing phase and the inert matrix (in the form of a powder) are thoroughly mixed in the desired proportions and pressed into pellets. Applied pressures generally range between 500 and 600 MPa. The pressed pellets are then sintered at temperatures between 1400 and 1700 °C, depending on the type of material, to achieve their final density.

By far most of the ceramic inert matrices have poor thermal conductivity, which may result in in-core temperatures well over 1500 °C (for ZrO_2-based IMF). Too high temperatures may result in melting and unwanted chemical interactions with the cladding material. In this respect only magnesia (MgO), with conductivity above 10 W/mK, can be considered an improvement over UO_2. MgO is however not considered a candidate for LWR application since it can react with water in case of cladding failure.

Finally, in a multi-recycling scheme, the inert matrix should be soluble in nitric acid in order to facilitate reprocessing. Unlike MgO, both $MgAl_2O_4$ (spinel) and ZrO_2 are insoluble in nitric acid and therefore incompatible with the multi-recycling scenarios considered for Fast Reactors. These Pu-IMFs are in fact designed for once-through scenarios, where the spent Pu-IMF is disposed after use. Therefore the stability of the Pu-IMF in the long term and low leaching rate in geological conditions are of importance. Studies on the leaching behaviour of U-IMF, with uranium used as a replacement for plutonium, suggest the good retention of plutonium in the fuel. The leaching rates of minor actinides (notably americium and neptunium) were however larger than expected.

2.1.2 Ceramic-Metallic Inert Matrix Fuels

The drive for high thermal conductivities and good solubility in nitric acid has led to the consideration of metallic matrices, most notably molybdenum (Mo) and to a lesser extent iron-chromium (FeCr). However, these elements are less inert with respect to neutron radiation. In the case of molybdenum, neutron absorption may be lowered by enrichment of the low-mass isotopes, since strongest neutron absorption is from Mo-95. Mo cermet irradiation experience within European Framework Projects indicates good performance up to significant linear heat rates, but at high central temperatures (1200 ^{o}C) significant swelling has been observed [14].

2.1.3 Thorium oxide fuel

Thorium oxide based fuel forms a second route to increased Pu burning. As is the case with the previously described inert matrices, thorium itself is not fissile, and additional fissile material is needed when using thorium-based fuel. Both U and Pu could fill this role. However, Th-232, thoriums only stable isotope, is a fertile material with a large thermal neutron absorption crossection, and this will negatively influence the Pu burning rate. A lot of research has been performed on the properties and in-core behavior of $(Th,U)O_2$ in the past, but existing data on $(Th,Pu)O_2$ is still somewhat limited [15].

Plutonium oxide forms a solid solution with thorium oxide. The mixed oxide can be fabricated by mixing of the ThO_2 and PuO_2 powders, pressing and subsequent sintering of pellets. Relatively small changes are needed with respect to existing industrial routes for standard MOX fuel. Comparing the fabrication of Th/Pu oxide and U/Pu-oxide, it was found that the fresh Th/Pu oxide could be fabricated with the same radioprotection equipment as for fresh standard MOX. In addition, from the existing data it was concluded that in-core performance of $(Th,Pu)O_2$ is comparable to that of UO_2 for Pu concentrations up to 15% percent [15]. Therefore it is concluded that introduction of Th-Pu fuels for enhanced Pu burning in LWRs is relatively straightforward compared to IMFs.

During the burning of Th-Pu fuels, U-233 is formed, which has a half life of $1.6*10^5$ years. U-233 is a fissile atom, which makes reprocessing an interesting option. Furthermore it should be noted that the radiological aspects of U-233 are similar to that of plutonium, which makes that it should be taken into account in the waste scenarios.

The fabrication of thorium fuels with the recycled uranium bred from thorium requires strong protection measures against gamma radiation due to the presence of U-232, which has strong gamma emitting daughter isotopes in its decay chain (mainly Tl-208). This is a major problem that makes it difficult to handle Th-U fuel; One option is the use of sol-gel fabrication techniques, which offer the possibility of dust-free fabrication in a shielded environment, but these techniques are at present not considered ready for industrial scale use. Another problem is that the allowed enrichment of U-233 in U is more strongly restricted by proliferation considerations than U-235, at about 10% (compared to 20% for U-235). On the other hand, the presence of refabricated uranium could also offer some advantages. First, the strong gamma radiation from U-232, when refabricated into LWR-fuel, enhances its proliferation resistance. Second, the use of U-233 instead of U-235 prevents the production of Np-237, which is of some proliferation concern. Finally, the addition of U-233 to LWR fuel improves its safety parameters. In this respect U-233 is similar to but more efficient than U-235. Therefore availability of U-233 could facilitate transmutation of Pu and MAs in LWRs as concerns safety.

2.2 Pu-burning and safety performance - comparison with MOX

Table 1 compares the Pu and minor actinide (MA) consumption rates for the different fuel options described above. In the table, the reference plutonium fuel is MOX, a mixture of uranium oxide and plutonium oxide, fabricated using the MIMAS process. Normally, MOX consists of about 7% plutonium (containing 65% fissile plutonium isotopes) with depleted or natural uranium as the carrier. During MOX use in the reactor, the uranium produces new plutonium, and the plutonium itself is fissioned. If the reactor is loaded with 70% UO2 and 30% MOX, the rates of plutonium creation and destruction are the same, and the Pu content becomes constant. The net plutonium consumption rate is increased for 100% MOX to 62 kg/TWhe. For a 1000 MW nuclear power plant, this corresponds to a plutonium consumption of about 500 kg per year.

To further increase plutonium consumption, the uranium in MOX can be replaced either by an inert matrix or by thorium, giving Plutonium Inert Matrix Fuels (Pu-IMF) or Thorium Plutonium (Th/Pu) Fuels. It should be noted, that an increased burning of plutonium by Pu-IMF or Th/Pu fuel is partly counterbalanced by an increased production of Minor Actinides (MA), mainly neptunium, americium and curium. However, the overall actinide production and associated radiotoxicity of the spent fuel for Th/Pu and Pu-IMF cores is significantly less, compared to UOX or MOX cores. The Pu consumption rates given in Table 4 for IMFs and Th/Pu fuels are higher by factors 1.9 and 2.3, respectively. The lower value for Th/Pu fuels is readily explained by the significant absorption of thermal neutrons by the fertile Th-232 as well as from fission of the formed U-233. As mentioned previously, MA formation is correspondingly lower.

Table 4 Comparison of the net plutonium and minor actinide (M.A.) consumption rate (in kg/TWhe) for different fuel loadings.

Reactor-type	Net consumption rate (kg/TWhe)	
	Pu	M.A.
LWR, 100% UOX	-25	-5
LWR, 30% MOX	1	-9
LWR, 100% MOX	62	-18
LWR, 100%Th/Pu core	115	-9
LWR, 100% Pu IMF	142	-23

Kloosterman et al. [16] directly compare the safety performance of Th/Pu fuel and Pu-IMF in LWRs, and conclude that compared to IMFs, the use of thorium considerably improves the temperature coefficient of the fuel as well as the moderator void coefficient, to values close to that of UO_2. This supposedly allows higher loading percentages of Th/Pu fuel compared to MOX, which could help offset the lower Pu burning rate found above.

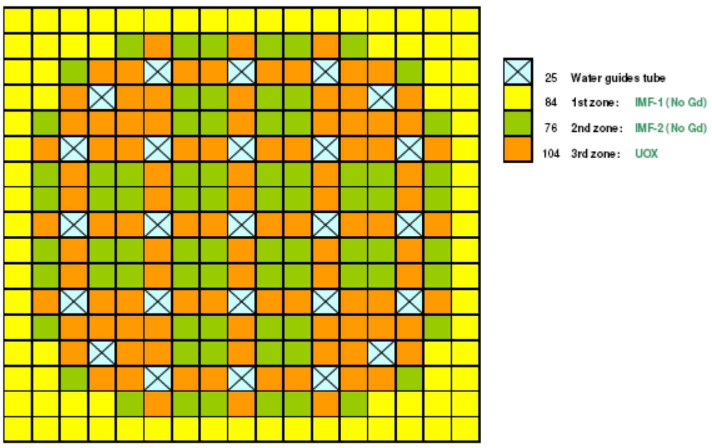

Figure 2 - IMF assembly design (IMF-1 in yellow, IMF-2 in green, UO_2 in yellow).

Given the fact that the current maximum loading of MOX fuel in LWRs is 33%-50%, it is very unlikely that these LWRs will have cores containing 100% of these innovative fuels in the near future. Instead, U-free fuels will more probably run at smaller fractions in parallel with U-based fuel. To investigate IMF safety performance, a combined assembly design with Pu-IMF rods (of the cermet type) and UO_2 rods (without using burnable absorbers) has been investigated. A standard 17x17 assembly was considered (Figure 2). For flattening the power profile at Beginning of Life (BOL) two IMF zones with slightly different PuO_2 volume fraction (84 pins IMF-1 with 16.8%vol. fraction and 76 pins IMF-2 with 12.4%vol. fraction) were considered. The remaining 104 pins are regular UO_2 rods (ca. 5% U235 enrichment) and 25 guide tubes. The Uranium Oxide (UO_2) pins were included in the IMF bundle in order to improve SA safety performance, but the UO_2 content was minimized to optimize Pu burning performance. Higher linear powers were accepted for IMF pins due to the higher cermet thermal conductivity.

Based on this design, a calculation benchmark was defined to validate methodologies and codes. Different calculation tools and nuclear data libraries have been considered for this purpose. The reactivity coefficients near nominal conditions were found to be favorable for reactor safety as confirmed by all partners. For the coolant void effect, a negative value (favorable for safety) was obtained by all partners except NNL. All partners also provided comparable results in terms of Pu burning (ca. 30% reduction) and MA production rates as indicated in Table 5.

Full core calculations were then carried out for a 3-loop Westinghouse PWR by KIT and NNL using the same SA design. The full-core calculations and SA calculations gave similar results, thus confirming that the SA analyses give representative safety coefficients. The calculations did show a necessity to optimize the SA design in order to decrease criticality at the beginning of life, the possible option being introduction of burnable poisons, a common option for modern optimized SA designs.

Table 5 – Pu burning and MA production rates.

	KIT	NNL	NRG	FZJ
	kg/TWh			
Pu	-24.74	-25.69	-26.59	-26.71
Np	0.30	0.27	0.25	0.30
Am	2.05	1.89	2.99	1.74
Cm	0.80	0.68	0.60	1.29

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3 Stakeholders

3.1 Stakeholder identification

In order to assess the feasibility of introducing plutonium burning fuels into the nuclear fuel cycle, the positions of the major stakeholders should be clarified. The following potential stakeholders can be distinguished:

- Governments
- Fuel vendors
- Reactor utilities
- Waste disposal organisations

Since in this report the choice has been made to focus on the fuel, it is mostly fuel development at the fuel vendor side that opens the essential prerequisites for innovative plutonium burning fuels to be successful. Therefore, in this chapter, focus is mainly on the fuel development and the role that fuel vendors are playing there. But first the various stakeholders are treated in more detail.

3.1.1 Governments

In various countries within Europe, various fuel cycle strategies are in place. Roughly these can be divided into two: i) the open fuel cycle without reprocessing and ii) the partially closed fuel cycle with a single reprocessing step of spent UO_2 and the use of MOX fuel.

As described in section 1.3, most European countries currently follow an open fuel cycle. The fuel cycle strategy is generally closely linked to a country's energy policy. For example, some countries, such as Germany, Belgium and Switzerland, have changed their fuel cycle strategy over the recent years. These countries traditionally used to reprocess their spent nuclear fuel, but have chosen in recent years to change their policy towards an open fuel cycle and abandon reprocessing. For Germany and Belgium this was connected to an intended phase-out of nuclear energy. A policy change from a closed to open fuel cycle, has immediate consequences for plutonium stocks. As described in section 1.3, one can directly see a transition from separated plutonium stocks towards plutonium contained in spent fuel.

3.1.2 Reactor utilities

Most utilities in Europe are now operating in a liberalised electricity market. This has a number of consequences; firstly it means that they have become more loosely connected to their government and to national energy policies. Secondly electricity utilities have become increasingly more market-driven. With respect to nuclear energy this means that the incentive to change energy policy has to come from the government, as utilities are generally focused on generating electricity 'business as usual' at low costs. Finally, some larger utilities have merged to become large European players in the electricity market, and the traditional role of governments in unifying energy policy (including nuclear energy & fuel cycle strategy) and electricity production has decreased.

Given the market-driven approach by most utilities, incentives towards advanced plutonium management strategies need to come from government. Utilities will then follow policy set out by the government. In case the use of an advanced plutonium management strategy by a utility might increase the public/politic acceptance of the NPP, this might be a strong incentive for the NPP. This is especially the case when the utility is of the opinion that the operational life time of the NPP (as allowed by politics) might be increased by using this strategy.

3.1.3 Fuel vendors

Fuel vendors are in principle most directly involved when it comes to the development of innovative fuel types. It should be noted, though, that fuel vendors generally take a similar market-approach concerning fuel development as utilities. That means, business as usual with currently licensed fuel types (UO_2 and MOX). The (short-term) R&D on fuel and cladding systems is aimed at optimising the energy output (burn-up and power per element) and reducing the fuel costs in nuclear systems. Nevertheless, some fuel vendors and developers are looking also at a more long-term strategy. This can be, for example, related to their market position in the whole fuel cycle, including mining, reprocessing and building nuclear power plants. Since all these items in the fuel cycle require a long-term vision, the (innovative) fuel development is being undertaken in parallel and in consistency with the other fuel cycle activities. As will be shown in chapter 4, the most important incentive to develop innovative fuels is connected to the efficient use of resources or to avoid scarcity of resources needed for nuclear fuels.

3.1.4 Waste disposal organisations

Waste disposal is the final step in the fuel cycle. Although waste disposal organisations form an important stakeholder, they do not typically have a strong view on plutonium management. In most research on final repositories, the assumption is made, that all containers preventing nuclear waste from being released into the underground environment have failed after a certain storage period. When taking that point of view, the exact composition of the nuclear waste and the fuel strategy followed is less important. To first order, the amount of radio-toxicity eventually ending up in the biosphere is proportional to the amount of fission products, and thus with the amount of nuclear energy produced. This is irrespective of the exact fuel cycle strategy and the amount of plutonium recycling or the burning of minor actinides. Note, that actinides in the geological underground are quite immobile, as compared to some of the (mobile) fission products, such as caesium, iodine and technetium. As a consequence, the burning of plutonium does not contribute strongly to short- to mid-term safety in repositories. It could, however, alleviate the long-term heat load of the total repository, and therefore lead to a size reduction of a final repository.

3.2 Which stakeholders to approach

In section 3.1 a number of stakeholders have been identified. Given the long time still needed to develop innovative fuels such as thorium-based plutonium fuel and inert matrix fuels, it is not straightforward to identify the crucial stake-holders. In the first place, governments are key to develop a long term vision on energy policy. However, if we look at a long term energy policy of the European countries involved in the LWR-Deputy programme (cf. section 1.3), this long term vision is either related to a phase-out of nuclear energy without reprocessing (currently Belgium, Germany, Switzerland), a continuation of the use of nuclear energy without reprocessing (Slovakia), or a strategy that makes no explicit choice with respect to nuclear energy or the nuclear fuel cycle, but leaves it to the (liberalised) energy market to make these choices (Netherlands, United Kingdom). In general one could therefore argue that the introduction of innovative fuels and the uncertainties associated with the actual fuel to be used are still too far away to consider the standpoint of governments. The fuel vendors, who do need a long-term vision with respect to fuel development, are therefore considered to be most inclined to consider advanced plutonium management strategies. Nevertheless, one should stress, that even fuel vendors look at innovative Pu-based fuels with a scoping view mostly, i.e. without any hard prospects of any of them being developed in the near future.

It is therefore concluded that the most active stakeholders are the fuel vendors, who invest in the long-term R&D of innovative fuels and who have the capability of introducing new fuels and new fuel cycles. In the following chapter we therefore describe how thorium-based and IMF-based fuels for plutonium burning are viewed by some fuel vendors, and what strategy these actors consider for innovative fuel development.

4 Results

European fuel vendors and developers do not appear to be developing a strong plutonium management strategy with respect to recycling and burning of plutonium. Without a clear framework for plutonium management set out by governments and related incentives, there are simply no clear economic benefits from doing so. Instead, the vendors are more concerned with issues of long-term uranium supply. The concomitance of the renewal of the existing reactors and projected growth of the nuclear park between 2030 and 2050 may lead to an important increase of demand for natural uranium (U_{nat}). A growing need for nuclear energy might lead to temporary imbalances in the natural uranium (U_{nat}) market, due to temporary disparities between supply and demand. Besides, today the utilities invest in new power plants whose life expectancy will be at least 60 years. The assurance to be supplied with fuel during at least these 60 years, could become a major issue. In the case of a shortage, even temporary, U_{nat} supply contracts will be signed over longer periods, and therefore the volatilities on the uranium ore price will increase for the other NPPs. In addition, the time required to implement the exploitation of new uranium deposits will intensify price tension and volatility of the ore price. Within this scenario, it is beneficial to be able to supply uranium-free fuel.

On the other hand, currently the vast resources of thorium are not exploited. There is no application for thorium, but thorium could serve well to alleviate future shortages in uranium supply, introducing a new fissile component, i.e. U-233, into the nuclear fuel cycle. A large projected growth in demand for uranium has proven in the past to be a major driver for thorium-based fuels. By the mid-1970s, the price of Uranium reached $40.00 / pound U_3O_8. This resulted in a perceived shortfall of cheap uranium based in part on one large nuclear power plant vendor being unable to meet uranium supply commitments to its customers.

In current days, the availability of large plutonium stock-piles provides an extra option to start up a thorium cycle. In this case, plutonium is used as start-up driver fuel, enabling a sufficient build-up of U-233 from reprocessing the $(Pu,Th)O_2$ fuel, while at the same time burning excess plutonium. Compared to thorium, the prospects of IMF for plutonium burning seem lower, mainly because:

- There is more experience with thorium as nuclear fuel, although this experience is primarily on uranium-based thorium fuels
- The main driver for innovative fuel development is resource preservation or efficiency and not waste or radiotoxicity reduction.

In the next paragraphs the options for plutonium management with thorium fuels are laid out in more detail.

4.1 Thor Energy - the Norwegian thorium initiative

Thor Energy has been set up to look at the prospects of using the vast thorium reserves available in Norway, with the aim to use these in nuclear fuel. Thor Energy is a daughter company of the Scatec group, looking at renewable energy solutions. In the view of ThorEnergy, thorium fuels can provide a valuable way to generate nuclear energy. Basically a similar set of advantages is envisaged as discussed in the introduction of this chapter. Thorium provides:

- A way for sustainable energy with effective use of resources, specifically by bringing into play U-233 as fissile component in thermal reactors. The possibility of a high conversion ratio to generate U-233 is an extra asset.
- A way to use and destroy nuclear waste, notable plutonium and minor actinides, and at the same time generating less problematic waste from thorium fuels.

ThorEnergy focuses on thorium-plutonium fuels for light water reactors. One major goal is to start a trial irradiation on suitable thorium MOX fuels in an international collaboration. Additional goals and activities are associated with the development of suitable fuel performance codes, core management and design methods, as well as solving license issues for thorium fuels. These are developed with a view deploy thorium MOX, but also more advanced thorium fuels, enabling a higher conversion or specific burning (transmutation) of minor actinides.

On the public website of ThorEnergy [17], , the reasoning behind choosing for thorium MOX is explained in more detail:

> The reasoning for thorium-MOX fuel draws on a number of key nuclear fuel cycle imperatives:
>
> - Uranium resources are secure for a long time, but prices are likely to be substantially higher at some point – probably after 2020. An alternative nuclear fuel will be more attractive at this time.
> - The light water reactor is here to stay as the nuclear power generating workhorse for the rest of the century.
> - Fast reactors are meritorious, but have proven slow to license and deploy. It will be at least three decades before there is a sizable fast reactor fleet. Thorium-MOX LWR fuels can be designed to meet actinide management or fissile conversion goals expected of fast reactors, but without the difficulty of licensing a new reactor type.

- The absence of workable waste management strategies and solutions will be a bottleneck in the development of nuclear energy in numerous countries. Thorium-MOX fuel offers a credible plutonium management option that leads to more sustainable nuclear fuel use than current modes of using UOX and uranium-MOX fuel.

Proliferation concerns will remain, and these center on inventories of accumulated plutonium in SNF and with the ubiquity of centrifuge uranium enrichment technology. Thorium-MOX fuels utilize/destroy plutonium in SNF and they do not require enrichment services.

4.2 Thorium fuels to alleviate future (natural) uranium shortages

Whereas ThorEnergy specifically looks at thorium MOX fuels, based on plutonium, there are, from a fuel vendor's point of view, other reasons to look at thorium. One of the future issues may become a shortage of uranium, especially when the renewal of the existing reactors and projected growth of the nuclear reactor park after 2030 leads to an important increase of demand for natural uranium. Although it is expected that from 2040, a large deployment of Generation IV fast reactor systems would reduce the need for natural uranium, the development of Generation IV systems still requires a very significant R&D effort. Development of new innovative fuels requires an equally significant and long-term R&D effort. However, starting now would open the option of an alternative route to secure resource efficiency, which could play as a fall-back scenario, when the introduction of Generation IV fast neutron systems is delayed, or deployed on a reduced scale only. In this case, focus is on thorium fuels with uranium, somewhat contrary to the focus of LWR-Deputy, which addresses plutonium burning.
Nevertheless, it provides an important driver for developing innovative fuels, albeit of a different kind, which does have the interest of fuel vendors. So far, the feasibility of different types of reactors based on Th fuels has been successfully demonstrated and significant experience has been accumulated so far, theoretical as well as practical and engineering-wise. However, much of this needs to be studied in the context of today's and tomorrow's NPPs.
The introduction on the market of thorium-based fuel options for the next generation of LWRs – whose aim is to use U_{nat} at best - would thus ease the increases and/or ore price fluctuations. This could provide an incentive for fuel vendors with a long-term strategy to look at thorium. Although it must be said, that the initiatives are put forward cautiously and, so far, with a limited effort. In any case, for innovative fuels to be successful, it is essential to design from flexible nuclear power plants which can use several types of fuel, based on uranium, plutonium and thorium. This would be one of the key answers to the

various challenges of the nuclear power future. In order for a thorium-uranium based fuel cycle and reactor concept to be as efficient in the reduction of the uranium ore needs as possible, it is necessary that the reactor has a good neutron economy. This might make the CANDU type reactor a good candidate concept..

A possible outcome of the use of thorium-based fuels in the future is depicted in Figure 3. For various fuel cycle scenario's, the potential savings of natural uranium have been calculated, taken from [18]. For a base case with an open fuel cycle, 151 tons of natural uranium is needed per GWd. With a single recycling of MOX, current practice in France, this can be reduced by 20% to 121 tons per GWd. An LWR seed blanket concept with thorium-uranium fuels and with plutonium recycling could increase the uranium savings with a further 16%. This is but one example, with one scenario considered, of how innovative fuels based on thorium could be of interest to fuel vendors.

More generally speaking, recent market developments and investigations, by R&D-labs and industry, of evolutionary Th-fuel concepts in LWRs have indicated that there is scope for a viable use of Th in LWRs with a multitude of objectives in mind, such as U_{nat} reduction of demand, improved fissile material balance, reduced amount of minor actinides in the ultimate waste. These results merit further investigations, but, again, it should be pointed out that a significant long-term R&D effort is needed before any new fuel type can make a significant introduction in the nuclear fuel cycle.

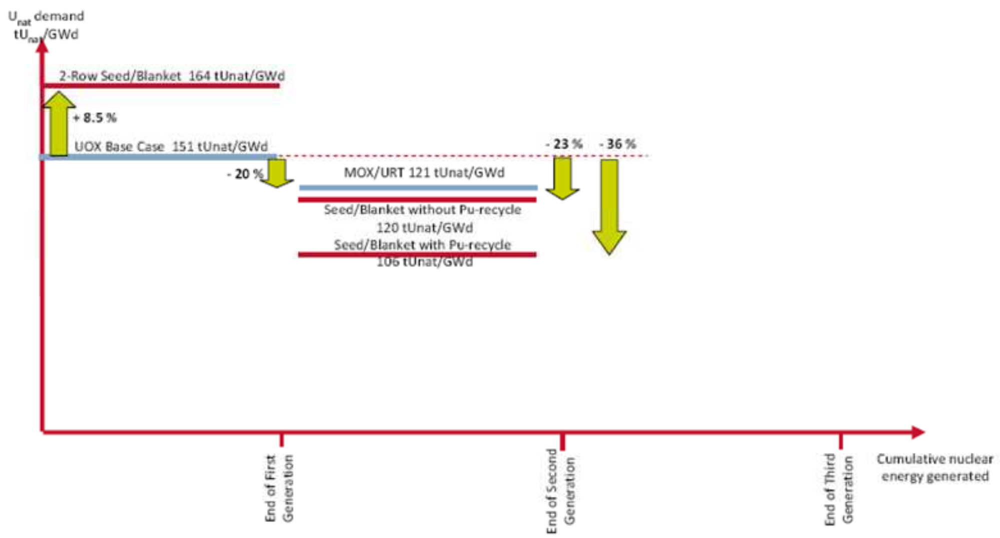

Figure 3. Prospects of thorium use and savings of natural uranium in an Seed-Blanket concept with uranium and uranium/thorium fuels. Depending on the recycling scheme adopted, savings of U_{nat} can be up to 36%

5 Conclusions

In this report, an overview is given of the introduction of plutonium burning fuels into the fuel cycle. Generally three different types of plutonium management strategies can be considered:

- stop reprocessing of UO_2 fuel and accept the risks involved with underground storage of plutonium
- a strategy towards a fast reactor era, where plutonium is used to fuel future fast reactor parks;
- a continuation of the light water reactor era, where enhanced plutonium use is needed to stabilize or decrease plutonium stockpiles;
- a phase out of nuclear energy, where there is no option to burn plutonium in nuclear reactors, such that plutonium needs to be immobilized.

It is, specifically, the third scenario that calls for a plutonium management strategy towards achieving a reduction of existing stockpiles with innovative plutonium fuels. Such fuels should burn plutonium at increased rates.

After providing an overview of current plutonium stock-piles, in the world and specifically in Europe in chapter 1, the various fuel cycle strategy in Europe are discussed briefly.

In Chapter 2, the potential for enhanced Pu burning in the current LWR fleet is considered. U-free fuels are needed to increase Pu burning rate. 2 fuel options were considered: so-called ‘inert matrix fuels’, where the host matrix is mostly transparent to neutrons, and thorium-based fuels, where the host (Th-232) is a fertile material producing the fissile U-233. It was found that while the maximum burning rate is achieved by IMFs, the thorium-based fuels have a smaller net production of minor actinides compared to IMFs. In addition, due to the strong similarities between $(Th,Pu)O_2$ and the currently used $(U,Pu)O_2$ fuels, with respect to fabrication, thermophysical properties and in-core behavior, the implementation and licensing of this uranium free fuel should be considered relatively straightforward. However, the use of $(Th,U)O_2$ containing recycled U-233 from the Th-U cycle is much less likely, considering the strong gamma radiation from U-232 impurities as well as the high U-238 content needed to comply with proliferation restrictions.

In chapter 3, a number of stakeholders have been identified, such as governments, fuel vendors & developers, reactor utilities and waste disposal organisations. Given the long time still needed to develop innovative fuels such as thorium-based plutonium fuel and inert matrix fuels, it is not straightforward to identify the most important stake-holders. In the first place, governments are key to develop a long term vision on energy policy. However, nuclear energy (policy) is highly political, which makes it difficult to address governments 'as one entity' in this technical assessment of introducing plutonium in the fuel cycle. It has been the choice, therefore, that the most active and crucial stakeholders are the fuel vendors and developers, who invest in the long-term R&D of innovative fuels and who have the capability of introducing new fuels and new fuel cycles. In the study we therefore describe how thorium-based and IMF-based fuels for plutonium burning are viewed by some fuel vendors & developers.

As discussed in chapter 4, various fuel vendors & developers do not appear to have a prominent plutonium management strategy. Without a clear framework for plutonium management set by governments and related incentives, there are simply no clear economic benefits from doing so. However, vendors are concerned with issues of long-term fuel supply of natural uranium. The concomitance of the renewal of the existing reactors and projected growth of the nuclear park between 2030 and 2050 may lead to an important increase of demand for natural uranium. Within this scenario, it is beneficial to be able to supply fuel that do not need natural uranium.

An option that is specifically advocated by the Norwegian company ThorEnergy, is to use plutonium as a start-up material for bringing thorium into the nuclear fuel cycle. In this strategy plutonium is burnt while U-233 is created as a new fissile component to generate energy for the future. This strategy brings into play thorium as a valuable mining product, since it is then used as a component in innovative nuclear fuels.

In view of these developments, there is a clear focus on thorium, based on the fact that the abundance of thorium is around 3-4 times that of uranium. Apart from the abundance of thorium in nature, there currently are a number of additional reasons for a raised interest in thorium:

- the absence of uranium resources but large amounts of identified thorium resources in some countries having an ambitious civil nuclear program, such as India;
- the ability of thorium to bring into play a new fissile isotope, namely U-233;
- good in-core neutronic and physical behaviour of thorium fuel under irradiation;

Another, not insignificant factor is the past interest in thorium-based fuel, which has produced significant irradiation experience with generally positive results. This has positioned the state of development ahead of that of IMFs.

In conclusion, one sees that the current long-term developments into innovative fuels are focused on resource preservation, by either reducing future demands on natural uranium, or by bringing into the nuclear fuel cycle the vast amounts of thorium in the earth as a resource for nuclear energy generation.

Recent market developments and investigations, by R&D-laboratories and industry, of evolutionary thorium-fuel concepts in LWRs have indicated that the possibility exists for a viable use of thorium in LWRs with a range of objectives in mind, e.g. reduction of natural uranium consumption, improved fissile material balance, reduced minor actinide vector in final waste and increased plutonium consumption. There is a clear lead that the experience on innovative thorium fuels has over IMF. In addition there is a more versatile range of compatible strategies for using thorium, namely to:

- reduce existing plutonium-stocks
- reduce future natural uranium needs
- make thorium a valuable mining product
- produce U-233 as new fissile isotope for nuclear power generation

Nevertheless, it should be stressed, that the development of innovative nuclear fuels requires a significant R&D effort that takes decades. Before any innovative fuel can make its introduction into the nuclear fuel cycle, a clear long-term fuel cycle strategy should be maintained. Both for thorium-based fuels and for IMF, the development efforts and initiatives in Europe are still rather small. As a consequence, the conclusions from this study should be treated with prudence, as the actual introduction of innovative, plutonium-burning fuels is still a long path with many uncertainties.

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