International Atomic Energy Agency (IAEA) Update on Spent Fuel Management Activities with Focus on Reprocessing - 8042

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ABSTRACT

The IAEA continues to give a high priority to safe and effective implementation of spent fuel management. As the options for spent fuel management may in the long term diversify due to evolving requirements and new priorities in strategic criteria, it is worthwhile identifying viable technical options for spent fuel treatment and their applicability to spent fuel management. The IAEA has issued several publications in the past that provide technical information on the global status and trends in spent fuel reprocessing and associated topics. The latest update of this information, collected from the experts in this field, covers currently available spent fuel reprocessing technologies as well as emerging technologies that are being investigated. The information exchange on advanced nuclear fuel cycles is also achieved through the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) initiated by IAEA.

Substantial global growth of nuclear electricity generation is expected to occur during this century, in response to environmental issues and to assure the sustainability of the electrical energy supply in both industrial and less-developed countries. Recent initiatives by (IAEA, USA and Russia) are proposing the internationalization of the nuclear fuel cycle. These proposals imply a need for the development of innovative means for closure of the nuclear fuel cycle as advanced reactors (Generations III and IV) are deployed and as the quantities of material in the fuel cycle are set to increase to levels several times larger than at present. Spent fuel treatment/reprocessing options have evolved significantly since the start of nuclear energy application. There is a large body of industrial experience in fuel cycle technologies complemented by research and development programs in several countries.

A number of options exist for the treatment of spent fuel. Some, including those that avoid separation of a pure plutonium stream, are at an advanced level of technological maturity. These could be deployed in the next generation of industrial-scale reprocessing plants, while others (such as dry methods) are at a pilot scale, laboratory scale or conceptual stage of development.
Innovative reprocessing methods would have to be developed for the treatment of fuel types that may be utilized in the future; these fuels may differ substantially from the UO2 or MOX ceramics used in current light water reactors. Continued research and development on these methods must continue in view of the expected evolution in fuel and reactor types.

The design of advanced reprocessing methods must deal in a comprehensive manner with (1) safety, (2) the control and minimization of plant effluents, (3) minimization of the waste generation, (4) the production of stable and durable waste forms, and (5) economic competitiveness. International collaboration on the development of advanced reprocessing methods, considering the magnitude of the challenges, is essential to facilitate the future deployment of these technologies. Several organizations (like IAEA and OECD) have developed modelling tools for analyzing nuclear fuel cycles.
There are a number of challenges to be addressed in development of new reprocessing strategies and technologies. Proliferation risk has to be reduced. One of the major obstacles to overcome is public acceptance of the advanced fuel strategies.

INTRODUCTION

Management of spent fuel arising from nuclear power production has long been considered an important issue due to the political, economic, and societal implications associated with it. In view of the large amount of spent fuel being progressively added to the cumulative inventory in the world, the significance of spent fuel management will continue to grow in the future.

While nuclear industry has successfully managed spent fuel quantities arising from nuclear power production in the past, a variety of issues have been raised through considerations of the long term strategy options for spent fuel management. It would be crucial to resolve or mitigate those issues for enhancing acceptance of the anticipated role of nuclear energy in the sustainable development in the future.

Substantial global growth of nuclear electricity generation is expected to occur during this century, in response to environmental issues and to assure the sustainability of the electrical energy supply in both industrial and less-developed countries. This growth carries with it an increasing responsibility to ensure that nuclear fuel cycle technologies are used only for peaceful purposes. Recently, proposals have been set forth by IAEA Director General ElBaradei (reference 1), U.S. President Bush, and Russian Federation President Putin for the internationalization of the nuclear fuel cycle. These proposals entail an implied need for the development of innovative means for closure of the nuclear fuel cycle as advanced reactors (Generations III and IV) are deployed and as the quantities of material in the fuel cycle are set to increase to levels several times larger than at present. Such increases can cause stress to the international non-proliferation regime and create undue problems for nuclear waste disposal if not dealt with through open and comprehensive international collaboration.

This paper describes the IAEA activities on spent fuel management with the focus on spent fuel reprocessing. The paper is based on inputs from experts from France, India, Japan, Russia and the U.S.A. The whole document on reprocessing options is going to be published in the IAEA TECDOC series.

Spent Fuel Statistics

Currently about 10 500 tHM spent fuel are unloaded every year from nuclear power reactors worldwide (Figure 1). This is the most important continuous growing source of civil radioactive materials generated, and thus need to be managed appropriately. Also, this annual discharge amount is estimated to increase to some 11 500 t HM by 2010. The total amount of spent fuel cumulatively generated worldwide by the beginning of 2004 was close to 268 000 t HM of which 90 000 tHM has been reprocessed. The world commercial reprocessing capacity is around 6 000 tones per year. Projections indicate that the cumulative amount generated by the year 2010 may be close to 340 000 t HM with a corresponding increase in reprocessed fuel. By the year 2020, the time when most of the presently operated nuclear power reactors will approach the end of their licensed operation life time, the total quantity of spent fuel generated will be approximately 445 000 t HM.

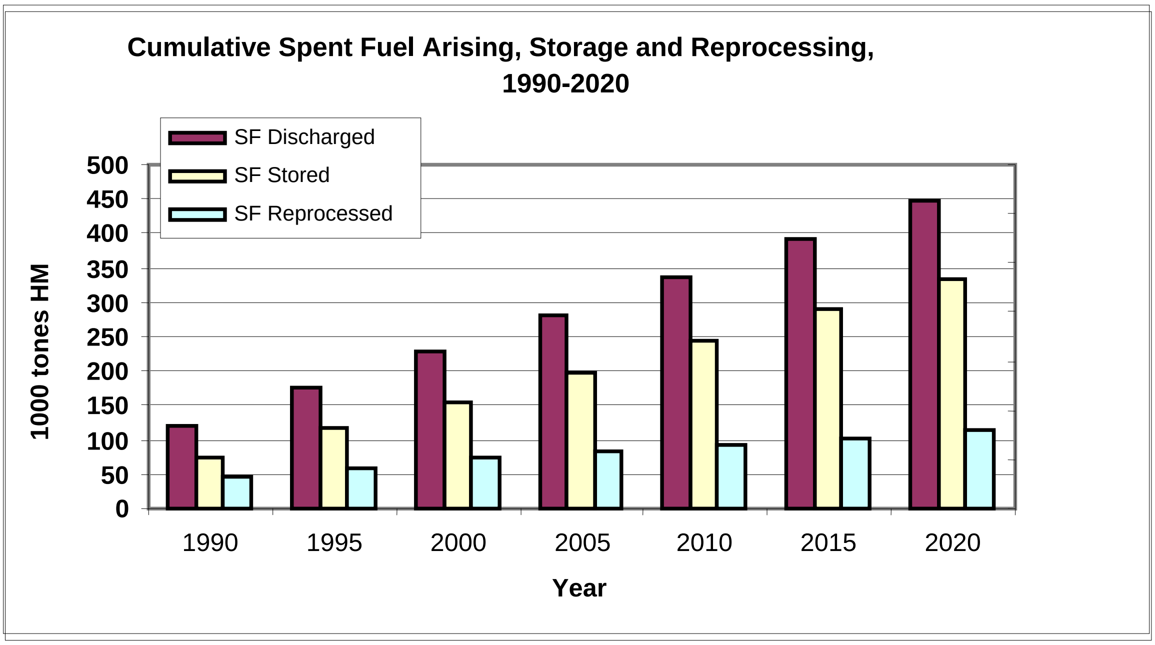

Figure 1: Trends in spent fuel management

IAEA Activities in Spent Fuel Management

The recent trend toward renewal of interest in nuclear power as a futuristic energy option calls for development of innovative nuclear systems in search of technical evolution for sustainable development. Several national and international initiatives have been launched for spent fuel reprocessing methods with a long term vision for technical innovation in spent fuel management.

Having recognized the needs for innovative systems, the IAEA has initiated its International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) several years ago, with a view to assist Member States in the development and deployment of nuclear systems by providing an umbrella for investigations in the field. With Phase I of the INPRO project being wrapped up, the INPRO assessment methodology is being validated on the basis of several case studies that have been performed by INPRO members. In recognition of the importance of fuel cycle issues, a Scientific Forum on the topic "Fuel Cycle Issues and Challenges", was held during the 48th General Conference of the IAEA (20-22 September 2004), which provided an opportunity to review technology and discuss several of the issues associated with spent fuel management. Another recent initiative launched by IAEA with an implication on spent fuel management is the Multinational Approach (MNA) to nuclear fuel cycles which was also a topic of the Scientific Forum during the 48th General Conference. In 2005, IAEA published an International Expert Group report on Multilateral Approaches to the Nuclear Fuel Cycle. This report formulated the initiative on Multilateral Fuel Cycle Facilities that would provide assurances of fuel supply and assurances of proliferation resistance.

The IAEA activities in spent fuel management have evolved in response to the changing needs and interests of its Member States. The status and trends in the Member States through the past decades have been closely surveyed and reflected in the formulation of IAEA programs which have dealt with a variety of technical and institutional topics.

In recognition of the importance of spent fuel reprocessing in the back end of the fuel cycle, the IAEA has provided a forum for exchange of information on the status and trends in spent fuel reprocessing since the 1970s, from which several publications have been issued (references 2, 3, 4, 5 and 6).

The latest publication (TECDOC-1467) had a scope enlarged to cover emerging technologies including dry processes, as well as the conventional PUREX based technologies which have been the focus of previous publications, with a view to provide a transition bridge toward new trends including a linkage to the INPRO initiative.

The Nuclear Fuel Cycle and Materials Section of the IAEA Department of Nuclear Energy has several programs that may, in the long run, provide additional inputs to spent fuel management options. Projects on Nuclear Power Reactor Fuel Engineering and on Topical Nuclear Fuel Cycle Issues are dealing with developments in their respective area that can in future widen spent fuel management options (references 7and 8). The latest work on thorium fuel cycle, management of reprocessed uranium and viability of recycling fissionable materials in reactors are all summarizing research results that may provide or affect additional reprocessing options (reference 9).

Spent fuel management unit of the IAEA Nuclear Fuel Cycle and Materials Section (NFMM) has the following topics on the agenda for years 2008/2009:

- Spent fuel performance assessment and research,
- Burnup credit applications,
- International conferences on management of power reactor spent fuel,
- Implications of damaged spent fuel for storage and transport,
- Storage facility operations and lessons learned,
- Systems integration considerations in spent fuel management,
- Influence of high burnup and mixed oxide fuel on spent fuel management,
- Spent fuel reprocessing,
- Spent fuel management economics,
- Regional/multinational spent fuel management facilities.

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management and the IAEA Safety Standards provide a framework for the international safety regime for spent fuel management.

Global Evolution of Spent Fuel Reprocessing Options

The objectives of the emerging fuel cycle strategies and their respective merits can be summarized as follows:

- Co-management of U and Pu to improve the proliferation resistance of spent fuel treatment.
- Selective separation and heterogeneous recycling of minor actinides to further reduce decay heat of the waste to be disposed of in a geologic formation. Heat load of the repository to host ultimate waste can already be significantly reduced with Pu removal as Pu is the major source of the decay heat and for long term potential radiotoxicity of PWR spent fuel. Selective separation and heterogeneous recycling

of minor actinides could further reduce the decay heat of the wastes disposed of in a geologic formation.

- Ultimately, a more challenging goal of achieving group extraction and homogeneous recycling of actinides in an integrated fuel treatment and refabrication facility to further simultaneously minimize the proliferation risk associated with the back-end of the fuel cycle, and the heat load of the repository for the waste to be disposed.

Existing facilities have significantly evolved by implementing new technological advances to address several key issues such as minimization/elimination of secondary waste stream, reduction of proliferation risk (no pure plutonium stream, e.g., Japan Rokkasho- mura plant).

Technical innovations addressed in recent international initiatives, such INPRO (IAEA), Gen IV and GNEP (USA), and MICANET (EU) are addressing several issues associated with future nuclear systems (reactor and associated fuel cycle) which are dealing simultaneously with energy supply, environmental impact, economics, non-proliferation, nuclear safety and security. These are key issues to the expansion of nuclear energy.

The envisaged strategy of reprocessing followed by recycling in breeder reactors from the beginning of peaceful use of nuclear energy has eventually evolved into a policy toward either (1) reprocessing followed by recycling in thermal reactors in some countries as a result of lengthy delays in breeder reactor deployment, coupled with the availability of international fuel cycle services in existing facilities, or (2) direct disposal of spent fuel in a growing number of countries as a result of concerns about nuclear proliferation and economic considerations as the growth in nuclear generation and demand for natural uranium resources failed to materialize in the latter part of the previous millennium. With the exception of a few countries, however, implementation of the policy calling for spent fuel disposal has encountered continuing delays due to controversies hampering geologic repository site selection and development.

From the beginning of the new millennium, there have been growing aspirations for innovative technologies in nuclear energy, given the anticipated, significant contributions by nuclear energy in mitigating global warming concerns. It is therefore essential to consider technical innovations in future nuclear fuel cycles, which can improve the sustainability of nuclear energy by (1) reducing substantially the uranium consumption per unit of energy produced, and (2) further reducing the long-term radiotoxicity of high-level waste through their ability to burn the majority of long-lived minor actinides, such as neptunium and americium, in addition to the major actinides (uranium and plutonium) as presently achieved by the PUREX separation process, while keeping the costs of energy products, in particular electricity, economically affordable.

It needs to be stressed that each country is facing a different situation with regard to the following:

- Global energy mix and energy policy, current status and prospects for the contribution of nuclear power, and commitment to the reduction of greenhouse gas emissions such as CO_2,
- Availability of fissile materials resources,
- Nuclear power fleet (number of units, reactor(s) type(s) and fuel cycle technologies implemented, etc.),

- Inventory of radioactive materials (including legacy waste) resulting from past and waste management practices,
- Choice and capacity of candidate geologic formations chosen for ultimate disposal,
- Public (and political) support for nuclear energy.

These current considerations are drivers for the choice of a national back-end strategy with the following possibilities:

- "Direct Disposal" or "Once-through Fuel Cycle",
- "Storage and Postponed Decision" or "Wait and See Option",
- "Reprocessing and Recycling" or "Closed Fuel Cycle".

Drivers for closed cycle and advanced recycling strategies

There are five key considerations for a closed fuel cycle strategy and R&D on advanced fuel cycles to further improve it (references 6 and 8):

- Conservation of natural resources
- Optimization of waste management and disposal conditions,
- Minimization of environmental impact,
- Fuel cycle economics,
- Proliferation resistance.

Compared to the once through fuel cycle strategy, the present approach based on the PUREX separation process and recycling of plutonium as mixed oxide fuel (MOX) in light water reactors offers the following advantages:

- Improve use of fissile materials resources by up to 25%,
- Leads to a reduction of conditioned/packaged high level and long lived waste volume to be disposed of, thanks to the removal uranium and plutonium,
- Decreases the long-term radiotoxicity of HLW to be disposed of.

Innovative separation method now under development would also allow for the removal of minor actinides, such as americium and neptunium, therefore further optimizing the utilization of fissile materials and alleviating the heat constraints on the final repository.

It must be noted that some countries are concerned with the potential disadvantages of the current fuel reprocessing strategies like the cost of reprocessing and potentially lower proliferation resistance.

Impact on Geologic Repository

The design and capacity of a geologic repository depends on:

- Decay heat release and time for packages to cool down,
- Long term radiotoxicity of the waste,
- Mobility and transport of radio-elements in case of loss of containment and rupture of all barriers surrounding the waste package (depending on the geochemistry of the selected site with either oxidizing or reducing conditions).

The long term environmental impact of the disposed HLW therefore depends on:

- Its inventory as a result of the nuclear power plants fleet composition (reactor types) and selected fuel cycle strategy,
- The solubility and migration of the elements in the selected geological site.

As a result, the relative radiological impact of each of the nuclides contained in the disposed HLW varies depending on the repository concept and the type of host rock.

REPROCESSING OPTIONS FOR SPENT FUEL

Irradiated nuclear fuels were first reprocessed in the 1940s using pyrochemical and precipitation processes.

These separation methods were soon replaced by the solvent extraction process (hydrometallurgy), which is better suited to continuous, large scale, remote operation, allowing for the separation of 3 main streams of nuclides (uranium, plutonium, and waste, i.e. fission products and minor actinides). Different solvent extraction systems were explored before the discovery of an efficient extraction system. The combination known generically as PUREX (which utilizes the extractant tributyl phosphate (TBP) mixed in a largely inert hydrocarbon solvent) soon replaced all earlier solvent extraction media because of its high performance in industrial scale plants. The PUREX process was used for several decades in the production of separated plutonium for military purposes; during that time, process was optimized for maximum efficiency of recovery and purification.

The first plant based on hydrometallurgy emerging on the market to reprocess spent fuel from commercial power plants was built in Belgium in the sixties on a multinational basis (EUROCHEMIC).

In the seventies, based on the assumptions of a rapid growth in nuclear energy and uranium demand, industrial implementation of the closed fuel cycle using the PUREX process was further extended with the reprocessing of used fuel coming initially from gas-cooled reactors, later on from LWRs (BWRs and PWRs), and then from PHWR reactors. The recycling of plutonium in the form of mixed-oxide fuel (UO_2-PuO_2 or MOX fuel) in fast breeder reactors (expected at that time to be deployed on a large scale) was regarded as the standard strategy.

In the eighties, the worldwide development in nuclear energy turned out to be more modest than originally planned and prospects for the implementation of fast reactors associated with a closed fuel cycle were progressively postponed in several countries (see country reports).

However, several countries including France, Japan, UK, Russia and India, continuously developed, improved and adapted the PUREX technology. In France for the MOX-fuel fabrication, in Russia for U recycling in RBMK fuel, in India for the U recycling in PHWR fuel and MOX for FBR.

As a result of this fuel cycle strategy based on PUREX, the volume (and radiotoxicity) of highly radioactive and long-lived waste to be disposed of in these countries were significantly reduced as compared to a once-through fuel cycle, with inventory high level waste restricted to fission products and minor actinides (which are conditioned in a very stable glass matrix), and very small losses of plutonium to the waste stream.

As a result of several decades of industrial feed-back in the development of the closed fuel cycle strategy based on the PUREX process, one can mention the following major achievements:

- High efficiency and reliability (large amount of used fuel processed with good statistics, see countries reports),
- The fabrication of high quality UO_2 and MOX fuels for LWRs and fast reactors,
- Continuous decrease of solid waste volume, effluents and environmental impact in terms of radiation doses.

It is also worth mentioning the distinct situation of the United States of America (U.S.A.).

After having developed the closed fuel cycle in the early days of nuclear power developments, the USA switched to a once-through cycle in 1978 mainly because of proliferation concerns. Early in 2006, a major political transition occurred with the launching of the Global Nuclear Energy Partnership (GNEP) initiative. This proposed return to the closed fuel cycle was decided both for domestic reasons (especially regarding the optimization of the capacity of the geological repository for ultimate waste) and for the implementation of a multinational approach to the fuel cycle in a context of a worldwide renaissance (and prospects for a sustainable development) of nuclear power and minimization of proliferation risk.

R&D IN SUPPORT OF ADVANCED REPROCESSING OPTIONS

As mentioned there is continued research on developing new reprocessing technologies and advanced fuel cycles. The Table 1 below shows the list of processes that are either in use or in various stages of investigation in countries working on closed nuclear fuel cycles. The table indicates the significant amount of effort distributed among only few countries.

Table 1: Processes being developed in leading nuclear countries

Processes implemented in commercial plants on industrial scale	Countries where applied or developed
PUREX	France, Japan, UK, Russia, India
Evolutionary technologies (Gen 3) based on aqueous separation methods (derived from PUREX)	Countries where developed
COEX	France
NUEX	UK
Simplified PUREX	Russia
THOREX	India
NEXT	Japan
REPA	Russia
Innovative aqueous processes using new extractant molecules	Countries where developed
DIAMEX-SANEX	France
UREX+3a	USA
UREX+1a	USA
GANEX	France
PARC	Japan

Water-extraction with the integrated process using two extractants	China
ARTIST	Japan
Non-aqueous technologies (dry route)-Pyrochemical processes	Countries where developed
DDP	Russia
Electro Metallurgical process	USA
Pyro-chemical process (liquid-liquid)	France
Hybrid methods combining Hydro and Pyro processes	Countries where developed
FLUOREX gas-fluorine separation method	Japan
Combined process including gas fluorine and extraction technologies	Russia
Other innovative processes	Countries where developed
Fluid extraction	Japan, Russia
Ion exchange processes	Belgium, Japan
Sedimentation processes	Japan

Major Actinides Separation

Three types of technologies are considered for major actinides separation:

1) Hydrometallurgical processes (aqueous technologies) as the reference route nowadays for industrial scale spent fuel reprocessing. They have a high potential of optimization to further address minor actinides, global actinides or fission products partitioning. This is the only mature process (fully closed cycle) to deal both with:

- The separation of major actinides such as U and Pu;
- The treatment and conditioning of ultimate waste for long-term storage.

The processes derived from PUREX are able to deal with a large variety of spent fuels (oxides, carbides, nitrides) whatever are the nature and shape of the fissile composite. They can also be adapted to the co-laminated fuel (U Mo, U Si, U Al, Pu Al).

2) Pyrometallurgical processes (non aqueous technologies) as another promising R&D route for the reprocessing of:

- Metallic fuel (electro refining process);
- Very radioactive fuels (early-processing of spent fuel) or fuel with a high content of minor actinides (transmutation fuels for ADS targets in heterogeneous recycling mode, or fuels assemblies dedicated to transmutation in fast systems in homogeneous recycling mode)

These methods are also aiming at the global actinide separation.

3) Other non-aqueous technologies: this section is dealing with a fluid (CO_2 or Freon) dissolution and extraction process, fluorination, etc...

Minor Actinides Separation

Most processes are developed to separate minor actinides in the raffinate of the PUREX process (either using standards PUREX or slightly modified PUREX process). Minor actinides separation can be achieved either by aqueous processes or non aqueous processes. Aqueous processes under investigation can be classified as one step processes, two step processes. In addition, processes are developed for Americium/Curium separation.

Group Actinide Separation Technologies

The principle of group actinide separation is shown in the figure 2 below:

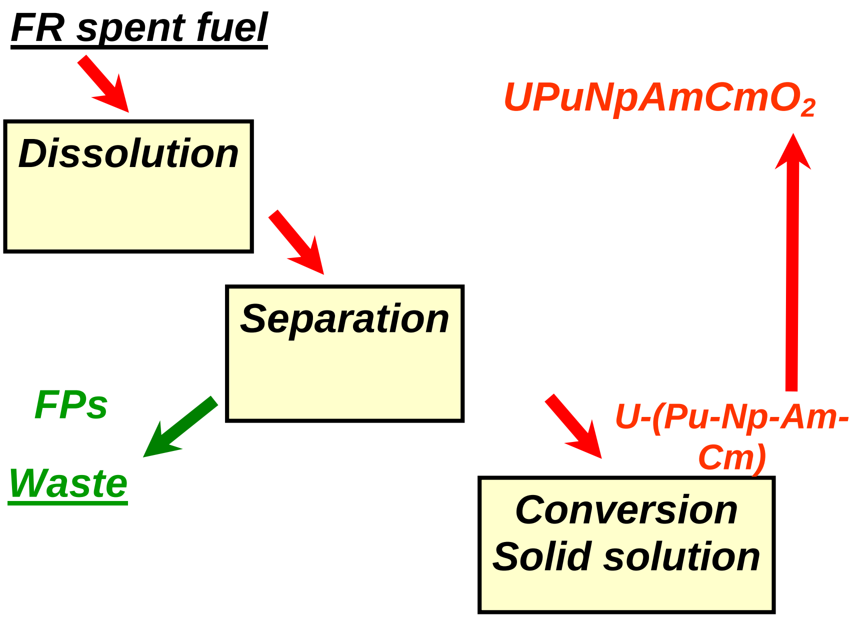

Figure 2: Principle of grouped actinides separation

The concept process to allow group management of actinides by their collective extraction from dissolution solution is known as GANEX and its broad outlines are shown in Figure 3 (reference 11).

Figure 4 shows the radiotoxicity of radionuclides that are components of spent fuel indicating the significance of major actinides in radiotoxicity of spent fuel.

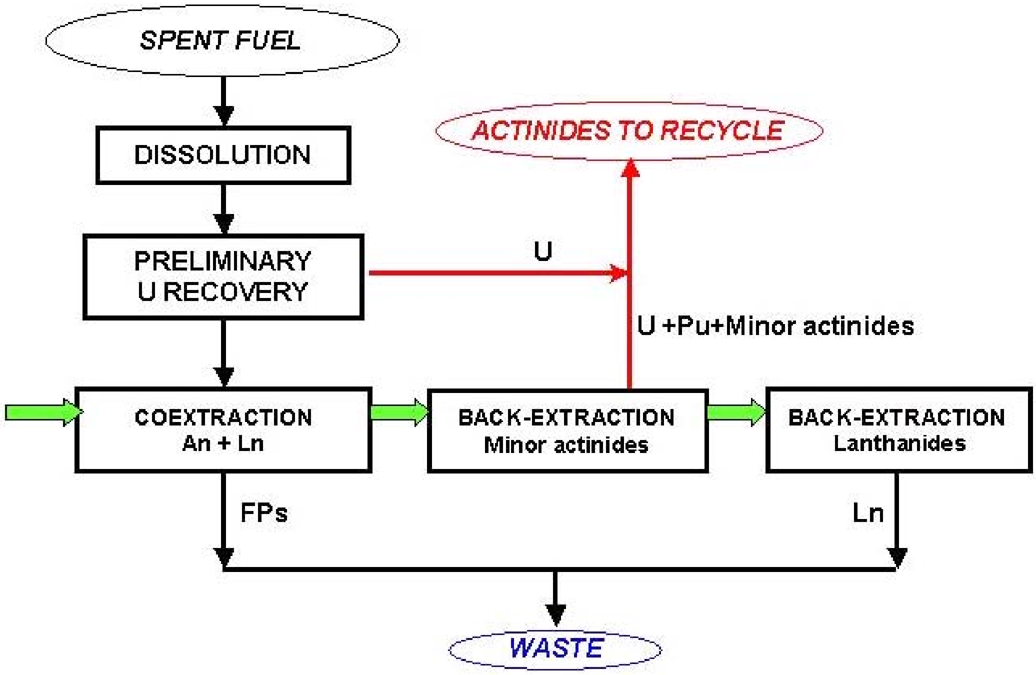

Figure 3: Group actinide extraction (GANEX concept)

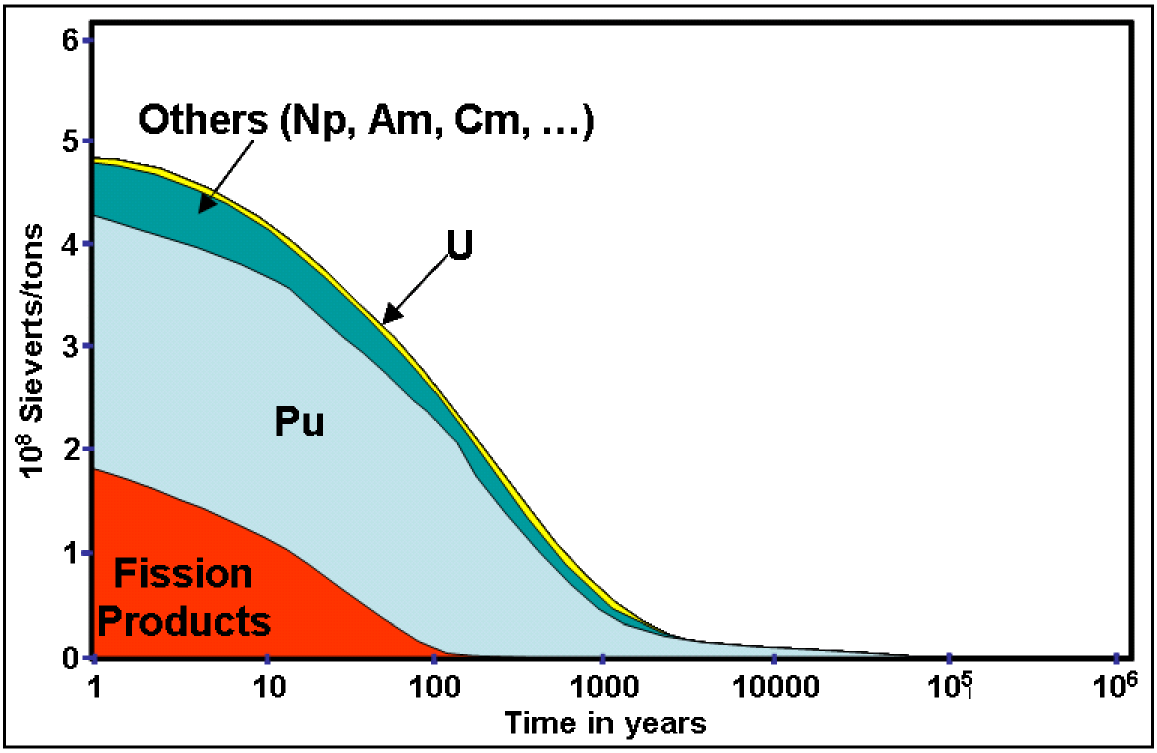

Figure 4: Radiotoxicity vs. time for radionuclide components of spent fuel

Fission and Activation Products Separation Technologies

The long-lived radio-nuclides (β and γ emitters) of relevance for HLW repositories are:

- Among the fission products (by order of decreasing half-life): ^{129}I, ^{135}Cs, ^{99}Tc, ^{126}Sn, ^{79}Se.
- Among the activation products: ^{36}Cl, ^{93}Zr, ^{14}C.

The relative radiological importance of these nuclides varies depending on the repository concept and geochemistry (oxidizing or reducing conditions) of the selected site. The Partitioning &Transmutation strategies are currently focused on the most abundant long-lived radionuclides, i.e. ^{129}I, ^{135}Cs, and ^{99}Tc[1], and on those radionuclides that generate substantial heat in the process of radioactive decay (i.e. ^{90}Sr and ^{137}Cs). Figure 5 shows decay heat decrease over time for several radionuclide separation scenarios.

Various processes for recovery of important fission products are under development.

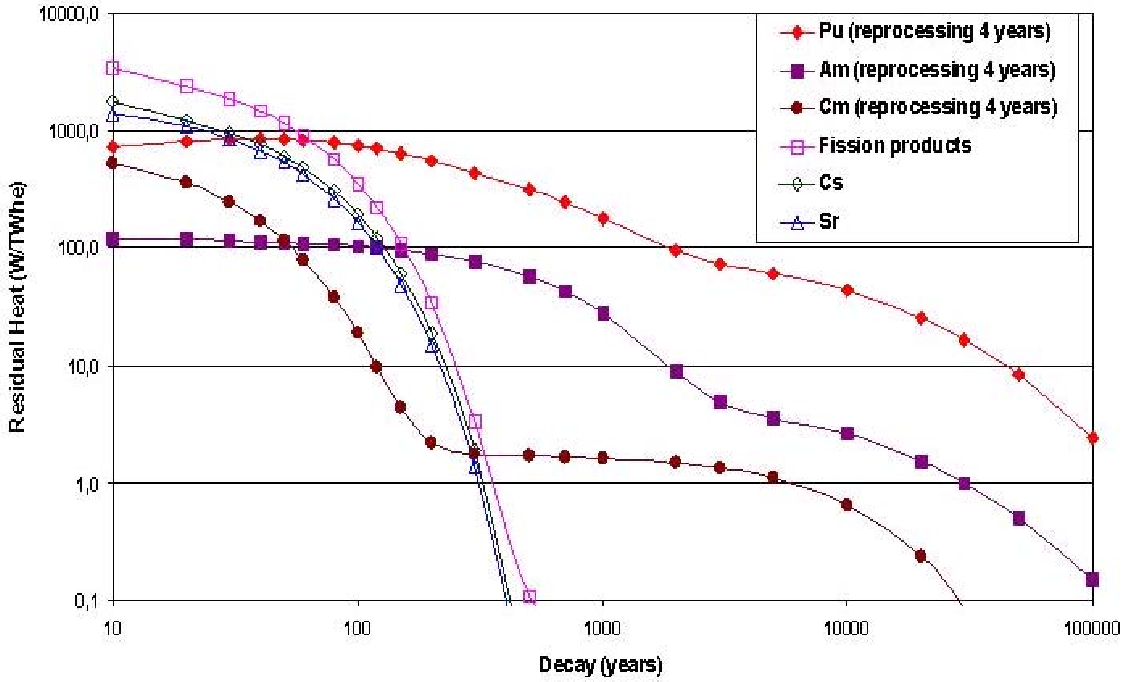

Figure 5: Decay heat vs. time for various components of the fuel cycle

Partitioning followed by conditioning is an intermediate strategy towards partitioning and transmutation. For waste management purposes the separated Np, Am-Cm could be mixed with very insoluble matrix and thus immobilized.

[1] In practice, only I-129 and TC-99 can be transmuted and the radiological impact of the other long-lived fission products can be reduced only by special conditioning and confinement. The practicability of fission products transmutation is problematic at present.

ISSUES AND CHALLENGES RELATED TO SPENT FUEL REPROCESSING

Resolving the challenges associated with emerging fuel cycle strategies include non-proliferation, minimization of industrial discharges from fuel reprocessing facilities, and economic competitiveness.

All nations that have signed the Non-Proliferation Treaty (NPT) have the right to pursue enrichment and reprocessing for peaceful purposes in conformity with Articles I and II of the Treaty. However, there is no "silver bullet" technology that can be built into an enrichment plant or reprocessing plant that can prevent a country from diverting its national fuel cycle facilities to non-peaceful use. Therefore, from the standpoint of resistance to proliferation caused by a national commitment to weapon development, there are technological limits to the non-proliferation benefits offered by any of the advanced chemical separations technologies, which can be modified to produce plutonium if a nation is willing to withdraw from, or violate, its safeguards obligations. This is one of the driving elements for the Global Nuclear Energy Partnership (GNEP) initiated by the U.S. (reference 12) and joined by China, France, Japan and Russia (joint statement on May 21, 2007), which aims to provide the benefits of nuclear electricity at a reasonable cost to those countries that choose not to pursue uranium enrichment and spent fuel reprocessing. By doing so, these countries can avoid the cost of building a fuel cycle infrastructure (enrichment, reprocessing, fuel fabrication and perhaps even high level waste disposal).

It should be noted that a commercial plant providing international fuel cycle services would essentially be prevented to do so as the scrutiny of its foreign customers would provide a strong extrinsic non-proliferation control.

Significant reductions have been achieved in the radiological discharges as illustrated by the 2000 Marina II Study by the European Commission (reference 13). The radiological discharges from the La Hague and Sellafield reprocessing plants were contributing ~5% to the collective dose from all industrial radioactive discharges into the North Sea. Oil and gas, and phosphates operations were contributing respectively ~35 and ~55%. However, the nuclear industry remains under pressure to further reduce environmental discharges from reprocessing facilities.

The competitive edge, or lack thereof, of innovative fuel cycle schemes as compared with schemes based on existing technologies is difficult to quantify with accuracy, given the various degrees of uncertainties affecting established versus conceptual technologies. Clearly, even if the back-end fuel cycle costs represent a small fraction of overall costs, they must remain reasonably competitive when all alternatives are considered. Maybe as important, if not more so, are the investment risks that have to be acceptable to those considering investing in fuel reprocessing options. These risks must be weighted against waste disposal benefits and intangibles such as global proliferation risk mitigation.

Political will and public acceptance will be required to construct the facilities needed to support advanced fuel cycles. Recognition of the societal significance of the potential benefits of the technology together with sufficient public involvement in handling environmental matters will be key in obtaining government and local public support.

CONCLUSIONS

- Civil reprocessing of spent fuel utilizing the PUREX process has been successfully practiced on a commercial scale for over 40 years without occurrences of diversion of special nuclear materials. These operations have been both for the purpose of spent fuel management and for the recovery of uranium and plutonium for recycle as UOX and MOX fuel for light water and fast reactors. Such a combination of spent fuel reprocessing and recycling is leading to benefits in ultimate waste disposal.

- Measures to improve the environmental protection performance of commercial reprocessing plants over the past 20-30 years have greatly reduced emissions and waste volumes.
- Growth in global nuclear electric generating capacity through this century will result in the production of increasing quantities of spent fuel that must be dealt with by reprocessing and recycling in order to minimize the stress on uranium resources and mitigate waste disposal issues and concerns with increasing inventories of plutonium and other fissile materials.
- The deployment of multi-national fuel cycle centres, operating under an international framework and most effectively implemented in those countries with a sufficiently large civil nuclear energy infrastructure, can serve to ensure a sustained supply of nuclear fuel and related services under conditions in which the risk of proliferation of technologies related to the production of nuclear weapons is minimized. Reprocessing of spent fuel will be an important function of these centres.
- A number of options exist for the recycling of spent fuel. Some, including those that avoid separation of a pure plutonium stream, are at an advanced level of technological maturity. These could be deployed in the next generation of industrial-scale reprocessing plants, while others (such as dry methods) are at a pilot scale, laboratory scale or conceptual stage of development.
- Next-generation spent fuel reprocessing plants are likely to be based on aqueous extraction processes that can be designed to a country specific set of spent fuel partitioning criteria for recycling of fissile materials to advanced light water reactors and/or fast spectrum reactors. The physical design of these plants must incorporate effective means for materials accountancy, safeguards and physical protection.
- Innovative reprocessing methods must be developed for the reprocessing of fuel types that may be utilized in the future; these fuels may differ substantially from the UO_2 or MOX ceramics used in current light water reactors. Continued research and development on these methods must continue in view of the expected evolution in fuel and reactor types.
- The design of advanced reprocessing methods must deal in a comprehensive manner with (1) safety, (2) the control and minimization of plant effluents, (3) minimization of the waste generation, (4) the production of stable and durable waste forms, and (5) economic competitiveness. International collaboration on the development of advanced reprocessing methods, considering the magnitude of the challenges, is essential to facilitate the future deployment of these technologies.
- A detailed mass balance analysis of fuel cycle scenarios is required for the deployment of advanced spent fuel reprocessing methods, taking into account waste production, safeguards, and the impact of partitioning on downstream operations such as the fabrication of fuel for the recycle of recovered actinides.

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