

Watching Brief on Reprocessing, Partitioning and Transmutation and Alternative Waste Management Technology - Annual Report 2008

NWMO TR-2008-22

December 2008

David P. Jackson and Kenneth W. Dormuth

David P. Jackson & Associates Ltd.

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MANAGEMENT
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ABSTRACT

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Abstract

This is the 2008 annual report of the Nuclear Waste Management Organization's watching brief on reprocessing, partitioning and transmutation and alternative waste management technology. International developments are reviewed based on recent published documents and on the presentations at the Nuclear Energy Agency Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation held at Mito, Japan in October 2008. Technical developments on reprocessing, partitioning and transmutation in national and international research and development programs are described. In some countries, reprocessing is part of an approach to achieve sustainable nuclear energy through closed fuel cycles and fast reactors. In Canada, the current policy is a once-through nuclear fuel cycle without reprocessing.

It is concluded that although there is extensive research in reprocessing, partitioning and transmutation, its realization is still many years in the future. In particular, the findings from studies on future nuclear energy scenarios suggested that it will take about 100 years or more (i.e., beyond 2100) before closed fuel cycles with reprocessing will achieve a sustainable nuclear future with fast reactors.

Also reported are recent developments in alternative waste management technology including the Very Deep Borehole approach to long-term management of used nuclear fuel and a new approach to the deep borehole concept.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is maintaining a watching brief on used nuclear fuel reprocessing, partitioning and transmutation (RP&T), and alternative technology for the long-term management of nuclear fuel waste (NWMO 2005; 2008). This is the first of a series of annual reports which summarize international developments on RP&T and alternative technology which build on previous NWMO's studies on RP&T (Jackson 2003; 2005).

Reprocessing is a general term for applying chemical and physical processes to used (spent) nuclear fuel from today's reactors to separate out (**partition**) its components generally into five streams, as described below:

- (1) The used reactor fuel elements are mechanically disassembled and the zirconium-based metal cladding structures that hold the fuel pellets are set aside for separate disposal.
- (2) The fuel pellets are next dissolved in hot nitric acid with uranium-238 forming most of the mass in the solution along with a much smaller amount of residual (unburned) uranium-235; the uranium-235 can be recycled in new fuel as "Reprocessed U" but is more commonly stored with the uranium-238.
- (3) Fissile isotopes such as plutonium-239 are also present in the solution and offer the option of recycling them in fresh reactor (MOX) fuel or leaving them in solution.
- (4) Short-lived and long-lived Fission Products (FP), and other radioactive isotopes formed by neutron activation, some of which require long-term management, are removed as a waste stream and typically stored incorporated in glass blocks.
- (5) The Minor Actinides that have long half lives and are responsible for much of the long-lived radioactivity of spent fuel are candidates for transmutation and the subject of much of the research and development on RP&T.

Broadly speaking **transmutation** means the transformation of radioactive isotopes into non-radioactive or stable isotopes by bombarding the target isotopes with neutrons or other high energy particles. In the context of current RP&T development transmutation is often narrowed to mean forcing the Minor Actinides to fission in an intense flux of high energy neutrons provided by a Fast Reactor (FR) and/or in an Accelerator Driven System (ADS) with the purpose of destroying them prior to placing the residual high-level radioactive waste in a Deep Geological Repository (DGR). The above activities are grouped together under the abbreviation RP&T.

At the moment, France, Russia, and the United Kingdom operate large reprocessing facilities and Japan is in the process of starting up a substantial reprocessing facility. China and India have smaller reprocessing facilities, which they plan to expand, and the United States has announced that it is planning a very large reprocessing facility.

This report begins with a review of the main programs in RP&T, firstly, the International Programs followed by those of the European Union, Japan, France, Russia and the United States. This part of the report is completed by a brief consideration of the RP&T programs of the emerging nuclear powers in Asia, namely, India and China. A discussion of the various fuel cycles follows including scenarios that could lead to a sustainable nuclear fission future. The next sections discuss the status of Reprocessing facilities and Fast Reactors (FR) as experimental facilities. Current developments in Partitioning and Transmutation are then

discussed and next the effect of RP&T on Deep Geological Repositories is covered. The final section considers new information on Alternative Waste Management Technology.

Much of this report is based on recent reports published by the IAEA, *Spent Fuel Reprocessing Options* (IAEA, 2008a) and the NEA, *Market Competition in the Nuclear Industry*, (NEA, 2008) in addition to the *Tenth Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation*, organized by the Nuclear Energy Agency, in Mito, Japan, 6-10 October 2008. (Mito, 2008)

2. NATIONAL AND INTERNATIONAL RP&T PROGRAMS AND THEIR FUNDING

2.1 INTERNATIONAL PROGRAMS

Since the RP&T policies and strategies of many countries are related to international agreements, it is useful to describe the main ones at the outset.

The Generation IV International Forum (GIF), originated and led by the United States, was established in January 2000 to investigate innovative nuclear energy system concepts for meeting future energy challenges. GIF members include Argentina, Brazil, Canada, China, EURATOM, France, Japan, Russia, South Africa, South Korea, Switzerland, United Kingdom, and United States, with the OECD-Nuclear Energy Agency and the International Atomic Energy Agency as permanent observers (GIF, 2008).

The name comes from a somewhat arbitrary time division of nuclear reactor development. Generation I comprised prototype reactors, Generation II was the first cohort of commercial reactors and Generation III reactors are the current commercial reactors. Generation IV consists of advanced reactor types which are being studied by the GIF. A joint research and development (R&D) program between the members was agreed in 2005 to investigate six reactor types which satisfy the GIF criteria of economy, safety, environmental protection, and proliferation resistance. Members can elect to participate in the programs on the reactor designs of most interest to them.

Three of the Generation IV reactors are Fast Reactors (FR), a type that has only a few reactors in operation today. These reactors have no moderator and so operate with fast neutrons. Present examples use liquid sodium coolant and convert ('breed') uranium-238 to plutonium-239 using fuel enriched with 10-20% uranium-235 and plutonium-239. Gen IV is looking at the following three advanced fast reactor designs.

1. Sodium-Cooled Fast Reactor (SFR): sodium-cooled reactor with fuel recycling, an advanced version of today's FRs.
2. Gas-Cooled Fast Reactor (GFR): helium-cooled with recycled fuel.
3. Lead-Cooled Fast Reactor (LFR): lead/bismuth eutectic liquid metal coolant and recycled fuel .

There is also an epithermal reactor that could be an FR under certain circumstances:

- Molten Salt Reactor (MSR): a circulating molten salt fuel mixture containing UF₆ which is also the coolant, which can have fuel recycling.

There are also two advanced thermal neutron reactors in the GIF collaboration, one of which is the focus of Canadian interest. Canada has had no history in FRs and, if in spite of very large uranium reserves fissile fuel breeding is required, Atomic Energy of Canada Limited (AECL) has done some R&D on the thermal breeder thorium cycle based on CANDU.

By way of clarification, a variety of actinides, elements with atomic numbers from 89 (actinium) to 103 (lawrencium), are important constituents of spent (used) reactor fuels. The actinides with atomic numbers greater than that of uranium (92) are called TRUs (meaning transuranic elements) and hence, uranium is an actinide but not a TRU. Generally, in a reactor, the actinides are produced in the fuel by neutron capture reactions with subsequent decay. The Minor Actinides (MAs) are those actinides other than uranium-238, uranium-235 and plutonium-239, the more abundant actinides in used fuel. The most notable MAs are isotopes of neptunium, americium, curium and some uranium and plutonium isotopes other than the main ones that are present in small amounts. Finally, there are the lanthanides [elements with atomic numbers from lanthanum (57) to dysprosium (66)], which primarily occur in the used fuel as fission products.

The FRs are a possible path to a sustainable closed nuclear fuel cycle with both recycling of fissile materials and burn up of Minor Actinides (MA) which may significantly reduce the geological repository space required for nuclear fuel waste. Thus, RP&T in various forms is an integral component of the GIF program.

While GIF is primarily a technical undertaking to develop a new generation of nuclear reactors, it appears to have been eclipsed in terms of the priorities of the United States government by the Global Nuclear Energy Partnership (GNEP), a political initiative to address the challenges and opportunities associated with the projected increase in nuclear power production. (GNEP 2008) Twenty-five nations, including Australia, Canada, China, France, Japan, Russia, and the United States have now signed the GNEP Statement of Principles. A major stated objective for cooperation in GNEP is as follows:

“Develop and demonstrate, inter alia, advanced technologies for recycling spent nuclear fuel for deployment in facilities that do not separate pure plutonium, with a long term goal of ceasing separation of plutonium and eventually eliminating stocks of separated civilian plutonium. Such advanced fuel cycle technologies, when available, would help substantially reduce nuclear waste, simplify its disposition and draw down inventories of civilian spent fuel in a safe, secure and proliferation-resistant manner”.

One of the objectives of reprocessing and recycling of spent nuclear fuel in the United States arises from the potential need to avoid siting and developing more geological repositories equivalent to the planned facility at Yucca Mountain in Nevada. The recycling plan in GNEP calls for extraction and long-term storage of heat-generating nuclides for hundreds of years along with destruction in fast reactors of longer-lived MAs (Minor Actinides). The objective is to effectively increase the Gigawatt-years of waste that can be placed in a deep repository. One major concern, however, is that reprocessing presents a proliferation risk by potentially making separated plutonium accessible or making the separation of plutonium for weapons more readily achievable in non-weapons states. To counter this, GNEP would employ a process that does not separate pure plutonium at any stage.

The GNEP strategy has been subject to significant criticism, most notably from a panel of the United States National Academy of Sciences, commissioned to review the Department of

Energy (USDOE) research programs and recommend priorities among those programs. (NAS, 2007) The Panel advised that it could see no economic justification for proceeding with GNEP R&D at the pace planned. USDOE spokespersons have indicated that the Panel review was based on misunderstanding of the program.

However, whatever the eventual fate of GNEP, it appears that a strategy that includes reprocessing and recycling of used nuclear fuel, as opposed to a once-through fuel cycle with direct placement of used fuel in a deep geological repository, has a level of international political support.

Independently of GNEP, other countries, including Russia, France, Japan, and India are developing advanced nuclear fuel cycles as a means of extending the sustainable lifetime of economical nuclear power production. These activities give some indication that, although there are an estimated 3.3 million tonnes of uranium recoverable at less than US \$130/kgU, a substantial part of the international community does not consider the once-through cycle to be sustainable in view of potential options to reduce the resource requirements and lower the radiotoxicity of the radioactive waste destined for a deep geological repository.

2.2 EUROPEAN COMMISSION

The governing policy on nuclear fuel cycles of the 27 nations in the European Commission is the Sustainable Nuclear Energy Technology Platform (SNE-TP) which started in September 2007. It is aimed at focussing public and private efforts on the concept of sustainable nuclear energy and the R&D necessary to achieve it. It comprises strategic research in the following areas:

- Support for Gen II and Gen III reactors
- Process Heat, Electricity and Hydrogen
- Advanced Fuel Cycles and Gen IV systems

The strategy of the SNE-TP is based on the following assumptions:

- Once-through cycles are unlikely to be sustainable simply because of uranium resource limitations.
- Reprocessing of the used fuel and transmutation of Minor Actinides (MA) in dedicated devices reduces the radiotoxicity of geological repositories.
- RP&T is important for non-proliferation measures and prevention of radiological terrorism and reduces risks in case of an inadvertent 'human intrusion' in a geological repository.
- A double-strata approach with Sub-critical Accelerator Driven Systems (ADS) and/or Critical Fast reactors is being considered. A decision on the choice is planned in a couple of years.

Placement of the remaining radioactive wastes, including separation/transmutation losses, in a deep geological repository will still be required.

European Commission research in nuclear areas under EURATOM is organized in Framework Programs (FP). These programs generally last for four to five years. For example, FP6 was conducted from 2002-06 and FP7 is now underway from 2007-11; FP7 may be extended to 2013. While fusion R&D funding dominates (824M€ in FP6 and 1947M€ in FP7), fission and radiation protection also receive substantial funding (209M€ in FP6 and 287 M€ in FP7).

Table 1 gives the RP&T programs funded under the European Commission Framework Program FP6. Some of the FP6 programs are continuing into the FP7 timeframe (Bhatnagar 2008).

Table 1: European RP&T Programs in FP6

Acronym	Abbreviated Title	Budget (M€)	
		Total	EC
PATEROS	P&T European Road map	0.8	0.6
RED-IMPACT	Impact study of P&T on Waste Management	3.9	2.0
EURO-PART	Partitioning techniques and processes	11.2	6.0
EURO-TRANS	All Aspects of Transmutation by sub-critical ADS	45.0	23.0
ELSY	Waste transmutation in Lead Cooled critical system	6.9	2.95
PUMA	Plutonium & MA Management by thermal Gas-cooled system	3.7	1.85
VELLA	Networking of lead loop infrastructures in Europe	3.3	2.3
LWR-DEPUTY	Light Water Reactor (LWR) fuels for deep burning of plutonium in thermal systems	2.4	1.25
EFNUDAT	Networking of EU facilities for nuclear data	3.0	2.4
CANDIDE	Networking of Nuclear data for EU Industrial Development	0.8	0.8
NUDAME	Trans-national access for nuclear data	0.2	0.2
Totals:		81.2	43.4

Source: (Bhatnagar, 2008)

Table 2 gives the RP&T programs funded under the European Commission Framework Program FP7.

Table 2: European RP&T Programs in FP7

Acronym	Abbreviated Title	Budget (M€)	
		Total	EC
ACSEPT	Actinide Recycling by Separation and Transmutation	23.8	9.0
GETMAT	Gen IV and Transmutation Materials	14.0	7.5
F-BRIDGE	Basic Research for Innovative Fuel Design for Gen IV Systems	10.2	5.4
CARBOWASTE	Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste	12.0	6.0
EUFROT	European Facility for Innovative Reactor and Transmutation Neutron Data	0.5	0.5
JHR-CP	Jules Horowitz Reactor-Collaborative Project	3.4	1.75
ACTINET-13	ACTINET Integrated Infrastructure Initiative	~6.0	~3.0
CP-EFSR	Collaborative Project on European Sodium Fast Reactor	~11.5	~5.8
FAIRFUELS	Fabrication and, Irradiation and Reprocessing of Fuels and Targets for Transmutation	~6.5	~3.0
CDT	Central Design Team for a Fast Spectrum Transmutation Experimental Facility	~5.0	~2.0
Totals:		~92.9	~44.0

Source: (Bhatnagar, 2008)

2.3 JAPAN

The Japanese government has the long-term objective of reducing greenhouse gases by 50% by 2050 (Ono 2008). Nuclear energy will play a large part in realizing this policy. Japan now has fifty-five Light Water Reactors (LWR's) of total capacity about 50 GW (e). However, with the revival of nuclear power now taking place throughout the world, uranium resources will be an increasing concern in terms of both availability and also energy security. Output is planned to grow to 58 GW (e) in 2030 by the addition of 10 more LWR's.

The Japan Atomic Energy Agency (JAEA) has developed a "Framework for Nuclear Energy Policy" (Ono 2008) which envisages commercial Fast Reactors (FR) starting in 2050 and eventually replacing first the current LWR's and later the next generation (Gen III+). The following are the basic assumptions of the strategy:

- Nuclear power generation continues to meet at least 30 to 40% of electricity supply in Japan even after 2030.
- Commercial FRs will be deployed in around 2050 to secure Japan's nuclear fuel supply and to reduce the environment burden.
- All the LWRs can be replaced by FRs within about 60 years.
- A second reprocessing plant for reprocessing LWR fuel will start up in 2047.
- The required maximum reprocessing plant capacities are: 1,200 ton U/year for LWRs and 600 ton HM/y for FRs. (HM=Heavy Metal, sum of uranium and plutonium)
- Plutonium recycling in LWRs will end around 2045 after about 35 years of operation.
- If MAs (Minor Actinides) from LWR and FR spent fuel are recovered and recycled in the FR fuel cycle, then the accumulated amount of MA disposed as High Level Waste (HLW) can be reduced by about a third or more compared to fuel cycles which don't recycle MAs.
- Recycling of the MAs leads to a large reduction of the potential radiotoxicity of the HLWs.
- Deployment of FR and fuel cycle systems with innovative technologies will result in the reduction of HLW generation and power costs in the long term.

Therefore, with appropriate fuel cycle technology FRs will lead to sustainable nuclear energy in the long term by greatly increasing the efficiency of uranium use. The strategy is such that with the deployment of an all FR fleet, it is believed that nuclear energy in Japan will become sustainable by not needing imported uranium by the beginning of the next century. Burning minor actinides with plutonium efficiently in a fast neutron spectrum, as is possible in FRs, will also result in the most effective use of space in deep geological repositories, and it would also offer better proliferation resistance, because fissile plutonium would never be separated from the radioactive MAs. However, MA burning would require more advanced reprocessing technologies than currently employed economically at a commercial scale.

In Japan, the R&D done in support of this strategy is performed in the FACT (Fast Reactor Cycle Technology Development Project). There is R&D on innovative concepts for RP&T leading to a decision in 2010 on the main fuel cycle to be adopted, which will be confirmed by 2015. In parallel, Japan has been pursuing FR technology, first with the experimental reactor Joyo, and then with the FR prototype Monju.

2.4 FRANCE

France participates in many of the European Community programs on RP&T described in the previous section, but it also has programs on a national basis.

The French Act of June 28, 2006 (Carré 2008) on "A sustainable management of nuclear materials and radioactive waste" laid out a strategy for the back end of the fuel cycle in France including a DGR (Deep Geological Repository) for high level waste to open in 2025. This Act envisages a strong research program on RP&T both to increase the sustainability of nuclear fission and to reduce the radiotoxicity of DGRs. Research on Fast Reactors (FRs) as the means of industrial scale transmutation is also tied into research on Gen IV reactors with closed fuel cycles. This Act requires the government to identify the most promising fuel cycles by 2012 with a plan to demonstrate them in a prototype FR by 2025. In support of this overall strategy the main players in the French nuclear industry (AREVA, CEA and EDF) do R&D on fuel cycles and on FRs.

France has been reprocessing used nuclear fuel from its Pressurized Water Reactors (PWRs) since the 1970s. The plutonium extracted is incorporated in MOX fuel and some of the uranium is also used in fuel. It is estimated that this reduces the requirements for enriched uranium by about 15%. The MAs and FPs (Fission Products) are now stored in glass pending the start of operation of the DGR in 2025. The R&D in France on advanced concepts of RP&T is done notably in the ATALANTE hot lab complex as well at the Phoenix experimental FR. The overall aim is to provide a sound basis for the decisions to be taken in 2012. Experimental fuels containing Minor Actinides are being developed with the aim of having pre-commercial prototypes ready by the 2020s.

2.5 UNITED STATES

The United States government made a decision in 1977 to stop reprocessing civilian used nuclear fuel, in part to set an example to other countries in terms of non-proliferation. The plan was that used fuel would go to the Department of Energy's Yucca Mountain Facility in Nevada, which was selected as the nation's deep repository site in 1987. The recent United States Administration removed the United States prohibition on recycling civilian nuclear fuel, in part because of problems and delays with the Yucca Mountain Facility, and that decision led to the Energy Policy Act of 2005. This legislation explicitly requires "*advanced fuel recycling technology research, development and demonstration*" with appropriate provisos related to proliferation, health and safety.

As described in section 2.1, the United States was the organizer of the Generation IV International Forum (GIF), established in 2000, to conduct collaborative R&D on advanced nuclear reactor concepts. Later, the United States formed the Global Nuclear Energy Partnership (GNEP) also discussed above. Therefore, to a large extent the United States policy on fuel cycle issues is embodied in these two international programs.

United States R&D in nuclear fuel cycles is partly driven by the legislative limitations of the Yucca Mountain repository which is currently limited to 70,000 metric tons of used commercial reactor fuel. It is expected that the cumulative amount of used fuel from current reactors in the United States will reach this limit by 2015. For example, the Advanced Fuel Cycle Initiative (AFCI) of the United States Department of Energy (DOE), the main program for fuel cycle R&D,

aims at extracting the short-lived high activity fission products (cesium-137 and strontium-90) to reduce the heat load in a repository. Reprocessing could also significantly reduce the volume of the waste to be stored. If both were done, it has been estimated that a 50 fold or higher increase could be achieved in the equivalent amount of used fuel that could be stored at Yucca Mountain. Alternatively, removing the legislative limit on the amount of used nuclear fuel at Yucca Mountain could affect the R&D programs. Regardless, in the long term AFCI is intended to result in a closed fuel cycle that would greatly reduce the space requirements, but not eliminate the need for, a deep geological repository, and that would support the long-term sustainability of fission power in the United States.

In 2007, the AFCI was integrated into the United States contribution to GNEP and is now known as GNEP/AFCI (GNEP 2008).

2.6 RUSSIA

Since the 1960s, Russia built up a nuclear industrial base with substantial reprocessing facilities which have now become available for civilian reactor use. Russia has a fully integrated nuclear system covering all aspects of the fuel cycle. It operates ten nuclear power stations consisting of thirty one reactors with a total capacity of 23,242 MW(e). There are five reactor types, one of which is the sodium Fast Reactor BN-600. The used fuel from Russian nuclear icebreakers and from research reactors also has to be managed. The used fuel from some of seven reactors (six VVER-440 and a BN-600) is reprocessed at the Mayak facility, which has been in operation since 1976. The remaining used fuel is stored in various wet and dry facilities. Mayak also reprocesses fuel from some of the former Soviet Republics, Hungary, Bulgaria and Czechoslovakia (IAEA, 2008a).

In addition to plutonium, Russia is the only country that recycles uranium-235 from spent fuel. This material, called "Rep U", is blended with uranium-235 for ship propulsion and breeder reactors and used in nuclear fuel (2-2.4% enriched) for RBMK reactors. Russia is an active participant in GNEP and other international R&D programs and is the main promoter of the IAEA INPRO program and MNA (Multinational Approach) to the nuclear fuel cycle. By virtue of its fuel cycle expertise Russia has a strong commercial presence in areas such as reprocessing and enrichment and actively seeks business opportunities.

2.7 INDIA AND CHINA

In India, reprocessing of used nuclear fuel has been on-going since 1964. Reprocessing of fuel from its CANDU-type reactors is done in two plants at Tarapur (Prefre-1) and Kalpakkam (Prefre-2). These plants also reprocess fuel from some research reactors and India's experimental fast breeder reactor. Thorium is abundant in India, which does extensive research on thorium fuel cycles for future use, since most of the uranium is now imported. India, through an Agreement with the Nuclear Suppliers Group, has recently been opened to nuclear trade after a long period of isolation due to the non-separation of India's civilian and defense nuclear programs.

China is now engaged in a large scale expansion of its nuclear power program, first to prevent the building of additional air polluting coal-fired stations, and eventually to replace them.

Reprocessing is carried out now in a small plant with a larger one planned to start in 2020. China is a member of GNEP.

3. NUCLEAR FUEL CYCLES

3.1 FUEL CYCLE TYPES

A large number of potential nuclear fuel cycles are possible. Dealing with the minor actinides (MA) is one of the most challenging problems in RP&T driven fuel cycles. There are several MA transmutation schemes that can be classified in two broad categories: homogeneous and heterogeneous.

Homogeneous cycles are those in which the MAs for transmutation are mixed into the fuel of a fast reactor (FR). Generally homogeneous cycles require multiple recycling. Fuel initially containing MAs that has already been irradiated in an FR is further reprocessed and its MAs, not necessarily the same distribution as in the first charge, are incorporated in fresh fuel for an FR. Several such cycles may be necessary to reduce the concentration of MAs to the desired level and in this case reprocessing losses are important.

Heterogeneous cycles involve the separation of the MAs and their incorporation into targets for irradiation in an FR. These targets typically have very high burnups and multiple cycles are not required. An important advantage of the heterogeneous approach is that it has little impact on the operation of the reactor and does not involve the development of special fuels.

Of course, a fuel cycle can be a mixture of both homogeneous and heterogeneous steps. For example, MAs could be present in both the FR fuel and in targets surrounding the reactor. A fuel cycle can have one or two tiers (or *strata*). In a two tier system, the MAs can also be consumed in an Accelerator Driven System (ADS) in addition to a FR.

An ADS consists of an accelerator that produces an intense beam of high energy protons incident on a lead-bismuth target yielding a very large flux of fast neutrons in a process called spallation. The target is in the core of a fast reactor assembly containing plutonium and a relatively large amount of MA. This assembly is only made critical (able to sustain a chain reaction) by the spallation neutrons. Ideally the heat generated by the fissioning of the MAs and plutonium could be used to generate electricity. There would be no need to extract the MAs from the plutonium which is desirable for preventing proliferation. The important point is that much larger quantities of MAs could be consumed in an ADS compared to a FR alone.

As mentioned above, this picture becomes even more complicated by the multiple recycling of FR fuel. In fact, a summary result of the October 2008 NEA P&T meeting in Mito Japan was that there are too many possible fuel cycles with related RP&T schemes. It was recommended that R&D should focus on a few reference cases with internationally agreed roadmaps and milestones.

3.2 PROLIFERATION ASPECTS

Making RP&T schemes as “proliferation proof” as possible has been an important theme of all the main national and international programs on fuel cycles. In part, this is achieved by making

sure that pure weapons materials are not available, e.g., by keeping the plutonium component of spent fuel together with MAs.

An interesting approach to the problem of assessing the proliferation resistance of various partitioning methods was presented by (Bathke, 2008) at the Mito meeting. A Figure of Merit (FOM) is calculated in the case of “an adversary intending to build a stockpile of nuclear weapons without purifying the materials.”

The general conclusion of this study was that there is a safeguards and security benefit with respect to diluting reprocessing end products with lanthanides or uranium (natural, depleted or reprocessed) but this does not justify any diminution of the protective measures. These calculations provide a quantitative “proliferation index”, and hence will be useful for comparisons among, for example, GNEP options.

3.3 SUSTAINABLE SCENARIOS FOR FISSION

At the October 2008 NEA P&T meeting in Mito Japan, scenarios were presented about how the world could achieve sustainable nuclear power based on various fuel cycles. Typical issues considered were the following:

- How fast will the demand for energy grow?
- How best to use the limited resources of uranium?
- How to manage plutonium stockpiles from reprocessing LWR fuels for the most efficient introduction of fast reactors?
- Optimum recycling of MAs to reduce radiotoxicity and heat loads in Geological Repositories
- What happens if transmutation in fuel cycles is terminated before completion?
- What new reprocessing plants based on advanced technologies will be needed?
- How to make closed fuel cycles more resistant to proliferation?
- How long will it take to put in place a fully sustainable FR economy and how much will it cost?

For example, the French Scenario study (Carré, 2008) anticipates commercial power deployment of FRs by about 2040. The important point is that the scenario sets a time scale for the completion of the necessary fuel cycle and FR R&D.

At the October 2008 NEA P&T meeting in Mito Japan, projections were made for one or two centuries into the future. Some of the more interesting results were as follows:

- Only 22% of reactors will be fast reactors by the year 2100.
- Closed nuclear cycles appear to cost 10% more than open cycles (McCarthy 2008).
- Location of reprocessing plants relative to the reactors can be very important since significant time is required for used fuel to cool before it can be transported.
- Fast reactor cycles with Minor Actinide (MA) burning will be deployed in Japan starting in 2050.
- Regional reactor scenarios of interest could involve both countries with stagnant or phasing out nuclear plants together with countries with expanding nuclear programs.

- Thermal reactor burning of MA, even in CANDUs with their high neutron fluxes, is not economically feasible because of the accumulation of undesirable isotopes such as the long-lived isotope californium-252.

4. STATUS OF REPROCESSING FACILITIES

The global market for reprocessing has been in the order of 3,000 tHM¹ per year and most of this has been done in three large plants: at La Hague, France operated by AREVA (Figure 1), at Sellafield, United Kingdom, owned by the UKNDA and, at Mayak/Chelyabinsk, Russia run by Atomenergoprom. A fourth large plant at Rokkasho-mura, Japan, operated by Japan Nuclear Fuel Ltd. (JNFL), is expected to start commercial operation in 2009.

As Table 3 shows, most of the reprocessing in 2006 was done at La Hague where about 1,015 tHM was reprocessed. The Sellafield THORP (Thermal Oxide Reprocessing Plant) was shut down for repairs due to a leak in 2005 and resumed operation in 2007. The capacity of the Mayak plant, nominally 400 tHM/year, is actually at the 250 tHM/year level because of regulatory limitations.

Table 3: Major reprocessing facilities with 2007 capacity and 2006 production

Owner/operator	Facility	Capacity in 2007 (tHM/year)	Production in 2006 (tHM/year)
AREVA	La Hague	1,700	1,015
JNFL	Rokkasho-mura	800	0
Atomenergoprom	Mayak	400	100
UKNDA	Sellafield	900	0
Total:		3,800	1,115

Source: NEA (2008)

¹ tHM is tonnes of heavy metal.



Source: COGEMA Archives / Phillipe Lesage

Figure 1: Reprocessing facility at La Hague France

The combined factors of anticipated growth in the deployment of nuclear power plants and the desire for sustainability in fission may increase the demand for reprocessing services. Thus, plans for new reprocessing facilities in China, India, Russia and the United States have been put forward as shown in Table 4 for the timeframe up to 2030.

Table 4: Expected future LWR fuel reprocessing facilities in the 2030 timeframe

Country/Company	Facility	Capacity (tHM/year)	Status in 2007
China/ CNNC		800	Planned
France/AREVA	La Hague	1,700	Operational
India	Tarapur, Kalpakkarn	500	Planned Extension
Japan/JNFL	Rokkasho-mura	800	Starting
Russia/Atornen.	Zheleznogorsk	1,000	Planned
UK/NDA	Sellafield	?	Restart
United States		2,500	Planned
Projected (approx.):		~7,000	

Source: NEA (2008)

The reprocessing facilities in France and Japan are continuations and upgrades of existing facilities. Depending on a review of its nuclear power program now underway, the United Kingdom may elect to continue THORP past about 2015 when its current contracts are done. The decision to go ahead with a new replacement for the current Russian plant will depend on the successful development of new reprocessing technologies. The current reprocessing capacities of China (50tHM/year) and India (two reprocessing facilities with total capacity 200tHM/year) are planned to be expanded by the addition of new facilities.

An interesting development is the plan to re-establish civilian reactor used fuel reprocessing in the United States. As shown in Table 4, a very large facility of 2,500 tHM/year capacity is planned.

Part of the GNEP program is the idea of international fuel cycle centres that would provide services to countries that don't have nuclear fuel cycle facilities such as enrichment and reprocessing. There already is one such concept for enrichment and that's an area where international partnerships are already in place. For example, the centrifuge enrichment consortium Urenco has Germany, the Netherlands and the United Kingdom as members and operates enrichment plants in each of these countries and will expand into the United States and France. It was set up under a treaty between the three and each owns a third of the company. Eurodif operates a large gaseous diffusion enrichment plant in France and is a joint venture of five countries (France, Belgium, Iran, Italy and Spain). In 2007, Russia established an International Uranium Enrichment Centre at its Angarsk facility but has only had Kazakhstan join so far. Germany is sponsoring another enrichment initiative under IAEA control.

It would also be possible to use the same approach for reprocessing although it's more complex because of the various fuel cycle choices that it might have to serve. Governments could buy a stake in a reprocessing facility under international control (the IAEA for example) and share its production. There could also be regional reprocessing facilities serving geographical areas. There has been much talk about this but relatively little progress. At the October 2008 NEA P&T meeting in Mito Japan, there was an interesting paper (Salvatores, 2008b) about pooling region stocks of spent LWR fuel from countries such as Germany, whose nuclear power plants are operating under legislation that will see them closed down after thirty years in service, with countries such as France where nuclear power will likely expand in the future.

5. STATUS OF FAST REACTORS

Many experimental fast reactors have been built but few remain in operation (IAEA 2008b). The Japanese Joyo reactor started operation in 1970, was extensively refurbished in 2003 and is now operating at an increased power level. In India, the FBTR started full power operation in 1996 after many years of construction. China's CEFR started construction in 2000 and is set to operate by 2010. France's Phoenix has operated since 1993 as an irradiation device in France's fuel cycle program but will close down permanently in 2009.

Monju, a larger demonstration-type reactor was built in Japan with first criticality in 1994. Shortly afterwards, in 1995, there was a serious sodium leak that was covered up by the reactor management. Many modifications were made and Monju is set to restart in early 2009. Russia's BN-600 fast reactor is the world's most successful because of its sustained reliable operation since 1980. India is building the PFBR reactor as a more powerful successor to its FBTR.

Super-Phoenix, France's entry into commercial scale fast reactors was not successful and closed down in 1998. France plans to build ASTRID (Advanced Sodium Test Reactor for Industrial Demonstration) by 2020. Many countries have plans for commercial fast reactors but Russia's BN-800 is the only one actually under construction since 2002 and scheduled for completion by 2012.

At the October 2008 NEA P&T meeting in Mito Japan, there was a compilation of dates for commercial introduction of fast reactors as given by the various players in the closed fuel cycle (Ono 2008):

- India 2020
- Russia 2020-2025
- France about 2040
- China: 2030-2035
- Japan about 2050

Currently, there is a shortage of fast reactors for experimental purposes, and an aggressive program of fast reactor development would be needed to meet these schedules.

6. PROGRESS IN PARTITIONING METHODS

6.1 LIQUID METHODS

The **PUREX** (Plутonium and Uranium Recovery Extraction) was developed in the early 1950's and is the basis of all the reprocessing plants now operating throughout the world.

The nuclear fuel assemblies are disassembled and sheared to extract the fuel pellets which are then dissolved in nitric acid. When the fuel is sheared, gaseous fission products mainly krypton-85, xenon-135, carbon-14 and tritium are released and must be managed in an appropriate manner. The uranium reacts to form uranyl nitrate which stays in solution and the plutonium is converted to a nitrate form. Solvent extraction is done using an organic solvent, Tributyl phosphate (TBP), in which the uranium and plutonium nitrates concentrate leaving the fission products in the nitric acid solution. In this manner highly efficient removal of the uranium and plutonium are achieved.

Plutonium is separated out of the uranium-plutonium solution by manipulating its valence and by means of other solvent extraction processes. Generally the MAs and FPs remaining in the nitric acid solution are stored or embedded in glass blocks for storage.

Even the 'simple' PUREX process can be very expensive: the high radioactivity of the used fuel requires handling, elaborate measures must be taken to protect the health of the employees and the environment, a high level of security is needed to safeguard the potential weapons materials produced, and a very efficient recycling of process solvents is essential to keep the plant economic.

Many variants of the PUREX process have been developed to meet the requirements of various fuel cycles.

For many years the United States has had a policy of not allowing the recycling of plutonium in commercial reactors. This leads to fuel cycles in which the plutonium and the MAs are kept together in order to prevent any diversion of the plutonium for weapons. This policy has greatly influenced fuel cycle selection, especially in the United States.

UREX (Uranium Extraction) is a process that is similar to PUREX but the removal of plutonium is halted chemically and only the uranium isotopes and a high percentage of the technetium are extracted. The chemical change to the raffinate (liquid “tails”) also makes it more difficult to subsequently extract the plutonium and other MAs. The primary motivation is that by removing the uranium the waste reduces the volume for long-term management in a deep geological repository, but the plutonium remains “contaminated” from a weapons point of view by many MAs. Thus, this is a proliferation resistant process.

There are many variations of UREX, designated as UREX +, for instance there are (IAEA, 2008a) UREX +, 1, 1a, 1b, 2, 2a, 3, 3a, 4 and 4a. All the UREX + processes start out as the basic UREX system plus the removal of the high-heat-producing isotopes strontium-90 and cesium-137 as a third extractant stream. UREX+1 and +1a support a homogeneous cycle where the MAs are burned in an FR and the other UREX+ variants are for heterogeneous fuel cycles. There are several sub-processes included. For example, the UREX + 1a process starts with UREX followed by FPEX for removing the strontium and caesium, then TRUEX for removing non-lanthanide fission products and then TALSPEAK to remove the remaining fission products. Various material streams are taken off at each stage.

Many aqueous partitioning methods are under development in several countries. **DIAMEX** and **SANEX** are extraction processes developed in France. DIAMEX uses a diamide solvent to extract fission products with resulting lanthanide and MA streams and is followed by SANEX to partition the MAs. **UNEX** is a Russian process that uses a variety of novel solvents.

Many of the recent developments in this area concern the use of new solvents for extraction although R&D is still concentrated on amides and other solvents. A summary comment at the October 2008 NEA P&T meeting in Mito Japan is that new ideas in this area would be helpful. However, there were interesting results from chromatographic and crystallization water extraction methods and in general progress is being made in the better understanding of actinide chemistry, in particular concerning the co-extraction of uranium and plutonium with neptunium.

6.2 PYROCHEMICAL REPROCESSING

Pyrochemical processes can provide more efficient means for extracting certain isotopes. In general these methods involve a cell containing an electrolyte, usually hot molten salt containing a mixture of isotopes. The current drives the desired isotope to plate out on one of the electrodes. Temperature, concentrations and current have to be carefully adjusted to make this happen. This type of system is known as electro-refining and a variant with fuel isotopes present as components of the molten salt is called electro-winning. Multiple cathodes can be used for specific isotopes.

One disadvantage of these “dry” (non-aqueous) processes is that they work with defined load of material in say an electrolytic cell; after a certain point the constituents of the cell must be replaced and the process restarted. This is in contrast to the uninterrupted flow of aqueous

systems. This can be an economic problem. However, losses in reprocessing are important and recent calculations (Liljezin 2008) have shown the acceptable losses in each step of a continuous process (e.g. aqueous) process must be lower than in a batch process (e.g. pyrochemical) process. Innovative pyrochemical methods may be essential to treat novel nuclear fuels in metal, carbide, oxide or nitride form containing high levels of fissile isotopes and/or with high burn-up. These are the fuel types that will be used in FR closed cycle schemes.

Uranium hexafluoride, UF_6 , is the gas used in uranium enrichment plants and analogous fluoride compounds can be formed for other actinides such as PuF_6 . The capability of forming these fluoride-based gases leads to isotope separation methods for partitioning. This pyroprocessing method, fluoride volatility, has been incorporated in the FLUOREX process developed by Hitachi (IAEA 2008a). It is particularly relevant to the Czech concept for transmutation based on molten salt reactors and recent developments in this area were reported at Mito (Uhlir 2008).

7. PROGRESS IN TRANSMUTATION TECHNOLOGY

7.1 FUELS FOR TRANSMUTATION

Transmutation depends on the success of nuclear fuels and targets containing mixtures of MAs and plutonium. Some fuel cycles have only a single FR insertion and the fuel must stand up under high burn-up conditions with a post-reactor composition suitable for a deep geological repository. If the fuel is to be recycled more than once through a FR high fissile content is important and the fuel must be amenable to reprocessing.

Because fuel containing uranium-238 results in more plutonium and MAs, it is more effective to use uranium-free fuels since as many neutrons as possible should be available for fissioning the MAs, the basic physical process for transmutation. Hence, uranium-free fuels are desirable and this has led to the concept of Inert Matrix Fuels (IMF). The required high rates of fission, exceeding any previously experienced in FRs, result in correspondingly high fission gas and helium production may cause swelling and undesirable chemical and mechanical effects ultimately leading to fuel failure.

Metallic fuels with dispersed mixtures with nominal stoichiometries such as: $Pu-12Am-40Zr$ and $U-29Pu-4Am-2Np-30Zr$ for example have been tested in the United States as part of non-terminated fast reactor programs (Pasamehmetoglu 2008). They were found to be promising vehicles for the transmutation of MAs. Mixed oxide fuels such as $(U-74Pu-24Am-2)O_2$ have performed well in irradiation tests (Fernandez 2008).

For reasons explained above, transmutation fuels in an ADS should be uranium-free fuel and the JAEA is investigating nitride fuels with MAs as the largest component. Their work has concentrated on $(MA-24Pu-16Zr-6)N$ which is produced by using ZrN as a diluting material in place of uranium (Arai, 2008).

IMF type dispersions of actinide oxides in inert ceramics ("CERCER" fuels) such as a dispersion of oxide particles of the composition $(Pu,MA)O_2$ in magnesia (MgO) have been reactor tested in Europe as have IMF metallic fuels ("CERMET" fuels) with molybdenum-92 matrix metal.

(Delage 2008) Composite transmutation targets of this type have been found to be more resistant to deteriorating radiation effects.

In summary, the irradiation behaviour of MA bearing fuels is being clarified and their basic properties defined. Several productive irradiation experiments have been done, particularly at the Phoenix FR in France. Not much is known about the role of curium isotopes since much of the attention on MA fuels has focused on americium and neptunium. Fabrication of these fuels and targets will need remote handling because of the high radiotoxicity of the MAs and fuel production processes now in the laboratory will need to be implemented on an industrial scale that is commercially viable.

7.2 TRANSMUTATION TECHNOLOGY

An industrial ADS will depend on the efficient production of neutrons in liquid metal spallation targets. Lead Bismuth Eutectic (LBE) and liquid lead targets are highly corrosive and further tests on new alloys are needed to identify technically feasible candidates. Papers on test programs for compatible alloys were reported at Mito but none has yet emerged as practicable.

The MEGAPIE (Megawatt Pilot Experiment) had the objective of building and testing a liquid lead-bismuth spallation target for use in an ADS. After a design and construction phase starting in 1999, the target was irradiated with a proton beam between August and December 2006 at the spallation neutron facility SINQ at PSI in Switzerland. MEGAPIE was a complete success and the analysis of the experimental data is continuing and newly derived data was presented at Mito (Latge 2008).

An interesting experiment was reported from the YALINA subcritical assembly in Belarus. This was operated as an ADS by injecting a proton beam into a lead target to produce spallation neutrons. It was found that fast trips in this ADS were feasible; that is switching the beam off caused criticality to be lost in a microsecond (Fernandez-Ordenez, 2008).

Nuclear data (e.g. fission and neutron capture cross sections) are essential for the accurate analysis of RP&T scenarios but much of these data have not been of interest for other nuclear applications and thus, it must be generated. Highlights of the October 2008 NEA P&T meeting in Mito Japan in this area were good progress in the uncertainty analysis of nuclear data that is determining the most important nuclear data by analyzing the consequences of inaccuracy. A new neutron time-of-flight (TOF) facility at CERN is providing useful nuclear data (Cano-Ott, 2008).

7.3 TRANSMUTATION EXPERIMENTS AND FACILITIES

Calculations for ELSY (European Lead Cooled System), a dedicated fast reactor for transmutation, showed the viability of an adiabatic core configuration. However, it was found that very high burnups would be required to achieve the desired level of transmutation (Artioli, 2008).

It was noted at the October 2008 NEA P&T meeting in Mito, Japan, that there was decreased activity on ADS technology as reflected in the number of papers submitted. The EFIT

(European Facility for Industrial Transmutation) was discussed mainly in terms of its fuel development requirements (Chen, 2008). EFIT is a liquid lead cooled ADS still in the design phase. Another European entry in the ADS field is GUINEVERE which is also in the design phase.

The meeting hosts offered a tour of J-PARC to participants. This facility, the Japan Proton Accelerator Research Complex, is located on the JAEA Tokai site. The facility will have 3 GeV, 50 GeV and 0.6 GeV proton beams for research in muon science, nuclear/particle physics, neutron science and nuclear transmutation. A portion of the 50 GeV proton accelerator is shown in Figure 2.



Source: D. Jackson

Figure 2: The 50 GeV accelerator at J-PARC

The main facility for P&T will be the TEF, Transmutation Experimental Facility which will consist of TEF-T, a spallation target test facility, and TEF-P which will be an ADS for transmutation experiments. The proton beam facilities have been built and other parts of J-PARC are under construction but the TEF is still in the detailed planning stage. The TEF area is now an open field.

8. IMPACT OF RP&T ON GEOLOGICAL REPOSITORIES

The impact of RP&T on the long-term management of radioactive wastes in a Deep Geological Repository (DGR) continued to be a central theme at the October 2008 NEA P&T meeting in Mito, Japan, as it had been at previous NEA P&T meetings in this series. The conclusions of the summary session on this topic are quoted in full as follows (Bhatnagar and Nutt, 2008):

- “Separation of the main heavy metals (U, Pu) and heat bearing components (e.g. Cs, Sr, Am) before disposal increases the repository capacity (3-100 times) in certain geological media.
- The Storage of caesium and strontium for 100-300 years in specialized (calcinated) waste forms is recommended. Due to the long-lived Cs-135 isotope, after storage, disposal would be required.
- Transmutation/burning of separated MAs (in ADS or FR) reduces the ‘long-term burden’ on repositories. This may aid the [DGR] community in securing a ‘broadly agreed political consensus’ of waste disposal in geological repositories.
- Transmutation of MA has also a favourable impact in the unlikely occurrence of ‘human intrusion scenarios’.
- The maximum eventual dose to human beings from a geological repository in ‘normal scenarios’ is likely to be due to fission products though evidence is appearing that MA also can be mobile under certain conditions.”

A further argument was that RP&T is necessary for the sustainability of nuclear fission power and thus, was vital to public/political acceptance. Some of those attending the meeting said that RP&T had to be better ‘positioned’ and mentioned the success of the nuclear fusion community in achieving much higher levels of funding for an alternative vision of the long-term nuclear future. There was also a plea to the DGR community on behalf of the RP&T community for recognition and closer cooperation with joint planning especially since the DGR community will have to deal with the residual radioactive waste forms of the RP&T community.

9. ALTERNATIVE TECHNOLOGIES

9.1 INTRODUCTION

NWMO is implementing Adaptive Phased Management, the approach selected by the Government of Canada in June 2007 for long-term management of Canada’s used nuclear fuel. As part of its R&D program, NWMO is continuing to maintain awareness of the development of alternative approaches for long-term management of used nuclear fuel (NWMO 2008).

One of the alternative waste management approaches identified for further study and evaluation is disposal in very deep boreholes.

9.2 DISPOSAL IN VERY DEEP BOREHOLES

The very deep borehole concept for disposal of nuclear waste consists of placing the waste packages nominally 4 to 6 km deep in individual boreholes drilled from the surface. The borehole, up to perhaps one metre in diameter at its bottom, would be cased to allow waste packages to be lowered into place, one on top of another. With the waste in place, the borehole would be plugged and sealed from depth to the surface. With this concept, the waste would be placed further from the biosphere than in the mined repository concept. Once sealed, the long-term safety of the system rests principally on the separation of the hydrogeological regime at the depth of the waste packages from that nearer the surface, and on the integrity of the borehole plugs and seals.

A previous report (NIREX, 2004), prepared by Safety Assessment Management Ltd. for UK NIREX, reviews the development of the deep borehole concept for the disposal of radioactive waste, from its initial development in the 1970s to the present day, and provides comparisons between this concept and more commonly discussed disposal concepts, such as the mined repository.

The report identifies several important characteristics of the very deep borehole concept in the following excerpts:

- The rate of fluid movement in the rock in the disposal zone is expected to be so slow under undisturbed conditions that any mass transfer will be by diffusion or by advection at rates approaching those of diffusive transport....Elevated fluid densities and the presence of a stratified groundwater system, combined with low hydraulic gradients suggest that these fluids will be hydrogeologically stable, with residence times of millions of years.
- The wastes for disposal would be only weakly heat emitting or would be sufficiently cooled prior to disposal, so that the thermal load they impose on the rock-fluid system over the first few hundred years after burial would not cause fluid convection sufficient to destabilise the density- and chemically-stratified groundwater system.
- A long system of borehole seals isolates the disposal zone from overlying rock formations and groundwater systems. The length of the seal zone and its design would be highly site-specific.
- Waste packages could be emplaced without the need for any of the additional engineered barriers (overpacks and buffer) that are familiar in conventional repository concepts.
- There are significant limits on the maximum diameter that a borehole can be drilled in hard rock to depths of about 4 km, so that, to allow the maximum amount of waste to be disposed of in any one borehole, it seems that it will only be possible to have a relatively small annulus between the canister and the borehole wall, thereby limiting the possibility for thick, low permeability backfill or buffer around the canister.

A 2007 evaluation of the very deep borehole concept for application in the United Kingdom was conducted for the UK Nuclear Decommissioning Authority (Baldwin et al., 2008). In the concept studied, simple packages with no overpack are emplaced in the lower region (the bottom 1,000 – 2,000 m) of a borehole drilled from the surface to a depth of about 3,000 to 5,000 m. The borehole is fully lined with metal casing from the surface and of sufficient diameter to leave a generous annulus to ensure ease of placement of the waste packages. Each disposal borehole is drilled either singly, from its own drilling pad, or as part of a group from a central location of limited area.

The report identifies several important characteristics of the very deep borehole concept in the following excerpts:

- The concept can result in a small disposal area at depth but, perhaps more importantly, the surface area required for the excavation (and emplacement) operations may be very small.
- The concept provides extremely secure disposal of waste with effectively little chance of recovering waste without major technological investment.
- The concept is flexible with respect to implementation in a range of host rocks since the key issue is the hydrogeological environment at depth...however, the properties of the rocks at depth must be capable of supporting the excavation of the borehole.
- There are uncertainties about the operational procedures for this concept as most evaluations have focused on the feasibility of borehole excavation and much less on the operational safety and practicality.
- The safety case relies on the isolation provided by the deep geosphere, but no detailed safety assessment has yet confirmed that this is sufficient.
- The size of the waste package for practical implementation means that the concept could be inefficient for [spent fuel] disposal.

It would continue to appear that no practical demonstration of this concept has taken place and that bringing it to the same level of understanding as the deep geological repository (DGR) concept, which is typically assumed to be located about 500 m to 1,000 m below surface, would require considerable additional R&D. Monitoring and retrievability would be more difficult for the very deep borehole disposal concept compared with the DGR approach, which is an issue in those cases where retrievability is considered to be a necessary feature of the long-term management approach. However, the ability to make retrieval virtually impossible has been noted as a favourable feature for protection against proliferation.

9.3 NEW APPROACH TO DEEP BOREHOLE CONCEPT

Three difficulties attributed to the very deep borehole disposal concept are (1) that in many designs the waste packages are subjected to high stress because of vertical stacking, (2) that retrievability is questionable, and (3) that long-term monitoring is difficult. A deep borehole system has been proposed (Brunskill and Wilson, 2009) that would incorporate knowledge from the development of carbon dioxide (CO₂) storage technology in deep geological formations to take advantage of the concept of very deep borehole disposal, while potentially imposing less stress on the waste packages, allowing easier retrievability, and incorporating long-term monitoring.

The new concept applies to a geological environment in which the hydrogeological regime is density-stratified to isolate the deeper hydrogeological system from that nearer the surface. An example of such an area could be found in deep sedimentary basins in western Canada (and perhaps elsewhere), where much of the Precambrian rock surface is covered by several kilometres of sedimentary rocks.

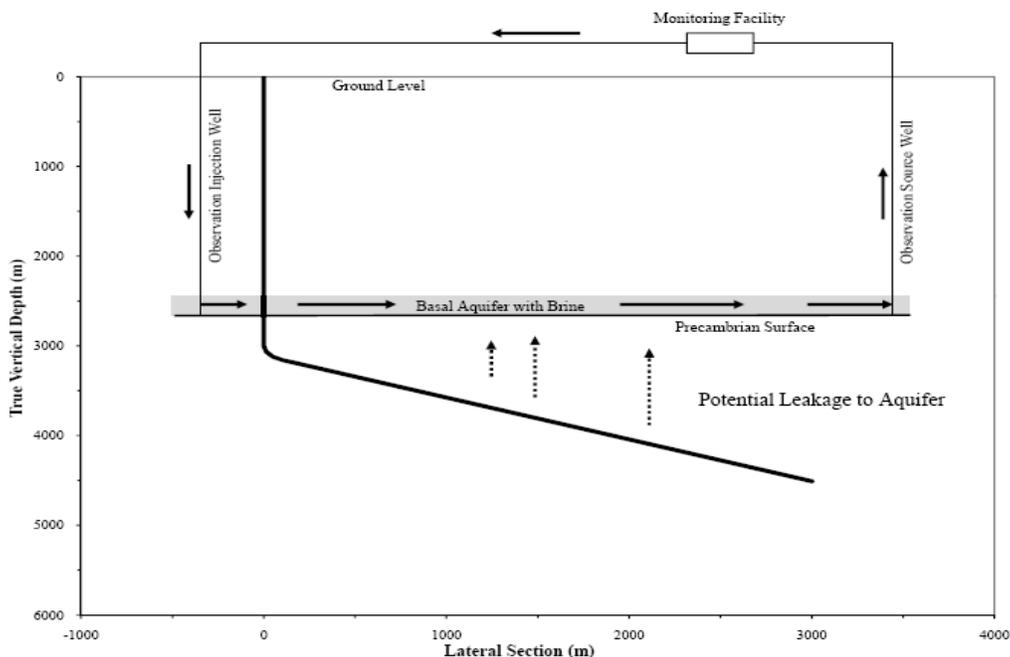
A hole could be drilled vertically from surface through this sedimentary section into the Precambrian basement; when into the Precambrian rock a sufficient distance, the hole would be turned sub-horizontal. Several long, sub-horizontal holes would be required to contain the waste packages. The drilling and completion of the holes could be accomplished with equipment currently used in the drilling industry in Canada. In the horizontal placement, the packages would be subjected to much less stress than in a stacked vertical placement.

Each horizontal hole would be lined with metal casing that is cemented in place. The used nuclear fuel bundles would be placed in pipe-shaped containers which would then be positioned in the horizontal holes.

Although the containers would be placed in a final position in the deep borehole, this conceptual design is intended to provide for retrievability of the nuclear fuel bundles for hundreds of years, as long as the integrity of the materials used remains sound. It is assumed that the encasement materials would be retrieved and inspected and if failure of the casing or bundle containers was observed or anticipated, the containers could be transferred to a new location in another deep borehole.

Figure 3 illustrates the monitoring of an aquifer above a hypothetical very deep placement borehole using a brine circulation loop. This is analogous to a design for monitoring for the effectiveness of CO₂ retention and potential migration in a brine-filled storage aquifer. The theory is that any material migrating vertically toward the surface would pass into the aquifer and be detected. However, for long-term management of used nuclear fuel, further study of used fuel container placement and monitoring methods in very deep boreholes and the potential migration of radioactive contaminants in sedimentary rock would need to be conducted to address the need for continuous monitoring and the potential for retrievability.

This new approach to the very deep borehole concept is at an early stage of development. It is likely that further information will be gained related to the concept through the Canadian research being conducted on CO₂ sequestration.



Source: Reproduced courtesy of Brunskill and Wilson (2009)

Figure 3: Brine circulation-loop in the basal aquifer to monitor leakage into the geosphere

10. SUMMARY OF PROGRESS FOR 2008

National and international nuclear energy policy in Europe, France, Japan, and more recently in the United States emphasizes sustainability. Sustainability could be achieved in the long term by a fleet of fast reactors, Generation IV and other reactor types, operating with closed nuclear fuel cycles that would both maximize the use of uranium resources and potentially minimize the waste burden on future generations by destroying as many of the long-lived actinides as possible prior to placement in a deep geological repository. At the October 2008 NEA P&T meeting in Mito, Japan, RP&T was positioned as an essential technology for this vision of sustainable fission power.

Future energy scenarios were presented by the United States, Japan and Europe about how this sustainable fission future of fast reactors with closed fuel cycles could be reached starting with reprocessing the fuel from today's light water reactors. The very long time scales to achieve a sustainable fission future, about 100 years and more, were the most remarkable result of these energy scenarios.

In Canada, sustainability is not a current issue for nuclear power and a once-through nuclear fuel cycle is considered sufficient given the country's large uranium reserves.

Another factor frequently mentioned in support of RP&T at the October 2008 NEA P&T meeting in Mito Japan was the imperative to make used nuclear fuel waste more compact and by the removal of the very active fission products, notably cesium-137 and strontium-90, to reduce the

heating load in a deep geological repository, thus allowing more waste to be stored in the same space. Clearly much of this concern has arisen from the legislative limitations on the capacity of the planned Yucca Mountain repository in the United States.

Canada's CANDU heavy water reactors use natural uranium fuel and hence, produce a factor of three to five times more spent fuel per unit of electricity generated than the light water reactors commonly used in other countries. (The used fuel scaling factor is approximately equivalent to the inverse of the uranium-235 enrichment factor in the fuel). However, the amount of space required in a deep geological repository is to a large extent determined by the heat generated by the used fuel, which increases with the fuel burnup. As the burnup of the natural uranium fuel is much lower than that of enriched uranium fuel from LWRs, the repository space requirements would not be expected to be much different on a per-unit-energy basis. It would be expected that, per unit energy, RP&T would likely be even more expensive than for LWR fuel, and therefore less economically viable as a means of saving space in a deep geological repository.

France, Russia and the United Kingdom already operate large reprocessing facilities with Japan to soon join them. In the longer term India, China and the United States plan to operate new or expanded reprocessing facilities. Hence, there is a strong commercial aspect involved in RP&T and this is another important consideration in how it is approached. It is not clear whether the GNEP program will continue under a new United States Administration in early 2009 and therefore, whether enrichment, reprocessing and other fuel cycle will be international, regional or remain essentially a commercial business, albeit mostly owned by governments.

Based on a review of the RP&T literature and the October 2008 NEA P&T meeting in Mito, Japan, it would seem that while collaborative R&D is ongoing under the Generation IV program, real progress on construction of new fast reactors is currently limited to Russia.

Currently, Canada does not collaborate on the fast reactor R&D in Generation IV but rather focuses its R&D efforts on the Very High Temperature Supercritical Reactor, a thermal reactor.

At the October 2008 NEA P&T meeting in Mito, Japan, considerable progress was reported in the relatively large world effort on R&D in RP&T. There were many papers on new partitioning methods, transmutation fuels and targets, various ADS issues, the potential influence of RP&T on deep geological repositories and other topics. The current level of global activity in this field merits the NWMO keeping a watching brief in RP&T.

In terms of alternative waste management technologies, there were interesting developments in disposal in very deep bore holes and a new concept was put forward on a system for deep horizontal boreholes that potentially would allow the retrieval of used fuel in the very deep borehole configuration and long-term monitoring. Further study and analyses of monitoring and retrieval methods would need to be conducted to support development of this approach.

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