REQUIREMENTS FOR NUCLEAR ENERGY IN THE 21st CENTURY

NUCLEAR ENERGY AS A SUSTAINABLE ENERGY SOURCE

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ABSTRACT

Nuclear energy must compete against other energy technologies in the 21st century. It must be economical and it must be proven that it fulfills the conditions for sustainability. This means that the requirements of

- no short term depletion of resources
- extremely low emission of noxious or radioactive substances to the environment
- extremely low release of radioactivity from a nuclear plant in case of the most severe accidents

and

- the present very long term problem of high active waste must be transformed into a few hundred years problem through destruction of plutonium, transmutation of the minor actinides and the most important very long lived fission products.

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1. INTRODUCTION

In 1999 there were 433 operating nuclear power plants providing about 350 GWe and producing about 16% of the electrical power worldwide. In the USA and Canada 118 reactors, in Western Europe 150, in Eastern Europe and the former Soviet-Union 68 and in the Far East 90 reactors were operated. Germany had 19 reactors with 22 GWe (7% of the world wide nuclear power capacity) in operation. In addition 36 nuclear power plants were under construction, 34 of them in Eastern Europe and Asia. As a capital intensive and advanced technology about 83% of the nuclear capacity was concentrated in highly industrialized countries. Some countries, e.g. France have a 75% share of nuclear power for their total electricity production. Most of the operating nuclear reactors are Light Water Reactors (LWRs), published by Nuclear Technology Review (2000).

Up to 1999, about 220 000 tons (Germany 8000 tons) of spent nuclear fuel have been discharged from civil nuclear reactors. Each year this value rises by about 9500 tons. About 1400 tons of plutonium have been generated worldwide (Germany 83 tons of plutonium) in the spent fuel until 1999. Part of this plutonium has been extracted by chemical reprocessing of spent fuel. But the major part of the plutonium is still contained in spent fuel intermediate storage. The spent fuel storage capacity world wide is roughly 100.000 tons. Additional storage capacity is under construction, published by Nuclear Technology Review (2000).

Plutonium recycling in LWRs is being practised in Germany, Belgium, France, Switzerland and in Japan. The Mixed Oxide (MOX) fuel production capacity worldwide was about 220 tons per year in 1999, published by Nuclear Technology Review (2000). For 2010 an increase of this capacity up to 550 tons of MOX fuel is envisaged. In Germany, Belgium, France, Switzerland and Japan a number of LWRs have been granted already the licence to operate with MOX fuel elements, published by Nuclear Technology Review (2000).

Radioactive waste disposal is one of today's dominant public acceptance issues. Nevertheless more than 100 disposal facilities for low level radioactive waste (LLW) have been built worldwide. Several countries are currently engaged in studies for deep disposal of highly radioactive waste (HAW) (Belgium, Canada, Finland, France, Germany, India, Japan, Sweden, Switzerland). However, the opening of civil HAW repositories is still more than one or two decades away, published by Nuclear Technology Review (2000).

2. FUTURE CONDITIONS (DESIGN AND OPERATING REQUIREMENTS) FOR NUCLEAR ENERGY TECHNOLOGY

Nuclear energy has to compete with a number of other energy systems already now. Most of these energy systems will still be present for the next few decades (gas, oil) or even for the next centuries (coal and the renewable energies: photovoltaics, wind power, biomass). Some of the renewable energy systems (photovoltaics, wind power, biomass) are striving to enter into the energy market now.

It is therefore necessary to compare nuclear energy with all these competing energy systems along the criteria of

- economical competitiveness

Sustainability of energy systems according to the Brundtland Commission can be cast into the requirements, published by Voss (1999):

- no short time depletion of resources
- extremely low emission of noxious or radioactive substances which could jeopardize the world climate, the environment (atmosphere, water, biosphere) or the health of the human population
- extremely low risk of the energy system for the population.

From the last two requirements one can ideally derive the requirements for nuclear energy also defined by Y. Fujii-e, published by Fujii-e (1994):
- almost zero release of radioactivity from the nuclear power plant and from the plants of the fuel cycle during normal operation
- extremely low release of radioactivity from the nuclear power plant during e.g. a core melt down accident. No emergency measures shall be necessary outside of the plant in such cases. (This requirement was cast into an amendment of the German Nuclear Law in 1994).
- The present issue of a very long term high active waste disposal problem should be transformed into a few hundred years problem through destruction of the plutonium, transmutation of the minor actinides and of the most important very long lived fission products.

In the following sections it will be analysed to which extent and how these above conditions can be satisfied by nuclear energy.

3. ECONOMICAL COMPETITIVENESS OF NUCLEAR ENERGY

Light Water Reactors (LWRs) do compete well on the energy market already now, despite of their relatively high investment costs. The capital requirements of a nuclear plant are typically 60% of the electricity generation cost, whereas the fuel cost are only about 15%. This is opposite to fossil plants which have much lower capital costs but much higher fuel cost contributions, e.g. 45% for coal and 70% for natural gas. Gas combined cycle plants and coal plants are the main competitors of nuclear plants now. But especially gas combined cycle plants which can be constructed presently in about 1/3 of the construction time of nuclear plants are vulnerable to rising gas prizes which are usually coupled to the oil prize. Fig. 1 shows present energy production costs in €/kWh for fossil energy technologies (coal, oil, natural gas), hydropower, nuclear fission and fusion reactors and other renewable energy technologies, e.g. solar (photovoltaics), wind and biomass. The data are based on the most recent studies of the European Community, published by Kröger (1999) and Voss (1999) and complemented by expected future fission and fusion breeder data. For wind and solar power also the present subsidized values for feeding electricity into the electrical grid in Germany are indicated. Future fission breeders or plutonium and actinide burner reactors will have higher (20-30%) electricity production costs than present LWRs. Also future fusion reactors might have higher electricity production costs than fission reactors, published by Kessler (2000), if their technical feasibility can be realized.

In addition to electricity production costs Fig. 1 contains also cost contributions based on an assessment for additional costs accounting for health and ecological damage by noxious gases, toxic pollutants and particular greenhouse gas emissions (GHG), published by Nuclear Technology Review (2000), Kröger (1999), Kessler (2000). Determining the cost impact of these external costs, is not simple and – of course – not yet accounted for in the energy market at present. However, a comprehensive Extern-E project of the European Commission (EC), published by Kröger (1999), Voss (1999) developed full chain methodologies to place a monetary value on health and climate impact so that the varying effects on the electricity generation costs can be seen. Coal and oil have the highest external costs. Fission reactors have only small external costs although their impact of emissions of radioactivity was fully accounted for. Wind power is presently subsidized by about 9 €/kWh and photovoltaics is subsidized by about 49 €/kWh (marked by * in Fig. 1) in Germany and in some other countries.

Fig. 1 shows clearly that nuclear fission power, natural gas and hydropower (large plants) are the most economic energy technologies followed by oil and coal. The often expressed hope that the renewable energy systems (photovoltaics, wind and biomass) will soon enter the energy market with a considerable share and competitive energy prizes will be very hard to become reality.
4. Nuclear Energy as a Sustainable Energy System

It will now be analyzed how nuclear energy can satisfy the criteria of sustainability as they were defined in Section 2.

4.1 Depletion of primary energy resources (published by Nakicenovic (1998), and Häfele (1991))

In Table 1 the energy resources of nuclear energy are compared with those for fossil energy and renewable energies. It is a well accepted fact now, that the world fossil energy reserves and resources have been underestimated in the 1970's (after the first oil crisis 1974). It can be hardly predicted now when fossil energy resources will be really depleted. Table 1 shows a presently widely accepted view over the timely availability of the different energy reserves. Coal and lignite will be available for at least several 100 years. Oil reserves might become depleted after the end of the first half of this century. But then oil shales and tar sands might come into the picture, but at higher prices. Hydropower can hardly be more extended in the future. Nuclear fission energy is presently based on the availability of the naturally occurring U-235 in natural uranium (0.7% enrichment of U-235 in natural uranium). But in a few decades Fast neutron breeders or spallation breeders, which utilize the 100 times more abundant U-238 and the Th-232, could take over. The technical feasibility of fast neutron breeders was already demonstrated in the USA, Russia, Europe and Japan, published by Häfele (1977).

Fusion breeders on the basis of the D-T cycle will also be timely limited by their breeding material lithium. But there will be enough lithium available for many 1000 years, published by Häfele (1977). However, the technical feasibility of fusion breeders must still be demonstrated, published by Kessler (2000).
4.2 Emission of noxious gases

CO₂ emissions are the main problem of present fossil technologies as this is considered to lead to global warming (Fig. 2). New energy technologies like wind power, fission and fusion reactors produce only very little CO₂ per energy unit generated. However, they are not totally CO₂ emission free, since in the course of their plant construction, carbon based energy technologies (e.g. production of steel, copper etc.) must be used which emit CO₂, published by Kröger (1999) and White (1998). The highest CO₂ emissions are attached to the carbon based energy technologies. Photovoltaics have a surprisingly high CO₂ emission, since the production of solar cells (steel and copper etc.) preceding construction of a photovoltaic plant produces CO₂, and also SO₂, NOₓ, published by Kröger (1999).

Similarly the emission of SO₂ and NOₓ is high for fossil energy systems, published by Kröger (1999). Coal as an energy system emits 750 kg/GWhe SO₂ and 730 kg/GWhe NOₓ. Gas emits only about 30% SO₂ and 67% NOₓ whereas photovoltaic generates also about 30% SO₂ and 36% NOₓ of that of coal. Wind power, hydropower and fission or fusion emit only about 10% and 5% respectively of these emission values for coal, published by Voss (1999).

![Fig. 2: CO₂ emission of different energy systems published by Kröger (1999), Voss (1999) and White (1998)](image1)

![Fig. 3: Yearly radiation exposure from fission reactors and coal plants compared to yearly natural background radiation and medical exposure](image2)

4.3 Emission of radioactivity during normal operation

Nuclear fission reactors emit small amounts of radioactivity during their normal operation. The maximum allowable emission is set to 300 μSv to the air and water environment by regulatory bodies in Germany. Experience and governmental control show that present LWRs emit only 1-2% of this allowable limit (Fig. 3). This corresponds to less than the deviations of the naturally occurring radiation at different location on Earth.

Coal fired plants emit as much radioactivity as nuclear fission reactors, published by Halbritter (1982), since coal contains the daughter products of uranium and thorium in ppm contents and a 1 GWe coal plant has a throughput of about 2.6 million tons of coal per year.

4.4 Risk of nuclear fission reactors

Fig. 4 shows risk data for coal, oil and gas collected by insurance companies. These data include the frequency of occurrence and the respective damage in form of fatalities as a consequence of severe accidents, published by Frischknecht (1998). Besides from data for coal, oil, and gas it includes also the results of risk studies for LWRs. It shows that coal and oil are responsible for severe accidents with up to
more than 1000 fatalities. The most severe accidents were: 3000 fatalities in a coal mine (Fushan, China 1931), 3000 fatalities during oil transport (crash of oil tanker with ferry boat, Philippines, 1989), 600 fatalities with liquid gas accident (Ufa, Russia, 1989) and 2500 fatalities after crash of a dam of a hydroplant (Machu II, India, 1979).

Also for nuclear fission reactors (LWRs) consequences of up to more than several 1000 early fatalities have been estimated, published by Bayer (1981). However, this would happen only with frequencies of occurrence which are by 3 orders of magnitude lower than for coal, oil and gas. Data on other renewable energies (wind, photovoltaics) are not available yet, published by Breitung (2001).

From Fig. 4 one might take the position that core melt down accidents in nuclear fission reactors can have similar severe accidental damages (fatalities) to the population as other energy systems (coal, hydro), but at much lower probabilities of occurrence. One must, however, admit that there is one essential difference between nuclear energy and other energy systems. In case of a core melt accident with very low frequency of occurrence – as it happened at Chernobyl – large areas of land can be contaminated by radioactivity, published by Egorov (2000).

Future fusion reactors will release several 100 gr of tritium to the environment as a consequence of a severe accident. This would lead only to a radiation exposure of 10-100 mSv which is well below the 250 mSv limit set by US-Federal Regulations in 10 CFR 100, published by Voss (1999). This would not lead to early fatalities.

In a Chernobyl type accident these contaminated areas must be evacuated for several hundred years. Table 2 shows that the Chernobyl accident caused a few 1000 km² of contaminated land, published by Egorov (2000). Similar results could be also obtained from risk studies (see Fig. 5), published by Ehrhardt. The financial damage would be by orders of magnitude higher than e.g. for oil spills in case of tanker havaries, pipeline breaks etc.

![Table 2: Cs¹³⁷ contaminated areas after Chernobyl accident [in 1000 km²]
published by Egorov (2000)](image)

<table>
<thead>
<tr>
<th>Contamination level</th>
<th>Resettlement possible</th>
<th>Evacuation necessary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5-15</td>
<td>15-40</td>
</tr>
<tr>
<td>European</td>
<td>5.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Russia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ukraine</td>
<td>3.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Belarussia</td>
<td>10.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Total:</td>
<td>19.1 km²</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Fig.4: Frequency of occurrence of severe accident and number of early fatalities for different energy systems, published by Frischknecht (1998) and Bayer (1981) complemented by data for future nuclear fission and fusion reactors.
In addition one should consider that nuclear fission reactors, e.g. in Europe, are built and operated in highly populated areas.

Therefore, nuclear fission reactor systems to be built and operated in the 21. century should be designed such that large scale contaminations causing evacuation cannot occur any more (amendment of German Nuclear law 1994). The argument that such severe accidents and following land contaminations can only occur at extremely low probabilities might not be sufficient for nuclear fission energy to be classified as a sustainable energy source.

5. FUTURE REQUIREMENTS FOR THE SAFETY DESIGN OF NUCLEAR FISSION REACTORS

Future nuclear fission reactors must be designed such that in case of a core melt accident, there will be no large scale radioactivity release to the outside environment. This means that the outer containment must remain intact and leaktight in case of a severe melt down accident. Many probabilistic safety and risk analyses have shown that there are essentially a few accident sequences which are responsible for containment failure after a core melt accident. If one can prove that these accident sequences cannot destroy the leak tightness of the outer containment one will have fulfilled the above requirement. The Research Center Karlsruhe (FZK) and the French Commissariat à l'Energie Atomique (CEA) are performing research along these lines since about 1990. The essential accident sequences, e.g. in a Pressurized Water Reactor (PWR), leading to outer containment failure and the corresponding actual research results are:

- the steam explosion after contact of molten core masses with remaining water in the lower part of the pressure vessel: FZK proved by theoretical analysis and experiments that as a consequence of a large scale steam explosion the upper part of the pressure vessel (cover and bolts) will not fail and therefore not jeopardize the outer containment leaktightness, published by Struwe (1999).

- the hydrogen deflagration to detonation (DDT): In the course of a core melt accident the cooling of the 1000 °C hot zircaloy claddings of the fuel elements by steam will generate about 1500 kg of hydrogen after a Zr-H₂O chemical reaction. The large masses of hydrogen can ignite within the containment and generate high pressure spikes during a DDT event. FZK proved that even in the case of large scale hydrogen DDTs and of detonations the leak tightness of the outer containment – if properly designed – will not be jeopardized, published by Breitung (2001). In addition hydrogen catalytic recombinators can decrease the amount of hydrogen after the core melt accident.

In case of loss of offsite power (LOOP) followed by a failure of the steam generators, core melt at high pressure can be initiated. GRS, published by Löffler (2001), proved that in the sequence of this accident chain, the primary piping will fail and the primary cooling system will depressurize prior to a melt through of the core at high pressure. In that case only a core melt through the lower part of the pressure vessel will occur at low pressure (several bars). The leak tightness of the containment will in such a case not be endangered.

- So called by-pass accidents can be avoided by proper design of the cooling circuits and the containment compartments.

- Core melt through the bottom of the containment can be avoided by a core catcher and proper cooling of the molten core masses as proven by FZK, published by Alsmeyer (2000).

The German-French design of the European Pressurized Water Reactor (EPR), published by Fabian (1999) is required by the respective Safety Commissions to be designed along the above outlined rules, published by Technical Guidelines (2000). The present probabilistic safety concept applied for fission reactors is only allowed for the optimization of the safety systems, not for the outside consequences of severe core melt accidents. The German future Boiling Water Reactor Design SWR-1000 shall follow the same rules as required for EPR, published by Brettschuh (1998). Some small reactor designs, e.g. the German pebble bed modular (PBMR) gas cooled reactor can – in principle – also fulfill the same requirements, published by Lohnert (1990). This safety concept relies on a strong negative temperature coefficient such that, in case of loss of offsite power and cooling, the maximum temperature of the fuel (ceramic coated fuel particles) will not exceed 1600 °C and the fuel particles will not release the accumulated fission products. The afterheat
can then be released through radiation to outside steam generator modules. Also future liquid metal cooled fast breeder reactors, e.g. IFR (ANL), published by Chang (1989) or the advanced HLMC reactor, published by Spencer (2000) can be designed to fulfill the above requirements. Similar aims are followed by the Generation IV initiative of the department of energy (DOE), USA, published by Generation IV Workshop and in Russia, published by Nuclear Power in the 21st Century (2000).

According to the amendment of the German Nuclear Law of 1994, published Artikelgesetz (1994) any future reactors must be built such that emergency actions (evacuation of the population etc.) outside of the nuclear plant shall not become necessary in case of core melt accidents.

![Evacuation areas (km²) as a function of different internal severe accident chains (radioactivity releases) and frequencies of occurrences for present and future fission reactors](image)

Consequently, for future fission reactors – according to the new R&D-results, e.g. for PWRs – the above discussed essential severe accident consequences (large releases of radioactivity caused by internal events) will not exist anymore. Then, land contamination and the necessity for evacuation of the population outside of the nuclear plant will not occur anymore (Fig. 5). Higher contamination will be restricted to the plant site itself. Also the number of early and late fatalities as displayed in Fig. 4 will shrink to a minimum value (indicated only qualitatively) on the left side of Fig. 4 (similar to fusion reactors, which would release essentially tritium), as the radiation exposure outside of the reactor plant remains at a low level (determined by the requirement of no evacuation) which does not cause early fatalities.

Such future reactor designs will fulfill all conditions for sustainability as they were defined in section 2. This holds not only for normal operation, but also in case of severe core melt accidents.

For the facilities of the closed fuel cycle (UO₂ and MOX fuel fabrication plant, reprocessing and HAW vitrification plant) the design conditions to be satisfied are less severe since the radioactivity inventory is lower and the fuel is neither at a high temperature nor is the cooling system under high pressure, published by Kessler (1983) and Koelzer (1989).
6. WASTE STREAMS FROM ENERGY PRODUCTION

Present energy systems produce different amounts of waste which are partly toxic or as in the case of nuclear energy technologies also radioactive. Table 3 shows the amounts of waste in t/GWe-h or in m³/GWe-h, published by Kröger (1999).

While coal as an energy source produces with 200 t/GWe-h by far the most (partly toxic) waste, oil, gas and wind generate only little of this waste category. Surprisingly photovoltaics produce also toxic waste (As, Cd, Pb). The nonradioactive waste associated to fission reactors is generated during their construction and decommissioning period. Low active waste is building up during the operation of the fission reactors and during operation of fuel cycle facilities. Highly radioactive waste contains the fission products and the higher actinides of the spent fuel of fission reactors, published by Kröger (1999). Fusion reactors will generate only low radioactive waste. Coal ashes contain K⁴⁰, uranium and thorium as well as their daughter isotopes. They must be classified as low radioactive waste, published by Halbritter (1982). Similarly, oil and gas processing pipings can approach levels of radioactivity which are classified as low level radioactive waste, published by OECD-NEA (1999).

Table 3: Waste generated by different energy systems, published by Kröger (1999) (slightly complemented by data for coal, oil, fission and fusion energy)

<table>
<thead>
<tr>
<th></th>
<th>Nonradioactive Waste t/GWe-h</th>
<th>Low radioactive m³/GWe-h</th>
<th>High radioactive m³/GWe-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>200</td>
<td>10-30 (coal ashes)</td>
<td>---</td>
</tr>
<tr>
<td>Oil</td>
<td>7</td>
<td>oil pipings</td>
<td>---</td>
</tr>
<tr>
<td>Gas</td>
<td>5</td>
<td>gas pipings</td>
<td>---</td>
</tr>
<tr>
<td>Fission</td>
<td>6</td>
<td>7×10⁻²</td>
<td>5×10⁻⁴</td>
</tr>
<tr>
<td>Fusion</td>
<td></td>
<td>3.5×10⁻¹</td>
<td>---</td>
</tr>
<tr>
<td>Hydro</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo-voltaics</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6: Worldwide spent fuel discharged and reprocessed, published by Nuclear Technology Review (2000)

6.1 Spent fuel and radioactive waste from fission reactors

Two spent fuel management paths are being pursued at present. On the one side it is the closed fuel cycle with reprocessing of the spent fuel elements (after intermediate storage) and recycling of the plutonium and uranium. The high active waste containing fission products and the minor actinides are vitrified and after further storage of some 40-50 years being deposited (final deep storage) in a waste repository. On the other side it is the Once Through Cycle with direct spent fuel disposal. The spent fuel elements - after 40-50 years storage - are further conditioned and shall also deposited in a repository (deep storage).
The cumulative spent fuel discharged worldwide (Fig. 6) over the past 4 decades amounts to some 220,000 tons by the end of 1999, with 75,000 tons (about 1/3) already reprocessed. As already stated in section 1, that amount of spent fuel contains about 1400 tons of plutonium. Part of this plutonium after reprocessing and MOX-fabrication was already recycled once in LWRs. Some 145,000 tons of spent fuel are still stored at or away from the reactor site, published by Nuclear Technology Review (2000).

Direct spent fuel disposal was promoted by the USA since 1982 mainly for nonproliferation reasons, published by USA Nuclear Waste Policy (1982) and INFCE (1980). Some countries e.g. Sweden, Finland, partly Germany and Switzerland follow this concept. The nuclear industry of these countries hopes that the direct spent fuel disposal concept has economical advantages. However, some of the decision parameters have changed over the past few years and will continue to change in the future:

- the economical advantage (about 15% lower fuel cycle cost) of direct spent UO\textsubscript{2} fuel disposal could fade out, as present contractual costs for reprocessing and MOX fabrication still have a potential for lower costs in the future. In addition one must consider that the fuel cycle costs are only 1/6 of the electricity production costs (section 3).

- the quantities of waste from reprocessing have been reduced enormously by special developments at the French reprocessing plant LaHague. The quantities of waste from direct spent fuel disposal and reprocessing are about equal now, published by OECD (2000).

- recent OECD studies show that the impact of radiation exposure of direct spent fuel disposal and of the closed fuel cycle are almost equal for workers (operational data). For the public the difference is only between 1.6 (for the direct spent fuel disposal) and 2.6 man Sv/GWe·year collected dose at 500 years (for the reprocessing case), published by OECD (2000).

- if the present 1400 tons of plutonium following the direct spent fuel disposal concept will be put in deep geological storage the plutonium will accumulate in the repository (plutonium mine). This holds the more for all future spent fuel elements to be deposited in the repository. Contrary to vitrified HAW glass the conditioned spent fuel elements cannot be released from IAEA safeguards, published by Gmelin (2000). The repository with spent fuel elements is vitrified HAW glass the conditioned spent fuel elements cannot be released from IAEA safeguards, published by Gmelin (2000). The repository with spent fuel elements (one ton UO\textsubscript{2} spent fuel element contains about 10 kg of plutonium, one ton MOX spent fuel element contains about 25 kg of plutonium) will have to be surveyed and inspected for all times, published by IAEA (1997) and Gmelin (2000). The physical protection of the spent fuel elements by radiation of the fission products decays away after about 300 years, published by National Academy of Sciences (1995).

- Plutonium contributes considerably to the long term radiotoxicity of the waste up to about 10\textsuperscript{5} years, published by Review of Modern Physics (1978).

- the closed fuel cycle with recycling of the plutonium in MOX fuel elements has the potential of burning the plutonium (and later also the minor actinides). In a one time recycling strategy – followed at present – one can only burn about 1/3 of the plutonium. However, with multirecycling essentially all plutonium can be burnt (destroyed), published by C.H.M. Broeders (1997).

Fig. 7: Pool of 8 UO\textsubscript{2} LWRs which are subsequently replaced by MOX-LWRs according to plutonium availability

Fig. 8: Plutonium in tons per GWe\textsubscript{el} for different scenarios as a function of time (year)
6.2 **Plutonium destruction by multirecycling**

Both for nonproliferation reasons (no accumulation in waste repository) and because of its high contribution to the radiotoxicity of spent fuel, plutonium should be destroyed with first priority. Recent studies in Germany show that special multirecycling schemes for plutonium in MOX fuel of reactors (LWRs), fast reactors (FRs) or accelerator driven systems (ADS) lead to a complete destruction (except the about 0.1% losses going the HAW) of the generated plutonium, published by Kessler (2001). Conditions are that the plutonium which is discharged from burner reactors in spent MOX fuel elements is always blended (mixed) during reprocessing with the plutonium coming from spent UO₂ fuel elements of UO₂ fuelled reactors (UOX). In addition there must always be enough plutonium available to feed the special burner reactors, e.g. full MOX core LWRs or full MOX core fast reactors (FRs) the core design of which is optimized for plutonium burning (these FRs are named CAPRA in Fig. 8).

A LWR completely filled with MOX fuel can incinerate about 420 kg Pu/GWe*year. The LWR, however, because of its thermal neutron spectrum, also builds up relatively high amounts of americium and curium. Therefore the multirecycling scheme with LWR MOX-burners should only be followed for a certain time period. Fast neutron reactors (FNR CAPRA), because of their fast neutron spectrum, have much better destruction properties. They can burn about 570 kg Pu/GWe*year. Accelerator Driven Subcritical Systems (ADS) can burn about 600-700 kg/GWe*year, but have in addition lower core inventories which makes them more efficient for plutonium burning, published by Kessler (2001), C.H.M. Broeders (1997), Bowman (1999), Wade (2000) and C.H.M. Broeders (2000).

Fig. 7 shows a scheme of UO₂ and MOX LWRs, in which always a new MOX fuelled reactor is started when enough plutonium is available. Fig. 8 shows as a function of time the plutonium per GW,t in tons for such a scenario which starts with a pool of 8 UO₂ LWRs. Depending upon the plutonium availability UO₂ reactors are – after some time – replaced by burner reactors (LWR-MOX-burner, FNRs (CAPRA) or ADS).

In Fig. 8 the upper straight line shows the amount of plutonium generated as a function of time for a direct spent fuel disposal strategy with UO₂-LWRs. The rising amounts of plutonium will accumulate in the repository. The lower curve shows as a function of time the amount of plutonium in tons per GWc for the above described multirecycling case (Fig. 7) with reprocessing and disposal of the HAW to the repository. The difference between both curves is the amount of plutonium burnt or not coming into existence because UO₂-LWRs are replaced slowly by LWR-MOX burner reactors, FNRs (CAPRA) or ADS which do not produce but burn plutonium. In a real case one would start with LWR (MOX)-Burner reactors and then, after several decades, switch over to FNRs (CAPRA) and to ADS reactors.

The time periods to burn the plutonium are in the range of 100 years. In reality one would not burn all the plutonium but rather go to some kind of an intermediate equilibrium level. The burn or destruction capabilities of different burners can certainly be still more optimized in the future by using e.g. uranium free fuel etc. or thorium and seed-blanket strategies, published by Galperin (2000).

6.3 **Transmutation of minor actinides**

The transmutation of the minor actinides – aside from the destruction of plutonium – is the second most important task to lower the long term radioactivity of the high active waste. Recent studies (e.g. the Japanese Omega program, the French Spin program) show that also the minor actinides can be transmuted and incinerated in reactors or ADS. Table 4 shows the transmutation capabilities of different reactor systems, published by OECD (1999), C.H.M. Broeders (1997), Baetslé (2000), OECD (1999), Bowman (1999) and Wade (2000). Only reactors with a fast neutron spectrum (FNRs and ADS) have good transmutation capabilities for minor actinides. Transmutation of Np and Am in LWRs is very problematic as these minor actinides would be transformed mainly into Pu-238 and Cm-244. This would increase the radiotoxicity.
Table 4: Transmutation capabilities of reactor systems in kg/GWe

<table>
<thead>
<tr>
<th></th>
<th>PWR</th>
<th>FR (CAPRA)</th>
<th>ADS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plutonium</td>
<td>420</td>
<td>570</td>
<td>580</td>
</tr>
<tr>
<td>Neptunium</td>
<td>very problematic</td>
<td>140</td>
<td>800</td>
</tr>
<tr>
<td>Americium</td>
<td></td>
<td>80</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 5: Separation efficiencies of different advanced reprocessing schemes for partitioning of minor actinides in laboratory tests

<table>
<thead>
<tr>
<th>Method</th>
<th>Neptunium</th>
<th>Americium/Curium</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIDPA</td>
<td>99.95%</td>
<td>99.99%</td>
</tr>
<tr>
<td>TRPO CYANEX 301</td>
<td>99.95%</td>
<td>99.95%</td>
</tr>
<tr>
<td>DIAMEX/SANEX/SESAME</td>
<td>99.9%</td>
<td>&gt;99%</td>
</tr>
</tbody>
</table>

Two alternative reprocessing schemes are followed in research at present:

- aqueous reprocessing schemes with ceramic fuel refabrication (mainly Europe, Japan), published by Madic (2000)
- pyroprocessing schemes (electrorefining) with metallic fuel (mainly USA), published by Chang (1989), Bowmann (1999), Wade (2000). But Europe and Japan will also investigate pyroreprocessing schemes in the future.

With aqueous reprocessing schemes plutonium and the different minor actinides (Np, Am, Cm) can be separated (partitioned) with high separation efficiency (Table 5). If the refabricated actinide fuel is loaded separately into the reactor core, high incineration rates (Table 4) can be achieved, published by OECD (1999), Baetslé (2000), OECD (1999), Bouquin (1996), Salvatores (1999).

With pyroreprocessing schemes uranium and fission products are separated from the transuranic waste (Pu, Np, Am, Cm). The latter are refabricated in Zirconium based metallic fuel elements, published by Chang (1989), Wade (2000), Mc Pheaters (1994). The incineration rates in ADS are about 750kg (Pu, Np, Am, Cm) per GWe-year, published by Wade (2000), Mc Pheaters (1994).

The feasibility of partitioning has been demonstrated in several laboratory tests but its verification in pilot test facilities and in larger technical facilities still will need another several decades, published by OECD (1999). Separation of neptunium is much easier than the separation of americium/curium. The latter must first be separated from the Lanthans and finally americium and curium must be separated.

Recycling of curium seems only feasible with the pyroprocessing scheme and metallic fuel element fabrication, because of the very high α-, γ-radiation and because of its neutrons radiation, published by Wade (2000), Mc Pheaters (1994). In the aqueous processing scheme followed by nitride fuel fabrication, this does not seem to be feasible. One option would be interim storage of curium for about 150 years and recycling of the remaining Pu-240/Cm-245 mixture.

First experience for the fabrication of special fuel pins containing high contents of Am (20%) and Np using the SOL-GEL process is available. One complete LWR-MOX fuel element containing 5% Np was already fabricated in France, published by OECD (1999).

Fig. 9 shows a possible 22 GWe scenario (Germany) adapted from, published by Salvatores (1999), with LWR-\text{UO}_2-Reactors, LWR-MOX-Burner reactors, FR-MOX-Burner reactors (CAPRA) and ADS-Burner which can incinerate all plutonium, all minor actinides and some long lived fission products. The reprocessing losses of 0.1% Pu and 1% minor actinides will go into the vitrified HAW. The scenario describes an equilibrium state. The inventory remaining at the end of the fission reactor episode (or age) in energy technologies is not taken into account in that consideration.
6.4 Transmutation of long lived fission products

The majority of radioactive fission products will have decayed after about 800 years. From the point of view of reduction of radiotoxicity the transmutation of the longer living fission products is of much less interest (about 3 orders of magnitude smaller) as for the minor actinides. But some of the fission products are very mobile in certain geological environments. One way to tackle the high mobility of some of the fission products could be to immobilize them by appropriate waste conditioning and special engineered barriers around the vitrified waste in the repository. Very long lived fission products which contribute to the very long term radiological effects of the HAW are Tc-99, Cs-133, I-129, Zr-93 etc.

I-129 which is a dominant isotope in both the radiological effects of reprocessing effluents and of spent fuel in certain geological formations can be recovered from the dissolver off-gas during reprocessing of the spent fuel. Tc-99 can also be separated from the TBP-streams during reprocessing. Tc-99 and I-129 are single isotopic species and can be transmuted by neutron capture into nonradioactive Ru-100 and Xe-130. The net transmutation of Tc-99 in fast reactors is about 110 kg/GWe and for I-129 about 18 kg/GWe, published by Bouquin (1996).

Cs can also be separated from HAW but it is not a single isotopic species. It is a mixture of Cs-135 (long lived), Cs-137 (short lived) and Cs-133 (stable). Transmutation is not considered feasible without using additional enrichment techniques, e.g. laser enrichment techniques. Other radiologically important fission products like Se-79, Zr-93, Pd-107, Sn-126 also must be addressed.
Some of the fission products (Se-79) exist either only in very small concentrations in the liquid HAW or they appear also with nonradioactive stable isotopes (Zr-93, Sn-126). Activation products like C-14 and Cl-36 must probably also be considered. They can lead to an accumulation in the biosphere and play an important radiotoxicological role.

6.5 The merit of separation efficiencies and transmutation

Fig. 10 shows a comparison of the radiotoxicity of HAW for different efficiencies of partitioning and transmutation for U, Pu and minor actinides (MA). As for the radiotoxicity the curve for the 99.9\% transmutation of U, Pu, minor actinides falls below the radiotoxicity of natural uranium after about 800 years.

![Fig. 10: Merit of partitioning and transmutation of U, Pu and minor actinides (MA)](image)

Fig. 10 demonstrates clearly the difference between direct spent fuel disposal and recycling and transmutation of U, Pu, and minor actinides. Much R&D work still has to be performed until these goals (99.9\% incineration of U, Pu, MA) of Fig. 10 can be attained.

Fig. 11 shows the radiotoxicity of the long lived fission products. Their contribution to the radiotoxicity attains about the same values as the 99.9\% U, Pu, MA case (Fig. 10) after about 10^5 years.

![Fig. 11: Radiotoxicity of long lived fission products](image)

The need for transmutation of the different long lived fissile products eventually depends on the

- chosen disposal concept in geological formation (salt, rock, clay)
- the encapsulation concept of the HAW (waste conditioning concept and engineered barrier)
- the sitedependent mobility of the fission product and its radiological significance

Which long lived fission product shall be included in a partitioning and transmutation concept can only be decided on the basis of the waste encapsulation and disposal (geological formation) concept, on the long term safety concept and on radiological consequence calculations which must fit to the radiological standards for long term exposure. Research is still going on in this area.
CONCLUSION

It has been shown that nuclear energy in the 21st century can clearly meet the requirements for a sustainable energy source. It also will remain an economical energy source which can compete with all other remaining or uprising renewable energy technologies.

It must however satisfy the design conditions for extremely low emission of radioactivity especially in case of severe accidents so that no emergency measures outside of the plant become necessary. Recent developments for the future of the fuel cycle show that new separation techniques for the actinides and long lived fission products (partitioning) and their transmutation in dedicated reactor facilities can modify the present waste disposal concepts drastically and satisfy the conditions for sustainability.

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