EUROPEAN PARLIAMENT

Directorate-General for Research

WORKING PAPER

Emerging Nuclear Energy Systems, their Possible Safety and Proliferation Risks

Energy and Research Series

ENER 111 EN

This publication is only available in English.

An abridged edition (ENER111A) is available in English and French.

A list of the most recent Energy Series publications can be found at the end of this document.

Publisher: **EUROPEAN PARLIAMENT**
L-2929 Luxembourg

……………………………………………………………

Authors: Dr. Annette Schaper (PRIF)

Ing.(grad.) Gerhard Schmidt (Öko-Institut)

in cooperation with Dr. Roland Bähr (Öko-Institut)

Peace Research Institute Frankfurt (PRIF)
(Hessische Stiftung Friedens – und Konfliktforschung)

……………………………………………………………

Responsible: **Gordon Lake**
Directorate-General for Research
Division for Industry, Research, Energy and Environment - STOA
Schuman Building
European Parliament
L-2929 LUXEMBOURG
Tel. (352) 4300.22979
E-Mail: glake@europarl.eu.int

……………………………………………………………

Manuscript completed in November 1999.

EUROPEAN PARLIAMENT

Directorate-General for Research

WORKING PAPER

Emerging Nuclear Energy Systems,

their Possible Safety and Proliferation Risks

Energy and Research Series

ENER 111 EN

02-2001

Contents

Summary

This study aims at identifying and assessing the safety and proliferation risks that new nuclear energy systems might pose. In the first chapter, the basic physical ideas within relevant nuclear research areas are outlined and their major research goals described. Special emphasis is given to projects within the Specific Programmes "Nuclear Fission" and "Thermonuclear Fusion" of the Euratom Fifth Framework Programme. Within the key action on “Nuclear Fission”, nuclear safeguards is a specific non-proliferation goal and waste management and disposal are detailed safety goals. The key action on “Controlled thermonuclear fusion” is the second area of EU research with major significance for nuclear safety issues. Nuclear energy systems that are taken into account in the study are nuclear reactor research in the EU, addressing reactor safety, fuel concepts, waste concepts, and safeguards research. Nuclear accelerators and accelerator driven reactor systems are included in the section on fission. Fusion concepts investigated in detail are several magnetic fusion schemes, and inertial confinement fusion.

The second chapter describes the criteria for the assessment of safety risks. Risks of new nuclear fission reactors include the accident risk of nuclear reactors, e.g. efforts to further decrease the probability of catastrophic events and the release fraction of the radioactive inventory in case of a nuclear accident, operational risks both to the public and to the nuclear work-force, and waste management risks. Criteria for the assessment of the safety risks of new fuel concepts are defined separately, because of the uniqueness of some of these concepts. Criteria for the assessment of the safety risks of new waste management concepts concern safety requirements for handling, accident risks, and safety requirements in final disposal for operational, fuel and decommissioning wastes. Criteria for the assessment of nuclear fusion concepts distinguish between accident risks, operational risks, and long-term waste management risks. Risks are compared to those of existing fission technologies.

The third chapter deals with the criteria for the assessment of proliferation risks, which can be developed from the study of proliferation mechanisms. New challenges for R&D arise from new arms control opportunities, from the availability of new technologies, and from the difficult situation in Russia and international cooperation projects which are intended to cope with it. Criteria to assess the risks of horizontal proliferation are the complexity of safeguards for a nuclear technology; the number of technical steps between the technology and a direct usable nuclear fission weapon component; possible civilian disguise; the creation of obstacles against technical non-proliferation measures; and the potential undermining or reinforcing of ongoing non-proliferation policies. Criteria for risk assessment of *"vertical proliferation"*, e.g. nuclear weapon possessors seeking the modernisation and innovation of their weapons, are the usefulness of a technology or project for R&D on advanced nuclear weapons, the circumstances of research, and the potential to undermine or to reinforce ongoing arms control and disarmament policies.

The fourth chapter deals with both safety assessment and non-proliferation assessment of critical nuclear fission research. Major conclusions concerning the safety of reactor concepts are that they currently are at a preliminary stage, that the elimination of off-site evacuations in case of severe accidents is not yet possible, that fuel supply safety risks are comparable to conventional reactors for all concepts, and that it is highly questionable whether the Energy Amplifier has realistic prospects. Assessed fuel concepts include conventional uranium use, MOX, thorium, and advanced fuel concepts. It is concluded that higher burn-up of fuel and the use of MOX fuel is problematic for a variety of reasons; thorium fuel schemes have some clear safety advantages but are currently not attractive enough, and other advanced fuel schemes are currently not realistic. Assessed waste management concepts assessed include the once through/direct disposal waste management concept and Partitioning and Transmutation (P&T). The conclusions for direct disposal are that direct disposal has several advantages but some aspects still require further investigation, and several very practical problems, including huge civil plutonium stocks in some of the Member States, require technically sound and timely adequate solutions. P&T is assessed in more detail. It would only make sense if no long-lived isotopes are omitted. Consequently, totally new techniques, intensive R&D and technical experience before moving up to a technical scale would be required which is currently unrealistic. The conclusions on P&T are that this waste management concept is not a general alternative to final disposal in geological formations.

The section on non-proliferation aspects of critical nuclear fission research distinguishes between nuclear reactor research, accelerator driven subcritical reactors, new fuel cycle and waste management concepts, and safeguards research. Several reactor concepts are assessed. The most proliferation risks are posed by HEU using reactors that undermine the non-proliferation policies. FBRs undermine any policy of discouraging reprocessing. Most technical obstacles against proliferation are posed by the HTR. Vertical proliferation risks might be reduced in cases where nuclear reactors play a useful role in the disposition of excess weapons plutonium. The Rubbia Waste Incinerator still will necessitate safeguards because it is still possible to divert uranium enriched in U-233. The non-proliferation assessment of new fuel and waste management concepts concludes that the safeguards efforts for direct disposal without reprocessing are much less sophisticated than with reprocessing, that non-proliferation measures are the most effective for direct disposal and the most difficult for P&T, and that the technical obstacles against fabricating a nuclear warhead are the highest for the direct disposal waste management, and the lowest for fuel cycles containing reprocessing. New challenges are posed for safeguards research because of several political and technical developments, e.g. the safeguards reform and new arms control treaties, or the analysis of environmental traces and the automatic generation and transmission of data, respectively.

The fifth chapter deals with nuclear fusion research. The safety assessment concludes that there are serious shortcomings. The radiological risks are only known with wide uncertainties, and it is also uncertain to what extent the production of the requisite low activation materials is realistic. It is therefore recommended that the further development of fusion reactors be linked to feasibility studies.

The non-proliferation section investigates risks of general fusion research and devotes a special section on inertial confinement fusion (ICF). As long as not many neutrons are produced, the risk of horizontal proliferation arising from fusion R&D is low, in case a reactor were to be available, safeguards will become necessary. ICF poses a high risk of vertical proliferation because it might be useful for nuclear explosion simulations.

The sixth chapter deals with implications for EU policy making. In the safety section, it is stated that the EU policy currently is not considered a relevant driving force towards enhanced nuclear safety. There are at least eight different safety standards in Western Europe for nuclear reactors. None of the analysed reactor safety projects clearly fulfils the requirements, so support or extended research in any one of these options cannot be recommended. The recommendations regarding the safety of nuclear fuel cycles are that a thorough investigation into safety risks should be launched. Investigations of nuclear fusion projects should be launched into the potential emissions of tritium.

In the non-proliferation section, it is stated that nuclear non-proliferation and disarmament has so far not played an important role in EU policy making. It is possible to identify proliferation risks in EU nuclear fission and fusion research and to take them into account in decision making. Several recommendations on fission and fusion research are listed, e.g. safeguards research should be strengthened, the amount of separated plutonium should be reduced, nuclear disarmament projects, e.g. plutonium disposition, should be strengthened, direct disposal is to be preferred to reprocessing, cooperation with Russia should be enhanced, or, ICF research should take place only in international cooperation. It is recommended to include specific proliferation risk assessments into decision making on R&D for nuclear projects.

1 Overview and selection of new energy systems

1.1 Relevant research programmes in the European Union with emphasis to new energy systems and nuclear safety and non-proliferation issues

New nuclear energy systems could be discussed in a very broad manner. A broad definition would have to consider many new systems, regardless of their technical and economic potential. In this study, new energy systems are defined in a limited way. They are only considered here if they have some attention in the EU's research programs, assuming that this attention is in some respect a measure for the technical and economical potential of a new nuclear system. In the basic goals formulated by the work programmes, often safety and non-proliferation aspects are included (the latter often also called "security").

In this chapter the emerging new nuclear systems are identified by extraction of the areas in which currently research is financed by the EU. The relevant research programmes are listed (Chapter 1.1.1) and the emerging new systems of nuclear fission (Chapter 1.1.2) and nuclear fusion (Chapter 1.1.3) are identified.

1.1.1 Relevant research programmes of the European Union

Research goals and objectives concerning new nuclear energy systems are best reflected in the Research Framework Programmes of the European Union. Currently the Fifth Framework Programme (FP5) is relevant <FP5 1999>. It runs from 1998 to 2002. Relevant documents are:

The **Council decision of 22 December 1998** concerning the Fifth Framework Programme of the European Atomic Energy Community (Euratom) for research and training activities (1998 to 2002) (1999/64/Euratom)[1];

The **Work Programme** of the Research and Training Programme in the field of Nuclear Energy (1998 to 2002)[2];

The Council decision and the work programme formulate the basic goals of the community's research towards nuclear energy.

The scientific and technological objectives of the community's nuclear research were defined in the Council Decision to FP5 as follows:

> *„Nuclear energy provides more than 35 % of the electricity generated in the European Community. It makes a significant contribution to the policy of diversifying energy supply and to reducing overall emissions of CO_2.*
>
> *Efforts to develop the safety and security of nuclear energy systems can strengthen, in the short and media terms, the Community's industrial competitiveness, through exploiting the European technological advance. In the longer term, technologies with promising prospects require considerable research efforts at Community and world*

[1] Council Dec. 1998.

[2] EC R&T Programme 1998-2002.

> *level. Minimising radiation exposure from all sources, including medical exposures and natural radiation, will improve the quality of life and health and will help in addressing environmental problems[3] "*

This defines two main goals: **promotion** of the use of nuclear energy and **protection** against radiation exposure from all sources.

The community research is subdivided into two key actions (Nuclear fission and nuclear fusion), research and technological development activities of a generic nature, and enhancing access to an optimising use of research infrastructure.

Additionally the research work of the Joint Research Centre (JRC) in the field of nuclear energy has to be taken into account. Its research programme contains specific nuclear research including research on safeguards related technologies[4].

1.1.2 Nuclear Fission research and safety and non-proliferation issues

The aim of the key action "Nuclear Fission" in the FP5 also reflects this double definition of the goals, but doesn't go far beyond the above cited basic definition into details:

> *„The aim of this key action is to help ensure the safety of Europe's nuclear installations and to improve the competitiveness of Europe's industry; to ensure the protection of workers and the public from radiation; to support the application of international safeguards on nuclear materials; and to help ensure the safe and effective management and final disposal of radioactive waste[5]. "*

Here, the material safeguards are named as a specific non-proliferation goal and the waste management and disposal as detailed safety goals.

Further details in this area of research of the Community are named in detail as being:

- the operational safety of existing installations, namely evolutionary concepts such as safety concepts and High burn-up and MOX fuel,
- safety of the fuel cycle, especially waste and final disposal systems, Partitioning and Transmutation and decommissioning of nuclear installations,
- safety and efficiency of future systems; anticipated deliveries are reactor, fuel and fuel cycle concepts that offer potential longer term benefits in terms of cost, safety, waste management, use of fissile material, environmental impact, less risk of diversion and sustainability,
- safeguards on nuclear materials,
- radiation protection.

The operational safety of existing installations is further detailed as being measures to maintain and improve the safety of existing installations, including safety aspects relating to prolongation of the life-span of reactors.

The safety of the fuel cycle includes in particular

- the technological aspects of severe accidents, strategies and methods for the prevention and management of accident and post-accident situations,

3 Council Dec. 1998.

4 JRC 1998.

5 Council Dec. 1998.

- a scientifically founded approach to the management and disposal of radioactive waste, especially long-lived radioactive waste, and its reduction to the minimum, including by the transmutation of long-lived isotopes into short-lived isotopes,
- technological and operational reliability of final repositories, including experiments in large-scale facilities,
- development of best practices and maintaining and updating databases, including on decommissioning of nuclear facilities.

The specification of non-proliferation goals includes in particular technologies and methods of nuclear materials safeguards to meet recent developments:

- changes in the fuel cycle,
- the sharp rise in the stock of fissile materials due to nuclear disarmament,
- the extra obligations arising out of new international agreements,
- the illicit traffic in fissile materials;
- and scientific and technological cooperation, as appropriate, with the International Atomic Energy Agency (IAEA) in Vienna.

The safety and efficiency of future systems is further detailed in the work programme[6] as being innovative and revisited concepts. The following examples are named as potential advanced future systems: fast neutron reactors, high temperature reactors, small reactors for decentralised electricity supply etc. Innovative fuel and fuel cycles to investigate are e.g. the thorium fuel cycle and integral reactors with online reprocessing and fuel fabrication. Some of these concepts are praised as being more proliferation resistant than existing reactors.

The Research Programme implemented by the Joint Research Centre in respect to nuclear fission safety is orientated on the following safety issues:

- Ageing of materials and components with reference to plant life management,
- Basic research on actinides with reference to fuel safety and performance, Partitioning and Transmutation of actinides, material processing,
- Study on the characterisation of spent fuel with reference to direct disposal (interim and final
  storage) and radiotoxicity,
- Severe accident study with reference to core meltdown at its FARO facility.

1.1.3 Thermonuclear Fusion research and safety and non-proliferation issues

The key action 'Controlled thermonuclear fusion', for which under FP5 approximately 80% of the Euratom research budget will be spent, is the second area of EU's research with major connections to nuclear safety issues.

The strategy and objectives of this research programme are as follows:

> *"The long-term objective of the fusion activities, embracing all the research activities undertaken in the Member States aimed at harnessing fusion, is the joint creation of prototype reactors for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability.*
>
> *The proposed strategy to achieve the long-term objective includes the development of an experimental reactor (the Next Step) followed by a demonstration reactor (DEMO),*

[6] EC R&T Programme 1998-2002.

accompanied by physics and technology R & D activities, also involving European industry[7]".

The implementation of this strategy will entail Next Step activities, concept improvements towards economic competitiveness and long-term technology development. Accompanied studies will investigate socio-economic aspects of fusion, including economic costs and social acceptability. Co-ordination with other Member States in inertial confinement and possible alternative concepts will be continued. Furthermore a fresh assessment of safety and environmental aspects, dissemination of results and the diffusion of information to the public as well as mobility and training activities will be financed under FP5[8].

Special attention to safety aspects of nuclear fusion in respect to safety issues is set in the Research Programme of the Joint Research Centre starting 01-Jan-99 for a 48-month duration. It names the following research areas among others:

- materials research and testing, with particular emphasis on low activation materials,
- the interaction of hydrogen and its isotopes with materials and components, and
- participation in safety and environment impact studies.

Non-proliferation aspects are not mentioned in these documents. The largest expenditure is devoted to magnetic fusion concepts, inertial confinement that has a larger proliferation potential plays a subordinate role.

1.2 Identification and characterisation of nuclear energy systems

In this chapter, the possible future nuclear energy systems are identified that have to be taken into account in this study, and a short description is given. (Further details of these systems, as detailed as necessary, are additionally given in the evaluation chapters.)

Chapter 1.2.1 identifies the current concepts in reactor research. This includes the different fuel concepts, that might be part of future reactor concepts, trends in the waste management aspects, and safeguards related developments. Fusion reactor concepts are identified in Chapter 1.2.2. Energy amplifier concepts, that are currently discussed as potential alternative to long-term waste management by disposal and are not in the first place seen as energy systems, are described in chapter 1.2.3.

1.2.1 Identification of critical nuclear reactor research

Nuclear reactor research in the EU, as shown in the above chapters, currently addresses mainly the following aspects:

- reactor safety: the safety of current, future and advanced nuclear fission reactors,
- fuel concepts: the safety of current, future and advanced fuel production and use,
- waste concepts: the safety of current, future and advanced nuclear waste management,
- safeguards research: the scientific and technical support necessary to implement safeguards according to existing and future nuclear arms control treaties.

These concepts are described in detail in the following subchapters.

---

7 Council Dec. 1998.

8 Council Dec. 1998.

1.2.1.1 Identification of reactor concepts

Current research on reactor concepts follows two main goals: reaching enhanced safety to gain better public acceptance, and reaching competitiveness in the rapidly changing energy markets. These goals are either followed by evolutionary or by advanced concepts.

Evolutionary concepts are mainly based on well-established technology such as currently operated pressurised or boiling light water reactors. Evolutionary changes in the well-known short-comings of these reactor types are included in the design to enhance the safety features of this reactor type, besides changes in their economic layout. Such safety changes are for example:

- replacing certain active safety systems by passive systems, that don't require external resources,
- adding safety systems to control phenomena that are currently not adequately addressed (e.g. hydrogen build-up, high-pressure meltdown),
- adding core catchers, that isolate and control molten fuel in case of a severe accident in order to reduce off-site consequences of such an accident.

These changes point in two different directions regarding safety issues: either reduction of the probability for severe accidents from the current probability in the order of 10^{-4} to 10^{-5} per reactor year or limiting the off-site consequences. Currently operated reactor types, that are subject to such efforts are Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs). Typical for these reactor concepts is the development of the European Pressurised water Reactor (EPR), under development by Framatome and Siemens. Revisions of other, older reactor types, like High Temperature Reactors (HTRs) and Fast Breeder Reactors (FBRs) also fall mainly under this category of evolutionary concepts, as they are mainly based on earlier design, and use the familiarity of the designers and potential operators with these types of reactor.

Revolutionary new reactor concepts are also mainly based on known principles of reactor design, but introduce major changes in that design such as:

- exclusive use of passive safety systems (that means replacement of all active systems by passive systems),
- massive reduction of the decay heat, e.g. by use a much smaller reactor core, to avoid the need for such reliable safety systems.

The reactor types to be included in this evaluation are: PWR, BWR, HTR, and FBR

Special attention has to be given to those evolutionary projects that are in a more advanced state of realisation (EPR, small scale HTR) and can be analysed in detail. Basically different revolutionary reactor designs usually need at least two decades to establish and need attention on their principle safety potential. A detailed analysis of these concepts usually is difficult because many design characteristics have not been developed to much detail yet.

1.2.1.2 Identification of fuel concepts

The basic difference between evolutionary and revolutionary concepts already discussed for the reactor concepts is applicable for fuel concepts, too. The two goals, that are addressed here are also enhanced safety features and enhanced economic features.

Evolutionary fuel concepts are mainly based on further developing the fuel for currently operating reactors by introducing smaller changes and addressing operational and safety problems of these changes. Typical for these evolutionary changes is the shift to higher burn-up of uranium fuel and the prolongation of the time-periods, for which the fuel is loaded in the reactor. Clearly driven by economic incentives (reduction in operational and maintenance costs, reduction of waste management costs) the steady rise of the burn-ups has adverse safety effects that need to be addressed.

The incentive to introduce and enhance the burning of plutonium as Mixed Oxide (MOX) fuel is mainly driven by the fact that reprocessing in the past has lead to huge stocks of civil plutonium. Due to comparatively low prices for natural uranium on the world market and the comparatively high costs for MOX fuel production the economic incentive (mainly: reduction of storage costs) is of a secondary nature. Main adverse safety features of the use of MOX fuel are: reduced safety margins in reactor operation, elevated actinide inventory in case of accidents, elevated long-term decay heat of spent fuel and elevated heat dispersion features in geologic disposal of the fuel. These effects have to be addressed.

In order to avoid the typical short-comings of uranium fuel (actinide build-up, vulnerability to proliferation issues, etc.) the thorium fuel has been introduced in the past and is still under discussion for evolutionary as well as for revolutionary concepts.

Even more advanced fuel concepts are more or less in the stage of theoretical discussion. They usually address the economic disadvantages of the current fuel and waste management schemes (waste volumes, separation between waste and reusable materials, etc.) as well as the related safety issues.

- The fuel concepts to evaluate in this study are:
- uranium fuel/High burn-up fuel
- MOX fuel,
- thorium fuel,
- Advanced fuel concepts.

1.2.1.3 Identification of waste management concepts

Analysis of the EU research shows two areas of future developments in the waste management section: the withdrawal from reprocessing and the shift towards direct disposal of spent fuel on one side, the research work on extended reprocessing on the other side.

Direct disposal of spent fuel is world-wide the preferred option of spent fuel management for oxide fuel. According to the data collected by UNSCEAR for 1990 approximately one third of the spent oxide fuel were destined for reprocessing, two-thirds for direct disposal. In the meantime some additional countries have ended reprocessing their spent oxide fuel (e.g. Belgium), declared that as a political goal (e.g. Germany) or are discussing that issue on the political level (e.g. Switzerland). As these decisions have some influence on safety implications, non-proliferation risks and future management strategies, this management concept should be included in this study and evaluated.

Extended reprocessing, often also named "Partitioning", intends the removal, and later treatment („Transmutation“), of long-lived constituents of spent fuel to an extend, that makes long-term final disposal (> 500 a isolation time) of these wastes unnecessary. The idea is to separate a set of selected nuclides from the fuel, e.g. by chemical separation processes to be developed, and to dispose of the remaining bulk of shorter-lived nuclides. This concept is currently discussed in the public and in parliaments as an alternative to geologic disposal, research work is underway and funded within the EU, and there is some tendency to influence the set-up of solutions for the final disposal of radioactive waste. The concept though is relevant enough to be discussed in this study, as it has several long-term safety and non-proliferation implications.

Both tendencies are, by the way, clearly opposite technological ways, as extended reprocessing more or less requires 'classical' reprocessing (removal of uranium and plutonium) as its first step to enhance the concentration of the relevant and, in terms of long-term isolation requirements decisive, elements like neptunium, americium, iodine and technetium. Enhanced reprocessing therefore only makes a technical sense, if 'classical' reprocessing is maintained.

Waste management concepts to be evaluated in this study are:

- Once-Through/Direct Disposal
- Extended Reprocessing (Partitioning)

1.2.1.4 Identification of safeguards research

Technologies for the control of nuclear materials are necessary for material protection, control, and accountancy (MPC&A) at individual plants and for verification obligations arising from international treaties, e.g. safeguards. The most important treaties are the Euratom Treaty and the Non-proliferation Treaty (NPT).[9] It is likely that in the coming years the Fissile Material Cutoff Treaty (FMCT) will be negotiated, also the possibility of further reforms of IAEA safeguards cannot be excluded. In addition, international cooperation projects with Russia, and other states in order to improve their MPC&A are necessary. The research taking place at the JRC aims at providing the technical support for these obligations, and to develop new, more efficient technologies. Another goal is combating illicit trafficking of nuclear materials.

Research activities include development and improvement of measuring and analytical techniques to detect and identify radioactive traces in the environment, sealing and confinement techniques, and monitoring of operating industrial equipment. These activities concern in particular large reprocessing plants and the plutonium cycle, including MOX fuel. New information technologies can be used for improvements and automation, and remote sensing as a method of detecting illegal nuclear activities.

The activities are an integral part of a European co-operation, the European Safeguards Research and Development Association network (ESARDA). EU funded R&D takes place especially at Ispra and Karlsruhe. A major purpose is support to the Euratom Safeguards Directorate and the IAEA in Vienna.[10]

1.2.2 Identification of fusion reactor concepts

The major fusion reactor concept followed in the EU is the magnetic confinement, the Tokamak principle. Alternative confinement principles like the Stellarator principle and the reversed Field Pinch principles as well as the inertial confinement fusion are on a different development stage. As these technologies do not differ generally in respect to their safety implications, they need not to be discussed and evaluated separately. However, as ICF is more proliferation relevant than magnetic fusion, a special ICF proliferation risk assessment will be discussed in the respective chapter. Additionally the state of preliminary design for the latter

[9] There are additional treaties, especially nuclear weapon free zones (NWFZs), the most prominent being the Tlatelolco Treaty that establishes a NWFZ in South America.

[10] JRC 1998.

technologies is not well developed enough to allow for a thorough safety assessment including emissions, accidents and waste issues at this stage of development.

The safety assessment is therefore concentrated on the magnetic confinement fusion reactor principle, differences are, if applicable, discussed for the other concepts

- Alternative confinement via Stellarator
- Alternative confinement Reversed Field Pinch
- Inertial Confinement Fusion (ICF)

The largest experiment based on magnetic fusion is the Joint European Torus (JET) at Culham, a European project based on the Tokamak principle.[11] It is planned to proceed with the International Thermonuclear Experimental Reactor (ITER), a joint co-operation between Europe, Japan, Russia and the USA. An experiment based on the Stellarator principle is also planned.[11]

1.2.3 Nuclear accelerator development and accelerator-driven reactor systems

In chapter 1.2.1.3, new waste management concepts for currently operated reactor systems and the related objectives were identified and described as alternative to the geological disposal of longer-lived radio-nuclides. For the transmutation of the long-lived radio-nuclide portion of wastes into shorter-lived wastes two different reactor concepts are currently discussed:

1.2.3.1 Energy Amplifier

The Energy Amplifier is a sub-critical fast reactor that uses thorium as fuel, combined with an external neutron source. Its main task is the transmutation of actinides and long-lived fission nuclides, energy is only produced as a 'by-product'. The required nearly complete destruction of the long-living materials requires additional high-efficiency reprocessing steps.

1.2.3.2 Accelerator Driven Transmutation of Waste

The accelerator-driven transmutation of the long-living waste nuclides (trans-uranium elements, Tc-99, I-129) follows similar principles as the Energy Amplifier. Technical energy production is not intended in the first place, but a transmutation using fast neutrons. A major conceptual difference is that high-efficiency reprocessing is not intended and a direct disposal of the „fuel“ is targeted.

The research in this area is encouraged by the 5th Framework Programme in its Key Action on Nuclear Fission under the sub-title of "Safety of the Fuel Cycle".

[11] Barabaschi et al. 1996.

2 Criteria for the assessment of safety risks of new energy systems

This chapter describes the criteria that will be used in this study to evaluate the status of new energy systems. Criteria for the assessment of safety risks of nuclear fission reactors and the associated fuel and waste sections are described in chapter 2.1. Chapter 2.2 describes the criteria applied in this study on the safety risks of nuclear fusion reactors and its associated fuel and waste schemes. The criteria for other areas of nuclear research are described in chapter 2.3.

2.1 Criteria for the assessment of safety risks of nuclear fission

Energy production by application of nuclear fission has safety risks concerning the reactor operation itself, its fuel supply and in the waste management section. The detailed criteria that are applied in this study are lay out in the following subsections.

2.1.1 Criteria for the assessment of safety risks of new nuclear fission reactors

New nuclear fission reactors are currently under development by a number of different suppliers, including suppliers in the EU. These projects more or less address the specific issues that are discussed for current operating reactors. Besides economic issues also the following safety issues of currently operating reactors are addressed.

One of the commonly addressed issues is the accident risk of nuclear reactors. This risk has two different focuses.

On the one hand, efforts for further decreasing the probability of catastrophic events could be one strategy. The probabilities for those events are in the order of 10^{-4} to 10^{-5} per operating reactor year, has methodological and systematic uncertainties of around one order of magnitude and depends strongly on different methodology and parameters decisions that have been used in the analysis. With that mean probability, approximately 450 reactors under operation worldwide and an assumed operational time of each reactor of about 25 years the probability of a catastrophic events is roughly 0.5, with uncertainties ranging from approximately 0.05 to 5 events. A reduction of accident probability down to 10^{-6} per reactor operating year would reduce this probability by a factor of 20, if this level of reliability could be reached. Typical for the resulting design requirements to reach such a reduction is the enhanced use of passive safety features in the design of safety systems. As a criteria of the assessment of new fission reactor designs the reliability in this respect has to be evaluated to see, whether this issue has been addressed in the design.

On the other hand the release fraction of the radioactive inventory in case of a nuclear accident could be addressed by new reactor designs. Reductions of this fraction for the radiologically relevant radio-nuclides such as the noble gases, Iodine-131, Cesium-134/137 and Strontium-90 reduce the off-site consequences of releases. Technical means for these reductions are, for example, enhanced qualification of release barriers, disabling of high-pressure core melt accidents or introduction of inertial atmosphere to avoid hydrogen explosions during core meltdown. A common criteria for sufficient reduction of off-site consequences for releases discussed today is the necessity for off-site evacuation and the definition of an area boundary (e.g. facility fence, 2 km, 20 km). As a criteria for the assessment of new fission reactor designs the reliability of reductions of the release fraction has to be judged.

Besides risks from severe accidents, operational risks have to be addressed in modern reactor design. Operational risks have, again, two focuses: the public and the nuclear work-force.

In order to give a baseline for the assessment of the different current risks, table 2.1-1 lists the results of UNSCEAR's last assessment (1993) of the nuclear electricity production, completed and recompiled by CEPN in 1994.

Table 2.1-1: Specific Collective doses per unit electricity generated for the main stages of the nuclear fuel cycle, taken from CEPN 1994

Stage	**Technical step**	**Collective dose, man·Sv**	
		man·Sv/TWh	**%**
1	Mining and milling of uranium	0.289	2.22
2	Conversion	0.00232	0.018
3	Enrichment	0.0000352	0.00027
4	Fuel fabrication	0.00715	0.055
5	Electricity generation	2.2.23	17.13
6	Decommissioning	0.0217	0.17
7	Reprocessing	10.3	79.14
8	LLW disposal	0.0258	0.20
9	HLW disposal	0.136	1.05
10	Transportation	0.00251	0.02
Total		13.01	100

Operational risks for the general public result from radioactive emissions and evaluation include gaseous and liquid effluents. Effects from those emissions are different for the local (e.g. 50 km radius) and regional (e.g. 2.000 km radius) public, where the more short-lived radio-nuclides such as tritium dominate the collective doses, and for the global public, where globally dispersed long-lived radio-nuclides such as Carbon-14 dominate the doses. Overall collective doses from emissions are dominated by C-14. The lesson learned from this analysis is that typical fission products in these emissions such as Iodine-131 or Cesium-137 and fuel by-products such as the transuranium elements (Np, Pu, Am and higher) do not play an important role, even though these nuclides dominate the total inventory of the reactor by far. Evaluations of the operational risks from emissions must therefore include all sources of nuclides, even the minor activation products.

Similar results are gained from the analysis of occupational doses for the work-force of the plants. Besides improvements in the work management enhanced material selection and low-activation-design have shown the most effects in dose reductions. Special cobalt-reduced steel, introduced during plant design in the late Seventies, have lead to enormous activation and dose reductions in more modern plants compared to older plants.

Both aspects of operational risks might be evaluated for new fission reactor designs, as far as applicable for the type of reactor analysed. In that cases targets and goals for the plant layout could be analysed if they address these aspects.

In an overall assessment of the life-cycle during operation of current nuclear fission reactors the fuel supply side plays an even more important role than the emissions of the reactor itself. This is mainly caused by the production of natural uranium, while conversion, enrichment and fuel production is only of minor importance. The main cause for the domination of the uranium production stage is the absence of common international long-term isolation requirements for the wastes from mining and milling. This causes emissions of radon and dispersion of radioactive waste constituents (Radium etc.) over a very long period of time. Changes in the utilisation of fuel by new fission reactors, in contrast to currently operated reactors, would therefore result in proportional dose changes of the fuel supply and reactor operation stages of the process. The assessment of new reactors has to take this effect into account, at least as long as international long-term isolation requirements for wastes from mining and milling are not in place and implemented in those countries, where the uranium supply depends on.

The last stage to be evaluated for new nuclear reactors that are based on nuclear fission is the waste management stage. From a dose standpoint this stage could by far dominate the doses of all supply, production and waste stages of the nuclear production chain altogether, as far as reprocessing of spent fuel is involved. (Doses from current reprocessing of spent fuel in the EU are at least equal to or exceed the doses from emissions of the 146 nuclear reactors in the EU together. See table 2.1-1 for quantitative details.) The whole waste management scheme not only includes high-level radioactive wastes like spent fuel, or the resulting waste from reprocessing of spent fuel, but also has to consider operational wastes, wastes from maintenance works and waste from decommissioning of the plant. This is due to the fact that in almost any cases in the EU these waste categories are disposed in facilities with substantially lower safety standards than geologic repositories (surface disposal of low-alpha wastes, conditional or unconditional exception from nuclear requirements for very low active wastes), so that emissions and doses from the reuse of material are allowed, while high-level wastes in geologic repositories might in many cases not give rise to any emissions to the biosphere at all. It is also evident that small amounts of high-level wastes are easier and more reliable to manage than high-volume low and intermediate level wastes (e.g. due to the different long-term reliability of packaging). The conclusion is that all types of radioactive wastes have to be considered no matter of its specific activity. For new fission reactor concepts it has to be discussed and evaluated, whether the design has any influence on the overall waste management requirements and are compared to the current settings under now applied nuclear technologies.

An overall assessment of new reactor concepts has to evaluate the following aspects in detail:

- Accident probability
- Barrier quality, release fractions
- Operational Emissions, Occupational Doses
- Fuel Supply Risks
- Operational, Maintenance, Fuel and Decommissioning Wastes

Baseline in all these cases is the current nuclear energy production.

2.1.2 Criteria for the assessment of the safety risks of new fuel concepts

New fuel concepts considered in this study are (see chapter 1.2.1.2 for identification):

- uranium fuel/High burn-up fuel
- MOX fuel,
- thorium fuel,
- Advanced fuel concepts.

Evaluation criteria for the assessment of safety risks of these different concepts are defined separately, because some of the typical properties of these concepts are unique and require special discussion and evaluation.

Safety risks of high burn-up fuel are mainly concerning additional risks during operation of the nuclear reactor and nuclear fuel waste management. The other stages of the fuel supply aren't much affected by these changes in terms of risk, because dose factors for occupational exposures and other basic data are at least in the same order of magnitude and additional handling steps are not necessary in that concept.

Reactor operation using high burn-up fuel schemes affects risks in the following areas:

The content of fission products and actinides in the fuel is elevated, affecting the release inventory in case of severe accidents, the residual heat to be removed in case of loss-of-coolant events or from the spent fuel storage ponds.

High burn-up usually prolongs the time-period, over which the fuel elements are kept under operation. This results in additional requirements concerning materials, layout and reliability of the fuel elements.

Additional in-homogeneous reactivity is introduced into the core requiring additional reactivity layout of the cores set-up.

These issues need to be addressed and potentially limit the further elevation of burn-ups, if safety risks could not be limited by technical or other means.

Elevated contents of fission products and actinides are also the main influencing factors in the area of waste management for spent high burn-up fuel. This affects the thermal layout of

- casks used for transportation and storage of spent fuel,
- heat dissipation in interim storages for spent fuel,
- final storages for spent fuel and other high-level radioactive wastes

In a relatively direct way. More indirect effects result from

- the elevated actinide content enhancing neutron generation (esp. Cm-244) and the associated radiation protection aspects,

- the reduction of the fissile rest content of U-235 and Pu-239 in the spent fuel, rendering reprocessing and reuse of the material even less economic than under today's fuel economic framework,
- the elevated content of unwanted fission products (Tc-99) and uranium isotopes (U-233, U-236) in reprocessed uranium with similar adverse radiological and economical effects.

These main issues need to be addressed in the evaluation of fuel concepts involving higher burn-ups of fuel in respect to waste management risks.

The safety aspects of new fuel concepts involving the use of plutonium in light-water-reactors as mixed oxide fuel (MOX) are of a similar influence on risks on the reactor operation and the waste management side, as far as the elevated actinide content in those fuels is concerned. The use of plutonium leads to even more elevated contents of actinides, while the fission product content is more or less equivalent to spent uranium fuel of a comparable burn-up.

Some major differences in terms of occupational exposure during fuel production have to be considered for the MOX path, compared to the standard uranium or the high burn-up uranium fuel. Maintaining the same level of collective exposures requires more sophisticated technology and elevated specific production costs per unit of thermal output, so optimisation is to be expected.

The use of a thorium fuel concept for new types of reactors is a completely different concept from the above variations of existing reactor technology. As the radiological characteristics of thorium production and handling do not differ widely and in general from the production of uranium fuel, a specific assessment of occupational doses and of the waste management aspects is not necessary.

For other advanced fuel concepts, a detailed comparison with the existing fuel concepts is useful. As a reference for this comparison, the current uranium-based concepts are chosen, either with or without reprocessing and reuse of the materials. Characteristical steps might be compared in respect to occupational risks and risks from emissions. As they are also very different in respect to waste management aspects, the reference for this aspect is either, if they fit into existing nuclear waste disposal options or require special technical treatment or solutions[12].

2.1.3 Criteria for the assessment of the safety risks of new waste management concepts

New waste management concepts to be evaluated were identified in chapter 1.2.2 to include:

- Once-Through/Direct Disposal
- Extended Reprocessing (Partitioning)

Criteria for the assessment of these two technologies in respect to safety aspects are:

Safety requirements for handling: This includes occupational risks and risks for the public during normal operation of the required facilities. Sub-criteria are the complexity of the

[12] As far as advanced fuel concepts target to reduce the long-term requirements of isolation of existing wastes from the biosphere, another set of evaluation criteria has to be used (see the following chapter 2.1.3).

technical handling procedures, the quantitative amount and the hazards from the handled materials and the emissions that have to be expected during the different technical steps.

Accident risks: Accident risks are assessed by discussing the necessary technical steps and the associated accident risks. Sub-criteria are the amount and hazards of releasable hazardous materials, the quality and strength of the enclosure during the different steps and, as far as applicable, the expected frequency of severe events.

Safety requirements in final disposal for operational, fuel and decommissioning wastes: Waste management steps and their associated safety requirements must be discussed for all relevant technical steps. This applies especially to extended or advanced reprocessing, because it aims to make long-term disposal of all resulting materials unnecessary and is a crucial criteria for the promised success of that concept in general.

2.2 Criteria for the assessment of safety risks in Nuclear Fusion

Criteria for the assessment of nuclear fusion concepts are as follows:

2.2.1 Accident risk

Accident risks of nuclear fusion reactors might be compared to existing nuclear reactors. The sub-criteria to evaluate are:

The inventory, its releasability and its radio-toxicity, of the reactor determines the worst-case releases and the maximum possible off-site consequences of an accident.

Power density, switch-off behaviour and reactivity characteristics, short- and mid-term cooling requirements and decay heat determine the probability of such an accident.

Barriers, their quality and reliability determine the fraction of events, that lead to worst-case releases.

2.2.2 Operational risk

The operational risk includes occupational risks and public risks during normal operation of reactors. It is clear and self-evident that this has to include all necessary technical steps, including fuel and on-site waste management (reprocessing of materials included, as far as applicable).

2.2.3 Long-term waste management

A relevant criteria for the assessment of the safety risks of a fusion reactor includes the management of the nuclear wastes and the associated safety requirements.

The reference in all these aspects are the characteristics of the current fission reactor technology.

3 Criteria for the assessment of proliferation risks

Criteria for the assessment of proliferation risks can be developed from the study of proliferation mechanisms.[13] A common distinction is between horizontal and vertical proliferation. *"Horizontal proliferation"* denotes the phenomenon of new beginner states seeking nuclear weapons. Such states or rulers with their apparatus are commonly called "*proliferators*". As has been shown in historic cases, proliferators have used several varieties of technical methods to acquire the technologies they needed. In addition to the technical methods, several procurement strategies have been observed. Finally, in all nuclear weapons programmes, disguise and secrecy methods have played an important role. *"Vertical proliferation"* is the term for the phenomenon that nuclear weapon possessors seek the modernisation and innovation of their weapons. Methods are indigenous research and development (R&D), either directly aimed at this purpose, or using civilian-military R&D that may also yield results for the improvement of nuclear weapons.

In the following, the acquisition methods and non-proliferation measures and policies are shortly described from which risk assessment criteria are concluded. Horizontal and vertical proliferation are dealt with in two separate sections.

3.1 Horizontal proliferation

3.1.1 Short overview on technical elements of a beginner's nuclear weapons program

A nuclear weapon programme has in principle two technical lines, one is the procurement of the nuclear materials and the other the acquisition of the weaponization technology. Both lines can be followed in parallel and can be completed independently from each other, since they involve different technologies. Both lines require the procurement or the production of materials and technologies as well as the acquisition of the relevant knowledge.

The nuclear materials that have occurred in nuclear weapons programmes are plutonium or highly enriched uranium (HEU). However, there are additional materials that theoretically can be used, especially uranium enriched in the isotope U-233 which can be bred from thorium-232, and several transuranium nuclides with varying usefulness and accessabilities for nuclear weapons[14]. plutonium and these isotopes are created in reactors. In case the proliferator seeks them, he will strive for the acquisition of spent fuel and reprocessing technology able to separate the isotopes he strives for. Spent fuel is a product of nuclear reactors. As an alternative, he might seek access to other plutonium using technologies, e.g. mixed oxide fuel (MOX) fabrication or use. These related technologies are also used in the civilian nuclear energy.

In case the proliferator chooses the HEU path, he will need enrichment technologies[15]. Examples of different enrichment technologies are gaseous diffusion, gas centrifuges, gas nozzles, laser isotope separation, or electromagnetic separation (calutrons). These technologies have very different levels of technical sophistication, the dependence on foreign

---

13 An example of the study of proliferation mechanisms is: Schaper/Frank 1998.

14 Isotopes with a finite critical mass are Pa^{231}, U^{233}, U^{235}, U^{238}, Np^{237}, Pu^{239}, Pu^{240}, Pu^{241}, Pu^{242}, Am^{241}, Am^{243}, Cm^{244}, Cm^{245}, Cm^{246}, Bk^{247}, and Cf^{251} according to Goodwin/Kammerdiener 1999.

15 Krass et al. 1983.

assistance and technology transfer in an acquisition programme therefore varies substantially. Enrichment technologies are used in the civilian nuclear industry for the fabrication of low enriched uranium (LEU) which is used for light water reactors but cannot be used for nuclear weapons. However, it is possible to modify an enrichment plant designed for LEU to produce HEU instead.

Parallel to the acquisition of weapons usable material, the proliferator will seek the weaponization technology, which in beginner states can be either the gun-type technology as had been used by South Africa, or the implosion technology, as was aimed at by Iraq[16] Weaponization involves either R&D on the gun barrel technology or the development of spherical implosions. The technology of the former is less sophisticated. However, the amount of engineering must not be underestimated. Its disadvantage for a proliferator is the large amount of HEU that is necessary for one warhead. It had been chosen by South Africa because of enough HEU supply. This technology cannot be used with plutonium because of preignition problems. A proliferator with only small amounts of weapon material is therefore likely to choose the other technology, the implosion of a hollow sphere (the so-called 'pit'). The acquisition of this technology requires substantial R&D on the generation of shaped shock waves. Examples of technologies involved in such a research programme are measuring equipment such as X-ray machines, high current short time electronics such as switches or capacitors and metallurgy and machine tools able of producing pits from uranium or plutonium with high geometric precision.

3.1.2 Non-proliferation measures and policies

In order to create obstacles against proliferation, several non-proliferation measures and policies have been implemented and strengthened over the years. They comprise international arms control treaties, export controls and joint export control principles, cooperation in the prevention of smuggling, cooperation in technical problems of nuclear disarmament, national protection of sensitive plants and materials, related international standards, regional control institutions such as *Euratom*, verification of several treaties, especially safeguards by the IAEA, and global and regional confidence building measures. In addition, there are grown habits, norms, and rules, informal cooperation and common beliefs. In political science, this set of elements is commonly called "non-proliferation regime".

3.1.2.1 Safeguards policy, nuclear arms control, and disarmament

The most important international treaty is the *Non-proliferation Treaty* (NPT) whose members comprise all countries except Cuba, India, Israel, and Pakistan. It is verified by the IAEA. In non-nuclear weapon states (NNWS), it controls the entire nuclear fuel cycle with so-called *"full scope safeguards"*. The legal document defining full scope safeguards is INFCIRC/153. The goal is to detect illegal diversion of fissile materials. After the experience with Iraq's proliferation[17], a reform has taken place which has expanded the IAEA's legal instruments and has defined additional verification goals (INFCIRC/540). Now the task is in addition to detect clandestine acquisition activities.

The positive role that safeguards can play in the non-proliferation regime has been increasingly recognised. It has led to the reform INFCIRC/540 and to an increased cooperation between Euratom and the IAEA. New information technologies will enable more

[16] Schaper 1993.

[17] Albright/Kelley 1995.

effectiveness and cost reductions, and new tasks will need new technologies. On the long term, it will be necessary to work on more fundamental safeguards reforms with the goal of a universal system for civilian nuclear energy with no more distinction between NWS and NNWS[18]. Such a future system as a whole must be different, characterised by a new safeguards culture, based more on technical and political judgement than on the schematic implementation of quantification measures. A reform will have to address several criteria: finances, organisation, decision making, effectiveness, concern about non-compliance, and finally also underlying principles, e.g. standards such as significant quantities. A reform will become necessary because of the various non-proliferation and disarmament problems that need new solutions, e.g. a new treaty on the cutoff of the production of fissile materials for nuclear explosives (FMCT), implementation of INFCIRC/540, verification of nuclear disarmament and safeguards on declared excess weapon materials.

The FMCT will ban the future production of fissile material for nuclear weapons or other nuclear explosive devices[19]. The task of the verification will be therefore to create confidence that all treaty members comply with this obligation, e. g. that all nuclear materials produced after entry into force are being used for known and non-proscribed purposes. This verification task is very similar to that of INFCIRC/153, e.g. the verification of the NPT.

Euratom could play an important role towards universal safeguards, e.g. safeguards also in NWS and states outside the NPT:

- Since it covers already the complete civilian fuel cycles of France and Britain, additional IAEA verification of all levels of intrusiveness can be implemented at any time, similarly to that of the NNWS. No further technical efforts to implement a SSAC are necessary. The two existing voluntary offer agreements between Euratom, the IAEA, and France and Britain, respectively, might be replaced by new ones.
- Since Euratom has also safeguarded dual-use facilities in both countries, it has gained experience in safeguarding facilities that are close to defence issues and lessons can be drawn for other states and regions.
- The acceptance of Euratom safeguards in France and Britain might be higher than that of IAEA safeguards. These countries are used to work with Euratom since decades which has resulted in a high degree of confidence.
- In case that the negotiated FMCT verification system should be less comprehensive than that of the NPT, Euratom’s more intrusive regional safeguards can at least constitute a supplement enhancing the international confidence.
- Because of the structurally stronger legal authority of Euratom and the Commission in comparison to that of the IAEA, any withdrawal or uncooperative behaviour is far less likely and is also much more deterred because it would disturb the European integration process as a whole.
- The more verification tasks are assigned to regional safeguards, the lower are the additional costs that are needed for IAEA verification.

[18] Gösele et al. 1994, Blankenstein 1995.

[19] The scope of the FMCT is not yet clear. Many delegations advocate the additional coverage of already existing military nuclear materials.

3.1.2.2 Cooperation with Russia

As a consequence of the nuclear disarmament in the U.S. and in Russia, hundreds of tons of HEU and Pu from dismantled nuclear warheads will be released and will become excess of the military cycle[20]. This creates new concerns. It must be ensured that even tiny fractions of this huge amount of weapon grade material cannot be diverted by unauthorized groups, such as a potentially well organized Mafia which could transfer it into the hands of states with nuclear ambitions or even of terrorists. Another danger would arise if Russia's democratic development would not remain stable and any undemocratic successor could reuse the material rather easily. The security of the Russian nuclear production complex is estimated to be far below Western standards and in danger of deteriorating even further, so that the probability of proliferation is high[21]. The problems have proven so huge and costly that it is not possible for Russia to cope with them without international assistance. A symptom of this development visible in the EU is nuclear smuggling.

Another potential proliferation danger is the brain drain of nuclear weapon specialists[22]. It is estimated that about 10000 to 15000 persons have special proliferation relevant knowledge. This includes specialists on aspects such as enrichment as they also exist in several industrialised non-nuclear weapon states. About 2000 employees have special knowledge that concerns directly the construction and functioning of nuclear warheads.

Also, a modern State System of Accountancy and Control (SSAC) which is the prerequisite for IAEA safeguards is still lacking in Russia.

Several international or bilateral studies and activities have been started to encounter these problems. One set of initiatives aims at physical protection of materials and installations, security of transports, implementation of material accountancy[23], reforms of export controls[24] and border controls, conversion and funding of jobs in the military nuclear complex, in order to prevent the emigration of scientists with sensitive knowledge. For this purpose, the International Science and Technology Centre (ISTC) in Moscow has been founded at the end of 1992 after a long negotiation period. The goal of the ISTC is to offer incentives to Russian scientists and engineers who have sensitive knowledge on the construction of nuclear weapons, to use their skills for the benefit of their own country for peaceful purposes. The centre mainly organises projects. Applied projects on subjects from environmental protection, energy, and nuclear safety prevail. It is financed by the European Union, the United States, and Japan with about 80 Mio. U.S. $. Also several smaller Western countries have contributed. In the beginning, the bureaucratic process has been very slow, so that in there was a long time delay between approval and arrival of money. Fortunately, meanwhile the Centre has been well established and can report on successful projects[25].

A large programme is the Tacis programme of the EU. It covers not only nuclear cooperation but also many other fields[26]. Tacis is a EU initiative for NIS assistance "which fosters the development of harmonious and prosperous economic and political links between the EU and

[20] For an overview on the security of the Russian nuclear complex see Bukharin 1996, for the worldwide inventories of civilian and military HEU and plutonium see Albright et al. 1996.

[21] Potter 1995, Orlov 1997.

[22] Moody 1996.

[23] Sutcliffe/Rumyantsev 1996.

[24] Kirichenko 1996.

[25] ISTC 1998.

[26] Tacis 1996, Tacis 1997.

the NIS". More than 2200 projects were funded from 1991 – 1995 with 2268 Mio. ECU. A large fraction is devoted to nuclear safety and cleanup projects. Disarmament and non-proliferation is only about 1-2 %.

Other remarkable European activities are

- A cooperation programme between Euratom and the Russian Federation that aims at training of inspectors and implementing safeguards[27].
- A cooperation programme between the Joint Research Centre and the Russian Federation that runs a training centre in Obninsk in order to develop materials accountancy and safeguards for Russian collaboration. A remarkable aspect of this project is that it made use of Russian technology and work as much as possible from its very beginning in February 1994 and avoided the bitter lesson of the early U.S.-Russian cooperation that initially imposed only U.S. technologies into Russia[28].

Another kind of initiatives aims at the nuclear disarmament process itself. Elements are the dismantling of warheads, the construction of secure storage sites, and technical solutions for the disposition of fissile material. The most advanced projects are a French-German-Russian plan to construct a MOX fabrication plant in Russia that will use plutonium from dismantled nuclear warheads, a Japanese project to use Russian technology for the fabrication of MOX fuel for Russian fast reactors (BN600), and joint U.S.-Russian studies aiming at the MOX option and at vitrification of weapons plutonium together with high level waste[29].

3.1.2.3 Other initiatives

Also the *export control systems* of the industrialised states and international cooperation have been strengthened.[30] International cooperation has increased. A lot of dual-use goods have been included in trigger lists. Now, decisions on export licenses take into account the intended end use of a product. To a certain extents, efforts are being made to verify the end use of a product.

Another policy issue is the *Guidelines for the Management of plutonium* (GMP) that have recently been negotiated[31]. They have been triggered by concern because of the increasing amount of world wide plutonium transfers and by the huge amounts of plutonium from dismantled weapons that are currently without international controls. The guidelines deal with safeguards, radiological protection, physical protection, nuclear material accountancy and control, international transfers, management policies, and transparency[32]. They go beyond existing agreements especially because of commitments to continuously adapt to the most modern standards, and because of the improved transparency of stocks: annual declarations give overviews on detailed figures of all kinds of unirradiated civil plutonium.

In the years 1978-1980, the *International Nuclear Fuel Cycle Evaluation* (INFCE) took place, under the direction of the UN, and coordinated by the IAEA[33]. The aim was to identify

---

[27] DG XVII 1997.

[28] EC 1996.

[29] Japan 1999, Yegorov 1997, GRS/Siemens/Minatom 1997.

[30] Müller 1994. On former loopholes and efforts to close them see: H. Müller et al. 1994.

[31] INFCIRC/549/Add. 5a, 6 April 1998.

[32] In agreement with already existing legal obligations, such as the Euratom Treaty, Safeguards Agreements with the IAEA, the International Convention on Nuclear Safety, and others.

[33] INFCE 1980.

possible sources of weapon grade materials and to evaluate possibilities of the prevention of undiscovered production, diversion, or theft. As a result, international efforts were started to reduce the enrichment of uranium in research reactors below 20% and to avoid the civilian use of HEU altogether.

Finally, also *national intelligence agencies* have the task to detect clandestine acquisition activities, including domestic technical activities as well as procurement abroad. Typical means are classical espionage, and technical means, e.g. measurements of environmental radioactivity and satellite imaging.

3.1.3 Acquisition strategies of proliferators

Because of these non-proliferation measures, access to proliferation relevant technologies has become more difficult for proliferators. In addition, because of the NPT and because of the strong norm against proliferation, they need to pursue their goals in secrecy. Several acquisition strategies have been observed in historic cases. In the following, those strategies are listed that may play a role in the derivation of non-proliferation criteria for the assessment of proliferation risks.

a) **One-step-down-the-proliferation-food-chain:** In order to circumvent export control restrictions that prevent the direct purchase of a controlled technology, for example centrifuge enrichment devices, the tools and design information for their domestic fabrication are purchased. This strategy leads to technologies that increasingly have a dual-use character. Iraqi companies have bought raw materials like maraging steel, machine tools and flow-forming machines, comparably innocent looking parts for centrifuges like ring magnets and have tried to built the centrifuges themselves. They also have managed to get access to design information. This evasion strategy represents the most important circumvention approach of the future. More and more countries would in principle be able to apply this strategy since knowledge and general technical capabilities are spreading. This development is inevitable because of industrialisation, and on the long term, only political measures will remain to prevent further proliferation.

b) **Decomposition strategies:** This strategy is oriented to the fact that in some cases only entire facilities or machines are controlled or observed, but not the parts of those installations. Proliferators bought the parts and assembled them in their home country. Saddam Hussein's regime used its elaborate procurement network to procure innocuous looking items like ring magnets, aluminium alloy tubes, ferrite spacers, bellows etc. from European firms. A variant is the indigenous production of parts as much as possible.

c) **Training of scientific staff:** A nuclear programme first starts with the acquisition of the scientific background and training of staff. Typically, students and scientists from a proliferating country are sent to institutes whose research is as close at possible to the science underlying nuclear weapons explosions, such as nuclear physics, physics and chemistry of conventional explosions, or astrophysics dealing with high energy, high density plasmas.

d) **Technical assistance and consultancy services:** A major factor is the acquisition of technological knowledge. As the Iraq example has shown, technical assistance can reduce the costs of indigenous developments and the time needed.

e) **Forgotten or emerging methods:** Technical processes that are not commonly in use such as the electromagnetic enrichment method (EMIS), that Iraq sought to acquire during its clandestine programme might be neglected by detecting measures or export controls. The work on EMIS was a complete surprise, when it was detected by inspections after the Gulf

War. The possibility of an invention of a new enrichment method cannot principally be excluded. Such a new method might not necessarily pose difficult obstacles for its technical realisation.

f) **Plausible civilian disguise and diversion:** The technologies for the production of fissile materials can be transferred between civilian and military programs. Officially, South Africa was producing enriched uranium fuel for exports, but it used its plant also for additional military HEU production. Such production of nuclear materials would not have been possible under full scope safeguards. However, the disguise as civilian industry of endeavours producing enrichment or reprocessing technology infrastructure is less likely to be detected as long as nuclear material is not yet involved. This has happened in the Iraq programme where the R&D on centrifuge and EMIS enrichment technologies has not been touched by IAEA inspections.

g) **False declarations of initial inventories:** North Korea had tried to deceive the IAEA with false declarations on its reprocessing history. This deception has been detected by the analysis of plutonium samples. This problem might arise especially with initial inventories of states whose nuclear industry has not been under safeguards from its very beginning as it was in states such as Germany. Yet it is a greater challenge to confirm that the quantitative declarations are correct, e.g. that the inventory is complete. Confirming records of initial civilian inventories will pose an even greater challenge when IAEA safeguards will be introduced in nuclear weapon states (NWS). This is a policy goal in many NNWS, mainly because of the need to enhance the security of nuclear materials in Russia. The nuclear industry of NWS never had the need for a discipline of national material accountancy as high as in non-nuclear weapon states (NNWS) party to the NPT where the strive for high accuracy is a consequence of the regular inspections. An exception are the NWS France and Britain whose civilian nuclear industry is under Euratom safeguards.

3.1.4 Criteria for the assessment of risks for horizontal proliferation

All technologies that are useful for the production or acquisition of HEU, plutonium, and weaponization technology pose a certain proliferation risk. In this assessment, only nuclear technologies are considered.

An important strategy to get hold of weapon grade materials is the strategy of *plausible civilian disguise and diversion*. All civilian technologies that use weapons relevant materials pose a certain risk that fuel might be diverted. The diversion risk is strongly dependant on the quality of domestic physical protection, material accountancy, control, and international transparency, e.g. IAEA or Euratom safeguards. IAEA safeguards are missing in the four states that are not party to the NPT, and in the NWS. France and Britain's civilian nuclear fuel cycle, however, are subject to Euratom safeguards. The safeguards efforts and their sophistication depend on the nuclear technology. In case, the nuclear facility involves bulk materials such as reprocessing or MOX plants, the efforts are much higher than in cases when only countable items, e.g. fuel elements in a nuclear reactor, are involved. The IAEA defines which detection probability is sufficient[34]. A criterion for the assessment of a nuclear technology therefore is:

Criterion 1: The risk of horizontal proliferation of a technology is the higher, the more complex and sophisticated the safeguards are that must be attached to it in order to create a sufficiently high detection probability of illegal diversion of nuclear materials.

34 For the quantitative definitions of terms such as "detection probability" see IAEA Glossary 1987.

The less technical steps are necessary between a technology or material and the direct usable weapons component, and the lower the level of their technical sophistication is, the more likely is a technology to be used in the *One-step-down-the-proliferation-food-chain* acquisition strategy, and consequently the higher is the proliferation risk it poses. As an example, uranium enrichment is considered: If a proliferator gets hold of a complete enrichment facility, there is only one step between this technology and the direct usable product, e.g. HEU. If he gets only a component, he must invest additional technical work for the additional step to build the facility. If this work is technically sophisticated, e.g. in case of centrifuges, he must overcome a higher threshold than if it is simple, e.g. in case of electromagnetic isotope separation. Another criterion therefore is:

Criterion 2: The risk of horizontal proliferation of a technology is the higher, the lower the number of technical steps is between the technology and a direct usable nuclear fission weapon component and the lower the level of their technical sophistication is.

A variant of this criterion is the so-called "*spent fuel standard*" which has been defined by the U.S. National Academy of Science and which applies specifically to the disposition of nuclear materials.[35] Options for the long term disposition should make the plutonium roughly as inaccessible as the plutonium in civilian spent fuel. The radioactive protection and the reprocessing technology needed to get hold of it form a barrier to be overcome by potential proliferators.

Not only nuclear materials, but also nuclear technologies or the technical knowledge about them might be diverted, using the strategies of *training of scientific staff* and *technical assistance and consultancy services*. Related items might be transferred by *decomposition strategies.* The success of such strategies depends to a large extent on the quality of export controls. The more possible and plausible civilian applications a nuclear weapons relevant technology might have, the more likely it is that such strategies will be successful. The risk is the higher, the more difficult the distinction between civilian and nuclear weapons applications, e.g. the higher the degree of civilian-military ambivalence is. It must be noted that for the same reasons of useful civilian applications, political decision making on such technologies are complex[36]. The respective risk criterion is the following:

Criterion 3: The risk of horizontal proliferation of a technology is the higher, the more possibilities it offers for potential nuclear fission weapon uses and at the same time for plausible civilian applications that can serve as disguise, and the more difficult the distinction between those different applications is.

Non-proliferation measures are also related to technologies, e.g. nuclear measurements, analytic tools, surveillance technologies, and so on. New technologies might be beneficial or detrimental to non-proliferation measures. An example for a technology that reduce proliferation risks are new analytic measurements which can be used for safeguards. This is expressed by the following criterion:

Criterion 4: The risk of horizontal proliferation of a technology is higher if it creates additional obstacles to technical non-proliferation measures, and vice versa, its probability of risk reduction is the higher, the more it may reinforce such measures.

Finally, there are also *non-proliferation policies,* e.g. the plutonium management guidelines, or the efforts to reduce the enrichment of research reactor fuel that have been triggered by INFCE. Sometimes, new technologies might be beneficial for such policies, e.g. new Pu

35 NAS 1994.

36 Cf. Chapter 6 of this report.

safeguards methods or the development of new low enriched fuels for research reactors. It is equally possible that new technologies could endanger such policies, e.g. civilian technologies that use HEU. Sometimes, prestigious projects with a certain proliferation risk might trigger similar projects outside the EU, thereby undermining ongoing export control policies and promoting further proliferation.

Criterion 5: The risk of horizontal proliferation of a technology is higher if it has the potential to undermine ongoing non-proliferation policies, and vice versa, its probability of risk reduction is the higher, the more it may reinforce them.

For the evaluation of specific technologies, these criteria must be applied in combination.

3.2 Vertical proliferation

3.2.1 Short overview on typical elements of nuclear weapons R&D in a state possessing nuclear weapons

The five NWS are in the possession of hydrogen bombs, also called 'nuclear weapons of the second generation'. or 'thermonuclear weapons' This is the next step that the states outside the NPT, India, Israel, and Pakistan, probably are striving for. In a hydrogen bomb, an implosion device, called 'fission trigger' or 'primary' and a so-called 'secondary', consisting of fusion material, are commonly enclosed a casing. Upon ignition, first the primary is ignited, releasing its energy into the casing. The secondary, bathed in this extreme radiation, is compressed and as a result acquires a condition that allows fusion which releases even much larger energy yields[37].

For the development of hydrogen bombs, extensive testing of primaries whose energy releases must be perfectly controlled and testing of full devices is indispensable. It may be speculated whether the Indian and Pakistani test in Spring 1998 were sufficient for this purpose[38]. Related research and substitutes for testing are computer simulations, non-nuclear testing of components, and all experiments that yield quantities that can be used in the computer simulations. Those quantities are nuclear properties and plasma properties of hot, dense matter close to that in a nuclear explosion.

All nuclear weapon states are in possession of hydrogen bombs. Since decades, they have been working on modernisation and improving with various goals: increasing the yield, precisely tailoring the yield, optimising the yield to weight ratio, fitting to new delivery systems, enhancing the safety against accidental detonation, minimising the risk of unauthorised use, improving the reliability, adapting to modernised components, enhancing specific energies such in the neutron bomb, developing miniaturised warheads, experimenting on new principles of nuclear weapons and so on.

The next step in discussion in the USA during the 80ies were nuclear weapons of the third generation. The new quality would have been enhancement and direction of one specific energy form out of the combination of mainly electromagnetic radiation, radioactive

---

37 Schaper et al. 1996.

38 Despite Indian allegations, those nuclear explosions were not already successful explosions of hydrogen bombs. But it is possible that the Indians have collected enough data to proceed with their development without further testing. See Schaper 1998a.

radiation, neutrons, and mechanic shock waves that is uniformly released by second generation weapons. Examples are the nuclear pumped X-ray laser, electromagnetic pulse weapons, microwave weapons, or thermonuclear shaped charges. Research and development in the last phase of the Cold War had already started, the major and indispensable experimental tool being nuclear test series. But much more testing would be required before any such weapon would be ready[39].

Apart from nuclear tests, useful for the further improvement of nuclear weapons are largely the same as for hydrogen weapons, e.g. computer simulations, non-nuclear testing of components, and all experiments that yield quantities that can be used in the computer simulations.

3.2.2 Measures and policies stemming the further development and proliferation of advanced nuclear weapons

The most important measure to stem the qualitative nuclear arms race, i.e. *vertical proliferation*, is the Comprehensive Test Ban (CTBT)[40]. Although it is not yet in force, the norm against testing has become very strong. A verification system for the CTBT is being set up whose technical components include a world wide sensor net that monitors seismic activities, underwater sounds, infrasound and radionuclides in the atmosphere[41].

In international diplomatic fora, the pressure towards nuclear arms reductions is strong. It includes the demand not to further modernise the nuclear arsenals in the NWS.

However, apart from the CTBT and its verification, there are hardly any concrete consensual policy initiatives and technical measures against further vertical proliferation that can be compared to those against horizontal proliferation. At least the international cooperation with Russia comprises conversion activities for the Russian nuclear weapons complex, including the search for new civilian projects for Russian nuclear weapon scientists.

Nuclear weapons related R&D in NWS and states outside the NPT naturally takes place without any international transparency. It is characterised by secrecy, but this is because of security and non-proliferation reasons, not because of strong norms against vertical proliferation. In less developed states, also espionage might play a role, although each such claim is also disputed[42]. Intelligence agencies in nuclear weapon states therefore have the task to prevent such espionage.

3.2.3 Criteria for the assessment of risks of vertical proliferation

Vertical proliferation mechanisms are very different from those of horizontal proliferation. The major reason are the different political conditions under which it takes place. However, what is similar, is the civilian-military ambivalence of many R&D and technologies that often plays an important role. An example is the physics of hot, dense plasmas that is useful in

39 For a detailed analysis of the potential of tests for the development of third generation weapons see Fenstermacher 1990.

40 Schaper 1997.

41 On detailed information see CTBTO PrepCom.

42 An example are the recent U.S. allegations about Chinese espionage on U.S. nuclear weapons. They have not only been refuted by China, but also by several U.S. experts on their nuclear weapons complex. See Cox-Report 1999.

nuclear weapons R&D as well as in civilian areas such as fusion research or astrophysics. Therefore it is possible to design an assessment criterion that to some extent is similar to criterion 2:

Criterion 6: The risk of vertical proliferation of a technology is the higher, the more it is useful for R&D on advanced nuclear weapons.

As long as R&D projects on such technologies take place in international cooperation, their goals will be the civilian and not the nuclear weapons application. NWS pursue the specific military projects only nationally. There are examples of large dual-use plants that are planned to be used part time for civilian international research, and part time for national military research[43]. The international use therefore can serve as an additional indicator that may modify assessments according to criterion 6 to a certain extent. On the other hand, it must be kept in mind that also civilian results from such R&D might be abused for nuclear weapons R&D.

Criterion 7: The risk of vertical proliferation of a technology is to a certain extent lower if a technology is used in international cooperation.

Finally, it is important whether a technology reinforces or weakens ongoing measures and policies stemming vertical proliferation. Positive examples are technologies that are useful for the verification of the CTBT or for the conversion of a nuclear weapons complex. The according criterion is similar to criterion 5:

Criterion 8: The risk of vertical proliferation of a technology is higher if it has the potential to undermine ongoing arms control and disarmament policies, and vice versa, its probability of risk reduction is the higher, the more it may reinforce them.

[43] Such plans are made for the ICF plant at the Lawrence Livermore National Laboratory, USA.

4 Critical nuclear fission research

4.1 Safety assessment of critical nuclear fission research

4.1.1 Safety assessment of fission reactor concepts

The overall assessment of new reactor concepts has to evaluate the following aspects in detail:

- Accident probability
- Barrier quality, release fractions
- Operational emissions, Occupational doses
- Fuel Supply Risks, and
- Operational, Maintenance, Fuel and Decommissioning Wastes.

As a baseline for the comparison of evolutionary concepts the currently operated modern Pressurised Water Reactors (PWR) are selected. Only the differences compared to this baseline have to be discussed.
The following chapters discuss the main safety assessment issues for the different reactor concepts.

4.1.1.1 Safety assessment of the European Pressurised Water Reactor (EPR)

The reactor concept that is closest to be marketed in Europe is the EPR, currently under development under co-operation by Framatome and Siemens. The concept is also very close to currently operated PWRs, so the discussion could focus on the conceptual differences.

The following safety targets and main protection goals are claimed by the developers[44]:

- Further reduction of the accident probability
- Enhanced barrier quality to reduce the release fraction in case of a severe accident

Additional four key issues were identified that need to be addressed by the evolutionary concept:

- Protection against external events (e.g. plane crash)
- Enhanced safety margins against severe accidents and loss-of-barriers
- Reduction of radiological consequences of accidents, including core melt accidents
- Reduction in the probability for the loss of safety systems.

The following measures address the reduction of accident probabilities. Safety systems should be less complex to reduce the probability of failures. The opportunities for common mode failures should be reduced by the enhanced separation and by additional diversification of safety systems. The time required for manual operations by operating personal should be prolonged by additional cooling water reservoirs within the components. And lower probabilities of human errors of operating personal should be reached by enhanced layout of the man-machine interfaces. While these features are mainly deterministic in nature, the defined goals are of probabilistic character. The target for the probability of core melts

[44] See Fischer 1997, p.36ff.

accidents during operational and non-operational[45] periods so should be reduced to less than 10^{-6} per year[46]. Probability of severe accidents with an early loss of the barriers should be reduced to 10^{-7} per year.

Additional measures that reduce the consequences of such severe accidents to below any evacuation necessities in the vicinity of the plant are addressed by the following planned strategies. It is crucial to ensure a high barrier integrity especially for the containment shell in order to reduce probabilities for severe accidents. The stabilisation of the molten core within this outer containment shell is the second strategy. Consequently the leakage through the outer containment shell must be prevented and the long-term cooling of the molten core must be maintained as long as necessary.

It is highly controversial if these targets and goals are reached by the design of the EPR in the current stage. The main controversial arguments currently discussed are focusing on the barrier integrity during core melt accidents, because the required reduction of releases of mobile radio-nuclide inventory to below the target values (no necessity for off-site evacuations!) is immense (> 99.9%) compared to second-level probabilistic assessments of the past and for currently operating plants. According to the critics the exclusive concentration on in-vessel steam explosions following fuel-coolant interaction as a singular event does not address possible longer term fuel-coolant interactions that could lead to in-vessel pressure build-up. It has not been shown so far, that this pressure build-up doesn’t lead to an early loss of the integrity of the outer containment shell. Other discussed issues are hydrogen explosions and the ability to relieve the high in-core pressure in case of small and medium pressure loss-of-coolant accidents. Furthermore, steam explosions with small water/core relations are not adequately addressed by current research on these phenomena. This includes research at the European research centres Karlsruhe, Grenoble and Ispra[47].

As concerns the reduction in accident probability by the EPR concept no detailed evaluation from an independent side has been published so far. As very detailed layout information is necessary to evaluate the reliability of the different safety systems, man-machine-interfaces, etc. this evaluation makes sense only on the basis of the final layout. It should be questioned in general, however, if these goals could be reached, because parts of these improvements have already been introduced in existing plants. As complex systems always tend to develop new safety problems, if certain safety issues are improved by measures in parts of the system, this task of reaching improvements of more than one order of magnitude in terms of probabilities is evaluated as rather ambitious.

The second phase of the development of the EPR was concentrated on the necessity to present a marketable solution to the electricity industry, that finances and supports the EPR project, called Basic Design Optimisation Phase. A number of remarkable changes in the Basic Design were introduced to fulfil the economic goals of being competitive with fossil powered electricity plants. Among these was the remarkable increase of desired electric power per plant from 1.525 MWe in the Basic Design, compared to 1.000 resp. 1.300 MWe currently, to more than 1.700 MWe. This trend is likely to increase within the next ten years, considering enhanced market conditions in electricity production in Europe and world-wide. As this trend

[45] Recent work on accident probabilities during non-operational periods (maintenance, etc.) show a relevant contribution to the overall accident probability, so these periods were underestimated in the past.

[46] This target corresponds to a probability of 1.1% for a severe accident, if the currently world-wide operated 450 reactors would already fulfil this target and would be operated each for 25 years.

[47] See Reimann, p.60 for a detailed critic of current research.

of increasing the net power per plant also has relevant safety implications due to increased core masses, increased residual heat power, increased radiological inventory etc., these developments might lead to further changes in the envisaged safety features of the EPR and might result in the question, whether safety or economy are put into the first row of layout priorities to be followed.

Operational emissions of the EPR are to be expected in the same order of magnitude as conventional currently operated reactors. No special mention is given to this aspect by the developers.

Occupational doses are also not specified. According to preliminary characteristics the EPR will not apply specific Cobalt-reduced component design, which was designed and applied by Siemens in the series of so-called convoy reactors build in the Eighties. A very effective drop in the occupational doses that are posed during repair works of the primary coolant circuit components was reached with that technology. As of current knowledge of the authors it is not planned to apply these principles to the EPR, mainly to ensure special know-how protection.

Fuel supply risks of the EPR are generally comparable to the current reactor technology. For economic reasons the EPR will be designed to apply very high fuel burn-ups of around 60 GWd/tHM[48], well above current reactors. As this reduces the mass and frequency of fuel loads/unloads and corresponding transportation characteristics, but also requires corresponding enhanced initial fuel enrichment, no relevant changes in the supply needs compared to modern reactors are reached. As the costs for consumed natural uranium do not play a relevant role in the total cost of ownership of modern reactors, this aspect is not expected to advance to a design criteria.

No general differences are to be expected in operational and decommissioning waste characteristics compared to other modern reactor concepts.

The state of knowledge on the EPR design currently does not allow a final evaluation of its safety issues, as a number of decisions and developments are still pending. Discussed relevant safety issues of currently operated reactors of the PWR type are in general not understood well enough to expect a general solution especially for the problems of core-melt accidents by a design, which is very close to reactor designs of the past. It is still open, if the EPR will fulfil its safety goals as required.

4.1.1.2 Other "advanced" Pressurised Water Reactor concepts

Besides the EPR concept world-wide a number of so-called advanced concepts for Pressurised Water Reactors are currently under development. The status of some of these projects was summarised in a recent review study[49]. They include the AP600 (Developer Westinghouse USA, 600 MWe, PWR) and CANDU 3 (Developer AECL Canada, 450 MWe, RWR).

These concepts do not generally differ from past designs. Remarkable is their very much smaller core and power-per-plant layout compared to the EPR (see chapter 4.1.1.1). Core melt

48 Traube 1999, p.95.

49 Liebert et al. 1999.

accidents were calculated for the AP600 for internal events with probabilities of $3.3 \cdot 10^{-7}$/a, severe releases with barrier damages 100 times smaller. Within this study no comparison could be performed on the compatibility with probabilistic assessments for European plants[50].

Besides the core layout, and the fuel in case of the CANDU also the design, the safety features and possible risk of these plants does not differ in general from those of conventional PWRs or from the EPR. As the development, and in part also the design, is not finished yet and no reactors of that type are currently planned to be built, a final assessment of their safety properties is still lacking. A general difference to currently operating reactors in that sense that severe accidents or their off-site consequences are resolved issues, cannot not be expected from these concepts.

The other aspects (emissions, occupational doses, fuel supply risks, wastes) are not changed in a relevant way. It is only worth noting that CANDU reactors breed more tritium because they use heavy water as coolant and hence show elevated emissions of that nuclide. The resulting dose differences to currently operated reactor types are not very relevant, if collective doses are taken as evaluation criteria.

4.1.1.3 Safety assessment of High Temperature Reactors

High temperature reactor (HTR) concepts were in the past mainly developed in the United States, Japan, Russia and Germany. Nearly all the demonstration reactors have been shutdown since, a few smaller plants are still operational. Research and development, including the nuclear industry, has also been limited in most of the above mentioned countries. Introduction of that technology is currently discussed in the Republic of South-Africa, a smaller project is currently build in China. The high-temperature reactor concept though is currently not a self-selling concept, but has some safety features that still draw some attention among experts and in the public, so it is discussed here briefly.

While PWRs are discussed with a high power-per-plant of several 100 MWe designs only, the HTR-concept has had two variations in the past. One variation follows more the line of electricity and heat production for huge industrial complexes, typically in the several 100 MWe class. The other concept are smaller units, that are closer to the smaller "users" and usually have a typical power of some 10 to less than 300 MW thermal. Several subtypes were developed. Both main variations were developed in the past, are still under discussion and some demonstration projects were build, but still lack their broader market introduction.

Typical for their safety features is their very much smaller core, compared to currently operated reactor types. This is a clear advantage and offers the opportunity to base accident cooling of residual heat power more on natural convection than on active safety systems. As the fuel could be well protected by coatings, their ability for releases could be designed to be much smaller than for huge conventional reactors. The typical metal-water reactions of core-melt accidents are less of a problem if their cooling is done by the use of inertial gases like Helium.

Typical safety properties of these reactor types with problem potential are the following (applies both for small or bigger HTR concepts):

[50] Probabilistic assessments use different methods, include different internal and external events, and could be more based on so-called "realistic" or more "conservative" input data. This results in different results for the same plant, so care must be taken in interpreting those results.

- A leakage between the first and second coolant loop can lead to intrusion of other media, depending on the media used there. If water, air or similar reactive material is used in the second loop and relevant material intrudes to the core the leak can develop to an accident, if reactions like $C + H_2O \Rightarrow CO + H_2$ or $2 C + O_2 \Rightarrow 2 CO$ can occur.
- Leaking water, if such is used in the second circuit and leakage occurs, could lead to reactivity events.
- The geometry of the core must maintain its integrity in every case, because it determines the reactivity characteristics of the reactor. Events which change this geometry above a relevant limit can potentially lead to accidents and activity releases.

Analysis of emission data for the German HTR Hamm-Uentrop shows that the emissions of tritium and carbon-14 are in the same order of magnitude like other reactors of comparable power characteristics and start-up year. No specific differences in occupational doses are to be expected.

The reactor concept requires a very specific and technically unusual infrastructure. Among these infrastructural pre-requisites is a very special fuel supply in terms of natural resources, enrichment and fuel production facilities. Fuel supply risks are to be expected only in respect to these unusual infrastructural requirements, because production and market conditions are not very flexible. Radiological risks in fuel supply are not very different from uranium fuel.

The siting very close to the industrial or public consumers of heat and electricity adds additional potential economic and safety problems (external events, etc.). This makes introduction not easier and is of a relevant influence on the overall safety features of such a nuclear system.

No relevant differences so far have been encountered concerning operational and decommissioning wastes, compared to other reactor types. A small, but notable difference is the fact that unusual infrastructure plays a relevant role here, too. This applies to casks, interim disposal and in part also to final disposal of spent fuel from HTR reactors. The differences are not of a decisive nature.

It can be concluded that from a safety standpoint high temperature reactor systems on one hand offer an alternative to reactor systems that are subject to catastrophic core-melt accidents. On the other hand, after several decades of R&D, HTR concepts still have unresolved specific adverse safety characteristics that need further efforts prior to a potential broader introduction. Economic properties have in the past proved as not being too advantageous, otherwise a broader introduction would already have happened during the several decades of research support in several industrialised countries.

4.1.1.4 Safety assessment of metal cooled fission reactors

Liquid metal cooled reactors have some specific safety features that are very different from water cooled reactors. That’s why they are discussed here as such, even though they are very different in other respects. The two reactor types discussed here are Fast Breeder Reactors (FBR) and Power Reactor Inherently Safe Module (PRISM), also called Advanced Liquid Metal Reactor (ALMR).

Liquid metal cooled reactors work with liquid sodium as coolant. This has the advantage that the metal is not subject to boiling, and coolant losses are less probably resulting in a loss of cooling of the reactor core. On the other hand liquid sodium reacts with water and oxygen, so that every leak, even a small one, leads to the risk of fire and results in enhanced damage to reactor components. The chemically aggressive coolant also is connected to very unusual corrosion protection requirements, for which no long term practical experience in industry is available.

While Fast Breeder Reactors in the past followed the track of elevated power per unit to achieve better economic characteristics, the ALMR is designed in the other direction. In order to keep a module small enough to maintain passive emergency cooling its thermal power is limited to 425 MW. Three separately operated modules feed their power into one power conversion unit. The passive cooling is planned to be guaranteed by self-sustaining open air coolant channels ("Reactor Vessel Auxiliary Cooling System", RVACS), that are open to the outside of the reactor building. This determines the safety features of such a reactor system, because any damage or leak of the "guard vessel" called reactor module results in direct releases of radio-nuclides to the air outside the building, no additional effective barriers are available for these heavier damage cases.

Emission data from FBRs collected so far is not very reliable, as FBRs were not operational over long periods of time. Specific discharges calculated by UNSCEAR show some elevated tritium emissions per GWa of about one order of magnitude[51], compared to water cooled reactors. Comparisons of occupational doses have to consider the fact that current operating experience shows lengthy repair periods with their dominating effect on total doses.

Fuel supply risks are comparable to conventional reactors, if the use of mixed oxide fuel is considered. FBRs allow the use of elevated plutonium as fuel compared to conventional reactors. That is the reason why they were considered for plutonium production as well as for plutonium burning. The ALMR concept is explicitly designed and meant for plutonium breeding[52]. FBRs initially were designed and optimised for the same purpose, but were under discussion as "plutonium burners". As the destruction rate for plutonium is far below other methods and destruction of relevant portions of undesired plutonium inventories would require extreme long operating time periods, this method is not meant to be seriously followed any more.

Liquid metal cooled reactors require additional and very unusual techniques to maintain clean coolant compared to water cooled reactors. This constitutes similar unusual operational and decommissioning requirements and wastes as well as very specific treatment methods and facilities for that purpose. In the evaluation of the PRISM concept as well as for conventional FBRs it must be clearly stated, that these concepts require additional reprocessing to fulfil their tasks. As wastes are concerned the specific voluminous wastes from reprocessing have to put into consideration.

Most of the fast breeders and development plans for that technology were either dropped or the facilities were shutdown earlier than initially planned. A number of research and commercial reactors face decommissioning today. There are no signs of relevant changes in national policies that point to a revival of that technology today. FBRs were considered for transmutation, because they provide higher transmutation rates than ordinary water moderated

---

51 UNSCEAR 1993.

52 Liebert 1999, p.54.

reactors. The rates measured and calculated weren't high enough to resolve the principal problem of Partitioning and Transmutation, as further described in chapter 4.1.3.2.

4.1.1.5 The PIUS reactor system concept

The construction of a series of so-called inherently safe nuclear reactors started at the end of the seventies. One of the first developments of that kind is the PIUS (Process Inherent Ultimate Safety) reactor. It was initiated by Asea Brown Boveri (ABB) and United Engineers & Constructors (UE&C). Its safety concept was exclusively based on passive measures. Subtypes of this concept are either based on the principle of pressurised water reactors or on boiling water reactors. The reactor is basically designated for electricity production at 640 MWe, but plans for smaller sizes of 220 to 400 MWth and heat production have also been presented.

The safety principle of inherent safety is technically realised by placing the reactor inside a pool of water with a high concentration of borate. Whenever coolant or pressure inside the reactor is lost this borated water floods the reactor and stops the chain reaction immediately. During normal operation the high density transient between coolant and borated water prevents inflow into the reactor. The water resource is designed to guarantee cooling for at least a week after shutdown, in other concepts this margin for active external activity is reduced in order to ease component design (e.g. PECOS-SWR, designed by ORNL).

So far it has not been shown that this principle is both technically sound and fulfils its task of reducing accident probabilities to below relevant margins. No detailed design or prototype application has been launched yet, so besides the conceptual design no detailed evaluation of the safety features, like the barrier qualities, release fractions, operational emissions, occupational doses, etc., is at present possible.

The fuel supply of the PIUS is based on uranium, no relevant differences compared to currently operated reactors are to be expected. The amount and character of operational and decommissioning wastes is not unusual compared to current characteristics. Emissions and wastes depend a lot from the frequency of the actuation of (necessary or unnecessary) emergency inflow of borated water. This is widely uncertain until more technical experience with such a system has been gained.

4.1.1.6 The Energy Amplifier concept

A very different reactor concept is the Energy Amplifier (EA), which was developed at CERN by a working group around Carlo Rubbia. The EA is a sub-critical fast reactor, which is driven by an external neutron source (proton accelerator, generating neutrons)[53]. Several passive systems, like interruption of the accelerator beam and passive reactor cooling by natural convection, are meant to guarantee sub-criticality and residual heat removal. The cooling media is a liquid lead-bismuth alloy. Fuel is thorium, which breeds U-233. Reprocessing and reuse of the fuel is mandatory, because the concept aims at destruction of its own and externally produced long-living actinides and fission products. Energy production, a thermal power of 1.500 MW is typical, is seen more as a by-product to this goal of reaching a destruction rate of 400 kg trans-uranium elements per year, not its main task. As the production rate of long-living actinides, including long-lived plutonium isotopes, and

[53] See Liebert, p.63ff, and the sources cited there for a detailed description of more aspects of the EA.

fission products in a modern 1,000 MW LWR is in the order of 800 kg per year and if the EA is fuelled with a thorium-plutonium-mixed-oxide instead of thorium then at least one of the above characterised EA is necessary for the destruction of the long-living actinides and fission-products of one LWR.

The main safety issues in this reactor concept are the safety margins against unwanted criticality of the reactor and the necessity to guarantee a certain core geometry. As the regulation of the accelerator beam is the only mechanism to guarantee sub-criticality its regulation mechanism must be designed to withstand spontaneous changes in the criticality parameters of the core and must work with a very high reliability to prevent from possible core-melt accidents and releases. No detailed accident sequence analysis and their expected probabilities are available on the current status of concept development. It is assumed that accident probabilities and release fractions will be comparable with currently existing reactors, but this has to be verified in more detail.

Operational emissions are expected by the developers to be in the order of 2.75 man·Sv/GWa collective dose for the local/regional public and, depending on the fuel used, 0.44 to 1.42 man·Sv/GWa for the global public. The respective average for PWRs, as calculated from data collected and published by UNSCEAR as world-wide average[54], are 0.29 man·Sv/GWa (BWRs: 0.97 man·Sv/GWa) for the local and regional and 11.1 (BWRs: 41.6) man·Sv/GWa for the global public[55]. These model calculations and their assumptions cannot be evaluated in detail within this study, but the operational doses of the EA as given by the developers seem to be in the same order of magnitude as the more modern PWRs of comparable plant dimension. As several reprocessing steps will be integral part of the whole EA system their operational emissions and the resulting doses must not be neglected. As these operations are very complex[56] the emission intensity of the whole system of partitioning and transmutation in an EA might be a many-fold higher than those for the reactor operation alone, and so might be the more relevant part to discuss here. Occupational doses are not given in literature for the EA reactor or the P&T system as a whole. For these doses the same problem applies.

No extra risks on the fuel supply side of the EA system are to be expected than those already discussed for conventional uranium/thorium-supplies and for MOX application.

Operational and decommissioning wastes from an EA reactor and of the whole system are to be expected mainly due to the necessary reprocessing of spent EA fuel and of the transmutation targets. As no reliable information on these wastes is possible on today’s basis of development, this must be evaluated as an open problem with a decisive importance for the whole P&T system.

Another aspect to be discussed, but not explicitly task of this study, is the question whether the EA reactor system and the whole P/T system is justified under all relevant technical, economical and ecological aspects or must be judged as being “just nice physics”. It is clear already from the above mentioned fact that each conventional LWR needs at least another EA and three reprocessing plants for LWR-, thorium-MOX- and target-reprocessing, along with three different fuel production plants, to fulfil the task of treating the waste of the whole

---

[54] UNSCEAR 1993.

[55] Note that for this calculation world averages and more advanced C-14 model calculations than in UNSCEAR 1993 were applied. The difference in the global collective doses to other calculations cited in this study are due to these two parameters.

[56] See the chapter 4.2.3.3 in this study on technical steps required for transmutation.

integrated system. This will not be a minor technical task but requires a very long-term commitment to nuclear energy and, if ever the design phase will be reached and the necessary economic resources will be available, is only interesting for countries with a huge nuclear industry.

4.1.1.7 Summary and conclusions on the safety assessment of fission reactor concepts

The following conclusion can be drawn from this analysis of safety aspects of new nuclear fission reactor concepts:

- The main safety goal of new reactor concepts is to eliminate the necessity of off-site evacuations in case of severe accidents not only by reduction of their probability but also by limitation of the releasable radio-nuclide fraction.
- The different concepts currently followed on various stages of concept and technical development do not fulfil this goal clearly or are on a stage, where final evaluation of that goal is not (yet) possible.
- Operational and occupational doses are currently not of a decisive character in the evaluation of reactor concepts nor is this property in the rank of a relevant design goal. This applies also to reactor concepts that are the closest to market introduction (EPR).
- Fuel supply safety risks are for all concepts comparable to conventional reactors.
- Waste production is currently not ranked as a decisive issue in most of the concepts, but is the main task of the Energy Amplifier reactor and its related system. It is highly questionable if this system has a realistic perspective at all.

From that conclusions the following recommendations for the policy regarding nuclear fission safety are derived:

- The main safety goal for potential future reactors of limiting their off-site consequences should be high-ranked as main requirement for any research and development activities in that area. Projects or activities in the field of nuclear fission energy should be evaluated on that background and should contribute to that goal.
- Projects should include all relevant safety phenomena that might have an influence on the task of fulfilling that goal. It doesn't make much sense to just concentrate on such phenomena that are already addressed and leave potential other paths out of research activities.
- New reactor concepts that are planned to be supported by substantial research efforts should qualify by first going through a thorough evaluation process of their potential future applicability, taking all technical, economical and ecological aspects of their potential future application into account. In this analysis it is insufficient to just focus on the isolated issues of the promised pro's of a process, but all framework has to taken into view in order to judge whether an investment in further developing know-how makes sense.

4.1.2 Safety assessment of new fuel concepts

In this chapter safety aspects of current and new fuel concepts are discussed. Four fuel concepts were identified, that draw some attention in nuclear research: new developments in conventional uranium use, application of mixed uranium/plutonium-oxide (MOX) fuel, new concepts and revival of the use of thorium as fuel, and advanced fuel cycle concepts, that aim to resolve some problems of current fuel supply and waste management[57]. These aspects are discussed in the following subchapters.

4.1.2.1 Safety assessment of uranium fuel at high burn-ups

Economic conditions lead in the past and will lead in the future to rising burn-ups of the uranium and MOX fuel that is applied in the predominating light water reactors.

The burn-up of fuel is a measure for the thermal energy, that is produced by the fission process during reactor application of the fuel per mass unit. It is, for historic reasons, usually handled in the unit of Mega- or Gigawatt-Days per metric ton of initial uranium and plutonium in the fuel, called "heavy metal", MWd/tHM, GWd/tHM. Burn-ups in the order of 30 to 40 GWd/tHM are normally reached in older LWRs, while burn-ups of > 40 GWd/tHM in more modern LWRs or the planned burn-up of 60 GWd/tHM for the EPR are considered high burn-ups. The burn-up of fuel in FBRs and HTRs is even much higher due to their core layout and their initial fissile content.

Elevated burn-ups in modern LWRs imply some changes in the conventional fuel and waste sections that have to be reflected and considered for their influence on safety and waste management issues:

- Fewer fuel assemblies are unloaded per year and per reactor, the time-span of their introduction in the core rises, implying elevated quality, corrosion and mechanical stability requirements, including the emergency shutdown system reliability[58], have to be controlled and fulfilled properly.
- Long-lived actinide and fission product inventory as well as residual heat is elevated per unloaded unit of fuel, implying elevated releasable inventories of these nuclides in case of severe accidents and elevated heat dissipation requirements for pond storage, transport and storage casks, interim and final storage of the fuel and of the vitrified high-level waste products, should reprocessing be performed.
- The rest content of fissile nuclides in unloaded spent fuel (U-235, Pu-239/241 in uranium and MOX fuel) is much lower than at lower burn-ups due to the prolonged introduction time-span[59]. Build-up of unfavourable (U-236, Tc-99) and in neutron moderated reactors non-fissile nuclides (Pu-238/240/242) is elevated compared to lower burn-up fuel. Reprocessing and reuse of this fissile rest content is though technically and economically more and more unfavourable, strong incentives to cease reprocessing and reuse of the spent fuel are to be expected.
- Build up of higher actinides with neutron emitting properties (like Cm-244) is elevated exponentially, so during transport and storage either additional neutron shielding

[57] Note that the use of the term "fuel cycle" for fuel supply and spent fuel management is somewhat misleading outside the expert world, because it implies a recycling of the fuel. This term is historical and is in most cases not useful any more. Most of the spent fuel world-wide and in the European Union is not and will not be reprocessed, and for the portion that is reprocessed only the reuse of about 1% of the mass (that is the plutonium) is considered useful under current and foreseeable future conditions.

[58] Emergency shutdown of PWRs requires fast insertion of the control rods into the core. Mechanical instability of the fuel elements could prolong insertion times above specified values or, if mechanical deformation is even more elevated, prevent control rods from insertion.

[59] That means that part of the earlier build up fissile plutonium inventory is already fissioned during the prolonged application period of the fuel.

requirements or elevated criticality issues (e.g. in pond storage) and occupational/public doses[60] (during transportation) will have to be resolved issues.

These change towards elevated burn-ups are of some influence on safety issues. These have to be resolved, but are currently mainly on the level of plant specific regulations and control and less on the general R&D level. Remarkable influence on the general fuel cycle scheme is to be expected by the smaller fissile rest content of fuel because of its strong technical and economical incentives[61].

4.1.2.2 Safety assessment of MOX fuel

Mixed oxide fuel as fuel for LWRs has been introduced in the Eighties. Incentive for its introduction was the fact that it was more and more realised that the formerly expected broad market introduction of fast breeder reactors, for which the separation of plutonium from spent fuel was initially designated for, was unrealistic. This trend has been maintained since, because nearly all formerly operated and planned FBR projects within the EU-15 were either decommissioned or are maintained only on a very small scale. On the other hand the separation of plutonium from spent fuel did not follow this trend and was even increased in the Eighties and Nineties[62]. Separation and reuse of plutonium has not been balanced since, so considerable amounts of plutonium stocks have been build-up, mainly stored at the reprocessing plants.

The following aspects have to be considered in the discussion on the reuse of plutonium as MOX fuel in the currently predominating LWRs:

- The share of MOX fuel, that could be applied in currently operated LWRs, is strongly limited by reactor core stability requirements. Usual modern reactors are limited to one fourth, in most advanced core designs up to 50% (planned EPR) MOX fuel could be loaded. Given this limited share, the limited MOX fuel production rate at the currently planned and operated fuel production plants and the fact that practically no new LWR projects are to be expected any reduction of accumulated stocks will be a very slow process. Production rate and reuse rate will be further unbalanced, even if more MOX fuel will be produced and loaded in the next years.
- Spent MOX fuel has some adverse technical properties that limit its use further on. Among these are its elevated decay heat and neutron production rates per unit spent fuel[63]. Combined with the trend towards elevated burn-ups in LWRs these adverse properties are even multiplied. All following waste management steps (cask design and loading, transports, interim and final storage of spent fuel and vitrified high-level wastes) are technically and economically affected and require redesign and re-adjustment, if certain shares of MOX fuel application are exceeded.

---

[60] Additional dose contributions through neutron emissions have to be seen on the background that neutron dose contributions for certain most exposed groups of the public (certain railway workers) are already a relevant issues during transportation and certain neutron dose relations are currently under discussion.

[61] See also chapter 4.1.3.1 (Once Through/Direct Disposal waste management concept) for additional waste management aspects that point into the same directions.

[62] Extension of the capacity of reprocessing plants UP3 and UP2 in France and THORP in the United Kingdom

[63] Consequences of these properties as already discussed for elevated burn-ups in chapter 4.1.2.1 Safety assessment of uranium fuel at high burn-ups.

- MOX fuel is currently not economic due to the remarkably low and steady prices for uranium fuel and other technical and economic reasons. Given the trend to elevated burn-ups in modern reactors and the rising market pressure in the electricity market the reuse of plutonium will be further unattractive. This will not bring more incentives towards a more balanced production and consumption rate.
- Due to the build-up of new plutonium in the uranium share of a mixed uranium/MOX core and due to the build-up of more higher actinides in the applied MOX fuel than in uranium fuel the reuse of plutonium as MOX in LWRs does not reduce long-term isolation requirements in the geologic repository in any relevant way.

These aspects should be sufficient incentives to develop realistic and more competitive alternatives for plutonium management other than its reuse as MOX. These alternatives would better fit to the trend of slowly decreasing nuclear application of nuclear energy in most of the EU-15 countries and resolve the problem of steadily rising plutonium stocks in a more timely manner.

4.1.2.3 Safety assessment of thorium fuel

Thorium as alternative to uranium fuel was already introduced with the first HTR projects and has a number of technical and proliferation protection advantages. Despite these advantages, that were already realised for a very long time and were discussed ever since, thorium based fuel concepts found no relevant market introduction yet. They are discussed here, because they still are under discussion and their advantages are still relevant.

The technical scheme of thorium fuel supplies (conventional and modern) are described in more detail in section 4.2.3.4, where the proliferation aspects are discussed. Concerning the safety features of reactor use of these fuels see chapter 4.1.2.3. Here, the safety features of the fuel supply and waste management are discussed and technical details are mentioned only, if these are necessary for better understanding.

The main safety features of the thorium fuel concept are as follows:

- Long-term waste management requirements of mining and milling, occupational doses in mining and fuel production, criticality issues in fuel production are typically not very different from the standard uranium fuel supply.
- Pure thorium fuel does not allow reprocessing nor is it attractive as management stage. So emissions, occupational doses and other adverse properties of that processing stage are not applying. As the reprocessing stage is responsible for the major dose contribution of the current nuclear energy production[64]. This is a major difference to conventional uranium fuel use.
- Finally disposed spent thorium fuel, if properly coated, is more resistant than spent fuel or vitrified high-level waste, especially under extreme conditions under certain geologic settings (elevated temperatures of up to 200°C, quaternary salt solution, mechanical deformation under high pressure, geologic formation disruption, etc.). The fuel itself can be considered a more reliable near field barrier than is the case with other high-level waste forms.

---

[64] See Table 2.1-1 in this study.

- The same applies in part for severe accidents involving spent fuel, but these differences are not relevant in most of the accident scenarios.
- Geo-chemically mobile actinides or their daughter nuclides (Np-237, Pu-241 ⇒ Am-241 ⇒ Np-237) are not build-up to a relevant extent, as is the case with uranium fuel. This portion of problematic nuclides in final disposal is eliminated.
- Heat dissipation in interim and final storage is technically easier due to smaller units that can be disposed. This difference is of relative small importance and can be outweighed through additional technical measures for other waste forms.

Overall the thorium fuel concept has some safety advantages over conventional uranium supply and waste management characteristics. In no case relevant disadvantages are to be expected. It must be noted however, that the whole infrastructure from mining and milling to chemical processing and to fuel production is currently not available, as most of the former facilities are not operational any more, partly for more than one decade. Hardware, know-how and supporting infrastructure would have to be reactivated if this technology would be chosen. The technical and financial difficulties of such an effort must not be underestimated.

4.1.2.4 Safety assessment of Advanced fuel cycles

For future applications several alternative or advanced fuel cycles are discussed and in part supported through national and/or EU-wide R&D projects. Among these are the following concepts:

- The Rubbia concept for the treatment and destruction of long-lived by-products of conventional uranium fuel of LWRs.
- In-reactor reprocessing of fuel.
- Pyro-processing of spent fuel.
- Alternative alloy fuels.
- etc.

Most of these processes are on a stage that is not scientifically sound enough to evaluate their principal scientific future, not to speak about their technical or economical prospects. The Rubbia concept has some support by the European Union and is therefore evaluated in more detail. As this concept aims to provide a solution for the unresolved issues of long-term waste management of other fuel this scheme and its safety characteristics is evaluated in chapter 4.1.3.2 on waste management.

4.1.2.5 Summary and conclusions of the safety assessment of fuel concepts

The following conclusions can be drawn from the analysis of different fuel concepts:

- Incentives leading to higher burn-up of fuel in conventional LWRs are a continuing trend and place strong technical and economical pressure on the classical reprocessing and reuse strategies. Several safety issues are to be resolved on a plant specific level.
- The application of MOX fuel, even if its use would be increased disregarding its economic disadvantages and currently small fuel production and use capabilities, does not fit to already accumulated separated plutonium and its still rising production from commercial spent fuel in the EU. Its use is limited also by several adverse properties that

have influence on all following waste management steps, if certain limits of its are exceeded. Development of more appropriate alternatives for its disposition is therefore unavoidable.

- Thorium fuel schemes have some clear safety advantages over conventional uranium or plutonium fuel and are comparable to these in the most other aspects, but are currently not attractive enough, as they would require rebuilding the whole infrastructure.
- Other advanced fuel schemes are currently not addressed by serious research or lack scientific soundness. (The Rubbia concept is discussed as waste management scheme.)

The following recommendations for the EU policy are deducted from these findings:

- The EU should follow the current trend of elevated burn-up in existing and planned LWRs, driven by economic reasons, very closely to set up, if necessary, standardised minimum safety margins required for protection of the public and to strictly guarantee high reactor safety standards even under increased market pressure in the electricity market of the future.
- The issue of accumulated and still rising civil plutonium stocks in the EU cannot be ignored by the EU policy. It seems actually unavoidable to substitute currently missing market mechanisms that lead to this situation, where production and use of plutonium are out of balance. Technical alternatives to the slow and costly reuse as MOX are at hand, but are currently not adequately recognised and supported by EU on the policy and on the administration level.
- Development of thorium fuel cycle schemes should be supported as alternative to main stream fuel cycles on at least a level, that keeps their scientific know-how basis. Supporting market introduction would currently not be useful or appropriate in the current situation.

Another fuel cycle scheme is analysed in chapter 4.1.3.2 of this study.

4.1.3 Safety assessment of waste management concepts

4.1.3.1 Once through/Direct disposal waste management concept

Some of the EU15 member states never chose to reprocess their spent fuel in the past, some have decided not to reprocess all of their spent fuel but only part of their inventory, some have ceased reprocessing after longer periods of reprocessing. As reprocessing has a considerable influence on a number of waste management and safety aspects, the assessment of this management option is included in this study.

Current status of reprocessing and expected future changes

The following Table 4.1-1 provides an overlook on the current policy regarding reprocessing of the EU15 member states.

Table 4.1-1: Current reprocessing strategies in the EU-15 member states

Reprocessing strategy	EU-15 Member State	Remarks
No nuclear energy production	DK, EL, IRL, L, A, P	-
No reprocessing	E, I	Italy has no reactors operational

Ceased reprocessing	B, FIN, S	-
Reprocessing of part of the fuel	F, UK	(see text)
Reprocessing entire fuel	D, NL	(see text)

French fuel is reprocessed partly. While the spent fuel unloaded per year is approximately 1.500 tons, the reprocessing capacity for French fuel at the La Hague UP2 plant was at 400 tons per year, with the current extension of UP2 it is suited for 800 tons per year. Additionally, a relevant amount of fuel already unloaded in the past has been accumulated and was not reprocessed then, so French fuel was not and will not be in the next future be reprocessed entirely.

Part of the spent fuel in the United Kingdom is reprocessed, because their fuel cladding is not stable enough for long-term storage in ponds or for disposal. Uranium oxide fuel reprocessing was partly reprocessed in the past, presently reprocessing is not planned.

Germany follows a policy to cease reprocessing. It is currently planned to end reprocessing whenever the necessary infrastructure for alternative on-site dry storages is available at the plant sites.

The Netherlands have only one electricity generating reactor on line, so can not be considered a relevant player.

The economics of reprocessing and the reuse of reprocessed uranium and plutonium is clearly not competitive to the use of enriched natural uranium. As market pressure is expected to rise within the next decade due to the economic mechanism of current changes in the electricity market, the expected changes to this current situation point into the direction of reprocessing less spent fuel than today.

Steps and options of the Direct Disposal concept

The necessary technical steps to be followed, if reprocessing is not chosen as waste management strategy, are either

a) to keep the spent fuel in extended pond storage at the reactor or in external storage ponds (preferred option e.g. in Sweden), or
b) to package the spent fuel into dry storage casks and store these either on-site or off-site in central storage facilities.

After an extended cooling time of at least 20 years the spent fuel is ready to be disposed directly into a final repository in deep geological formations, if such a facility is available at that time. Prior to final disposal repackaging of the fuel into specially designed casks is foreseen in most of the currently followed waste management plans.

Compared to the reprocessing route, the necessary technical steps are less complex, lead to smaller waste volumes[65] and a much smaller number of different waste forms[66] to be stored and finally disposed.

[65] The difference is mainly caused by secondary wastes from reprocessing that have to be treated (conditioned), stored and disposed off separately. Reprocessed uranium as the main mass fraction (95%) of the spent fuel is currently, and most likely in the future, not used due to its adverse technical, radiological and economical properties and must therefore be added to the waste forms and volumes to be disposed off. At least part of the plutonium, that will not be reused due to economic and other reasons, will also add to the wastes that have to be treated and finally disposed.

[66] Waste forms from reprocessing are at least: vitrified high level waste, compacted and conditioned high radioactive hulls and structural parts of the fuel elements, medium active various solidified sludges from

Safety assessment of the direct disposal route

Several detailed studies on the safety assessment of the direct disposal route have been prepared, most of them in the Eighties. Due to the less complex operations and handling the direct disposal causes essentially smaller public and occupational doses, compared to the reprocessing route. As plutonium currently is not recognised as a relevant contributor to doses in the long-term safety analysis of geologic repositories, the overall assessment shows clear advantages for direct disposal. This is also the case if the whole fuel supply is also taken into consideration: Because collective doses from the reprocessing stage are in every case higher than those in the uranium mining and milling stage[67], the result of the overall assessment is consequently favouring direct disposal. Sensitivity analysis of this data shows that emissions and doses from reprocessing must be reduced to near zero to change this picture essentially.

A specific difference between the two variations of direct disposal, wet and dry storage, is the accident vulnerability. Wet storage requires carefully maintained active cooling of the spent fuel, so loss of coolant accidents (e.g. by longer-term disruption of the energy supply or damage to the pond walls and bottom) are still an issue. Dry storage uses casks, that maintain cooling by natural convection. Overheating of the spent fuel so is only possible in large accidents, where e.g. fallen debris of very big size blocks natural convection around or on top of the cask for a longer time period. The casks usually are designed to withstand several external events and do not need extra protective buildings. No operational emissions take place, as long as at least one of the two independent cask sealing systems is intact. Continued monitoring of the cask sealing and, after detection of leaks, repair or re-packaging is possible.

Another aspect of direct disposal is often discussed: Human intrusion scenarios in geologic disposal sites. Unintended intrusion into geologic repositories has to include probability aspects and the fact that subsequent enhanced spreading of all disposed long-living and geo-chemically mobile nuclides is widely independent from the question, whether spent fuel or high level wastes from reprocessing are disposed.

Another aspect that is currently discussed is the opportunity of re-criticality excursions of disposed spent fuel. This scenario assumes water intrusion into the repository, leaching of the disposed waste, subsequent geo-chemical separation and element-specific sedimentation of the leached material in sufficient quantities and in a geometry that leads to re-criticality. These scenarios are currently under investigation. They might in the worst cases lead to consequences for the repository design or to technical prevention measures (e.g. by-packaging of neutron poisons, depleted uranium), depending on the repository host rock type and other parameters[68].

Currently unresolved problems from past practices

Unresolved issues stem mostly from past reprocessing and are not altered, if the direct disposal route is selected. They must nevertheless be resolved in several of the EU-15 member states:

- In several member states reprocessing plants on the pilot or research scale, in several cases including relevant parts of their radioactive inventory, are still to be decommissioned.

chemical separation and treatment of various liquids, low to intermediate wastes from different sources (contaminated tools, parts and components, protective clothes, etc.), several low to high active wastes from decommisioning of the facility, unused uranium and plutonium.

67 See the doses per unit of generated electricity listed in table 2.1-1 at page 9 of this study.

68 Bowman/Venneri 1996, Kimpland 1996.

- plutonium inventories from past and present reprocessing have been piled up, for which realistic chances for their reuse are still missing. According to the thorough investigation of a Commission of the House of Lords for the UK case, most of these inventories have to be viewed as being waste. This situation is comparable with other member states. Alternative solutions for this problem, that do not prolong this dilemma for additional tens of years from now or base on theoretical solutions requiring additional decades of intensive research, so far haven't been investigated by the EC.
- Other materials with relevant inventories requiring similar long-term solutions are: depleted uranium (several ten thousands of tons), reprocessed uranium (some thousand tons), low- and intermediate decommissioning wastes from several reactors on the research-, pilot- and production-scale, wastes of very low activity from decommissioning and from the clean-up of contaminated sites (from nuclear and non-nuclear applications and sources), incompletely or inadequately sealed sites from past practices (e.g. surface-near low-level waste disposal sites, tails from past uranium mining).

Conclusions and recommendations

The following conclusions can be drawn from this analysis:

- Reprocessing of spent fuel is not the preferred option in most of the EU member states, including those with a considerable current application of nuclear energy.
- direct disposal as management concept has several advantages, including favourable radiological and safety properties, when compared to reprocessing, and is already the favoured option in most of the EU-15 countries.
- Some aspects of direct disposal still require further investigation as is the case with other disposal concepts, but the outcome of these investigations are not expected to be of a decisive nature.
- Several very practical problems, that have been accumulated mostly in the past and are currently unresolved, including huge civil plutonium stocks of some of the member states, lack attention on the EC level, but require technically sound and timely adequate solutions.

The following recommendations for the policy level are deducted:

- Currently unresolved issues in nuclear waste management, especially the plutonium stocks and other nuclear material from fuel production and reprocessing, that has been accumulated in the past, requires more attention. The development of alternatives for their timely handling should be supported. This includes encouragement of solutions, that balance production and use of fissile materials more adequate than this is the case today and has lead to these stocks of materials.
- Some of the accumulated material, namely uranium from enrichment and from reprocessing, requires reliable long-term storage in deep geological disposal. It is currently not well recognised as a potential future problem. Some of the aspects to be further investigated on the EC level would be: minimisation of these wastes, general and practical management of unavoidable wastes of that category, waste treatment and conditioning and their economic and ecological implications, long-term isolation requirements of these wastes, etc.

- Currently still outstanding investigations into some of the long-term aspects of the disposal of spent fuel and reprocessing wastes should be promoted, as all the member states with considerable nuclear applications will face similar problems. This includes scientific and technical aspects of the re-criticality issue and the long-term proliferation protection of final disposal sites for high active wastes, including uranium disposal sites.
- The policy of the EU should more encourage member states to exchange experiences gained in practical solutions for a number of unresolved problems resulting from several past practices and requiring technical as well as scientific support.

4.1.3.2 Assessment of Partitioning and Transmutation as waste management concept

Partitioning and Transmutation is one of the technologies in the waste management section that currently the European Union is giving relevant research input. The assessment of that concept is therefore done in more detail.

Targets of Partitioning

Extended reprocessing or partitioning is the first step of a two-step-process. The whole process is discussed as an alternative to the final disposal of high-level radioactive wastes (HLW) and long-living waste with elevated alpha activity (transuranic wastes TRU, etc.). In the partitioning process, the isolation of certain long-living waste components is the task. The destruction of these waste components is an additional task, that usually is called Transmutation.

Partitioning and Transmutation (P&T) undertakes to isolate and destroy the longer-living waste components. The remaining waste should only consist of shorter-lived radio-nuclides, that decay within a limited, “medium term” time period of some 100 years. The required long term reliability of the isolation for several million years, usually associated with spent reactor fuel and vitrified HLW would not be required for such waste disposal. The targets and advantages claimed for that methods are:

Reduction of burdens that are left for the future generations, as most of the radio-toxicity is destroyed or avoided, seen as an alternative to long-term disposal in geologic formations.

No isolation requirement for the waste, alternative to the isolation in geologic formations for over several million years (half-life time of neptunium-237).

Administrational and safety requirements for final disposal would be less strict, as damage to or failure of the geological formations, selected to isolate the waste constituents from the biosphere, is no longer a decisive issue.

Overall, this alternative promises a solution for one of the currently practically unresolved issues of nuclear energy application, as it is seen by large parts of the general public.

Technical requirements to meet these targets

In order to understand the nature of the required processes Table gives the quantity of some long-living and geologically mobile radio-nuclides, produced by a 1.000 MW reactor in any one year of operation at a burnup of 43 GWd/tSM and 90% operational time.

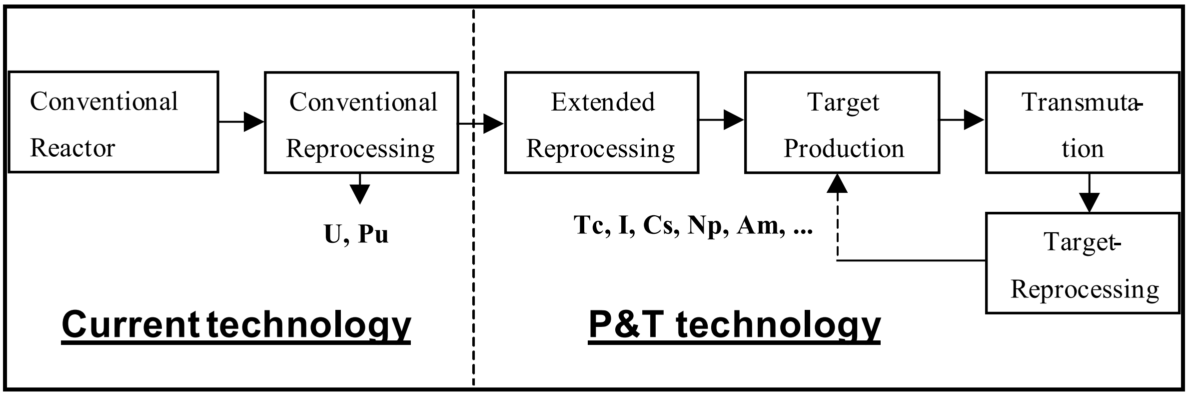
The table shows that the produced long-living radio-nuclides of potential concern in geologic disposal, that would have to be treated in order to reach the target, are in the order of some ten kilograms per year for each nuclide and some hundred kilograms for the long-living Pu-isotopes[69]. Note that it does not make much sense to concentrate on any one single nuclide as the others would still require geologic disposal.

Table 4.1-2: Selection of relevant long-lived nuclides in spent fuel, per year of reactor operation

Nuclide-group	Radio-nuclide	Mass in kg/a produced
Long-lived Fission products	Tc-99	80.4
	I-129	21.4
	Cs-135	40.5
Long-lived Actinides	Np-237	63.0
	Pu-239/240/241/242	536.0
	Am-241	29.5

The necessary technical steps for any reduction or complete treatment of the long-lived radio-nuclides are shown in graph Graph 4..

Graph 4.1-1: Technical steps for Partitioning and Transmutation



The conventional technical steps yield the long-lived products uranium and plutonium, which also would need a complete treatment. Their conventional reuse (re-enrichment of uranium and MOX-fuel production from plutonium, recycling in conventional reactors) does not solve the problem, because the production of long-living actinides (Pu-239 from U-238, Pu-240/241/242 from Pu-239) is always higher than their reduction by the fission process.

Separation of the other long-lived fission products and actinides from conventional reprocessed spent fuel then requires extended separation of these from the high-active waste solutions. The separated nuclides have to be fabricated into target elements, which then would undergo transmutation, either in conventional reactors or in special converters. As the transmutation process is always incomplete, these spent targets require in every case additional separation of the transmutation products and the re-fabrication of the incompletely transmutated mass fraction. For a high destruction rate this recycling process has to be repeated several times, even if high-yield transmutation converters might be available in the

[69] Including Pu-isotope Pu-241 because of its long-lived decay products Np-237 and U-233.

future. All steps require several nuclide specific radiochemical sub-processes and, due to the masses involved, layout on a technical scale.

Completeness criteria for Partitioning and Transmutation

The wastes to be included in this treatment concept must be complete in a sense that no waste category, waste source or potential process leading to waste production can be left out of scope. Otherwise the target of creating an alternative to disposal in geologic formations would only be met for certain parts of the wastes, while others still require geologic disposal.

Besides the economic aspect (two concepts would have to be followed, technically built and operated and separately completed), a principal problem would arise: both solutions require thorough attention and considerable R&D resources, and a decision towards one or the other has consequences, that, in a lot of cases, reach deep into the technical processes that are connected to the production of the wastes.

The completeness requirement has drastic consequences for certain currently established technologies. To demonstrate this, the following example is discussed in more detail:

Currently high level wastes from reprocessing are vitrified using borosilicate glass. These vitrification facilities currently work on a high through-put basis, or are designed and built for such a high rate. The situation in 10 to 15 years will be that a relevant part of the waste inventory of HLW in a number of European countries will then be reprocessed, the fission product solutions are vitrified, filled into steel containers and stored either at the reprocessing plant or in dry storage and transport containers on a storage site. Another relevant part of the spent fuel has not been treated and still remains as such in casks or cooling ponds.

Any further effort to separate long-lived parts of the inventory from these wastes will require to handle three different waste forms, each on a technical scale: liquid high-level waste, vitrified high-level waste, spent fuel. These three different sources all are in a different chemical and mechanical form, requiring special facilities and technical processes.

The separation of the relevant nuclides from its vitrified form, for example, would require dissolving the glass and performing a separation of certain actinides and fission products from the more than 100-fold higher amounts of the borate and silicate from the waste glass matrix. This process must be designed without introducing new potential for the build-up of neutron-captioning, long-living and geo-chemically mobile radio-nuclides in the following transmutation process. The separation of the relevant nuclides, in liquid concentrations of at best a small fraction of one percent, have to be separated then. For these small concentrations separation performances of 99.9% and more have to be performed, otherwise the remaining, now much more bulky wastes still would require geologic disposal[70].

As the chemical properties of the relevant radio-nuclides are all very different, several separation processes for each species are required. In all stages radio-nuclides with high radiation levels are handled. Some of the relevant radio-nuclides (such as Cs-135) are even accompanied by radio-nuclides that emit high-energy gamma rays at a high dose rate (Cs-137, activity > 5 orders of magnitude higher than Cs-135), for which chemical separation isn't possible in general. This task of reaching high separation performances for all the different nuclides and under extreme conditions will require totally new techniques, intensive R&D and technical experience before going to a technical scale.

[70] To reach this performance also means, that any secondary waste streams require own techniques for their treatment.

The other two waste forms (liquid high-level wastes, spent fuel) still would require similar attention, but in large parts very different technical processes due to their different mechanical and chemical form. Compared to currently existing reprocessing technologies, the required technical scheme to treat all three waste forms with the required high performance separation is a highly complex task. The handling of large amounts of highly radioactive intermediate and end products, numerous waste streams of a different chemical form and the decommissioning wastes from all the different facilities add to this complex scheme.

In total, the technical steps to remove the relevant radio-nuclides add up to at least four to five times the technical steps of currently operating reprocessing facilities.

As most of the countries that currently produce nuclear power have a more or less mixed inventory of long-living wastes of very different categories, from different sources and in various forms, the completeness of the partitioning process to replace disposal of HLW in geologic repositories will practically be a very complicated task.

Required performance of Partitioning and Transmutation

To fulfil the task of being a substitute to the disposal of HLW in geologic repositories, partitioning must fulfil certain performance requirements. The radio-nuclides of concern for the long-term safety of the repository have to be removed to a certain extend, otherwise the disposal of the remaining wastes would require geologic disposal anyway. To achieve this,

- the partitioning process must be complete for 99 to 99.99% of the radio-nuclide content of the waste (depending on the radio-nuclides involved),
- the transmutation process must be either complete in the same quantitative sense, or otherwise a multi-step partitioning-and-transmutation process is started, leading to a many-fold of technological wastes, and
- all wastes produced in the necessary technological steps must be treated to reduce the losses of these radio-nuclides via that waste streams.

While the necessary performance (e.g. certain extraction steps) might well be reached in laboratory experiments using substances of well-known composition and chemical form, and under strictly controlled conditions, it must be noted that this requirement is especially important, because it must be applied to processes on a technical quantity level, with several radioactive and non-radioactive by-products of more or less elevated concentration, different mechanical, physical and chemical waste forms, etc. The current technical extraction processes in (conventional) reprocessing is by far not selective enough, because up to 1% of the initial spent fuel is lost into the different waste streams.

It must be clearly stated that the development of these technical processes to the required performance is widely unresolved. The current status of research does not allow a clear perspective, if these requirements could generally be met.

Flexibility of Partitioning and Transmutation to changing needs

Based on currently available reactor technologies (Light Water Reactors, Fast Breeders), most of the radio-nuclides of concern have a very limited capability for transmutation. At best one third of the treated target materials is “burned”. The material then has to go through several cycles, with each reactor cycle being some to some tens of years long. In some cases, nuclide properties are so adverse that transmutation is technically impossible (e.g. for Cs-135[71]). Currently discussed concepts therefore would need several tens of years to fulfil the task.

The required time to treat the wastes requires a very long-term perspective of nuclear power use. Past and current use of nuclear power in all of the EU member states is not such a steadily developing process with clear long-term perspectives. Variations in the political, economical and technical framework of that use have lead to slowly or quick changing perspectives in many countries in the past. In nearly all member states these changes are currently limiting the further use of nuclear energy to the actually operating power plants, practically without any outlook for major changes. Waste management options are only a sub-part and so are a function of these changes. Flexibility in terms of masses, activities, waste forms, etc., is therefore a central requirement for modern waste management. A sophisticated waste management scheme with complex facilities, technologies and multiple steps, lasting for several tens of years, is only appropriate for a very long-term use of nuclear energy on a high base-line of use with a clear view towards, at least, constant or rising contribution. On the other hand, a limited use with a widely uncertain perspective requires an appropriate, easy and unsophisticated waste management scheme and associated facilities, that are flexible and follow the major trends.

Partitioning requires a very long-term perspective of nuclear energy use to be an attractive concept, given the huge necessary investments to achieve a technically sound stage of realisation. This requirement is not met in the current situation, where the longer term use of nuclear energy is under discussion. From the current perspective partitioning is not an appropriate concept to be followed.

Justification of the Partitioning and Transmutation concepts

Partitioning and Transmutation would only be justified, if the net benefit is immense. Those benefits are either of a technical, financial or ecological nature. As the treatment scheme for partitioning is extremely complex, while current waste disposal schemes are rather easy, there is no technical benefit. Financial benefits are not claimed by the proponents of these concepts, and are not to be expected, because of the relatively small net energy production in transmutation[72]. Given also the extreme long time scale of the necessary treatment, financial benefits are not to be expected. The reduction of long-term safety requirements for geologic disposal by reduction of the waste volume and toxicity does not bring relevant financial benefits as most of these costs are fix investment costs (site characterization, site preparation, site closure). The remaining portions of the cost structure of final disposal are operating costs, depending mainly on the operational time. These costs are even higher with P&T, because of the drastically longer time-span necessary. As conventional reprocessing already reaches costs that are a relevant part of the total production price for the electricity, the several additional reprocessing steps for high-level waste and spent targets are at least a many-fold of these costs. There are no financial benefits from P&T.

The ecological benefits of Partitioning and Transmutation are at best a reduction of the toxicity of the wastes to be finally disposed in the order of some 10 percent, depending on the index used to calculate the waste toxicity[73]. As the task of transmuting the entire long-living waste constituents is technically unrealistic (see above), the small reduction of toxicity must be compared with the radiological risks that are introduced by Partitioning and

[71] See U.Wehman et al.: Transmutation of long-lived radionuclides by advanced converters, p.12f.

[72] For the net energy production of advanced converters see Wehmann 1995, p.21ff.

[73] On the problem of defining waste toxicity indices see Kane&Hill 1995.

Transmutation. As has already been shown in chapter 2.1, conventional reprocessing accounts for approximately 80% of the total collective dose of nuclear energy production today, including all necessary fuel supply and waste management steps. Additional reprocessing of the actinides and fission products and of spent targets would cause several times higher collective doses, because the necessary technical steps are more complex and require more steps than conventional reprocessing[74]. The total collective dose from nuclear energy production would be dominated by the P&T activity, if this technology would be introduced.

Conclusions on Partitioning and Transmutation

The following conclusions can be drawn from the analysis:

- Partitioning and Transmutation is not a general alternative to final disposal in geologic formations, because the reduction of all relevant nuclides to negligible levels is technically (and financially) not possible.
- The technical requirements for reducing relevant radio-nuclides to below a relevant extent are extremely complex as different wastes would have to be treated in different facilities and need extended reprocessing.
- Time and resource requirements for Partitioning and Transmutation are extreme, and research and development in that area are only justified, if there is a very long-term commitment to that technology.
- It is, from the current point of view, not shown that there would be any net benefit from such a technology that balances the necessary enormous technical and financial investments.

Recommendations on Partitioning and Transmutation

The following recommendations are derived from these conclusions:

- Investments into research and development on Partitioning and Transmutation should be kept very low until it has been shown on a very detailed basis, that there could be a clear net benefit by the introduction of that technology.
- Adverse technical, financial and environmental effects of that future technology are currently not adequately recognized. These effects should be analyzed in detail.

4.2 Non-proliferation assessment of nuclear fission

4.2.1 Critical nuclear reactor research

4.2.1.1 The EPR as an example of a light water reactor

The European Pressurised Water Reactor (EPR) is a French-German project run by Nuclear Power International (NPI) which is a daughter of Framatome and Siemens AG[75]. It combines

[74] It should be noted that Iodine-129, which is considered a candidate for P&T due to its high mobility and dose contribution in final disposal, is currently mainly discharged to the sea, if conventional reprocessing is chosen. Filtering and final disposal of that radio-nuclide in geologic formations would therefore reduce its dose contribution by far more than P&T currently offers.

[75] Kern 1997.

projects of Electricité de France (EdF) and the German energy suppliers which were separate before 1992. The goal is to develop a nuclear power plant for the international markets, including the EU market. The envisaged power is 1,5000 MW[76]. The safety concept is understood as an evolutionary development based on experiences of French and German plants.

The technical differences between the EPR and existing PWRs stem mainly from the new safety goals. There are no differences relevant for proliferation risks, and therefore, the proliferation risks of an EPR correspond to those of other PWRs or generally to those of light water reactors (LWR).

The proliferation risks of LWRs depend on the fuel cycle used, e.g. whether it is an open fuel cycle in which the spent fuel is disposed of in a final waste storage or whether it is recycled and MOX fuel is used (cf. section 4.2.3 Fuel cycles). In an open fuel cycle, the most proliferation relevant material is the spent fuel which contains plutonium. However, its diversion is difficult for two reasons: Firstly, spent fuel elements are large items and highly radioactive which creates a barrier against diversion[77]. Before the plutonium can be used, the spent fuel must be reprocessed. Secondly, safeguards that create assurance against illegal diversion are comparatively simple because spent fuel elements are countable items[78]. Material accountancy is done by item counting and identification, non-destructive measurements and examination to verify the continued integrity of the item. In addition to the spent fuel, also the fresh fuel elements undergo safeguards which are also simple. Fresh LWR fuel consists of LEU which a proliferator must first enrich before it is weapons usable. Both reprocessing (of illegally diverted spent fuel) or enrichment (of illegally diverted fresh fuel) constitute certain technical barriers against direct nuclear weapons use, which however can be overcome, but whose operation is also likely to be detected (cf. section 4.2.4 Safeguards research). The plutonium gained from reprocessing spent LWR fuel, so-called *"reactor grade plutonium"*, is weapons usable, however has technical disadvantages in comparison to so-called *"weapons grade plutonium"* which has a different isotopic composition[79].

In case of a closed fuel cycle, MOX fuel is used in LWRs. MOX contains plutonium which is normally reactor grade. Fresh MOX is more attractive for proliferators than spent fuel because it does not have a highly radioactive radiation barrier. In case it is diverted, the separation of the plutonium is technically much easier than reprocessing or enrichment. Safeguards on MOX fuel elements are technically the same as on LEU fuel elements. Legally, MOX falls into another category of nuclear materials than LEU which underlies stricter safeguards regulations[80]. The plutonium contained in spent MOX fuel elements is even less favourable for nuclear weapons abuse than that in spent LEU fuel elements, however in principle still weapons usable.

More proliferation risks stem from the other elements of the LWR fuel cycle, e.g. enrichment, fuel fabrication, and reprocessing facilities which are necessary for the operation of LWRs. They are discussed in the section 4.2.3. Fuel cycles.

[76] Nucl. Week 6/99.

[77] For this reason, the U.S. National Academy of Sciences has defined the so-called "spent fuel standard" to be used in proliferation risk assessments of weapons plutonium disposition options. Spent fuel is considered the least proliferation risky state of plutonium. See NAS 1994, cf. also section 3.1.4, criterion 2.

[78] Harms/Rodriguez 1996.

[79] NAS 1994, Kankeleit et al. 1989, and Mark 1993.

[80] LEU is classified as "indirect-use material", MOX as "direct-use material" according to IAEA categories.

4.2.1.2 High temperature reactors (HTRs)

HTRs use graphite as a moderator, and helium as a coolant. Helium, being an inert gas, will not react with graphite at high temperatures, and consequently, allows high coolant outlet temperatures. This results in high thermal efficiencies. The concept of the HTR module has initially been developed by Siemens in the year 1979[81]. In 1988, the efforts of Siemens/Interatom and HRB have been combined in HTR-GmbH. The module is a small HTR with an electric power of 80 MW and a thermal power of 200 MW. The intended use is the combination of electric and thermal power for industrial applications. The intended fuel is LEU (enriched 8%). Its form are particles containing UO_2 coated with pyrocarbonate and silicide carbide imbedded in a graphite matrix. The diameter of a particle is about 1 mm. The fuel elements are spheres containing up to 40 000 of such particles embedded in graphite. The fuel elements can be reused up to a high burn up.

The U-238 contained in the LEU could also be replaced by thorium. As a result, the production of plutonium would be avoided, and instead U-233 would be bred (proliferation aspects of thorium fuel cycles are discussed in section 4.2.3.4). The U-235 contained in the LEU could be replaced by other fissile isotopes (Pu or U-233).

Similarly as LWRs, HTRs can be run without the use of the direct-use materials HEU or plutonium. A proliferator would have either to extract the LEU and further enrich it, or he would have to extract the spent fuel and reprocess it. Because of he special form of the fuel, the process of extraction is technically very complicated and therefore much more unattractive that the comparable process for LWR fuel, though not entirely impossible. In order to gain about 10 kg Pu, about 1 Mio fuel element spheres have to be diverted, fuel extracted and reprocessed. However, the diversion of few fuel elements is easier than in case of LWRs because they have a small size. Because of the high burn-up, much plutonium is fissioned in situ, and larger fractions of higher Pu-isotopes than in LWRs are built. Therefore, less plutonium is contained in HTR spent fuel than LWR spent fuel, and its isotopic composition has a less favourable composition. The incentives for proliferation therefore are rather low. However, this does not eliminate the need for safeguards because diversion is still possible, in case no other more favourable source for nuclear materials is available. As the fuel elements are exchanged continuously, safeguards are somewhat more complicated than in case of LWRs, however feasible.

Theoretically, HTRs could also be used for the disposition of weapons plutonium as is in discussion for LWRs[82]. Because of the higher burn-up, more plutonium could be eliminated. If U-238 is replaced by thorium, no new plutonium would be bred in contrast to LWRs[83]. However, an important aspect in the evaluation of disposition options is their feasibility within the foreseeable future, which is nevertheless measured in decades the least. Therefore, the availability of operating reactors is an essential requirement for this kind of disposition option. As there are not enough operating HTRs in contrast to LWRs, the potential use of HTRs for nuclear disarmament will remain theoretical, at least in the foreseeable future.[84]

---

81 Barnert et al. 1996.

82 Several studies have been conducted about the fabrication of MOX fuel from excess weapons plutonium for LWRs. See as examples US-Russian Study 1997, NAS 1994 and NAS 1995 for the disposition of U.S. excess Pu, and GRS/Siemens/Minatom 1997 for the disposition of Russian excess Pu.

83 Barnert et al. 1996.

84 For Russian disposition scenarios, Russian VVERs are considered as suitable to take MOX, in contrast to RBMKs (Chernobyl-type), see GRS/Siemens/Minatom 1997.

In sum, HTRs pose less proliferation risks than LWRs.

4.2.1.3 Fast breeder reactors (FBRs)

The principle of breeding has been recognised at the very beginning of the development of nuclear fission reactors, and the intended use of the fertile isotopes U-238 and Th-232 for breeding fissile fuel has motivated the development of FBRs. In contrast, LWRs make very uneconomic use of uranium. Principally, FBRs can be designed in a way that they breed more plutonium than is fissioned during the operation, which then can be separated from the spent fuel by reprocessing. In contrast to plutonium from LWRs which is classified as "reactor-grade" except when the burn-up and consequently the quantity gained after discharche are very low, the plutonium from FBRs always has an isotopic composition with a very high Pu-239 content and only a very small percentage of higher isotopes[85]. Therefore it can be classified as "weapon-grade". Such weapon-grade isotopic composition is preferred by NWS, and also by beginner proliferators. The operation of a FBR therefore triggers reprocessing.

Fast reactors principally can also be operated without breeding by taking away the breeding blanket. In German/French/Russian studies on the disposition of Russian excess weapons plutonium, the option of producing MOX FBR fuel from the excess plutonium for the Russian BN600 is seriously considered.[86] The disposition process would indeed be accelerated, as the number of reactors potentially available for taking the disarmament MOX is limited. An important criterion in the disposition decision making is the political acceptance by Russia who insists to include the BN600. The Russian motivation is mainly the continued use of their BN600 reactors and the long-term prospect of the continuation of reprocessing. Technically, it would later be possible to convert a plutonium consuming fast reactor into a plutonium breeding one. The final decision making in this option must weigh the prospect of a nuclear disarmament action in a comparably fast time against the prospect of motivating the continued operation of breeders and reprocessing.

Because of the weapon-grade isotopic plutonium composition and the motivation of a closed fuel cycle, FBRs must be judged as posing more proliferation risks than LWRs.

4.2.1.4 HEU fueled research reactors: the example of the FRMII

There are many variations of research reactor designs. In this section, the focus is placed on research reactors fueled with HEU because they pose special proliferation risks. An example is the research reactor FRMII which at the time is being constructed by Siemens for the Technical University Munich (TUM). One reactor core will contain 8 kg HEU, and five cores would be needed per year. The fuel is planned to be made of uranium silicide. HEU is directly usable for nuclear weapons. The technical barrier to gain metallic HEU from the silicide compound is very low and can be accomplished within a few days, also in less developed states[87]. Spent HEU fuel still contains 70 – 80% of U-235. The protection of the radiation barrier decreases with time and finally disappears, which makes the material readily available.

Because of the high risk of diversion as a result of the extensive global trade in this material, the USA began in 1978 (followed by the Federal Republic of Germany in 1979) to make considerable efforts to minimise the civilian use of HEU, with a view to eliminating it

---

[85] OECD 1989.

[86] See e.g. GRS/Siemens/Minatom 1997.

[87] Nevertheless, the operators maintain that the material is not weapons usable, in contrast to official categories. See TUM 1999.

altogether in the long term.[88] International consensus was gained at INFCE to support this policy (cf. section 3.1.2), and international efforts were started to reduce the enrichment of uranium in research reactors below 20% and to find LEU substitute fuel for use in research reactors. Within the framework of the American RERTR Programme (Reduced Enrichment for Research and Test Reactors), around 50 million dollars were spent on these efforts, and a parallel German programme spent a further 51.1 million marks. Since then many reactors in the USA and Europe switched to the replacement fuel, however some reactors that cannot be converted, and some additional reactors have been left out. But they have a restricted lifetime and their future HEU requirements are also limited. Not a single research reactor designed to use HEU has been built since these efforts began, which means that the end of civilian HEU usage seems to be in sight.

The effect of the FRM II project is therefore undermining this policy efforts of the reduction of civilian HEU use, as it will send a signal to potential imitators in many states, some of them by no means trustworthy, followed by a revival in the almost extinct global trade in HEU[89]. Indeed, there are plans to purchase HEU from Russia, as the amount HEU in the EU is limited. This might create incentives for Russian HEU supply also to other interested parties. Meanwhile, the project is advanced, and a conversion at this time has certain disadvantages which would have been avoided if it would have been designed differently at an earlier time[90].

4.2.1.5 Summary: Risk assessment according to the criteria

Horizontal proliferation (section 3.1.4):

Criterion 1: In all nuclear reactors, the form of the nuclear material are countable items and not bulk material. This applies to fresh fuel, cores, spent fuel, and blankets, if existing. However, the size and number of these countable items might vary considerably, and accordingly, there are differences in the sophistication of safeguards attached to them, however, not specially relevant. As an example, fuel elements in certain types of HTRs are exchanged daily, and on the site, tens of thousands are located. In contrast, the core of the FRM-II consists of just one fuel element. However, what is more important is the kind of fuel. Nuclear material classified as “direct use”, e.g. HEU, plutonium, or spent fuel, necessitates more intense safeguards as “special fissionable material”, e.g. LEU.

Criterion 2: In the comparison of proliferation risks of different reactors, this criterion is the most important one. The number of technical steps towards a nuclear weapon is the lowest in case of reactors that contain unirradiated direct use materials, e.g. HEU or plutonium. This is especially the case in HEU using research reactors whose fuel is directly weapons usable. Fast reactors can produce plutonium of high weapons quality,

[88] A historic case was the Iraqi clandestine nuclear weapon project, in which the plan existed to divert research reactor fuel between two IAEA inspections. The diversion did not take place because of the prior bombardment of the Tuwaitha nuclear complex. See CIA 1996.

[89] It must be emphasised that the likelihood for diversion in Germany is very low because there is no proliferation incentive, good physical protection, and compliance with safeguards. Instead, the proliferation risks stem from the undermining of ongoing non-proliferation policies. See Schaper 1996.

[90] In Spring 1999, a commission implemented by the German Federal Ministry of Research and Education has has evaluated several implications of conversion scenarios to other fuel during the current advanced construction stage, see BMBF 1999.

however there is still the step of reprocessing. LWRs produce plutonium of low weapons quality which results in additional technical steps before a nuclear weapon is constructed. In this comparison, the most technical obstacles are posed by the HTR.

Criterion 3: In most historic cases, civilian nuclear energy has been the disguise in order to cover a clandestine nuclear weapon program. This applies to all kinds of nuclear reactors. Principally, nuclear energy and nuclear reactors therefore pose a certain proliferation risk according to this criterion. The credibility of a recipient that he uses the technology only for civilian purposes must be judged under consideration of additional political circumstances[91].

Criterion 4: Whether a reactor poses additional obstacles to technical non-proliferation measures or whether on the contrary it facilitates them, depends more on the specific design than on the type. Safeguards need key measurement points and technically defined material balance areas. In NNWS and in the EU, such features are already included during the design phase, in contrast to some NWS and states outside the NPT.

Criterion 5: New research reactor projects that use HEU undermine the ongoing non-proliferation policy to minimise the civilian use and the trade of this material. This policy is supported by a broad international consensus. FBRs undermine the policy to discourage closed fuel cycles and to minimise reprocessing, e.g. the production of separated plutonium. There is no international consensus to support this policy.

Vertical proliferation (section 3.2.3):

Criterion 6: Nuclear reactors are not useful for R&D on advanced nuclear weapons, and therefore do not pose risks of vertical proliferation according to this criterion.

Criterion 7: This criterion applies only if there is a risk according to criterion 6.

Criterion 8: Some nuclear reactors can play a useful role in the disposition of excess weapons plutonium and might thereby play a positive in nuclear disarmament. Especially R&D projects focusing on this application will reduce the risk of vertical proliferation.

4.2.2 Accelerator driven subcritical reactors: the example of Rubbia's Energy Amplifier

In accelerator driven concepts, a subcritical core is used that cannot sustain a chain reaction. Additional neutrons are provided by an external neutron source in order to sustain criticality. In the system proposed by Rubbia, this external source is a high energy spallation neutron source[92]. The neutrons are produced by a beam of high energy protons (of the order of 1 GeV) that hit a target of heavy metal and thereby produce spallation neutrons. So far, neutron

[91] This is especially relevant in export regulation of dual-use goods. Recent reforms in several EU states have placed more emphasis in end-use controls. E.g. see: Müller et al. 1994, Müller 1995.

[92] Rubbia et al. 1996 and Rubbia et al. 1997.

sources that would meet the requirement for the proposed systems are not yet a technical reality, and the intensity of the beams still has to be increased. The core will be made of thorium fuel with additional fissile seed, e.g. Pu from spent fuel. Part of the energy gained at the reactor will be needed to feed the accelerator. Because of the high neutron energy, a lot of actinides, e.g. plutonium or actinides from light water reactor spent fuel will be fissioned, but neutron losses by capture are minimised. The reactivity of the system is controlled by the beam power ('a negative control rod'). After a lifetime of about 5 years, the fuel is reprocessed, the actinides are reintroduced, and the fission products are disposed of. The consequence of reprocessing is less radiotoxicity of the waste than from ordinary reactors.

Among the advantages the authors list for their concept are inherent safety, because supercriticality is not possible, minimum production of long lived waste, and proliferation resistance.

4.2.2.1 Proliferation incentives and disincentives

The authors claim that the energy amplifier has "no appreciable proliferation risks" because the diversion of fissile products is ineffective and difficult[93]. The spent fuel will contain hardly any U-235, and the plutonium content will be far less that before burning. But the material streams at the end of the reprocessing process also contain U-233 which, however, is mixed with U-238 that has initially been inserted together with the plutonium seed. The U-233 amount bred is about 170 kg/year, and its content in the U-mix is 63%. The authors maintain that this excludes military diversion[94]. However, this isotope mix is still weapons usable without further enrichment, and therefore must be safeguarded.

The spent fuel will also contain U-232, which will result in the formation of the gamma-emitter Tl-208, as explained in the previous example. It creates additional difficulties for nuclear weapon uses of U-233. But its maximum concentration will be achieved later than the equilibrium of U-233, so that it also seems possible to gain uranium with only a low U-232 content. It also may be questioned whether a radiation barrier will really constitute a strong disincentive for diversion[95].

The technologies involved, e.g. high current neutron beams and reprocessing, also pose a separate proliferation risk. Any neutron source can be abused for the breeding of fissile materials, e.g. plutonium by using a U-238 target or U-233 by using a pure thorium target which would be a rather efficient production method. The absence of such abuse of accelerators therefore must be verified and included in safeguards. In nuclear weapon states and states outside the NPT, neutron beams can be used for the production of tritium by irradiating a lithium-6 target[96]. Tritium is an important component of nuclear warheads. This is not prohibited by any treaty, and does not promote the development of *new* types of nuclear warheads. However, in case more nuclear disarmament will be negotiated on the international agenda, it must be assessed to which extent also the production of tritium should be reduced or stopped. At least it must be possible within the verification of a Future Fissile Material Cutoff Treaty (FMCT) to create sufficient assurance that no illegal production of nuclear weapons material is taking place.

---

93 For a critical assessment of the Rubbia EA see: Pistner 1998.

94 Rubbia et al. 1997.

95 Recent discussions and negotiations whether the highly radioactive americium-241 should be submitted to international safeguards confirm these doubts. U.S. nuclear weapon specialists maintain that it is possible to use this material for nuclear explosives despite its radioactivity. However, this is doubted by specialists from some other nuclear weapon states.

96 This is currently under consideration in the U.S.

The incorporation of reprocessing also poses a certain proliferation risk because this technology can be diverted for other operations than declared. Proliferators in less developed states therefore would have less problems in the acquisition of clandestine reprocessing technology in case they possess already an energy amplifier.

4.2.2.2 Summary: Risk assessment according to the criteria

The above listed criteria will be applied also to this example:

Horizontal proliferation (section 3.1.4):

Criterion 1: Safeguards of the reactor will be necessary in order to create assurance that no illegal diversion of uranium enriched in U-233 takes place. The technical methods are as sophisticated as in ordinary light water reactors. Additionally, verification that the target which is irradiated by the neutrons is composed as declared, will be necessary. Technical methods are available and their sophistication is comparable to that of other verification task. Safeguards at reprocessing facilities are much more complex than at a reactor, because bulk material and not only accountable items such as fuel elements must be accounted for. The inclusion of reprocessing therefore necessitates more complex safeguards than an open fuel cycle.

Criterion 2: In case a proliferator diverts the U-233, it is likely that he faces additional technical difficulties to use it for a nuclear warhead because of the radioactive contents of Tl-208. The risk of proliferation is therefore somewhat smaller than that of ordinary light water fuel cycles according to criterion 2.

Criterion 3: The degree of civilian-military ambivalence of a Rubbia energy amplifier is comparable to that of an ordinary light water reactor. The plausible civilian disguise that proliferators would use is in any case the civilian energy supply, in case of the energy amplifier also the transmutation of actinides.

Criterion 4: According to this criterion, there would be a higher risk for the fuel cycle that incorporates reprocessing.

Criterion 5: The Rubbia energy amplifier runs counter the policy of discouraging closed fuel cycles, e.g. reprocessing. Therefore, according to criterion 5, it constitutes a higher proliferation risk than the ordinary concepts. However, promoting the civilian use of fuel that poses more technical obstacles to nuclear weapons abuse could constitute a policy that reinforces non-proliferation goals.

It must be noted that non-proliferation is only one aspect of the Rubbia concept. The major motivations for its proposal are safety and disposal benefits, which have not been discussed in this paper.

Vertical proliferation (section 3.2.3):

Criterion 6: Nuclear accelerators can also be used for basic physics research, e.g. measurements of special **cross** sections and other nuclear data. In principle, these data can also be used for nuclear weapons research, however only on a very theoretical level. Therefore, this risk must not be overestimated.

Criterion 7: In case an accelerator would be operated in international collaboration, specific nuclear weapons experiments and abuse for the clandestine production of fissile materials for weapons become more unlikely.

Criterion 8: The verification of an FMCT and the policy goal of implementing safeguards also in nuclear weapons states might face some more obstacles, in case the EA would be used for military tritium production.

4.2.3 Fuel cycles and waste management concepts

4.2.3.1 Direct disposal

Direct disposal is a strategy that is increasingly being used by many states, including in the EU. As an example, the German Atomic Law that until a few years ago prescribed reprocessing now also allows intermediate storage of spent fuel with the final goal of geological disposal. However, German utilities have problems ending reprocessing because of a shortage of intermediate storage. It must be expected that with the strategy of direct disposal, spent fuel will be still stored at reactor sites or at intermediate storage sites for some time to come. As long as spent fuel is still retrievable, there is always the possibility that it might be diverted for non-peaceful uses, and therefore it must be safeguarded. In case of diversion, the proliferator will still have to surmount the step of clandestine reprocessing which has a certain detection probability. Safeguards on spent fuel in an intermediate storage site are comparatively simple. While for medium time scales, it can be assumed that safeguards will create sufficient assurance against diversion, this does not hold for very long times[97].

In a final repository, safeguards are planned to cease, under the assumption that the fuel is practically irrecoverable. Nevertheless, the radiation barrier that spent fuel poses against diversion will fade, and principally, it cannot be excluded that in the far future, also a final storage site might be mined for retrieval of plutonium, although technically it is perhaps easier to mine new uranium for new plutonium production. The necessity to continue with safeguards and physical protection also on a final repository will depend on the accessibility of the fuel[98]. For intended intrusion into a geologic repository, it has to be compared if the clandestine intrusion, removal and processing of the material is more likely and technically easier than the clandestine production of materials with a comparable or better suited quality for that purpose in other facilities. This scenario must be viewed on the background that every repository will contain material requiring some proliferation protection measures (e.g. uranium in huge quantities and of various fissile content) and mining activities to some hundred meters depths with the intention to transport heavy shielding casks of at least some tons of weight are comparatively easy to detect (e.g. by satellite monitoring).

In the assessment of proliferation risks of disposition options for excess weapons plutonium, the U.S. National Academy of Sciences recommended two options, the vitrification of the plutonium together with HLW for direct disposal in a final geological site or use as MOX including irradiation in reactors and subsequent similar final disposal[99]. Intermediate storage of separated plutonium was not recommended because it is direct use material and the technical barrier against a reuse for nuclear weapons is much lower. Especially in Russia, the long term political developments cannot be foreseen, and the option of reuse for nuclear weapons would still be available. The emphasis in this study was placed on the "spent fuel standard", which is served by spent fuel and irradiated MOX elements and which is less

[97] For democratic NNWS, it can additionally be assumed that there is no such incentive in foreseeable time scales. Neverthelss, nobody questions the need for safeguards.

[98] Kurihara et al. 1997.

[99] NAS 1994.

proliferation risky than separated plutonium (cf. criterion 2 in section 3.1.4). The strategy of direct disposal avoids the occurrence of separated plutonium. Practically in the next future, it will result of intermediate storage of spent fuel.

The vitrification option in the excess plutonium disposition discussions also serves the spent fuel standard. But is disliked by the Russians who prefer recycling. However, at nuclear weapon factories, there are scraps and residues that are unsuitable for MOX production. It is likely that they will be disposed of with vitrification. The costs of this disposition option depends very much on the amount of plutonium that can be added to vitrified HLW without causing criticality problems. The long term behaviour of such plutonium containing glass blocks still needs R&D.

It is recommended to devote such R&D efforts in order to maximise the amount of plutonium per glass solution. The French-German-Russian project of disposition of Russian weapons plutonium as MOX should also be pursued, as it would constitute the first practical nuclear disarmament step that would result in enhanced irreversibility of nuclear disarmament, and in international safeguards on the processes (cf. section 3.1.2.2). It is also recommended to invest in R&D that focuses on safety and security of final geological storage sites[100].

4.2.3.2 Conventional reprocessing

Conventional reprocessing is used for the retrieval of plutonium and uranium. Both materials are recycled for civilian use, especially as MOX fuel for LWRs or FBRs. The fuel cycle therefore contains elements that contain or produce the unirradiated direct use material plutonium. Plutonium can be used for nuclear weapons without the technical barriers of enrichment or reprocessing. There are different qualities of plutonium, depending on the isotopic contents (cf. section 4.2.1.3 Fast breeder reactors (FBRs)), nevertheless, they all are principally weapons usable. The technical barrier to gain plutonium from unirradiated MOX fuel is also very low.

Safeguards at reprocessing plants are more complex and more expensive than at any other facility.[101] In contrast to reactors, reprocessing plants and fuel fabrication plants deal not only with countable items but also with bulk material. Furthermore, reprocessing requires the dealing with very high radioactivity, and a plant consequently contains a lot of special equipment for its containment. The processes involves many material streams of different compositions in shielded pipes, tanks, and reservoirs whose material compositions and plutonium contents must be measured and assurance must be created that any illegal diversion from these flows will be detected. Such measurements have a certain inaccuracy which depends on the intrusiveness of the inspections and on the type of the facility, e.g. whether during its construction, it has already been designed to be submitted to safeguards, and whether its instrumentation is reliable or not. Errors in calculated plutonium contents can at times exceed a significant quantity[102]. They stem from biases in solution measurements, difficulties to determine the exact Pu content in spent fuel, time delays of sample analyses, and measurement limitations because of radioactivity. Similarly, at fuel fabrication facilities, complicated material streams may occur, although far less radioactive.

---

[100] An example for such research is Sylvester/Simonson 1996.

[101] Shea 1999.

[102] A *significant quantity* is a definition by the IAEA meant as the approximate quantity of nuclear material in respect of which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded. In detail, the amount of material for one warhead can vary considerably.

There are variations whether a reprocessing plant is used only for plutonium separation or also for separation of americium and neptunium. At the time being, negotiations at the IAEA are underway on the proposal to submit Am-241 and Np-237 to international safeguards. It is uncontested that a nuclear explosive can be made from Np-237. If this material is separated during reprocessing of spent LWR fuel, considerable quantities become available. U.S. nuclear weapon specialists maintain that it is also possible to use Am-241 for nuclear explosives despite its radioactivity[103]. However, this is doubted by specialists from some other nuclear weapon states. At least, extreme technical sophistication would be necessary for this purpose. Although the negotiations are not yet completed, it must be expected that new control regulations concerning both or one of these materials will be implemented.

The worldwide accumulated quantities of separated civil and military plutonium amount to several hundred tons, sufficient for MOX fuel for many decades[104]. The secure conversion and disposition of military plutonium will take many decades, which is a longer time than the predictability of political stability in several states where this material is located. As the technical barrier for military abuse is low, it is recommended not to increase the quantities of these materials even further and to work instead on disposition options that serve the spent fuel standard.

4.2.3.3 Multiple recycling with Partitioning and Transmutation (P/T)

P/T has been recommended as an option for the disposition of plutonium, e.g. nuclear disarmament[105]. The quantity of plutonium declared as "excess" to defence needs is about 50 tons in the U.S. and in Russia, respectively. One of the most important criteria in the evaluation of disposition scenarios is a relatively short time scale. In case it would be possible to eliminate tens of tons within the next decades, this option should be seriously considered. However, as has been shown in section 4.1.3.2, the technical realisation of such disposition scenarios in the foreseeable future is highly uncertain. Therefore, soon benefits for non-proliferation and disarmament cannot realistically be expected. Because of the complicated reprocessing technology involving even much more complicated waste streams than in conventional reprocessing, very sophisticated safeguards will be necessary that first must be developed.

4.2.3.4 Thorium fuel cycles – the example of the Radkowsky-Concept

A new reactor concept that has been praised as "proliferation-resistant" is the Radkowsky-concept that uses thorium fuel[106].

thorium-232 is a fertile but not fissile material. Exposed to a neutron flux, it results in fissile uranium-233 which can be used for nuclear energy but is also regarded as an effective nuclear weapon material:

$$\text{Th-232} \xrightarrow{(n,\gamma)} \text{Th-233} \xrightarrow{\beta} \text{Pa-233} \xrightarrow{\beta} \text{U-233}$$

---

103 Goodwin/Kammerdiener 1999.

104 Albright et al. 1996.

105 This proposal was especially promoted by the Los Alamos National Laboratory, USA.

106 Galperin et al. 1997. For a critical assessment of this article see: Glaser 1998, see also: Kasten 1998.

Pure thorium has no fissile component. Therefore, in order to start a fuel cycle fissioning U-233, a fissile seed material, e.g. U-235 or Pu-239 is necessary. Upon irradiation, fuel containing thorium builds up U-233. Additional non-fissile uranium isotopes are created within the thorium transmutation chain, e.g. U-232, U-234, and U-236, reducing the weapons usability of the uranium contained in the fuel.

In the Radkowsky concept, a heterogeneous fuel assembly is proposed. Each fuel element consists of a thorium part which is a subcritical blanket and of a core which is a supercritical seed. In the blanket, U-233 is generated and fissioned in-situ. The goal is to have full compatibility with existing pressurised water reactor power plants which are mainly the western PWR design and the Russian VVER design. The core will consist of LEU. The core fuel is replaced more frequently than the blanket fuel in order to achieve a large accumulated burnup of the thorium part of the fuel. The geometric parameters can be optimised in order to reduce the build-up rate of plutonium isotopes and to produce a high U-233 build-up and efficient fission-rate.

The authors argue that this concept is much more proliferation resistant because the quantity and the quality of the fissile material for military use is far less than that of standard PWRs[107]. The incentive for reprocessing the spent fuel is reduced in comparison to standard PWRs because its contents of potentially reusable materials is lower. Quantitatively, the core fuel of a standard reactor whose annual discharge would be 24 tons of uranium with 1.0 % of U-235 and approximately 250 kg of plutonium with 73 % fissile content (Pu-239 + Pu-241) would contain only 3 tons of uranium with 4.7 % U-235 and 37 kg plutonium with 62 % fissile content, in case it would be loaded as proposed by the authors. The blanket would contain 120 kg of “low-quality” plutonium with 53 % fissile content and 3.9 tons uranium, with 16 % U-233 and 1.4 % U-235, in addition large amounts of 'poison' uranium isotopes. The low quality and the comparatively lower quantity would cause reprocessing to be much less attractive than for a corresponding PWR fuel cycle.

It must be counter argued that this holds only if alternatives are available. The author’s claim that the “low-quality” isotopic composition of the plutonium eliminates the attractiveness for nuclear weapons is based on the assumption that the proliferators have only access of a primitive nuclear weapon technology, comparable to that of the earliest U.S. design. With higher assembly speeds and more sophisticated designs, it would still be possible to use this material for a nuclear warhead, which is also admitted by the authors[108]. The reduced attractiveness therefore does not eliminate the need for safeguards.

The complexity required to separate the fissile component from the normal material flow of the fuel cycle is higher. In order to reduce diversion risks of U-233 from the blanket, it is denatured by addition of slightly enriched uranium. As consequence, the accumulation of pure U-233 is avoided. In principle, the uranium may be chemically separated from the blanket spent fuel and further enriched. The authors list the following barriers against this route:

- The recycle material will be contaminated by Tl-208 which originates in the U-232 chain and which is a hard-gamma emitter.

---

[107] Galperin et al. 1997.

[108] NAS 1994. On the weapons usability of low grade Pu, (e.g. reactor-grade Pu) see Kankeleit et al. 1989 and Mark 1993.

- The enrichment will be inefficient: removal of U-234 and U-236 will also remove the U-235, and residual U-234 and U-236 will reduce the criticality.
- Enrichment in U-233 will also enrich U-232, exacerbating the Tl-208 gamma problem.

It would be much easier to enrich natural uranium. However, the poisoning effect of U-234 and U-236 is much less than that of U-238, because the fission rate is still much higher[109]. An enrichment process could be optimised for extraction of the atomic masses from 233 to 235 without losing too much of the product's nuclear weapons usability.

The concept still necessitates fresh LEU fuel enriched to 20%. Although this fuel is not directly weapons usable, the investment for further enrichment is much lower than for the enrichment starting with natural uranium. In non-nuclear weapon states, the production and use of LEU is subject to IAEA safeguards.

It would also be possible to extract the intermediate nuclide protactinium-233 which has a half life of 27 days. After a short irradiation time of the fuel, its concentration is not neglectable any more, and immediate reprocessing could gain a substantial quantity which then would decay into U-233. If a pure thorium assembly would be irradiated, even extended irradiation would be possible.

4.2.3.5 Summary: Risk assessment according to the criteria

In order to compare the proliferation risk of the fuel cycle presented, the above listed criteria can be applied:

Horizontal proliferation (section 3.1.4):

Criterion 1: The safeguards efforts for an open fuel cycle without reprocessing are much less sophisticated than those for one that includes reprocessing, because it involves many additional processes and facilities. According to criterion 1, S/T would pose the largest risks, direct disposal the smallest. The **safeguards** efforts for the Radkowsky fuel cycle would be just as sophisticated as for the current open light water reactor fuel cycle, as the designs of the reactors are very similar. The probability that a country might chose recycling is much reduced in case of the Radkowsky fuel cycle. For this reason, the risk according to criterion 1 might be judged as reduced in a general comparison to standard light water reactor fuel cycles.

Criterion 2: The technical obstacles that proliferators face until they manage to fabricate a nuclear warhead are the highest for the direct disposal waste management, because they would still need either **reprocessing** or enrichment. In closed fuel cycles, these technologies or unirradiated direct use material would be available. The Radkowsky fuel cycle poses additional technical obstacles. In case a proliferator tries to divert weapons usable material, e.g. U-233, U-235, or Pu, the number of steps towards a nuclear weapons has increased, and therefore, this fuel cycle can be judged as less proliferation risky than the ordinary LWR fuel cycle. It must be noted, however, that the obstacles are not insurmountable and that the risk is not reduced to zero.

Criterion 3: The **plausible** civilian disguise that proliferators would use is the civilian energy supply, similarly for all waste management and fuel cycle concepts.

[109] Glaser 1998.

Criterion 4: Technical non-proliferation measures are the most effective for the open fuel cycles and the most difficult for C/S. Thorium or uranium open fuel cycles can be judged the same according to criterion 4.There is no difference in technical non-proliferation measures such as analytic tools or surveillance technologies.

Criterion 5: Some states, especially the U.S., have the policy of discouraging closed fuel cycles, e.g. reprocessing, **because** they pose additional proliferation risks[110]. Reprocessing is a contradiction to such a policy. The Radkowsky concept has the potential of reinforcing this policy, and therefore, according to criterion 5, constitutes a smaller proliferation risk than the ordinary concepts.

Vertical proliferation (section 3.2.3):

Criterion 6: None of the presented concepts has any special use for R&D on advanced nuclear weapons, and therefore **none** does pose risks of vertical proliferation according to this criterion.

Criterion 7: This **criterion** applies only if there is a risk according to criterion 6.

Criterion 8: There is the remote prospect that C/S one day could play a useful role in the disposition of excess weapons plutonium and might thereby play a positive role in nuclear disarmament. However, this remote prospect is outweighed by other disadvantages.

4.2.4 Safeguards research

Science and technology have played a prominent role in safeguards since many decades. Many technologies are in a mature stage and a lot of experience has been assembled. However, today we are witnessing a period of transition in nuclear arms control, disarmament, and reforms of the non-proliferation regime, which will necessitate further developments and their deployment.

The activities are an integral part of a European co-operation, the European Safeguards Research and Development Association network (ESARDA). EU funded R&D takes place especially at the JRC institutes at Ispra and Karlsruhe. A major purpose is support to the Euratom Safeguards Directorate and the IAEA in Vienna. Moreover a call for tender was made to organise a network of laboratories.

On a practical level, the relationship between Euratom and the IAEA has been defined in cooperation agreements[111]. In contrast to INFCIRC/153, the agreement between Euratom NNWSs and the IAEA (INFCIRC/193) makes the distinction between sensitive (i.e. those dealing with HEU and Pu) and non-sensitive facilities. At sensitive facilities, there had been joint teams of inspectors from both agencies. At other facilities, the principle of observation was applied, and the IAEA only verified Euratom safeguards. The problem emerging from this agreement was a lot of unnecessary duplication. This has led to the New Partnership Approach (NPA) in April 1992 which has enhanced cooperation and effectiveness and

[110] Several other countries using nuclear energy do not share this policy.

[111] The safeguards agreement between the Agency, Euratom, and the EU's NNWS; this agreement, INFCIRC/193, is modeled after the NPT-model safeguards agreement INFCIRC/153; the agreement with the EU, the UK, and the IAEA: INFICIRC/263; the agreement with the EU, France, and the IAEA: INFICIRC/290, and the partnership agreement of April 1992.

reduced duplication of efforts[112]. A new agreement between the IAEA and Euratom incorporating the 93+2 reform is on the negotiation agenda.

4.2.4.1 Overview on safeguards methods

Safeguards methods include declarations on status, design information, and material accountancy, containment and surveillance (C/S) techniques, inspections, and detection of undeclared activities. Material accountancy is carried out on a first level at each nuclear facility by the operators. Methods of material accountancy depend on the kind of facility, and they include *non-destructive analyses* (NDA) which are based on the physics of spectroscopy, *destructive analyses* (DA) based on radiochemistry. In NNWS, a national material accountancy is set up by a national authority, the *State's Systems of Accounting for and Control of nuclear material* (SSAC) whose task is also to report to the IAEA and to be responsible for the technical and for the national legal implementation. EU member states do not have national SSACs, instead their common SSAC is Euratom. SSACs are based on a structure of *material balance areas*, on each of which the inventory must be accounted for. The inventory and all entries and removals must be measured physically with defined precision for each balance areas.

The next components of the verification are technical equipment that the verification authority will install in the facilities, so-called containment and surveillance techniques. It includes seals, detectors, monitors and cameras recording any action occurring in a particular area of a nuclear installation. They allow detection of undeclared movements of nuclear material, and potential tampering with containment and/or surveillance devices. In light water reactors, as an example, cores are usually not opened more than once per year. Therefore, it is often possible to seal the reactor pressure vessel head. The more sophisticated such an instalment is and the more automatisation it incorporates, the less on-site inspections are necessary for the same level of assurance that no material has disappeared. Automated data transfers to the verification agency adds to the reduction on necessary on-site inspections.

The verification is completed by inspections. The goal is to provide assurance that all declarations are correct, e.g. that the operational status and design of facilities is as declared. Also, containment and surveillance equipment must be checked. Particularly, the material accountancy must be verified, e.g. physical inventories and streams of nuclear materials must be confirmed. The methods to achieve the inspection goals depend on the type of the facility. The details of activities during an inspection depend on the plant and will include combinations of the following:

- observations, measurements and tests whether the design information is correct;
- installation of containment and surveillance technologies;
- installation of detection technologies for proscribed activities;
- auditing of accounting records and comparison with reports;
- measurements for the control of accountancy, which include volume and concentration and enrichment measurements of nuclear materials in streams, tracking the movement of solutions, and taking samples in case of bulk facilities, or in case the material is in the form of countable items as in a reactor, counting, identifying, and examining them by non-destructive means to verify their continued integrity;

[112] Thorstensen 1994.

- additionally, environmental samples may be taken, as a means to detect additional undeclared operations.

Measurement data taken from inspections and from laboratory analyses are used to establish an independent material accountancy which is compared to the operators declaration.

The proliferation cases of Iraq and North Korea triggered the safeguards reform INFCIRC/540 which has enhanced the IAEA's capability to detect undeclared activities[113]. An important component of the reform among many elements is taking environmental samples not only at an inspected facility which is already legal but also in the vicinity under certain circumstances. Environmental samples can be taken on a random basis from the atmosphere or as part of inspections at suspicious locations or from their vicinity. Operating clandestine facilities, e.g. reprocessing and enrichment plants, reactors, fuel fabrication plants and others release characteristic effluents whose chemical and isotopic compositions can be analyzed. The results allow to establish well defined suspicions.

Another element of the reform is the possibility of information gathering. This allows the inclusion of information from many sources. This information can be *national technical means* (NTM), e.g. all activities that are not regulated by an international organisation and that is passed on by States to the verification authority.

The reforms include enhanced safeguards training, improving the efficiency of the safeguards system, increased cooperation with national or regional SSAC, especially with Euratom.

4.2.4.2 New challenges to safeguards and new research tasks

New challenges to safeguards arise from following developments:

- the implementation of INFCIRC/540,
- cooperation with the newly independent states (NIS) in establishing national SSACs and improving their installations at nuclear facilities for MPC&A,
- submitting excess material from dismantled nuclear weapons under international verification measures,
- the improvement of the effectiveness and efficiency of the present system,
- preparations for the verification of the FMCT.

The elements of INFCIRC/540 that necessitate the most R&D are environmental sampling and information gathering. They will also play a prominent role in the verification of the FMCT. Samples taken from the environment must be analysed much more precisely than samples taken from nuclear materials at plants. So far, most of the research has been done by U.S. laboratories. The techniques have been used the first time in Iraq inspections. Euratom considers them as essential to be applied also for Euratom safeguards.[114] Several problems must still be solved: more laboratories must be able to perform such analysis in order to allow counter checks, and there are still problems of how to interpret the results, e.g. there is still a high probability that false alarms will be raised[115]. These challenges arise especially at large reprocessing plants and in the plutonium cycle, including MOX fuel.

---

[113] This reform has formerly been known by the name “93+2”.

[114] Gmelin/Kloeckner 1997.

[115] False alarms can be caused by cross contamination. An example is the scenario in which visitors from a HEU producing enrichment plant leave traces of HEU at a plant that produces only LEU. The new techniques are able to detect such traces.

Also information gathering is not only based on legal reforms[116], it needs additional technologies that have not been used before in safeguards. They include especially satellite images which can be used for the detection of power and effluents of clandestine enrichment and reprocessing facilities, and reactors, and other clandestine nuclear acquisition activities, e.g. uranium mining, construction of facilities, or test preparations[117]. R&D must focus on the specific interpretation of satellite images. So far, this kind of activity is pursued mainly in the U.S. A European candidate for such projects also in nuclear arms control could be the Space Applications Institute in Ispra, Italy, that is part of the Joint Research Centre. The use of satellite imagery will also play an important role in FMCT verification[118].

For the improvement of the effectiveness and efficiency of the present system, including cost effectiveness, the use of technology must be consistently increased[119]. Manpower of inspectors must be replaced by using unattended measurement stations, data loggers and other automatically operating devices. R&D needs are the incorporation of new information technologies for improvements and automation, system analysis with the goal to reduce inspector presence, the automatic generation of data and their transmission to the safeguards office, the development of generic instrument software packages for use and training, maintenance cost reduction and standardisation.

Requirements for the further improvement of measurement technology comprise a long list including calibration of detectors, miniaturisation, or improvement of on-site analysis capabilities[120]. Also objectives for the development of C/S equipment exist, they include high performance multi-camera systems, archival software for large data sets, cheap seal technologies based on electronics and fibre optics enabling remote interrogation, electronic tag technology, remote transmission of signals, and more.

Efforts should be made for maximum standardisation in safeguards which will result in savings and rationalisation. It will also be beneficial for the cooperation with the NIS and improving their safeguards instalment.

4.2.4.3 Summary: Risks assessment according to the criteria

Horizontal proliferation (section 3.1.4):

Criterion 1: R&D on safeguards technologies naturally does not need any safeguards themselves, therefore, this criterion is not applicable.

Criterion 2: Safeguards technologies as such do not offer any benefits for nuclear fission weapons components.

Criterion 3: A side-effect of safeguarding sensitive facilities might be that it is abused for spying. This applies especially to human inspections[121]. automatisation therefore would be a means to reduce this risk. The risk is rather remote and well known at Euratom and the IAEA. Safeguards therefore must be shaped in a way that too

[116] Before the implementation of INFCIRC/540, a lot of information could not be used by the IAEA because of legal restrictions.

[117] Fischer et al. 1994; Jasani 1996; Zhang/von Hippel 1999.

[118] It can also be used as NTM in the CTBT verification.

[119] Gmelin 1996.

[120] Gmelin 1996.

[121] A historic example is the clandestine nuclear weapons programme of Iraq. Iraqi inspectors tried to spy on nuclear technologies, and they also systematically studied IAEA safeguards in order to circumvent them. See Hamza 1998.

sensitive information is protected while at the same time assurance can be created that operators comply with their obligations. This requires sometimes so-called *managed access* procedures which have become increasingly common in arms control. They are individually negotiated between inspectors and plant operators[122]. They will play an especially important role in the implementation of INFCIRC/540 because these new measures will be more intrusive than before. Managed access methods will also be necessary used for safeguards on nuclear materials stemming from dismantled nuclear weapons, because sometimes, this material will still reveal sensitive information. Many safeguards technologies are beneficial for reducing this risk, such as seals and authentication which allow to lock materials in containers while assuring that the containers have not been opened. Another example is monitoring of the entrance and exit of a nuclear weapons dismantlement facility that might become relevant in future nuclear disarmament[123]. Sealed and authenticated computer automatisation of nuclear analysis that protects sensitive measurements while giving only final results is one more example[124].

Criterion 4: Nuclear safeguards technologies are aimed at reinforcing non-proliferation measures and thereby reduce horizontal proliferation risks.

Criterion 5: Non-proliferation policies that are reinforced by nuclear safeguards technologies are listed in the **beginning** of the preceding section 4.2.4.2. INFCIRC/540 is especially aimed at the early detection of clandestine nuclear weapon programmes, in order to avoid the repetition of the Iraq experiences. The new techniques will play an important role in it. Rationalisation and cost effectiveness will enhance the acceptance. Cooperation with the NIS is especially important for further nuclear non-proliferation and arms control measures. It is also reinforcing measures to stem illicit trafficking of nuclear materials.

Vertical proliferation (section 3.2.3):

Criterion 6: Safeguards technologies do not offer any benefits for advanced nuclear weapons.

Criterion 7: This criterion can only be applied if criterion 6 gives a meaningful answer.

Criterion 8: Ongoing arms control and disarmament policies that will benefit from new safeguards technologies are the FMCT, the implementation of safeguards on nuclear materials from disarmament, and the implementation of SSACs in the NIS. SSACs are a necessary prerequisite for the implementation of full-scope IAEA safeguards (e.g. INFCIRC/153-type safeguards). Many NNWS advocate full-scope safeguards on the civilian nuclear fuel cycles also in NWS. While this would be no technical problem for France and Britain whose civilian nuclear fuel cycles are subject to Euratom safeguards anyway, and probably only a minor technical problem for the U.S who has high accountancy and control standards, substantial technical problems would be created in Russia and China, and in the future also for the states outside the NPT, should they decide to adhere to it. International cooperation on the necessary technologies would greatly reduce these risks, promote transparency, and thereby promote the acceptance for verification measures and safeguards. Euratom as a regional safeguards system incorporating both NWS and NNWS is especially well suited to serve as model for other regions, e.g. East Asia, or, still more utopian, the

[122] Similar problems and solutions arise often because of the need to protect commercial information.

[123] A future START III Treaty is intended also to verify the dismantlement of nuclear warheads, as announced by presidents Clinton and Yeltsin at the Helsinki Summit in March 1997.

[124] Suggested in Fetter et al. 1990, see also Tian et al. 1995.

Middle East. The technical measures on which cooperation is likely to start must go beyond the traditional methods. Especially rationalisation and cost effectiveness will be important criteria for their acceptance.

5 Nuclear fusion research

Energy generation by fusion reactors represents a physically and technically completely §innovative approach compared with customary fission reactors. Whereas in nuclear fission heavy atomic nuclei (e.g. uranium and plutonium) are split by bombardment with neutrons, in fusion light atomic nuclei (e.g. deuterium, tritium, helium) are fused. In both principles useful heat is generated by the released binding energy of the atomic nuclei. In nature, fusion takes only place in fix stars like the sun.

The principal problem that this research faces is the fact that fusion reactions take only place when the hydrogen is heated to an extreme temperature, about 100 millions degrees, and when additionally it is confined at a sufficiently high pressure and a sufficiently long time. At these conditions, the hydrogen is a plasma which means it consists of completely ionised atoms and electrons. The isotopes that fuse the easiest are deuterium (D-2, composed of a proton and a neutron) and tritium (T^{-3}, composed of a proton and two neutrons). The fusion reaction products are a helium nucleus (He-2) and a neutron. Gaining energy from the fusion of fuels without radioactive tritium (e.g. only deuterium or deuterium with helium-3 and boron-11) would also be conceivable physically. However, reactions of these nuclides require higher plasma temperatures and deliver lower energy yields. Because of the difficult technical implementation resulting from this, the current development efforts are concentrated on reactors with tritium as fuel.

As it is impossible to confine such a hot plasma just by vessels made of ordinary matter, other confinement methods are needed. The research works on confining and heating the plasma. It can be divided into two classes, magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

In magnetic confinement fusion, which is the major fusion reactor concept followed in the EU, large and strong magnetic fields of complicated forms are explored, along whose magnetic lines the ionised particle move. As consequence, the hot plasma can be confined in a "magnetic field cage", whereby direct contact with the surrounding walls and thus rapid cooling can be avoided. The current most widely advanced concepts for fusion reactors are based on annular (toroidal) magnetic confinement of the plasma. The plasma is held on an annular orbit by magnetic fields inside a vacuum-tight plasma vessel (torus). In nuclear fusion, apart from heat, the products of combustion and free electrons, there also arise free neutrons which penetrate the surrounding walls and cause activation of the structural materials by nuclear reactions. New tritium as fuel can also be bred with these neutrons. Lithium, for instance, which is introduced into the wall directly adjacent to the plasma ('plasma facing components') and thus is exposed to a high neutron flux, can be provided for this. As the developer see a closed fuel circuit within the plant should be made possible in this way.

In the current developments research is concentrated on the two experimental types of stellarator and tokamak. They differ essentially in the geometry of the confining magnetic field and in the type of plasma heating. The currently most advanced concept for a future fusion reactor, which is also used as the basis in the following discussion, is based on the tokamak type. The first concepts for reactor models are already available for this type.

An enormous development effort is still required up to the technical implementation of a fusion power station, for example with regard to achieving a permanently burning plasma and with regard to optimising the material composition to minimise radiological problems with the largest possible load carrying capacity and durability of the components. As next development step a test reactor with which an independently burning plasma is generated and the required technologies for a future fusion reactor will be tested is planned with the ITER ("International Thermonuclear Experimental Reactor", thermal power 1.5 GW). The results of this experiment should flow into the design of the DEMO reactor planned to follow, which already should fulfil all functions of an energy gaining power station, but not yet work economically. The middle of the 21st century is aimed at by the development engineers for the first availability of an economically working reactor[125].

The essential safety-related aspects of a future fusion reactor on the basis of the currently available concepts are described and discussed below. These aspects are compared with corresponding data on the customary fission reactors currently in operation. In this case pressurised water reactors with high output (> 1000 MWe) are used as scale for comparison.

5.1 Safety assessment

5.1.1 Accident risk of fusion reactors

5.1.1.1 Inventory of radioactive materials in a fusion reactor

The radioactive inventory of a fusion reactor is determined essentially by the radioactive fuel of tritium as well as by structural materials of the reactor components which have been activated by neutron bombardment. The entire tritium inventory in the fusion reactor should amount to approx. 2 kg according to the SEAFP study in 1995[126]. This amount corresponds to an activity of around $7*10^{17}$ Bq.

The amount of activity in the structural materials depends upon the composition of the materials and the neutron flux to which they are exposed. The components of the "first wall" are of especial importance here, since these are located closest to the plasma and therefore receive the highest neutron dose. Two models of fusion reactors are discussed in the SEAFP 1995[127] report. The stated activity inventory due to activated structural materials is between $1.7*10^{20}$ Bq and $1.3*10^{21}$ Bq for these models[128].

The total activity inventory in a fusion reactor is thus comparable with the inventory of a fission reactor of comparable size. Nevertheless no safety engineering statement can be derived as yet from these data alone, since both the radiological properties of the activated nuclides and their chemical properties codetermine the radiological risk.

5.1.1.2 Possibilities of releases of radioactive material from fusion reactors

The overwhelming share of the tritium inventory of a fusion reactor is located in the structural materials of the first wall ("Plasma Facing Components" - PFC) and in fuel storage (Buffer

---

[125] HGF 1996; Barabaschi et al. 1996.

[126] SEAFP 1995, p.28.

[127] SEAFP 1995.

[128] SEAFP 1995, p.29.

Storage Bed). Because of the high mobility of the tritium, in the case of accidents with the loss of the surrounding retention barriers (piping of the fuel circuit including the torus, reactor building) a considerable amount of the tritium inventory can be released.

The overwhelming part of the activity inventory is formed by the activated structural materials. The activated nuclides are bonded in these materials and the possibilities of their release due to an accident are much lower in comparison to accident processes with core melt in the currently operating fission reactors. A part of the activated materials is present in the torus as dust, which is generated by plasma tearing or bombardment by electrons and is in the cooling circuit of the fusion reactor. These components can be mobilised relatively easily and released in the case of accidents with loss of the retaining barrier.

Several accident processes are discussed in the SEAFP 1995 report[129]. In the accident processes considered there no confinement loss is assumed and therefore credit is obtained from filter effects. Occurrences with a loss of all barriers are considered possible in the SEAFP 1995 report only in external events with extreme energies[130]. Such scenarios were not investigated. A restriction was made that the danger potential which results from activated dust may have to be corrected when the results of the next fusion experiments are available. However, it cannot be concluded from these investigations that no larger releases will result in all conceivable accident processes in future fusion reactors. It must be considered that the final design of future fusion reactors is not yet determined and that in current accident considerations marginal conditions, which can change in the future, are assumed.

5.1.1.3 Radiotoxicity of the inventory of fusion reactors

Because of its chemical properties (tritium is an isotope of hydrogen) tritium is very mobile in the biosphere and is easily absorbed by organisms (e.g. through water). The radiological assessment of tritium has been discussed controversially internationally for a long time. Whereas there is no radiation exposure due to direct radiation from the outside with tritium because of its radiation properties, radiation exposure occurs after incorporation of tritium in the body through inhalation or through food consumption (ingestion). The particular problem of tritium results, according to the evaluation in Öko-Institut 1995[131], from the fact that because of different radiological effects, which occur after incorporation of tritium, the radiation exposure after incorporation calculated according to the current method is not appropriate to the possible resulting risk. According to that report it appears by all means appropriate to assume that the calculated effective equivalent dose after incorporation due to tritium can increase by a factor of 3 to 4 compared with the current calculation methods.

In contrast to a fission reactor, the radioactive nuclides arise nearly exclusively due to neutron activation in a fusion reactor. No relevant actinides and fission products, as arise in a fission reactor, are formed. Radioactive noble gases, which are of importance in the early phases of accidents in fission reactors, play no role in fusion reactors. The radiotoxicity of the neutron-activated structural materials of a fusion reactor is comparable with the activation and fission products which arise in the operation of a fission reactor. Radiation exposure after accidents can result from direct radiation or from incorporation of the released radioactivity. Direct radiation into the surroundings from activated plant parts or in areas which are contaminated with activated materials (e.g. dust) result from the intensive gamma radiation of the activated

129 SEAFP 1995.

130 SEAFP 1995.

131 Öko-Institut 1995, p.17.

nuclides. Radiation exposure due to incorporation of radio-nuclides can occur due to the inhalation of released radioactive aerosols or due to the ingestion of deposited contamination through food and drinking water.

5.1.1.4 The worst-case releases from fusion reactors

As the worst-case release of tritium due to an accident, an order of magnitude of 1 kg (corresponding to 10 MCi = $3{,}7 \cdot 10^{17}$ Bq) is assumed[132]. It is assumed there that the largest share of the released activity in the case of accidents in a fusion reactor is due to the tritium. The amount of activation products released in the worst case in an accident is estimated to be significantly less[133]. However, reliable estimates can be made only if the detailed design of an economically operating fusion reactor is available and sufficient experience with regard to the creation of mobilisable activation products is available.

Because of the different physical and technical principles, comparable accident scenarios with core melt, which must be assumed in the worst case in nuclear fission reactors, cannot occur in fusion reactors. Especially since the overwhelming share of activity in fusion reactors is bonded in the structural materials, scenarios with the release of activity amounts of the order of magnitude of severe accidents in fission reactors (order of magnitude of 10^{19} Bq) are therefore not be expected in fusion reactors. However, accident processes in which parts of the radioactive inventory are released and lead to catastrophic effects in the surroundings cannot be excluded even in fusion reactors.

5.1.1.5 The maximum possible off-site consequences of an accident in a fusion reactor

The data on the worst conceivable radiological consequences of accidents fluctuate considerably in the literature. In earlier work, it is assumed that the worst possible dose under the most unfavourable conditions is less than 2 Sv[134]. In the Pease report, a maximum individual dose under the most unfavourable conditions of 100–200 mSv is stated in the case of tritium release[135]. SEAFP 1995 values less than 4 mSv were determined for all examined accident processes[136]. By comparison much higher ingestion dose values were determined according to the calculation principles for the German radiation protection ordinance in Öko-Institut for these accident paths investigated by SEAFP (for Model 2 solely taking account of tritium emissions more than 100 mSv or even at 3 Sv)[137]. By other authors, these calculations are clearly contradicted and it is stated that unrealistic or incorrect calculation principles are responsible for such extremely high estimates[138]. Natalizio assumes that a value of 1 Sv can be set as conservative reference dose for a severe accident in a fusion reactor[139].

These values are some orders of magnitude below the maximum radiation doses which are expected in severe accidents in fission reactors. The highest individual doses in accidents in

---

132 Natalizio 1996.

133 Natalizio 1996; SEAFP 1995, p.56f..

134 OTA 1987, p.107.

135 Pease 1989, p.26.

136 SEAFP 1995, p.57-59.

137 Öko-Institut 1995, p.52.

138 Schittenhelm 1995.

139 Natalizio 1996.

large PWRs in the surroundings of the plant are around 100 Sv according to Öko-Institut[140]; the maximum collective dose according to the "Deutsche Risikostudie Phase A" is $2.6*10^6$ man·Sv[141]. UNSCEAR calculates the collective dose of the Chernobyl accident to a total of 600,000 man·Sv[142]. Nevertheless the discussion about the radiological consequences of severe accidents shows that according to the previous state of knowledge, severe accidents with considerable transgressions of radiological limits outside the plant cannot be excluded in fusion reactors as well.

5.1.1.6 Power density, switch-off behaviour and reactivity characteristics of fusion reactors

The power density in a fusion reactor at 3 to 20 Watt/cm^3 in the plasma and blanket is clearly lower in comparison to the power densities of 50 to 100 Watt/cm^3 in the core of large pressurised water reactors.

Certain parameters must be complied with to maintain a fusion reaction in a tokamak. These include:

- The temperature of the plasma must be very high (of the order of 100 million degrees).
- The plasma density must be sufficiently high (approx. 10^{14} particles / cm^3, this corresponds to a vacuum).
- The energy may not be dissipated too quickly (sufficiently high energy confinement times – impurities increase the heat transport from the plasma).

To maintain these conditions, the products of reaction (helium) and other plasma impurities must be dissipated sufficiently quickly from the plasma chamber. Any change of the operating conditions leads to plasma instabilities and causes the burning process to fail.

Moreover the plasma contains only a low amount of fuel (burn duration in the minutes range) and must be constantly supplied with fuel.

For these reasons, disturbances of the magnetic field, disturbances of the fuel supply, disturbances of the vacuum or impurities in the plasma lead to instabilities and to termination of plasma burning. Power excursions because of an uncontrolled increase in reactivity (as is possible in chain reactions for example) cannot occur in a fusion reactor. A power excursion due to uncontrolled increase of the fuel supply would lead to an end of the burning because of the high temperature loading of the surrounding structures and the release of gaseous impurities connected with this.

5.1.1.7 Short- and mid-term cooling requirements and decay heat of fusion reactors

After a fusion reactor is shut down, the residual heat is determined essentially by the radioactive decay of the activation products in the structures. According to the data in the SEAFP report the total decay heat immediately after the shutdown (in the 1st minute) is around 100 MW (PWR approx. 150 MW)[143]. The mean after-decay power within the first day is 13 or 22 MW for the two models (PWR approx. 40 MW) and in the first month 4 or 8 MW (PWR approx. 10 MW).

[140] Öko-Institut 1994.
[141] DRS 1980.
[142] UNSCEAR 1993.
[143] SEAFP 1995.

Thus the residual decay heat in a fusion reactor is comparable with a large PWR. However, while the heat-generating nuclides in a PWR are concentrated in the fuel elements and in this way high specific reheat powers arise, from which a core melting necessarily results if there is a loss of cooling, corresponding nuclides in the material of the first wall are distributed over a larger volume in a fusion reactor. Thus considerably lower specific thermal outputs arise and thus longer heating times. The development engineers assume that even in the case of complete failure of the cooling, the melting points of the structural materials are not reached[144].

5.1.1.8 Barriers in fusion reactors

In the reactor models presented in the SEAFP report a distinction is made in total between three barriers for retaining the radioactive inventory[145]:

- 1st barrier: The vacuum vessel for the plasma (torus) including the supply units (e.g. fuel supply, vacuum system).
- 2nd barrier: An expansion volume made of pre-stressed concrete into which the vacuum vessel should blow off in the case of a pressure failure.
- 3rd barrier: A confinement made of pre-stressed concrete surrounding the reactor building which envelops these units completely.

If one compares these barriers with a conventional PWR, then the first barrier corresponds closest to the primary circuit with reactor pressure vessel and the third barrier to the PWR containment. Moreover, the fuel matrix and fuel element cladding are viewed as barrier in a PWR. An analogous barrier exists in fusion reactors solely for the activation products which are bonded in the structural materials. A corresponding barrier does not exist for the tritium and the activated dust.

Failure of the first barrier is conceivable in accidents with coolant incursions into the vacuum vessel. The water vapour spreads into the expansion volume through a rupture disk. Accident processes in which leakages occur from the expansion volume into the reactor building are described, the released products can reach the environment from there in a filtered form. A failure of the third barrier is not assumed in these scenarios.[146]

To what extent the named barriers of a fusion reactor can be considered as independent in accidents and the examined scenarios cover the worst cases can be determined in the final analysis only by accident analyses on the basis of a fusion reactor designed in detail. This appears not yet to be sufficiently possible on the basis of the current state of knowledge.

5.1.2 Operational risk of fusion reactors

5.1.2.1 Radiation exposure of the operating personnel of fusion reactors

Radiation exposure of the operating personnel can result from the radioactive fuel (tritium) and from the irradiation of the activated structural materials. According to SEAFP the main

[144] SEAFP 1995, p.38.

[145] SEAFP 1995.

[146] Bunz 1996.

part of the radioactive exposure of the operating personnel results from the activated structural materials[147].

According to SEAFP the expected doses of the operating personnel for the Model 1 will be at 0.2 manSv/a and thus in the magnitude of the values for PWR optimised over long operational experience.[148] In the case of Model 2 the value is clearly higher at 15 manSv/a and is thus comparable with the exposure which has occurred in the past with PWR[149].

Here the question arises whether at the present time all radiation exposure caused by possible planned and unplanned repair and maintenance measures can be covered with such estimates. Because of the high exposure of the materials of components inside the vacuum vessel to thermal radiation and particle bombardment, these must be replaced cyclically. The effectively required maintenance and repair effort cannot be determined at the present time, since the determination of essential design parameters of a fusion reactor requires further development steps. The replacement, handling and storage of these components will be scarcely possible without remotely controlled devices and expensive shielding measures because of the high activity. Thus the resulting operational radiation exposure for the personnel depends from

- the frequency with which the components have to be changed,
- the extent to which the individual working steps can be performed remotely controlled or automatically, and
- how fail-safe the corresponding procedures can be implemented.

It therefore appears questionable whether in a completely new concept with novel techniques and advanced solutions for the different material problems, the expected collective doses can be complied with or bettered from the start. On the basis of experience with LWRs, it can be expected that the collective dose can be reduced only after lengthy operating experience with a larger number of fusion reactors, combined with certain improvements in material selection.

5.1.2.2 Operational releases of fusion reactors

The main contribution to the radiation exposure of the general population in the surroundings of a fusion reactor will presumably result from tritium emissions. According to older evaluations, it should be possible to limit the annual tritium release to 1 g (= 3.7×10^{14} Bq) per plant[150]. In SEAFP it is assumed that the radiation exposure due to emission of tritium in normal operation (in both models $2\text{-}3 \times 10^{14}$ Bq/a[151]) can be limited to less than 0.002 mSv[152]. However, such high retention of the very mobile tritium is doubted in the discussion[153]. The statements on the possible tritium retention fluctuate by three orders of magnitude. Stating reliable values will be possible probably only from experience with plants in reactor size and corresponding tritium inventories.

The tritium emission values stated for fusion reactors are at least a factor of 10 higher than the highest operational tritium emissions of all German PWRs[154]. In 1995, the average of the

---

[147] SEAFP 1995, p.35.

[148] SEAFP 1995.

[149] UNSCEAR 1988.

[150] Cannon 1983.

[151] SEAFP 1995, p.31.

[152] SEAFP 1995.

[153] Kalinowski 1993.

[154] BMU 1997.

nineteen operating reactors in Germany emitted $5 \cdot 10^{11}$ Bq per year atmospheric tritium, the ten more advanced plants ≥ 1 GW averaged to $7 \cdot 10^{11}$ Bq/a per plant[155]. The individual radiation exposure from all emitted radio-nuclides in the surroundings of German nuclear power stations caused by the exhaust air are essentially between less than 0.001 mSv/a and about 0.005 mSv/a.

Collective doses from local, regional and global dispersion of atmospheric releases of tritium are estimated to $4.4 \cdot 10^{-15}$ Sv/Bq for reactors in areas with population densities typical for industrialised countries[156]. Currently operated modern reactors ≥ 1 GW would cause typical collective doses of 0.03 man·Sv/a caused by atmospheric tritium emissions, while emissions of $2\text{-}3 \cdot 10^{14}$ Bq/a tritium per year from a future fusion reactor would cause collective doses in the order of 1 man·Sv/a. This is in the same order as currently operated reactors, if all their emissions on all pathways are included in the calculation[157].

Care must be taken in interpreting the individual and collective dose figures in a comparison, as more than 90% of these dose are caused by Carbon-14. Carbon-14 emissions are currently not discussed for fusion reactors, because the basis for an evaluation is even less reliable than for tritium emissions. Emissions of C-14 result from different neutron interactions. It cannot be excluded on that stage of knowledge that similar interactions occur within a fusion reactor, e.g. with the carbon content of structural materials. In that case, the individual and collective doses might be totally dominated by the emission of other radio-nuclides than tritium. Re-evaluation of the doses from operational emissions in more detail in the future could therefore as well come to different results.

Thus the stated operational radiation exposure in the surroundings of fusion reactors is at least comparable with radiation exposure of PWR currently in operation. However, in view of the controversial discussion about the retention of tritium and the large uncertainty about emissions of radio-nuclides other than tritium such comparisons can be made at the present time only under reservation.

5.1.3 Long-term waste management and handling of nuclear wastes from fusion reactors

Because of the high exposure due to thermal and particle radiation when operating a fusion reactor, the plasma facing components must be replaced regularly. The waste arising in this case contains neutron-activated materials and in part also tritium. Other plant parts can also be contaminated by carry-over of radioactive nuclides (tritium diffusion; activated corrosion products, cleaning processes), whereby further radioactive waste can arise. These waste quantities must be handled when operating the plant and when it is dismantled.

Compared with the waste from pressurised water reactors, the waste from fusion reactors shows a more favourable decay behaviour because of only insignificant amounts of long-lived fission products and actinides. However, long-lived radio-nuclides are also present in waste from fusion reactors. Indeed it is attempted to keep the activity of the long-life nuclides as low as possible by optimising the steel composition. Under the intensive neutron bombardment in a fusion reactor certain additional amounts or even very small impurities can lead to long-life nuclides. Nuclides with half-lives of up to some millions of years cannot be avoided completely, if those materials are produced on a technical scale. Some of the nuclides

[155] Calculated from individual plant emission data from all operating european reactors as published for various 5-year periods by DGXI.

[156] UNSCEAR 1993, UNSCEAR 1998.

[157] As calculated from 1985 to 1995 emission data and the UNSCEAR 1998 collective dose relations.

considered are e.g. Be^{14}, C^{14}, Mn^{53}, Ni^{63}, Nb^{93m}, Ag^{108m} and Pb^{205}, as listed in the SEAFP report[158].

One of the nuclides that are currently not addressed in these analyses is Be-10. It is build up from natural Beryllium (Be-9, 100% abundance) by neutron capture. Beryllium is the best candidate as cover material and so will be the material that is most exposed to neutrons from the fusion process. Be-10 has a half-life time of 1.51 million years, its specific activity after the use in a fusion reactor is to be expected in the order of some 10^5 Bq/g. That specific activity is very far above any criteria for an uncontrolled release as being harmless in the radiological sense. It is not short-lived and does not reach current release criteria after an institutional control time of some hundred years. Hence, it requires isolation times like those typical for current high-level wastes in a deep geologic repository (approximately 10 million years). Above all, it must be expected as being geo-chemically very mobile, in a comparable hydrochemical mobility class like Iodine-129, Calcium-41, Chlorine-36 and Technetium-99 (in the +V stage. It therefore requires special attention in any long-term safety analysis for a deep geologic repository. Similar to this radio-nuclide other long-living nuclides with half-life times much longer than 100 years have to be considered. Thus in the operation of a fusion reactor wastes requiring geologic final disposal also arise in an considerable amount.

As Beryllium as one of the key materials concerns, a larger scale application of fusion energy production could be limited by natural resources of that material. To extend its availability it is considered to recycle and reuse it in the fusion reactor process[159]. As it has the above mentioned specific activity already after its first use in a fusion reactor, any further treatment and handling of that material is subject to

- radiological control measures (like emission control, shielding, accident prevention measures, etc),
- public and occupational collective doses,
- long-lived secondary waste production.

Any reuse cycle adds up roughly the same amount of specific activity to the material, so the reuse would not reduce but enhance these requirements and problems[160].

Not only long-living nuclides are sources for potential material problems, but these also arise from the tritium content of the fusion waste insofar as tritium can be released during storage of the waste. Large-scale storage and disposal of tritium-contaminated materials still has to be demonstrated as being technically and economically feasible[161].

The waste amounts arising from a fusion reactor correspond to the waste amounts from a fission reactor (including the waste amounts from reprocessing)[162] or are higher. The SEAFP report estimates approx. 58,000 t or 93,000 t of radioactive waste for the two models considered for the total operating time of a fusion reactor[163]. If the service lives of the plasma

158 SEAFP 1995, p.62.

159 SEAFP 1995.

160 The high accumulated specific activities of the materials can also be a serious limit for its reuse, when the necessary material properties change with the number of cycles.

161 SEAFP 1995, p.61.

162 Bartels 1992.

163 SEAFP 1995, p.60.

facing components should be shorter than hoped for, a corresponding increase of the waste requiring ultimate disposal would be expected[164].

Therefore, whereas the amount of waste is presumably larger and thus more unfavourable in comparison to the reference PWR, the composition of the waste can be estimated as much more favourable with regard to long-term storage. Because of the absence of relevant amounts of actinides, no criticality problems occur. For parts of the waste, cooling over some years will be required because of the production of heat in the decay of the activation products. However it can be expected that the corresponding cooling problems are low in comparison to cooling the highly active spent fuel elements of a fission reactor.

It is stated by the development engineers that a large part of the waste arising can be recycled again after an adequate intermediate storage time and can be used in new reactors. The provision and supervision of enormous intermediate storage capacities over many decades is required for this. According to the SEAFP report recycling rates of 70% to 90% are hoped for after a intermediate storage time of 50 years[165]. Nevertheless such high recycling ability is considered to be much too optimistic[166].

5.1.4 Summary of the safety aspects of fusion reactors

The above analysis shows that there are serious shortcomings concerning the assessment of safety risks in nuclear fusion to the following respects.

The radiation exposure of the public from a fusion reactor under operation as well as under accident conditions depends mainly on the radio-toxicity of tritium, the emissions of radio-nuclides other than tritium and from the released amounts of these radio-nuclides. But there is neither a consensus in the assessments of possible resulting risks of incorporated tritium nor is the amount of released tritium sufficiently known at present. Therefore the radiological risks resulting from future fusion reactors are only known with wide uncertainties. Because the radiological risks are probably an essential factor regarding the public acceptance for new nuclear energy plants, it is necessary to estimate the maximum possible risks resulting from the release of tritium, taking all these uncertainties into account.

Therefore we recommend to commit the further development of fusion reactor with examination of the resulting maximum radiological risks from tritium and other radio-nuclides. Such examinations should, beside the accident and operational risks from a fusion plant, also include the risks from all necessary fuel supply facilities and other handling stages (like tritium production plants, transportation of tritium and wastes, recycling facilities, primary and secondary waste treatment and storage, final disposal of long-lived wastes).

Up to now, it is uncertain to what extend the production of necessary low activation material is realistic in the required technical amounts, taking technological, radiological as well as economical aspects into account. If such a production is technically impossible or economically unrealistic, the realization of a fusion reactor fulfilling the intended radiological targets (regarding the direct radiation from components and the radio-toxicity of the waste) is jeopardized. Another essential aspect of material production is a possible non-radioactive public risk resulting from plants processing toxic materials (for example: Beryllium as a

---

164 Öko-Institut 1995, p.37.

165 SEAFP 1995, p.64.

166 e.g. in Öko-Institut 1995, p.39.

covering for the first wall). It is essential for the further development of a fusion reactor to establish the feasibility of the production of low activation materials and other materials needed in fusion reactors in the required amounts to build several fusion plants.

Therefore we recommend to commit the further development of fusion reactor with feasibility studies regarding the technical and economical aspects of producing the materials for fusion reactors in the required technical amounts. These studies should also include the assessment of radiological and non-radiological risks resulting from all materials which are processed in supply, recycling and disposal facilities.

5.2 Non-proliferation assessment

5.2.1 Proliferation risks of fusion reactors

The major civilian research goal of fusion research, especially MCF, is a reactor for energy supply. A fusion reactor would provide neutron fluxes which would be much larger than those of ordinary light water reactors. Although a reactor based on pure fusion would not use or produce nuclear weapon usable materials, the neutrons could be used for breeding plutonium or U-233. As the neutrons have a hard energy spectrum, the isotopic composition of the gained plutonium would be more favourable than that of ordinary LWRs. However, safeguards for creating assurance that no clandestine production takes place are feasible and comparatively simple.

In case the reactor would be used for breeding civilian fissile materials, e.g. a so-called fission-fusion hybrid reactor, the necessary safeguards would be more sophisticated because the quantity of produced materials must be accounted for and assurance must be created that no illegal diversion takes place. So far, no detailed assessment of such safeguards exists. In a preliminary assessment it seems likely that the degree sophistication of hybrid reactor safeguards will be roughly the same of those of LWRs. The measures attached to control a LWR reactor core can be assumed to be comparable to those attached to a breeding blanket because both, LWR core elements and breeding blanket elements, are countable items. Safeguards attached on countable items are significantly less difficult than safeguards on bulk material as in fuel fabrication and reprocessing facilities because the material accountancy necessitates much more complex technologies and procedures. Material accountancy is the basis of safeguards.

A hybrid reactor, however, would trigger reprocessing which involves bulk material. It would need more sophisticated safeguards in order to create sufficient assurance against illegal material diversion. The incentive for diversion of plutonium would be higher than that of plutonium stemming from LWRs because of the more favourable isotopic composition. A hybrid reactor would also stimulate policies of closed fuel cycles.

Advanced fusion experiments will work with deuterium-tritium (DT) fuel. DT fuel is also an important component of advanced nuclear weapons, where it is used for “boosting” the fission chain reaction by additional fusion neutrons. For beginner proliferators, however, tritium does not yet play a role because simple nuclear weapons operate without boosting. However, the three states presumably possessing nuclear weapons that are not party to the NPT, e.g. India, Pakistan, and Israel, probably have reached a technical stage in which tritium supply might be very interesting for them.

Legally, tritium underlies export controls in the EU, but its production is not subject to any international arm control treaties, and it is also unlikely that it will be included in the scope of a future FMCT. The reason is that tritium decays with a half life of about 12 years and that any ban on the long term would lead to a short-cut of tritium and thereby constitute an indirect disarmament measure. Although this might be a desirable policy goal, so far it is not yet accepted by the NWS[167]. Breeding tritium from Li-6 in a fusion reactor to be used as its own fuel is part of the civilian fusion energy concepts. But it is very likely that NWS will use tritium produced this way also for nuclear weapon supply. As a result, there will be dual-purpose facilities, e.g. used for civilian and for military tritium supply.

This poses a challenge for a nuclear disarmament policy: The FMCT will necessitate verification of the absence of illegal plutonium or U-233 production and diversion. Many states, including several EU states, prefer verification measures similar to the safeguards in NNWS[168]. Principally, neutrons are needed for plutonium production. Consequently, all neutron sources must be subject to verification measures also in NWS. In case a neutron source, e.g. a fusion reactor, is used not for plutonium but for tritium production, the facility will be subject to certain secrecy measures which poses additional challenges for verification[169].

5.2.2 The role of ICF research and development for nuclear weapons

In ICF, the deuterium-tritium mix is placed in a small shell with diameters of the order of one to a few millimetres. This so-called "*pellet*" is then heated rapidly by intense laser or heavy ion beams. As a result, the outer skin ablates, and the recoil pushes the rest of the pellet inward where it is compressed to very high density. In the centre, the collapsing matter is heated to the extreme temperature, so that the fusion processes can start. Fusion of most of the compressed fuel takes place more rapidly than the re-expansion. This method is called inertial confinement fusion.

The risks described in section 5.2.1 hold for all fusion reactor concepts, including MCF and ICF. However, there are additional proliferation risks posed by ICF stemming from the nature of research.

In contrast to MCF most of which takes place as internationally organised projects, the largest ICF projects are organised and financed nationally. The reason is that ICF is much more significant for nuclear weapons research and poses more risks for vertical proliferation than MCF. Some aspects of R&D are therefore classified in nuclear weapon states and take place only nationally. Nevertheless, R&D on ICF has also civilian goals, and on these, international cooperation takes place and projects in the EU exist.

The processes involved in ICF research are very similar to those in a hydrogen bomb. Upon ignition, the secondary of a hydrogen bomb which contains fusion material is exposed to the extremely hot radiation released by the primary which is a bomb based on nuclear fission. The processes that then take place in the secondary are physically the same as in an ICF fusion pellet: the outer skin ablates, and the resulting recoil compresses the inner part in whose

---

167 In case, concrete steps towards a nuclear weapon free world are envisaged and implemented, the restriction of tritium production for military purposes might become an option to be considered. However, other political prerequisites will be necessary.

168 These safeguards are based on INFCIRC/153 and INFCIRC/540. The goal of universal full-scope safeguards is a policy goal that makes sense for many reasons, not only for the FMCT. See Schaper 1998b.

169 This argument holds equally for other tritium production facilities.

centre fusion processes start. A fraction of the fuel will have fused before it re-expands. The temperature, pressures and many physical processes are comparable, however, the size and energy of a hydrogen bomb is much larger than in a laboratory ICF experiment[170]. Also, the fusion materials are normally somewhat differing: while most ICF experiments use deuterium-tritium (DT), in a hydrogen bomb, deuterium-lithium-6 (DLi-6) is used, however, its more complex reaction also involves the D-T reaction[171].

Therefore, in physical terms, ICF can be illustrated as a "hydrogen bomb explosion in the laboratory scale[172]". The hydrogen plasma that is generated during ICF experiments is very similar to that generated during an explosion of a hydrogen bomb. This sort of experiment is therefore well suited to simulate the physical conditions in a nuclear explosion. Its significance has increased after the negotiations for a Comprehensive Test Ban Treaty (CTBT). The U.S. and France are constructing large facilities in order to replace functions of former underground nuclear explosions. The American facility, called “National Ignition Facility” is being constructed in the Lawrence Livermore National Laboratory (LLNL), and the French facility, called “Laser Megajoulé”, in the Centre d'Etudes de Limeil-Valenton.

Experimentally, the hot hydrogen plasmas can be used for several purposes related to nuclear weapon research. The properties of materials under extreme conditions can be measured. These properties are the relation between pressure and temperature (so-called "equations of state"), ore radiation transport parameters. No other experiment would yield data so similar to those in nuclear explosions. Instead of fusion, it is also possible to generate some fission reactions. Also, the properties of new materials can be measured under these conditions. All such measured data are useful in computer simulations of existing or new warheads. In this respect, ICF is also useful for the development of new nuclear weapons, including those of the third generation[173]. It is also possible to do research into various basic physical principles, e.g. the possible uses of new laser materials which can only be pumped involving extremely high energy densities. ICF can also be used to test the effect of nuclear weapons radiation on military equipment. In the USA, ICF always has played an important role in the acquisition of new, qualified scientists. Since the CTBT negotiations, ICF has become even more important in keeping nuclear weapons expertise alive.

However, it is impossible to construct the new weapons themselves on the basis of these experiments. This would only possible with extended testing series which are banned by the CTBT[174]. Nevertheless, theoretical preparations can be substantially advanced.

---

170 Although in a hydrogen bomb the driving energy stems from a nuclear fission bomb, and in laboratory ICF; it stems from lasers or from heavy ion beams, the mechanisms are very similar: the lasers or particle beams don’t heat the pellet directly, instead they are directed on a casing around the pellet which on its part emits the radiation that then heats the pellet. Similarly, in a hydrogen bomb, the energy from the primary first heats a casing that then emits the radiation that compresses the primary.

171

$$\text{Li-6} + n \rightarrow \alpha + T$$
$$T + D \rightarrow n + \alpha$$

172 Schaper 1991.

173 In the U.S., at the time being, no new nuclear warhead is under development, however, the option is still open.

174 The entry into force of the CTBT uncertain. On 13 October 1999, the U.S. failed to ratify this treaty. Other necessary ratifications are also missing. Nevertheless, the five nuclear weapon states party to the NPT are observing a testing moratorium, and the norm against nuclear testing is strong.

ICF facilities are large and expensive, and it is impossible for less developed countries to conduct ICF R&D on a large and national scale. Beginner countries seeking nuclear weapons are less interested in fusion plasmas but much more in the acquisition of nuclear materials and technologies for nuclear warheads based on fission, not fusion. The R&D involved in these efforts are much different from those in the acquisition of hydrogen bombs.

However, there are three states possessing nuclear fission based warheads: India and Pakistan, and presumably also Israel. At least India is reported to be interested in hydrogen bombs. Measurement results as described above would be very useful for their development. The huge investment in an own facility, however, is rather unlikely, and experimental results specifically related to nuclear weapons, are classified. The U.S. and France intend to use their facilities part time only nationally for military purposes, and the rest of the time they intend to open them for international, civilian research.

The most important policy stemming vertical proliferation is strengthening the norm against nuclear testing. In this policy, ICF plays an ambivalent role. During the many years of debates whether a CTBT should be concluded, advocates listed ICF as an important tool to replace nuclear tests. In the U.S., the plans for the National Ignition Facility have contributed to reduce domestic opposition against the CTBT[175]. However, as ICF has the potential to contribute to research on new nuclear weapons, though not to their development, critics claim that it is undermining the spirit of the CTBT which is ending all vertical proliferation. As an example, India has justified its refusal to sign the CTBT with the vertical proliferation potential of the U.S stockpile stewardship. However, many more political factors play more important roles in the development of the norm against testing. Explaining them is beyond the scope of this paper[176]. The impact of ICF on this policy therefore can be judged as moderate, whereby a distinction must be made between international civilian projects whose impact on CTBT-related policy hardly exists, and military projects and facilities that do play a role.

The civilian side of ICF research aims mainly at future energy systems whose proliferation risks are described in the preceding section. A smaller additional civilian application is research for astrophysics. Civilian experiments in the context of these research goals are to a certain extent different than those specifically aimed at nuclear weapon research: Physical properties of special materials that might be used in nuclear weapons are only of low interest for energy research, but the most proliferation relevant aspect of military research. Civilian research instead aims at frequent repetition rates of ICF explosions which would be an essential prerequisite of a reactor based on ICF. For military goals, frequent repetition rates are irrelevant. With high power lasers, frequent repetition rates would be impossible as they need hours for cooling down. Heavy ion beams seem more promising, but there power is still far below of what is necessary. Both civilian and military research aim at the achievement of high energy gains. This research goal is central to all applications. A working reactor capable of energy supply and based on ICF must not be expected in the next decades.

---

175 The National Ignition Facility is part of the so-called "Stockpile Stewardship", aimed at keeping the safety and reliability of the nuclear arsena alife. It must be also understood as a bargain in the U.S. national decision making, see Stockpile Stewardship 1994.

176 A useful information source is the Web-Site of the Coalition to Reduce Nuclear Dangers: http://www.crnd.org. The most deplorable recent development is the refusal of the U.S. Senate to ratify the CTBT.

5.2.3 Summary: Risk assessment of fusion research according to the criteria

According to the criteria developed in 3.1.4 and 3.2.3, the following summarising risk assessment can be derived:

Horizontal proliferation (section 3.1.4):

Criterion 1: The risk of horizontal proliferation arising from fusion R&D according to criterion 1 is low, because it does not result in the production of weapons usable materials. As long as not much neutrons are produced, safeguards are not necessary. However, a reactor based on fusion might be producing neutrons in **which** case safeguards must be attached. The details of such safeguards have not been investigated, a preliminary assessment indicates that they would be less sophisticated than those necessary for an ordinary reactor as long as no nuclear materials are being produced. In case of the civilian production of nuclear materials, their sophistication would be comparable.

Criterion 2: The risk of horizontal proliferation according to criterion 2 is low because the technical sophistication of R&D **on** fusion is high, and its usefulness for beginner proliferators is low.

Criterion 3: Civilian fusion reactors can be abused for production or diversion of weapons usable materials and therefore pose a proliferation risk according to criterion 3, especially in the states not member of the NPT. The **risk** that R&D is abused is rather low, however, from the theoretical background of ICF, lessons on high energy plasma physics can be learned that might be useful in the design of computer codes of nuclear explosion simulations[177]. For this purpose, theoretical ICF research offers a convenient civilian disguise. In case of a secret nuclear weapon program, experts on ICF theory might play a useful role. The theory is largely known and can also be drawn from the open literature. Useful experimental results are quantities that can be used in computer codes, however they arise only in specialised experiments. Participation in ICF R&D might constitute a training background for nuclear weapon scientists, however, more for advanced nuclear weapons and less for pure fission nuclear weapons. The risk of horizontal proliferation according to criterion 3 is therefore assessed as existing, however limited.

Criterion 4: R&D on fusion has no impact on technologies that are relevant for safeguards, physical protection or other technical **non-proliferation** measures. Therefore, according to criterion 4, it does not increase or reduce the risk of horizontal proliferation.

Criterion 5: There are no **ongoing** policies specifically aimed at *horizontal* non-proliferation that are affected by fusion research. Therefore, according to criterion 5, it does not increase or reduce the risk of horizontal proliferation.

Vertical proliferation (section 3.2.3):

Criterion 6: As explained in **section** 5.2.2, ICF is an important tool for R&D of advanced nuclear warheads. It therefore poses a high risk of vertical proliferation. For beginner states without experience with fission warheads, its military usefulness is very limited. Other fusion concepts such as MCF do not pose similar risks.

Criterion 7: As long as ICF projects take place in international cooperation, their goals will be the civilian and not the nuclear weapons application, the risk of vertical

[177] Examples are calculations on radiation transport, cross sections, or equations of state.

proliferation according to criterion 6 is there for reduced to a certain extent. On the other hand, it must be kept in mind that also civilian results from ICF might be abused for nuclear weapons R&D.

Criterion 8: Fusion-fission hybrid reactors trigger reprocessing and therefore undermine policies that aim at discouraging closed fuel cycles. Fusion reactors would also offer an additional possibility for military tritium production, and might complicate attempts to submit them under safeguards in NWS. Large ICF experiments can **be** used to replace underground nuclear testing to a certain extent, and thereby undermine the policy to stem vertical proliferation.

6 Implications for EU policy making

6.1 Policy making that affects safety

6.1.1 General implications for EU policy making regarding nuclear safety issues

The EU policy currently is not considered a relevant driving force towards enhanced nuclear safety, as far as facilities, regulations and safety control measures of currently operated reactors in their current member states are concerned. While radiation protection regulation for the workers and the public are well developed, among the most advanced and modern regulations in the industrialised world, and guarantee minimum safety requirements in all member states on a comparatively high protection level, reactor safety, fuel and waste safety and similar issues are currently not at all regulated or even discussed. These issues could affect the public of all the member states, no matter if they are among the seven member states that do not generate any nuclear energy or among the other eight member states that do use nuclear energy to a various extent. Safety regulation of these plants and of the fuel supply and waste management schemes and facilities is completely up to the member states in which those plants and facilities operate. In that respect policy making in the EU so far did not affect or influence these safety issues at all.

An example for this surprising absence of policy and regulation in that field is the development of the EPR concept for the introduction of an “advanced” new reactor type, further discussed in detail in that study. Practically no contributions from the EU policy or administrational level have played a major role in this process yet, even though the “technical” decisions in this process are of some relevance for a number of member states, be it in the positive (economic) or in the negative (risk) direction.

An interesting process regarding reactor safety issues is the possible extension of the EU-15, if the candidate states own and operate reactors and these will have to fulfil so-called modern western safety standards. It is then realised, that there are at least eight different Safety Standards in Western Europe for nuclear reactors; and probably even more, because reactors constructed and build in the Sixties, still operated in Western Europe to some extend, reactors build in the Eighties and reactors planned to be build in the upcoming century are in many aspects very different worlds of Reactor Safety Standards even in a single member state. It isn’t even possible today to compare results of probabilistic safety analyses for nuclear reactors from different EU-15 countries, because any one country has more or less developed its own methodology, criteria and requirements. Not to speak about comparable standards on which results of this analysis requires shutdown or back-fitting of the reactor and what level is considered safe enough.

Several nuclear safety issues were analysed in that study, where policy and subsequent administrational activity on the EU level would make good sense. Several activities could clearly enhance the claimed commitment to the protection of the people from the potential hazards of nuclear applications and add increased balance to the already well developed commitment for the promotion of nuclear energy use. Some of these issues listed in brief:

- Thorough investigation of the potential hazards of new technologies, namely nuclear fusion and advanced nuclear fuel cycle schemes, before and during their introduction and promotion by research activities.
- Enhanced attention to the unbalanced production of hazardous materials, namely separated Plutonium, reprocessed and depleted Uranium, for which currently and in the foreseeable future no marketable use is to be expected, and development of alternative methods of management of these materials, better suited for current needs and more timely available to resolve the rather urgent issue.
- Enhanced clean-up and solutions to still outstanding unsustainable past practices in several of the member states. Necessary scientific and technical support and exchange as well as some guidance would be most welcome.

6.1.2 Specific implications for EU policy making regarding reactor safety

In this study different options for future nuclear fission reactors were evaluated for their safety characteristics. None of the studied alternatives was clearly ranked as inherently safe. For the EPR it is still unclear whether the targeted safety features could be reached in the final design. Some problems already known from past reactor safety research (core melt accidents, hydrogen build-up, in-vessel pressure build-up, etc) are still to be resolved. The HTR was evaluated as being advantageous in many respects, but still unresolved safety issues remain uncertain. Other reactor concepts of potential future interest were also evaluated, but clearly do not fulfil the current requirement, that consequences even of a serious accidents in the plant have to limited to an extent, that no off-site evacuation will be necessary.

The following implications for EU policy making regarding reactor safety result from that analysis:

- None of the analysed projects does clearly fulfil the requirements, so support or extended research in any one of these options cannot be recommended.
- The most promising reactor technology from some of the safety perspectives is the HTR, but market introduction would require a whole new infrastructure and is currently unrealistic. Further studies in this technology would be helpful to clear some of the uncertain safety features, but a clear commitment to this technology cannot be recommended on that stage.
- Other reactor types analysed are currently not attractive enough to boost their further development. This includes the reactor type based on accelerator technologies, designated for destruction of long-lived actinides and fission products from current fission reactors.

6.1.3 Specific implications for EU policy making regarding the safety of nuclear fuel cycles and nuclear waste management

Several options for future fuel cycles were analysed. Some safety risks were identified for the current trend towards increased uranium fuel burn-ups. Similar safety risks and consequences, but even multiplied by additional adverse properties, were found for the Plutonium-Uranium-Oxide fuel. Thorium fuel was evaluated as having some safety advantages over Uranium fuel, but is currently too far away from getting marketed.

Spent fuel management options analysed in this study are Direct Disposal and Partitioning and Transmutation. Spent fuel management as direct disposal of spent fuel was analysed as being a widely used method in the EU-15, in principle feasible, economically favourable and a method to avoid further build-up up of the already huge inventory of civil Plutonium in the EU-15. The technical requirements for implementation of Partitioning and subsequent

Transmutation of actinides and long-lived fission products from wastes were analysed as possible future waste management option. It was shown that the necessary scheme requires several steps, requires very high efficiency of waste treatment, a very long-term commitment to nuclear power use and enormous technical and financial investments, before such a process works in principle. It doesn't fit to the current situation with a number of smaller users of nuclear energy in the EU-15 and the limited use of nuclear energy.

The following implications for the EU policy making result from this evaluation:

- Safety risks from new developments in the current fuel supply and use, namely elevated burn-ups and MOX fuel use, and their consequences for the different stages of waste management should be better understood. A thorough investigation into the consequences should be launched, especially on the waste management consequences of MOX use in light water reactors at elevated burn-ups.
- Direct disposal of spent fuel should be studied further as it is the preferred option in most of the EU-15. Some possible side effects of that option should be cleared by development of feasible technical solutions in the different host geologies currently favoured in the EU-15 member states.
- Partitioning and Transmutation is currently not justified, taking its technical, financial and ecological effects into account. Any further EU support for this technology should be connected to the results of thorough system studies, that take all these aspects into account. Otherwise a technology chain is supported that has the potential to exhaust all available research resources for long times without leading to useful results at the end.

6.1.4 Specific implications for EU policy making regarding the safety of nuclear fusion reactors

Future fission reactor technology, currently supported by the EU, was evaluated for its safety features. The main sensitive points found were the emissions of tritium and other nuclides from such reactors resp. from the necessary fuel supply facilities and the potential long-lived by-products of materials in the plasma facing components. Other potential concerns are the occupational doses during the regular exchange of plasma facing components.

The following implications for the EU policy towards nuclear fusion are resulting:

- The potential emissions of tritium need thorough investigation. Especially any necessary readjustment of the currently rather low dose factors of Tritium would have a considerable influence on the overall radiological evaluation of that technology. It is therefore recommended to launch investigations especially on currently discussed radiological aspects of this nuclide.
- By-product content of materials that are candidates for the plasma facing components, their removal and other material requirements might play a major role for the feasibility of nuclear fusion. It is currently not well understood, which technical requirements will result from radiological and waste management issues in this respect. These aspects require thorough attention during the whole research and development process. To improve knowledge already in the current development stage, thorough investigations of these determining factors are recommended.

6.2 Policy making that affects non-proliferation

6.2.1 General considerations regarding nuclear non-proliferation issues

Nuclear non-proliferation and disarmament has so far not played an important role in EU policy making. In the descriptions of technology policy and R&D goals, e.g. of the Fifth Framework, non-proliferation criteria play an even much less important role than safety aspects. Only for safeguards research, non-proliferation criteria are mentioned, and R&D for safeguards constitutes only a small fraction of the whole programme. However, the last years were a time in which a lot of reforms and developments for nuclear non-proliferation and nuclear disarmament have taken place. More opportunities can be expected in the coming years, however there are also dangers that they might be missed. In contrast to the U.S., the EU has only a very minor and subordinate role in these processes and does not show much engagement. Technological contributions, especially safeguards related R&D and cooperation with Russia, could accelerate progress quite substantially and could give the EU a more influential role in international fora.

EU nuclear fission and fusion research hardly takes non-proliferation aspects into consideration. In the decision making on project funding, this aspect has not played a significant role. Therefore, any public debate on these criteria has been missing. However, it is possible to identify proliferation risks and to take them into account in decision making. Depending on the technology, these risks might vary quite substantially. It is therefore recommended to include specific proliferation risk assessments into decision making on R&D on nuclear projects.

6.2.2 Recommendations on fission research

A criterion for the assessment of proliferation risks that is rather easy in its application is the analysis of the sophistication of the safeguards that must be attached to the technology. According to this criterion, nuclear technologies that involve only *countable items* such as fresh or spent fuel elements pose significantly lower risks than those that incorporate also *bulk material*, e.g. streams and flows in reprocessing or fuel fabrication plants. Direct disposal of spent fuel is therefore more recommendable than reprocessing as it involves mainly countable items and far less bulk materials.

A second criterion assumes that the proliferation risk of a nuclear technology is the higher, the lower the technical threshold is to use it for a nuclear warhead. This applies especially to separated plutonium and highly enriched uranium. In contrast, plutonium contained in spent fuel still needs reprocessing before it can be used for a nuclear weapon, low enriched or natural uranium still needs further enrichment. Also according to this criterion, direct disposal is recommended in contrast to reprocessing. The world-wide accumulated quantities of separated civil and military plutonium amount to several hundred tons anyway, sufficient for MOX fuel for many decades. Thorium fuel cycles, as long as they work without reprocessing, pose additional technical obstacles. It can therefore be judged as less proliferation risky than the ordinary LWR fuel cycle. A special proliferation risk pose research reactors that use HEU fuel such as the new reactor being constructed at Garching (FRMII). It is strongly recommended to support projects for the fuel conversion of such reactors.

The plausible civilian disguise that proliferators would use is the civilian energy supply, similarly for all waste management and fuel cycle concepts.

Another criterion investigates whether ongoing non-proliferation policies could be undermined. Thorium fuel cycles, e.g. the Radkowsky reactors, reduces the incentives to chose recycling. For this reason, the proliferation risk might be judged as reduced in comparison to standard light water reactor fuel cycles. Fast reactors can produce plutonium of high weapons quality, therefore they create an additional incentive for reprocessing in order to gain plutonium for nuclear weapons. The Rubbia energy amplifier runs counter the policy of discouraging closed fuel cycles, e.g. reprocessing. Therefore, it constitutes a higher proliferation risk than the ordinary concepts and is not recommended.

New research reactor projects that use HEU undermine the ongoing non-proliferation policy to minimise the civilian use and the trade of this material. This policy is supported by a broad international consensus. It is recommended that the EU explicitly joins this policy.

Some fission research can be useful for the disposition of excess weapons plutonium and might thereby play a positive role in nuclear disarmament. Especially R&D projects focusing on this application will reduce the risk of vertical proliferation. Such recommendable projects are especially research on the question how much plutonium could be added to vitrified high level waste without creating criticality problems. The French-German-Russian project of disposition of Russian weapons plutonium as MOX should also be pursued, as it would constitute the first practical nuclear disarmament step that would result in enhanced irreversibility of nuclear disarmament, and in international safeguards on the processes. It is also recommended to invest in R&D that focuses on safety and security of final geological storage sites.

6.2.3 Recommendations on fusion research

A reactor based on fusion might be producing neutrons which could be abused for the production of military plutonium. In this case, safeguards must be attached. In case the reactor would be used for the civilian production of nuclear materials (fusion-fission hybrid reactors), the sophistication of the safeguards would be comparable to those of LWRs. Current R&D however is far from this stage and does not yet involve the production of sufficient neutrons.

The usefulness of this R&D for beginner proliferators is low, however, in contrast to magnetic fusion, from the theoretical background of ICF, lessons on high energy plasma physics can be learned that might be useful in the design of computer codes of nuclear explosion simulations. For this purpose, theoretical ICF research offers a convenient civilian disguise for the study of the relevant physics. But these studies would not be sufficient for technical design. In case of a secret nuclear weapon program, experts on ICF theory might play a useful role. ICF is an even much more useful tool for R&D of advanced nuclear warheads. It therefore poses a high risk of vertical proliferation.

Fusion-fission hybrid reactors would trigger reprocessing and therefore undermine policies that aim at discouraging closed fuel cycles. Fusion reactors would also offer an additional possibility for military tritium production, and might complicate attempts to submit them under safeguards in NWS. Large ICF experiments can be used to replace underground nuclear testing to a certain extent, and thereby undermine the policy to stem vertical proliferation.

In sum, the proliferation risks of magnetic fusion can be assessed as comparatively low. In contrast, the risks of ICF research for *vertical* proliferation are rather high. Specific military ICF projects however are conducted only on a national basis. It is therefore recommended to press for an international use of existing ICF facilities without leaving room for national military experiments, in order to minimize the military abuse. Such international use of large experimental plants corresponds anyway to the nature of science and especially to R&D in the EU.

6.2.4 Safeguards research

For nuclear non-proliferation and disarmament, safeguards play an essential role. It is therefore recommended to maintain an extended and flexible basis for R&D in order to keep up with the upcoming safeguards needs. R&D should include

- Analysis of environmental traces for the detection of clandestine nuclear weapons acquisition activities, including interpretation and reduction of the false alarm probability,
- Improvement of measurement technologies,
- The incorporation of new information technologies for more effectiveness and cost reduction, automated data transfer,
- The use of satellite imagery for nuclear arms control needs,
- Seals and tagging technologies,
- Managed access procedures for different kinds of nuclear facilities that on the one hand create assurance of compliance and on the other hand protect commercial or military secrets
- Preparatory studies for the verification of dismantling of nuclear warheads, examples are automated distinction between shielded real warheads and shielded decoys or the design of verification measures at the entrance and the exit of a warhead dismantlement facility
- Enhancement of effectiveness of the division of labour between the IAEA and regional safeguards agencies,
- Enhancement of effectiveness of the existing safeguards inspection regime, examples are standardisation, or randomising inspections by maintaining high confidence of compliance,
- Studies how to implement safeguards at facilities that have never been designed for them (e.g. Russian reprocessing facilities which must be submitted to verification measures under an FMCT)[178].

6.2.5 Cooperation with Russia

New proliferation risks have arisen because of the deteriorating situation in Russia. The need urgent action. The cooperation that has been taken place with Russia so far includes some promising starts, but its extent is not sufficient. In order to prevent proliferation dangers stemming from this situation and its further deterioration, the cooperation with Russia towards non-proliferation must be intensified significantly. Especially, the fraction of non-proliferation projects in the Tacis programme should be much larger (cf. section 3.1.2.2).

On the short time agenda, the cooperation should achieve the following goals:

- Implementing western standards of material accountancy and control

[178] Britain brought a large reprocessing plant (B205) under Euratom safeguards some 20 years after it was designed. Although the safeguards applied there might not meet IAEA criteria, Euratom is satisfied that it can verify non-diversion from the plant. It would be worth a study how the UK brought B205 under safeguards and draw lessons for future arms control.

- similarly of physical protection of civilian and military nuclear facilities
- similarly of nuclear transport
- centralisation of nuclear material accountancy
- reform of the export controls
- conversion of jobs in the military nuclear establishment
- construction of safe and secure storage sites
- safe and secure dismantlement of nuclear warheads

Technical projects should include cooperation projects similar to those in the above list (section 6.2.4).

7 List of sources and additional literature

[Albright/Kelley 1995] Albright D., Kelley R., *'Has Iraq Come Clean at Last?'*, Bulletin of the Atomic Scientists, November/December 1995, p.53-64.

[Albright et al. 1996] Albright D., Berkhout F., Walker W., *Plutonium and Highly Enriched Uranium 1996 – World Inventories, Capabilites and Policies*, SIPRI, Oxford University Press, 1997.

[Barabaschi et al. 1996] Barabaschi S. (Chairman) *et al*., *Fusion Programme Evaluation 1996 – Findings and Recommendations,* XII-373/96, November 1996, http://europa.eu.int/comm/dg12/fusion/fusion96.pdf.

[Barnert et al. 1996] Barnert H., et al, "Die Entwicklung des Hochtemperaturreaktors", *Atomwirtschaft/Atomtechnik*, p. 552, August/September 1996 (The development of the HTR.)

[Bartels 1992] Bartels H.W., "Abfallprobleme bei der Kernfusion", *Physikalische Blätter*, 48, 1992, S. 926-928 (Disposal problems with nuclear fusion).

[Blankenstein 1995] Blankenstein H., *Political Considerations on the Future of Safeguards,* (Proceedings of the 17th Annual Symposium on Safeguards and Nuclear Material Managements), p. 21, Aachen (Germany), 9-11 May 1995.

[BMBF 1999] Bericht der vom Bundesministerium für Bildung und Forschung eingesetzten Expertenkommission zur Prüfung der Umrüstbarkeit des Forschungsreaktors München II von HEU auf LEU, Bonn, July 1999 (Report of the expert commission implemented by the Federal Ministry for the evaluation of the convertability from HEU to LEU of the FRM-II).

[BMU 1997] Das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, *Umweltpolitik: Umweltradioaktivität und Strahlenbelastung*, Jahresbericht 1994, Januar 1997 (Environmental policy: environmental radioactivity and radiation).

[Bowman/Venneri 1996] Bowman C. D. and Venneri F., "Underground Supercriticality from Plutonium and Other Fissile Material", *Science & Global Security*, Vol. 5, p. 279, 1996.

[Bukharin 1996] Bukharin O., "Security of fissile materials in Russia", *Ann. Rev. Energy Environ*, Vol. 21, p. 467-496, 1996.

[Bunz] Bunz H., *et al*, *SEAFP Accident Sequences, Source Terms and Public Doses*, (no year).

[Cannon 1983] Cannon J.B., *Background Information and Technical Basis for Assessment of Environmental Implications of Magnetic Fusion Energy*, Oak Ridge National Laboratory, Tennessee, 1983.

[CIA 1996] World-wide Threat Assessment, Brief to the Senate Select Committee of Intelligence, John M. Deutch, 22 February 1996, http://www.odci.gov/cia/public_affairs/speeches/archives/1996/dci_speech_022296.html.

[Council Dec. 1998] Council Decision of 22 December 1998 concerning the Fifth Framework Programme of the European Atomic Energy Community (Euratom) for research and training activities (1998 to 2002), 1999/64/Euratom, Annex II, Broad Lines of the area's scientific and technological objectives. http://www.cordis.lu/fp5/src/eur-en3.htm.

[Cox-Report 1999] *Select Committee on U.S. National Security and Military/Commercial Concerns* *with the People's Republic of China*, Congressional Report, Mai 25, 1999 (http://www.fas.org/spp/starwars/congress/1999_r/cox/index.html); see also, "How Right Is Report? Caveats by Experts", *The New York Times*, 26 May 1999; China Lifts Veil On Nuclear Weapons Program, Inside China Today, July 15, 1999.

[CTBTO PrepCom] Website of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organisation (CTBTO PrepCom), Vienna. http://www.ctbto.org/.

[DG XVII 1997] Commission of the European Communities, DG XVII, Euratom-Russian cooperation in Nuclear Materials Accountancy and Control, Luxembourg, 31 March 1997.

[DRS 1980] Gesellschaft für Reaktorsicherheit (GRS), *Deutsche Risikostudie Kernkraftwerke Phase A*; Köln, Verlag TÜV Rheinland, 1980 (German risk analysis of nuclear reactors phase A).

[EC R&T Programme 1998-2002] European Commission: Research and Training Programme in the Field of Nuclear Energy (1998 to 2002) - Work Programme. - Document h_wp_en_199901, http://europa.eu.int.

[EC 1996] European Commission: Communication from the Commission to the Parliament and the Council. Illicit Trafficking in Nuclear Materials and Radioactive Substances – Implementation of the guidelines laid down in the communication from the Commission of 7 September 1994 (COM(94)383) and in the conclusions of the Essen European Council, COM (96) 171, Brussels, 19 April 1996.

[Fenstermacher 1990] Fenstermacher D. L., "The Effects of Nuclear Test-Ban Regimes on Third Generation Weapon Innovation", *Science and Global Security*, Vol. 1, 1990, p. 187.

[Fetter et al. 1990] Fetter S., *et al.*, "Detecting Nuclear Warheads", in: von Hippel F., Sagdeev R. Z., *Reversing the Arms Race — How to Achieve and Verify Deep Reductions in the Nuclear Arsenals*, p. 265, New York 1990.

[Fischer et al. 1994] Fischer W., *et al.*, *The Role of Satellites and Remote Data Transmission in a Future Safeguards Regime*, Proceedings of the Symposium on International Nuclear Safeguards', Vol. I, p. 411, International Atomic Energy Agency, Vienna, March 14-18, 1994.

[Fischer 1997] Ulrich Fischer , "Entwicklungsstand und Sicherheitsfragen des europäischen Druckwasserreaktors (EPR)", in: Ministerium für Finanzen und Energie des Landes Schleswig-Holstein, *Der geplante Europäische Druckwasserreaktor*, Workshop am 20.11.1997 in Kiel (Germany), p.34 ff (State of development and questions of safety of the EPR).

[Galperin et al. 1997] Galperin A., Reichert P., Radkowsky A., "Thorium Fuel for Light Water Reactors – Reducing Proliferation Potential of Nuclear Power Fuel Cycle", *Science & Global Security*, Vol. 6, pp. 265-290, 1997.

[Glaser 1998] Glaser A., 'The thorium Fuel Cycle: A Noteworthy Gain in Proliferation-Resistance?' Draft paper presented at the Xth International Summer Symposium on Science and World Affairs, July 14-21, 1998, MIT, Boston (USA).

[Gösele et al. 1994] Gösele J. H., Remagen H. H., Stein G., *A German view on safeguards beyond 1995*, Proceedings of the Symposium on International Nuclear Safeguards, Vol. II, Vienna, 14-18 March 1994, p. 701.

[Gmelin 1996] *Keynote on the Expectations from Science and Modern Technology in Support of Nuclear Safeguards*, Proceedings of the Workshop on Science and Modern Technology for Safeguards, p. 7, 28-31 October, 1996.

[Gmelin/Kloeckner 1997] Gmelin W., Kloeckner W., *Euratom Safeguards – An Update On Present Developments*, Proceedings of the IAEA Symposium On International Safeguards, IAEA CD-Rom, Vienna, Austria, 13-17 October 1997.

[GRS/Siemens/Minatom 1997] Gesellschaft für Reaktorsicherheit, Siemens, Minatom, Deutsch-Russische Kooperation im Rahmen des Abkommens über Hilfeleistung für die Russische Föderation bei der Eliminierung der von ihr zu reduzierenden nuklearen und chemischen Waffen, Abschlußbericht, 28.2.1997 (German-Russian cooperation for the agreement on aid for the Russian Federation for the elimination of the nuclear and chemical weapons that must be reduced).

[Goodwin/Kammerdiener 1999] Goodwin B., Kamerdiener J., Future Proliferation Threat, Oral presentation at the Workshop on Proliferation-Resistant Nuclear Power Systems, Livermore (USA), June 2-4, 1999.

[HFG 1996] von Helmholtz Hermann –"Gemeinschaft Deutscher Forschungseinrichtungen (HFG)"; *Brochure: Kernfusion*; März 1996 (Nuclear fusion).

[Hamza 1998] Khidir Hamza, "Inside Saddam's secret nuclear program", *Bulletin of the Atomic Scientists*, S. 26, September/October 1998.

[Harms/Rodriguez 1996] Harms N., Rodríguez P., "Safeguards at Light-Water Reactors – Current Practices, Future Directions", *IAEA-Bulletin* Vol. 38, No. 4, 1996, IAEA Web Site: http://www.iaea.org/worldatom/inforesource/bulletin/bull384/harms.html.

[IAEA Glossary 1987] *IAEA Safeguards Glossary*, 1987 Edition, Vienna, 1987.

[INFCE 1980] International Fuel Cycle Evaluation (INFCE), *Summary Volume*, IAEA, Vienna 1980.

[ISTC 1998] The International Science and Technology Centre, *Annual Report 1998*, Moscow 1998, http://www.istc.ru/istc/website.nsf/html/98/index.htm.

[Japan 1999] "Japan's Technological Cooperation Concerning Plutonium from Dismantled N-Weapons", *Plutonium*, p. 5, Spring 1999 No.25.

[Jasani et al. 1996] Jasani B., *et al*., *Space-Based Monitoring of Proliferation of Weapons of Mass Destruction*, Proceedings of the Workshop on Science and Modern Technology for Safeguards, p. 275, 28-31 October, 1996.

[JRC 1998] Joint Research Centre (JRC), *Safety and Security of Nuclear Energy*, - JRC EURATOM Specific Programme Cadre, Starting 16-Oct-98, Record ID Number 372, Last Update 22-Mar-99 12:09:42 PM,
http://www.jrc.org/scripts/db/cache/pgm.

[Kalinowski 1993] Kalinowski M., "Uncertainty and range of alternatives in estimating tritium emissions from proposed fusion power reactors and their radiological impact", *Journal of Fusion Energy,* 12 (1993), 391-395.

[Kane&Hill 1995] Kane&Hill, *Comparision of waste toxicity index and repository performance assessment approaches to providing guidance for R&D on Partitioning and Transmutation*, EUR 16167, Brussels, 1995.

[Kankeleit et al. 1989] Kankeleit E., Küppers C., Imkeller U., "Bericht zur Waffentauglichkeit von Reaktorplutonium", *Report IANUS-1/1989*, this report has been translated by the Livermore Laboratory under the title 'Report on the weapon usability of reactor-grade plutonium'.

[Kasten 1998] Kasten P. R., "Review of the Radkowsky thorium Reactor Concept", *Science & Global Security*, Vol. 7, pp. 237-269, 1998.

[Kern 1997] Kern R., *Projektierung des EPR – Integrierte Werkzeuge der Datenverarbeitung*, Atomwirtschaft, Oktober 1997 (The project of the EPR – Integrated tools of data processing).

[Kimpland 1996] Kimpland R., "Dynamic Analysis of Nuclear Excursions in Underground Repositories Containing plutonium", *Science & Global Security*, Vol. 5, p. 323, 1996.

[Kirichenko 1996] Kirichenko E., "Evolution of the Russian Non-proliferation Export Controls", *The Monitor*, Vol. 2, No. 3, p. 8, Summer 1996.

[Krass et al. 1983] Krass A.S., *et al*., *Uranium Enrichment and Nuclear Weapon Proliferation*, (Taylor & Francis), London 1983.

[Kurihara et al. 1997] Working Group 5 (Chairman H. Kurihara), 'Non-Proliferation and Safeguards Aspects', Key Issue Paper No. 5, in: *Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities*, International Symposium held in Vienna, Austria, p. 225, 3-6 June 1997.

[Liebert et al. 1999] Liebert, *et al*, "Fortgeschrittene Nuklearsysteme", *Review Study,* Schweizerischer Wissenschaftsrat, Bern, 1999 (Advanced nuclear systems).

[Mark 1993] Mark C., "Explosive Properties of Reactor-Grade plutonium", *Science & Global Security,* Vol. 4, p.111, 1993.

[Moody 1996] Moody R. A., "Reexamining Brain Drain from the Former Soviet Union", *The Non-proliferation Review*, Spring-Summer 1996, Vol 3, No. 3, p. 92.

[Müller 1995] Müller H. (ed), *Nuclear Export Controls in Europe*, Brussels 1995.

[Müller et al. 1994] Dembinski M., Kelle A., Schaper A., "From Black Sheep to White Angel? - The New German Export Control Policy", *PRIF Report,* No. 32, January 1994.

[NAS 1994] National Academy of Sciences (NAS), Committee on International Security and Arms Control (CISAC), *Management and Disposition of Excess Weapons Plutonium*, Washington 1994.

[NAS 1995] NAS, CISAC, Management and Disposition of Excess Weapons plutonium: Reactor Related Options, Washington 1995.

[Natalizio 1996] Natalizio A., *et al*., *Fusion Reactors (Radiation Hazards and Risks)*, Paper for presentation to the IAEA TCM on Developments in Fusion Safety; Naka, Japan, Oktober 1996.

[Nucl. Week 6/99] MacLachlan A., "It's nearly official: first EPR will be at 1,5000 MW after all", *Nucleonics Week*, June 24, 1999.

[OECD 1989] Nuclear Energy Agency, *Plutonium Fuel – An Assessment*, OECD, Paris 1989.

[Orlov 1997] Orlov V. A., *Accounting, control, and physical protection of fissile materials and nuclear weapons in the Russian Federation: Current situation and main concerns*, Paper presented at the International Seminar on MPC&A in Russia and NIS, Bonn, April 7-8, 1997.

[OTA 1987] Office of Technology Assessment (OTA*), Starpower. The U.S. and the International Quest for Fusion Energy*, U.S. Congress, Washington 1987.

[Öko-Institut 1994] Hahn L., Küppers C., *Berechnung der möglichen Strahlenbelastung von Bürgern der Stadt Schweinfurt nach einem Unfall mit frühzeitiger Freisetzung radioaktiver Stoffe im KKW Grafenrheinfeld* (Studie i. A. der Stadt Schweinfurt), Darmstadt, März 1994 (Calculation of the possible radioactive contamination of the citizens of the city Schweinfurt after an accident with early release of radioactive materials in the nuclear reactor Grafenrheinfeld).

[Öko-Institut 1995] Bähr R., *et al*, *Gutachten zu den Umweltaspekten des SEAFP-Berichtes*, Gutachten im Auftrag des Bundesministeriums für Umwelt der Republik Österreich, Darmstadt, Mai 1995 (Analysis of the environmental aspects of the SEAFP report).

[Pease 1989] R.S. Pease *et al*., Environmental, *Safety-Related and Economic Potential of Fusion Power*, Main Report by the EEF Study Group, Brussels 1989.

[Pistner 1998] Pistner C., Emerging Nuclear Technologies – The Example of Carlo Rubbia's Energy Amplifier, Paper presented at the 10th International Summer Symposium on Science and World Affairs, MIT, Boston, July 14-21, 1998.

[Potter 1995] Potter W. C., "Before the Deluge? Assessing the Threat Of Nuclear Leakage From the Post-Soviet States", *Arms Control Today*, October 1995, S. 9-16.

[Reimann 1997] Reimann M., "Unsicherheiten und Risiken bei Kernschmelzunfällen im EPR.", in: Ministerium für Finanzen und Energie des Landes Schleswig-Holstein, *Der geplante Europäische Druckwasserreaktor*, Workshop am 20.11.1997 in Kiel (Germany), p.54 ff (Uncertainties and risks of core melt-down accidents in the EPR).

[Rubbia et al. 1996] Rubbia C. and Rubio J.A., *A Tentative Programme Towards Full Scale Energy Amplifier*, CERN/LHC/96-11(EET), 1996.

[Rubbia et al. 1997] Rubbia C., *et al*., *Fast Neutron Incineration In The Energy Amplifier As Alternative To Geologic Storage: The Case Of Spain*, CERN/LHC/97-01(EET), 1997.

[Schaper 1991] Schaper A., "Arms Control at the Stage of Research and Development? The Case of Inertial Confinement Fusion", *Science & Global Security*, vol. 2, p. 279, 1991.

[Schaper 1993] Schaper A., "Kernwaffen der ersten und zweiten Generation: Forschung und Entwicklung", in: Müller E., Neuneck G. (Ed.), *Rüstungsmodernisierung und Rüstungskontrolle*, Baden-Baden 1991/92, Office of Technology Assessment, 'Technologies Underlying Weapons of Mass Destruction', Washington 1993 (Nuclear weapons of the first and second generation: research and development).

[Schaper et al. 1996] Schaper A., De Becker M. and Müller H., *Essais Nucléaires - Fin de Partie*, GRIP, Brussels 1996 (Nuclear tests – end of the game).

[Schaper 1996] "Der geplante Forschungsreaktor in Garching - Rückfall in alte Sünderzeiten deutscher Nichtverbreitungspolitik?" *HSFK-Standpunkte* Nr. 3, März 1996 (The planned research reactor in Garching – Fallback in old times of sins of German non-proliferation policy?).

[Schaper 1997] Schaper A., The Comprehensive Test Ban Treaty from a Global Perspective, in: M. McKinzie (Ed.), *The Comprehensive Test Ban Treaty: Issues and Answers*, Cornell University, Peace Studies Program, Occasional Papers, S. 11, June 1997.

[Schaper/Frank 1998] Schaper A., Frank K., Ist eine kernwaffenfreie Welt verifizierbar?, *HSFK-Report*, 6/1998, November 1998. (Is a nuclear weapon free world verifiable?) An English translation is in print.

[Schaper 1998] Schaper A., "Nuclear smuggling in Europe — real dangers and enigmatic deceptions", in: Kouzminov V., Martellini M. (Ed.): "Illegal nuclear traffic: risks, safeguards, and countermeasures", Proceedings of the International Forum, *Science for Peace Series*, Vol. No. 4, Venice, 1998.

[Schaper 1998a] Schaper A., "Bombenstimmung in Indien und Pakistan", *Spektrum der Wissenschaft*, Juli 1998, S. 110 (Bomb mood in India and Pakistan).

[Schaper 1998b] Schaper A., "The Case for Universal Full Scope Safeguards on Nuclear Material", *The Non-proliferation Review*, Vol. 5, No 2, p. 69, Winter 1998.

[Schittenhelm 1995] Schittenhelm M., Raeder J., *Comments on the Report of the Öko-Institut concerning SEAFP*, 7.12.1995

[SEAFP 1995] Raeder J., *et al*., *Safety and Environmental Assessment of Fusion Power (SEAFP),* Report of the SEAFP Project, European Commission, Dir. Gen. XII, EROFUBRU XII-217/95, Brussels, June 1995

[Shea 1999] Shea T., *Reconciling IAEA Safeguards Requirements in a Treaty Banning the Production of Fissile Material for Use in Nuclear Weapons or other Nuclear Explosive Devices*, Disarmament Forum, UNIDIR, p. 57, Vol. 2, 1999.

[Stockpile Stewardship 1994] JASON and the MITRE Corporation, *Science Based Stockpile Stewardship*, Report JRS-94-345, November 1994.

[Sutcliffe/Rumyantsev 1996] Sutcliffe W., Rumyantsev A., "The Accounting and Control of Nuclear Material and Radioactive Substances in Russia", Yaderny Kontrol*, English Digest*, No. 1, Spring 1996.

[Sylvester/Simonson 1996] Sylvester K. W., Simonson S. A., "An Assessment of Diluents in the Vitrification of Weapons-Grade Plutonium", *Science & Global Security*, vol. 6, p. 31-58, 1996.

[Tacis 1996] *Tacis Contract Information*, Published by the European Commission, DGIA, December 1996.

[Tacis 1997] *Tacis Interim Evaluation Synthesis Report*, European Commission, July 1997.

[Thorstensen 1994] Thorstensen S., Chitumbo K., "Increased Cooperation Between the IAEA and Euratom – The New Partnership Approach", in: *International Nuclear Safeguards* 1994, Proc. of a Symposium, Vienna, March 1994, p. 271-283.

[Tian et al. 1995] Tian Dongfeng, Xie Dong, Liu Gongliang, "High Energy Gamma-Ray 'Fingerprint' – A Feasible Approach to Verify Nuclear Warhead", in: Institute of Applied Physics and Computational Mathematics, *Programme for Science and National Security Studies* (Arms Control Collected Works), p. 63, Beijing 1995.

[Traube 1998] Traube K, "Zu ökonomischen Aspekten des Europäischen Druckwasserreaktors EPR.", in: Ministerium für Finanzen und Energie des Landes Schleswig-Holstein, *Der geplante Europäische Druckwasserreaktor.*, Written paper following a presentation at the Workshop on the 20.11.1997 in Kiel (Germany), p.94ff (Economic aspects of the EPR).

[TUM 1999] Technical University Munich, FRM-II-Pressemitteilung 27, Januar 1999. Kommission der Bundesregierung weiß es genau: FRM-II-Brennstoff nicht bombentauglich – Konzeptänderung ist FRM3 (Press declaration of 27 January 1999. Commission of the Federal Government knows exactly: FRM-II fuel is not weapons usable, a change of the concept would be FRM3).

[Unscear 1988] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Report to the General Assembly*, New York 1988.

[Unscear 1993] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), *Report to the General Assembly*, New York 1993.

[Unscear 1998] United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Draft recalculation, unpublished.

[US-Russian Study 1997] Final Report of the US-Russian Independent Scientific Commission On Disposition Of Excess Weapons Plutonium, June 1, 1997, http://www.whitehouse.gov/WH/EOP/OSTP/html/Holdren.htm.

[Wehman 1995] Wehman U., Sperber F., Strehlen U., *Transmutation of long-lived radio-nuclides by advanced converters*. – EUR 16605, Brussels 1995.

[Yegorov 1997] N.N. Yegorov *et al*., The AIDA-MOX 1 Program, "Results of the French-Russian Study on Peaceful Use of plutonium from Dismantled Russian Nuclear Weapons", *in IAEA: Nuclear fuel cycle and reactor strategies: Adjusting to new realities*, Proceedings of an International Symposium held in Vienna, 3-6 June 1997, p. 93.

[Zhang/von Hippel 1999] Hui Zhang, F. von Hippel, *The application of Commercial Observation Satellite Imagery for the Verification of Declared and Undeclared plutonium Production Reactors*, Pu/CEES Report No. 319, Princeton, August 1999.

8 Appendix: Abbreviations

ABB	Asea Brown Bovery
ALMR	Advanced Liquid Metal Reactor
Am	americium
Bq	Bequerel (unit for radioactivity, eq. 1/second)
BN600	breeder reactor of Russian design
BWR	Boiling Water Reactor
C	carbon
C/S	containment and surveillance
CANDU	pressurised heavy water reactor of Canadian design
Cs	caesium
CTBT	Comprehensive Test Ban Treaty
D	deuterium
DA	destructive analysis
DT	deuterium-tritium fuel
EA	Energy Amplifier
EdF	Electricité de France
EMIS	electromagnetic isotope separation
EPR	European Pressurised water Reactor
ESARDA	European Safeguards Research and Development Association network
FBR	fast breeder reactor
FP5	Fifth Framework Programme
FMCT	Fissile Material Cutoff Treaty
FRMII	Forschungsreaktor München II = Research Reactor Munich II
GeV	giga electron volt (energy unit in particle physics)
GmbH	Gesellschaft mit beschränkter Haftung = Public Limited Company
GMP	Guidelines for the Management of plutonium
GW	gigawatt
GWd/tHM	gigawatt days per tons of heavy metal (unit for burn-up)
HLW	high level waste
HTR	high temperature reactor
I	iodine
IAEA	International Atomic Energy Agency
ICF	inertial confinement fusion
INFCIRC/153	model agreement between NNWSs and the IAEA for full scope safeguards
INFCIRC/540	Additional Safeguards Protocol
INFCE	International Fuel Cycle Evaluation
ISTC	International Science and Technology Centre
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
JRC	Joint Research Centre
LEU	low enriched uranium
LLNL	Lawrence Livermore National Laboratory
LLW	low level waste
LWR	light water reactor
MCF	magnetic confinement fusion
MOX	mixed oxide fuel

MPC&A	material protection, control, and accountancy
mSv	millisievert (unit for radioactive dosis)
MW	megawatt
NDA	non-destructive analysis
NIS	newly independent states
NNWS	non-nuclear weapon state
Np	neptunium
NPA	New Partnership Approach
NPI	Nuclear Power International
NPT	Nuclear Non-proliferation Treaty
NWS	nuclear weapon state
NWFZ	nuclear weapon free zone
P&T	Partitioning and Transmutation
Pa	protactinium
PIUS	Process Inherent Ultimate Safety
PFC	Plasma Facing Components
PRISM	Power Reactor Inherently Safe Module
Pu	plutonium
PWR	pressurised water reactor
R&D	research and development
RBMK	graphite moderated reactor of Russian design (“Chernobyl-type”)
RERTR	Reduced Enrichment for Research and Test Reactors
RVACS	Reactor Vessel Auxiliary Cooling System
SEAFP	Safety and Environmental Assessment of Fusion Power
SSAC	State’s System of Accounting for and Control of nuclear material
Sv	sievert (unit for radioactive dosis)
T	tritium
Tacis	technical aid for the CIS
Tc	technetium
Th	thorium
TRU	transuranic wastes
TUI-JRC	Transuranium Institute of the Joint Research Centre
TUM	Technical University Munich
TWh	terawatt hours (unit for energy)
U	uranium
UE&C	United Engineers & Constructors
VVER	light water reactor of Russian design

Directorate General for Research

Directorate A

Division for Industry, Research, Energy and Environment - STOA

Division for International and Constitutional affairs

Full list of the most recent Energy Series Working Papers.

N° and date	Title	languages
Working Paper * ENER 110 EN 11/1999	Towards a Re-orientation of National Energy Policies in the EU? Germany as a Case Study	EN
Summary ENER 110 EN 11/1999	Towards a Re-orientation of National Energy Policies in the EU? Germany as a Case Study	EN - DE - FR
Working Paper ENER 109 EN 08/1999	New Developments in the Field of Photovoltaic Cells	EN
Summary ENER 109 EN 08/1999	New Developments in the Field of Photovoltaic Cells	EN - DE - FR
Working Paper ENER 108 EN 09/1999	The European Parliament and EU R&TD Policy 1994-1999	EN
Working Paper ENER 107 EN 02/1999	The Opening-up of National RTD Programmes to Applicants From Other Member States: A comparative study	EN
Summary ENER 107 EN 02/1999	The Opening-up of National RTD Programmes to Applicants From Other Member States: A comparative study	EN - DE - FR
Working Paper ENER 106 EN 12/1998	Administrative Burdens and Procedural Rules in the European Union's Research Programmes and in those of the Individual	EN
Summary ENER 106 EN 12/1998	Administrative Burdens and Procedural Rules in the European Union's Research Programmes and in those of the Individual	EN - DE - FR

Working Paper ENER 105 EN 11/1998	US Climate Change Policy: Trends and Perspectives for International Cooperation	EN
Summary ENER 105 EN 11/1998	US Climate Change Policy: Trends and Perspectives for International Cooperation	EN - DE - FR
Working Paper ENER 104 EN 10/1998	From Kyoto to Buenos Aires: Global Climate Change and International Cooperation	EN
Summary ENER 104 EN 10/1998	From Kyoto to Buenos Aires: Global Climate Change and International Cooperation	EN - DE - FR
Working Paper ENER 103 EN 04/1998	Innovations for the promotion of renewable energies Innovations pour la promotion des energies renouvelables	EN - FR
Working Paper * ENER 100 EN 05/1998	Directory of the most important Community legislative measures in energy policy	EN

These publications are available on line on the Intranet at the following address:

www.dg4.ep.ec.

(*) Asterisked publications are also available on the Internet at the following address:

www.europarl.eu.int

To obtain paper copies of these publications, please contact:

E-mail : DG4-publications@europarl.eu.int