Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology - Annual Report 2010

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ABSTRACT

Title: **Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology – Annual Report 2010**
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Abstract
This is the 2010 Annual Report of the NWMO watching brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technologies. International developments are reviewed based on recently published documents and on the presentations at the Nuclear Energy Agency information exchange meeting on RP&T held in San Francisco in November 2010 where significant technical progress made since the 2008 meeting was reported. The US, several European countries and Japan are in the process of reviewing their RP&T programs. The former by means of a specially appointed Blue Ribbon Commission, whereas France and Japan have major decision points in 2012.

In this report the current status of RP&T is summarized in terms of seven key questions relevant to assessing the possibility of reprocessing of used CANDU fuel based on conclusions from all three Annual Reports. While there have been some progress in R&D on advanced closed fuel cycles, they remain many decades away from commercial deployment and will require a very large investment in nuclear infrastructure. In addition, closed fuel cycles will not eliminate the need for a deep geological repository. Therefore, there is no compelling reason at this time to alter from the reference APM strategy of a deep geological repository for used CANDU fuel.

The possible use of very deep boreholes for long-term management of used nuclear fuel was the subject of increased interest and more detailed investigation in 2010. However, its cost effectiveness for used CANDU fuel has not yet been determined.

TABLE OF CONTENTS

Page

ABSTRACT v

1. INTRODUCTION 1

2. INTERNATIONAL RP&T PROGRAMS 3

2.1 UNITED STATES 3
2.2 EUROPE 4
2.3 JAPAN 4
2.4 SOUTH KOREA 5

3. PROGRESS IN RP&T 6

3.1 FUEL CYCLE STRATEGIES AND TRANSITION SCENARIOS 6
3.2 WASTE FORMS AND GEOLOGICAL REPOSITORIES 7
3.3 TRANSMUTATION PHYSICS, EXPERIMENTS AND MATERIALS 8
3.4 TRANSMUTATION FUELS AND TARGETS 8
3.5 PYRO AND AQUEOUS PROCESSES FOR PARTITIONING 9

4. ALTERNATIVE TECHNOLOGIES: VERY DEEP BOREHOLES 11

4.1 INTRODUCTION 11
4.2 SUMMARY OF PRIOR REPORTING 11
4.3 STATUS 14

5. KEY QUESTIONS CONCERNING THE REPROCESSING OF CANDU FUEL 16

5.1 RATIONALE 16
5.2 REDUCTION OF RADIONUCLIDES 19
5.3 EMERGING TECHNOLOGIES 20
5.4 ISSUES FOR DECISION AND THE DECIDERS 21
5.5 TECHNOLOGY STATUS AND PROJECTIONS 23
5.6 REQUIRED FACILITIES AND THEIR COST 24
5.7 ALTERNATIVE SCENARIOS FOR A DGR 26

6. SUMMARY OF PROGRESS IN 2010 28

7. REFERENCES 29

LIST OF TABLES

Page

Table 1: Very Deep Borehole Design 12
Table 2: Performance Assessment Scenarios 12
Table 3: Performance Assessment: Excluded Processes 13
Table 4: Summary of Sandia Very Deep Borehole Concept 15
Table 5: Summary of Reprocessing Issues 27

LIST OF FIGURES

Page

Figure 1: Fuel Cycle Options (from Warin (2008)) 6

1. INTRODUCTION

This is the third in a series of Annual Reports in fulfilment of the mandate of the Nuclear Waste Management Organization (NWMO) to provide the NWMO with an annual watching brief on international developments in reprocessing, partitioning and transmutation (RP&T) of used[1] nuclear fuel, and alternative technologies for long-term management of nuclear fuel waste. The first Annual Report (Jackson and Dormuth, 2008) was a broad survey of recent developments in RP&T based on the Nuclear Energy Agency meeting at Mito, Japan in 2008 (NEA 2008). The second Annual Report (Jackson and Dormuth, 2009) concentrated on selected topics in RP&T: the US situation arising from the cancellation of the Yucca Mountain facility, the new European Union policy on nuclear power, the apparent revival of interest in thorium fuels, an update on reprocessing costs and some new information on alternative waste management technology. Relevant developments reported at the Global 2009 conference were also cited in the second Annual Report.

In this, the third Annual Report, the status and progress of RP&T since the Mito meeting, as presented at the Nuclear Energy Agency meeting held in San Francisco in November 2010 (NEA 2010), is reviewed and seven key questions related to the assessment of the possibility of reprocessing for CANDU fuel are discussed based on the conclusions of all three Annual Reports.

The following definitions are repeated from the first and second Annual Reports in order to make this report more self-contained and accessible to non-specialist readers. Reprocessing is a general term for applying chemical and physical processes to used fuel from today's reactors to split out (partition) its components generally into five streams:

(1) the metal fuel cladding materials that hold the fuel pellets;

(2) uranium-238, which forms most of the fuel mass;

(3) fissile isotopes such as plutonium-239, which can be recycled in fresh reactor fuels;

(4) Fission Products (FP) and other radioactive isotopes formed by neutron activation, which are generally for placement in a deep geological repository; and,

(5) Minor Actinides (MA) that have long half lives and are responsible for the long lived radioactivity of used fuel.

Broadly speaking, transmutation involves the conversion of one element or isotope into another through nuclear processes. In this report, we focus on inducing transmutation of Minor Actinides and certain Fission Products, which are the primary source of very long-term radiotoxicity of used fuel, by subjecting them to an intense flux of neutrons provided by a Fast Reactor (FR) and/or in an Accelerator Driven System (ADS). Neutron-induced fission and radiative capture destroy the target nuclides prior to placement in a deep geological repository. These activities are grouped together under the abbreviation RP&T.

[1] In this report we employ the terminology "used", in preference to "spent", in referring to nuclear fuel that has been irradiated in a reactor. An exception is made for quotations in which "spent" is the word used in the original.

A further distinction can be made in partitioning. Today's commercial reprocessing plants routinely partition used fuel into the five streams delineated above. Advanced partitioning technologies are needed to perform separations within the fission product and the MA streams in order to isolate isotopes suitable for transmutation. This is now a subject of intense R&D in several countries.

As stated in the previous Annual Reports, the Final Study report of NWMO recommended that NWMO maintain a "watching brief" on RP&T and continue to study alternative technologies for managing nuclear fuel waste (NWMO 2005). Therefore, one of the principal objectives of the NWMO's technical research and development (R&D) program is to maintain awareness in these areas. The NWMO's 5-year plan, (NWMO 2008), includes preparation of an Annual Report which documents alternative technologies for long-term management of used nuclear fuel including RP&T. Note that the watching brief is for information purposes only. Canada's national policy and the current practice of Canada's nuclear fuel waste owners remain focussed on a once through fuel cycle followed by placement in a deep geological repository.

2. INTERNATIONAL RP&T PROGRAMS

A good picture of the current status of RP&T was given by the presentations at the San Francisco NEA meeting and the following two sections are largely based on the reports at that meeting (NEA 2010). Note that these international programs are generally based on a strategic national energy plan (with a several decades or more outlook horizon), which shows how future nuclear energy systems fit into the overall national strategy. Research and development is funded by the national government to support the objectives of the plan. This type of strategic national energy planning is not done in Canada.[2]

2.1 UNITED STATES

The US nuclear power program, and in particular its nuclear waste management component, is still in a state of confusion following the cancellation in early 2009 by the incoming US administration of the Yucca Mountain project to develop a deep geological repository (DGR) for US nuclear fuel waste. Since then, opinions have been expressed that this decision could be reversed on legal grounds or simply for pragmatic reasons but it is difficult to assess the probability of such a reversal happening.

In March 2010, the US government's Department of Energy (DOE) constituted a Blue Ribbon Commission, officially "The Blue Ribbon Commission on America's Nuclear Future", to advise it on all aspects of its nuclear energy program including nuclear waste management (BRC 2010). It is mandated to report by March 2012. There have been many submissions both in favour of a US RP&T program primarily from industry and government labs and against from some universities and non-governmental organizations.

In 2009, MIT issued an update (MIT 2009) of its influential report assessing nuclear power in the US (MIT 2003). The 2003 report concluded that RP&T was not the correct direction for the US:

> *"For the next decades, government and industry in the U.S. and elsewhere should give priority to the deployment of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies."*

Supporting this view is the consensus outcome of a US nuclear engineering workshop held in 2009, (Rosenstein and Roy 2009) that recommends the so-called 'Plan D', interim storage of used nuclear fuel in dry casks, as the best nuclear waste management strategy for US in preference to RP&T and other alternatives.

The 2009 MIT update also criticizes the GNEP program, in effect the 'Plan C' favoured by the previous US administration, which has now been abandoned:

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[2] Although consensus exists in some areas, Canada lacks a strategic Canadian energy policy, most likely as the result of conflicting federal, provincial and territorial constitutional responsibilities for various aspects of energy

> *"Initially DOE undertook an R&D program to explore fuel cycle options. DOE then launched the GNEP program that included deployment of closed fuel cycle facilities. The unfortunate feature of GNEP is a premature move to reprocessing commercial reactor spent fuel, signalling exactly the opposite to the restraint on reprocessing being urged for new nuclear power users."*

At the San Francisco meeting the US DOE representative (Savage 2010) said the US RP&T effort was in the process of transitioning from GNEP (see section 2.1 of the 2008 Annual Report for more on GNEP) to a science program to investigate generic and fundamental issues that would not consider engineering, demonstration and realization of RP&T in the US. The DOE is currently focused on intermediate to long term storage of used fuel for decades with no decisions on fuel cycle strategy and geological repositories for perhaps 50 to 100 years. All options are now open, including deep boreholes for long-term management of used nuclear fuel and high-level waste (HLW) and extracting uranium from seawater. In reply to a question, the representative said that industry, rather than government, had to undertake RP&T related activities. Presumably this policy could change when the recommendations of the Blue Ribbon panel are issued.

The foregoing is not an attempt to predict the outcome of the Blue Ribbon process but merely to indicate that, in the view of the authors at this time, the USA may be tending away from a domestic RP&T program.

2.2 EUROPE

In contrast to the US situation the European Union (EU) RP&T program is going well (D'Hondt 2010). Very successful programs in partitioning (ACSEPT (2008-12)) and transmutation (EUROTRANS (2005-2011)) have been conducted as part of the Sustainable Nuclear Energy Technology Platform (see the last two Annual Reports for more detail on this program). Europe's intention is to review the national facilities of EU members and derive plans for joint facilities in 2015.

France continues to be the EU's strongest player in RP&T (Warin 2010). The French fuel cycle program continues to make progress with a major decision point in 2012 set by the National Assembly. At that time they expect to move forward with an ADS prototype to be in place by 2020 and they will select a DGR site by 2015 to be in operation by 2025. The plan for next Sodium Fast Reactor (SFR), ASTRID, may also be taken on the same time scale.

In addition to ASTRID, Belgium (Abderrahim 2010) has made a strong pitch to construct MYRRHA (Multi-Purpose Hybrid Research Reactor for High-Tech Applications). If built, it would play an important role as an ADS experiment with many other applications in areas such as fusion materials and isotope production. The Belgian government has agreed to fund 40% of the project (total ~ $1B) if the remainder is contributed from other sources.

2.3 JAPAN

The results of the 2009 technical committee review of the Japanese RP&T program were very positive (Oigawa 2010). However, in common with all Japanese R&D programs, it is being subjected to a government financial review because of that country's economic difficulties.

Apparently cuts will be made but the details won't be known until March 2011. Nevertheless technical progress has been good, and Japan's current plan includes a demonstration fast reactor with a fuel cycle facility by 2025. Commercial fuel cycle operations are planned for 2050.

With respect to commercial operations, a study applying the Technology Readiness Level (TRL) technique developed by NASA was done to assess the TRL of RP&T in Japan (Minato 2010). It was concluded that the TRL for MA removal is now in the range of 3 to 4 whereas full scale industrial application would require a TRL of 9. Broadly speaking industrial implementation of MA removal is about half way there.

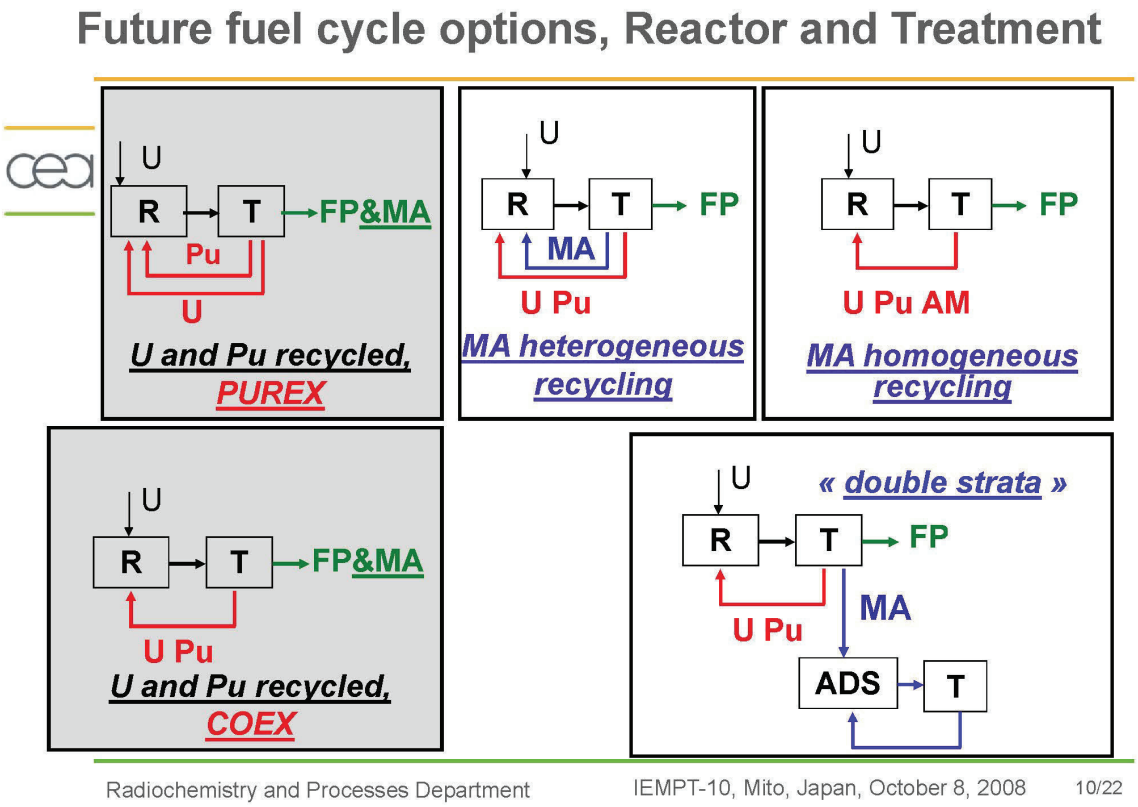
2.4 SOUTH KOREA

Korea is committed to RP&T and is concentrating on pyroprocessing (J-G Kim 2010). However, in response to a question, it is expected that Korea will not attempt to reprocess fuel from its CANDU reactors.

3. PROGRESS IN RP&T

There are a great many possible fuel cycles involving RP&T. Figure 1 (Warin 2008) illustrates the complexity of these schemes. In this figure “R” represents a Reactor, thermal or fast, “T” stands for Treatment essentially a reprocessing plant, FP are Fission Products and MA stands for Minor Actinides. In some processes uranium and plutonium are extracted separately from each other and the MA, and in others there are groupings which are mainly to make the fuel cycles proliferation resistant.

Figure 1: Fuel Cycle Options (from Warin (2008))



3.1 FUEL CYCLE STRATEGIES AND TRANSITION SCENARIOS

As discussed in the Annual Report for 2008, at the Mito meeting there was an emphasis on scenarios by which the world could achieve sustainable nuclear power based on various fuel cycles. Assuming a prediction for the growth of the world energy demand, these scenarios considered issues such as the most efficient use of a limited uranium resource, how to optimize fuel recycling to minimize the radiotoxicity and decay heat load in a deep geological repository (DGR), the rate of introduction of the fast reactors and reprocessing plants needed to implement the required fuel cycles and the time scale needed to transition to a fully sustainable

fission economy. Incidentally, the consensus answer to the last question is at least a century and more likely 150 years.

There were relatively fewer scenario papers at the San Francisco meeting as compared to the Mito meeting two years earlier. A comparison of five scenario codes was reported (Boucher 2010) that showed some differences between them, more artefacts of the models than due to any fundamental problems. A presentation from the French CEA (Varaine 2010) considered both heterogeneous and homogeneous reprocessing schemes using the planned French SFR (presumably ASTRID) and concluded that the reduction in the MA concentration might only be an unimpressive 15%.

One paper (Romanello 2010) used pessimistic assumptions about uranium supply to derive a pessimistic scenario. Another presentation argued (T. Kim 2010) that sustainability of nuclear energy depends on maximizing the utilization of uranium using as examples, the CANDLE concept and the Travelling Wave Reactor (TWR). Both burn fuel that is bred in front of the reactivity zone in a traveling wave, 1-dimensional for CANDLE and two dimensional for TWR.

3.2 WASTE FORMS AND GEOLOGICAL REPOSITORIES

There were several interesting papers at San Francisco projecting the effects of reprocessing on geological repositories. A comprehensive summary of the volume and forms of US used fuel waste was presented using data published elsewhere but drawn together in a useful single source (Jones 2010). By the end of December 2009, it was estimated that 218,756 used fuel assemblies with total mass of 63,195 MTHM (metric tonne heavy metals) had arisen from the US civilian nuclear power industry. In addition, there were about 2,500 MTHM from various Department of Energy operations, 65 MTHM of used naval reactor fuel and several 1,000 of high level waste cannisters from a variety of reprocessing undertakings. These data are useful for estimating the requirements for US DGRs.

Based on studies done in support of the Yucca Mountain studies several DGR concepts were reviewed (Swift 2010a). It turned out that all of the concepts had about the same dose to the public but differed in terms of advection and diffusion processes. For example, clay is diffusion dominated and granite is dissolution dominated. In answer to a question, the author indicated that one effect of reprocessing was to make a DGR appear more complicated than it really was.

Another presentation (Wigeland 2010) viewed the performance of a DGR as dependent on two factors:

i) a source term dependent on the amount and type of radioactive material deposited; and

ii) the human exposure pathway which depends on the conditions of the repository.

The argument was that as in reactor safety it is always a good idea to reduce the source term and this could be done by reprocessing. Moreover it is also very difficult to assure the safety of repositories that have been disturbed (disrupted) by human intrusion or natural events. Again reduction of the source term would be prudent. In the same spirit, it was stated that the pathways by which radionuclides could migrate to the surface from a DGR consisting of deep boreholes would be driven by decay heat which could be considerably reduced by reprocessing.

The Korean DGR concept was reported (Yoon 2010) and it was noted that after the planned pyroprocessing the heat load would be reduced by a factor of 67. Iodine-129 and technicium-99 would be removed by pyroprocessing and reserved for future transmutation thus, avoiding two long-term hazards in the repository.

EDF (Camarcat 2010) is investigating the industrial implications of RP&T. Because the French DGR is a clay concept, Minor Actinides (MA) won't migrate through clay out of the repository. Therefore, it is only necessary to remove the americium for heat reduction and not the neptunium or curium.

3.3 TRANSMUTATION PHYSICS, EXPERIMENTS AND MATERIALS

As explained in the 2008 Annual Report, an Accelerator Driven System (ADS) consists of an accelerator that produces an intense beam of high energy ions incident on a lead or lead-bismuth target yielding a large flux of high energy neutrons via a process called spallation. The target is in the core of a subcritical 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. 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 in a fuel cycle using a fast reactor alone.

An outstanding achievement reported at the San Francisco meeting was the world's first ADS experiment (Pyeon 2010). Experiments in the Kyoto University Critical Assembly (KUCA) used neutrons generated by beams from the FFAG accelerator to in effect form an ADS. A beam of 100 MeV protons was impacted on a tungsten target to produce spallation neutrons in KUCA. Two methods of neutron generation and two KUCA fuel configurations were used to verify that the experiments were in good agreement with neutronics calculations.

Severe corrosion and temperature demands are placed on the structural materials in ADS transmutation devices by the flowing liquid lead and Lead Bismuth Eutectic (LBE) that comprise the spallation targets. There are many challenges and among them loop chemistry will be critical to control oxygen levels and thereby controlling impurities (Fazio 2010)

Progress has been made on calculations of ADS nuclear reactivity using Monte Carlo methods. The results of one were compared to data from the GUINIVERE assembly (Carta 2010) and the other to the Yalina experiment using the "source jerk" method (González-Romero 2010). Both gave good agreement with the calculations.

For ADS calculations there is an urgent need for better nuclear data and for benchmarking experiments with which calculations could be compared (Hambsch 2010), (Nishihara 2010)

3.4 TRANSMUTATION FUELS AND TARGETS

ADS transmutation systems will require special fuels containing a substantial proportion of Minor Actinides (MA). The EU's EUROTRANS program has produced excellent results and

AFTRA, its fuel development component, has made progress on three types of MA bearing transmutation fuels:

i) the oxide fuel CERCER with added MgO

ii) another oxide fuel CERMET but with Mo enriched in Mo-92

iii) nitride fuels of the type (Pu, MA, Zr) N.

Several irradiation tests were done and samples are now awaiting Post Irradiation Examination (PIE) (Delage 2010).

In another approach, Japan has been developing metal MA fuels. Calculations show that it will take 40 years after the introduction of SFRs (Sodium Fast Reactors) to consume the projected stock of MAs. Metal fuels have been irradiated in an 8 year test in the Phenix reactor that just ended. The results appear good but PIE is awaited (Ohta 2010).

The fuel for the US Deep Burn program (Bell 2010) was presented. The idea is to reprocess LWR fuel into the TRISO fuel developed for PBR (Pebble Bed Reactors) even though South Africa recently closed down its PBR program (Venneri, 2010). This spherical fuel consists of a fuel kernel of Trans Uranium (TRU) elements, Pu and MA coated with a SiC layer and an outer graphite layer. These fuel spheres would be burned in a high temperature reactor, DB-HTR, designed to achieve very high burn up, up to 60% of the TRU. The fuel integrity is excellent as shown in tests.

It was reported that a demonstration MA fuel fabrication laboratory line (ALFA project) had been designed for the ATALANTE site at Marcoule. The decision to proceed will depend on the French government review of 2012 (Royet 2010).

3.5 PYRO AND AQUEOUS PROCESSES FOR PARTITIONING

The highlight of the San Francisco meeting (NEA 2010) was the excellent progress made in the last two years on the advancement of chemical partitioning technologies both aqueous and pyroprocessing. These technologies fall into the advanced partitioning category in that many of them are targeted at extracting specific fission products and MA in support of transmutation.

The EU's ACSEPT program has made excellent progress (Bourg 2010). Using a combinatorial chemistry strategy literally hundreds of new molecules were tested for their efficacy in partitioning. Some of them have led to new partitioning schemes. Interestingly, the ACSEPT program also has a training component with funding for training post-doctoral (2) and summer students (7).

In Japan, there was also progress in partitioning (Morita 2010). Excellent separation factors were achieved for TRU and some fission products (Sr, Cs and Mo) using novel organic compounds (e.g. TDdDGA, Oct-PDA, calyx-arane, HEDTA). These extraction results were obtained in the lab and an important issue is to investigate their scalability to the demonstration level especially in terms of recycling the solvents.

Partitioning R&D in France has also done well (Warin 2010). For example, GANEX, group extraction of TRUs, has been improved. A new process, EXAm to extract Am at the front of the partitioning process has been developed using the TEGDA amide molecule. A hot test is required with HLLW to verify EXAm. Centrifugal contactors have been used to develop a one cycle SANEX process with two exotic molecules CyMe4BTBP and TODGA. (Wilden 2010)

Research at Chalmers University Sweden (Aneheim 2010) combined the well known partitioning solvents BTBP and TBP, the latter the basis of PUREX, into a mixture to develop an improved GANEX process. The new system is able to extract U, Pu, Np and Am from strong nitric acid and simultaneously separate them from the lanthanides.

A new voloxidation method (oxidizing gases to stabilize them in the form of solids) for the front end (head end) of reprocessing was reported (DelCul 2010). NO_2 and O_2 are used together as oxidants and were shown to be more effective than air for example. Very good iodine and tritium removal was observed.

The Czechs (Uhlír 2010) continue to develop fluoride volatility method for partitioning in which fluorine gas is used to create fluorides from powdered used fuel and separation is done by differences in the volatility of fluorine-based gases so produced. The Molten Salt Reactor concept proposed in the Gen-IV initiative has also motivated pyrochemical studies based of fluoride salt mixtures.

At CRIEPI in Japan (Uozumi 2010) pyro partitioning experiments were performed using 520 g of High Level Liquid Waste (HLLW) from MOX processing. Excellent separation results were achieved using real waste.

4. ALTERNATIVE TECHNOLOGIES: VERY DEEP BOREHOLES

4.1 INTRODUCTION

The very deep borehole (VDH) concept for long-term management of nuclear waste consists of placing the waste packages nominally 3 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. In this concept, the waste would be placed further from the surface 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.

The interest in this concept internationally has increased somewhat, particularly in the U.S., with the discontinuing of the Yucca Mountain Project and the formation of the Blue Ribbon Commission on America's Nuclear Future (BRC 2010) and its Disposal Subcommittee.

It should be noted that proposals to the BRC have included a case for reviewing the acceptability of sub-seabed disposal as an alternative to land-based disposal (Parker 2010). This alternative has been rejected in the past because it would contravene the London Protocol of 1996. It has been pointed out, however, that the Protocol was modified to allow sequestration of CO_2 in the sub-seabed, and that early work had indicated that sub-seabed disposal of nuclear waste could be radiologically a very safe option. Nevertheless, this alternative is not considered part of this watching brief because it would contravene current international agreement.

4.2 SUMMARY OF PRIOR REPORTING

As reported previously, Sandia Laboratories has been developing technical aspects of the VDH concept, including design, cost and schedule, and performance assessment (Brady *et al*, 2009). This work indicates that the VDH method has the potential for long-term safety at a competitive cost. The used fuel is assumed to be placed in relatively low cost containers placed in basement rock in the bottom ~2 km of a ~5 km deep borehole. A similar method could be applied for used CANDU fuel; however, the cost of construction would likely be significantly higher than for LWR fuel on a unit energy basis due to the larger borehole space requirement of CANDU fuel per unit of energy generated. Costs comparisons with a mined repository cannot be made without including other elements of the waste management system in the analysis. As well, use of the very deep borehole design described in the Sandia study would virtually eliminate the possibility of demonstrated long-term retrievability, a key feature in Adaptive Phased Management (Jackson and Dormuth 2009).

Table 1 provides a summary of the VDH design employed in the Sandia study. Table 2 and Table 3 describe the scenarios included in the performance assessment and processes excluded from the analysis, respectively.

Table 1: Very Deep Borehole Design

Design Element	Discussion
Waste Canisters	Only emplacement of intact, unconsolidated PWR or BWR fuel assemblies is considered. The canister is assumed to be made of a 5 m length of standard oilfield casing (318 mm ID, 340 mm OD) with welded endcaps, which would hold one assembly. Each canister would then contain 666 kg of PWR used fuel or 297 kg of BWR used fuel. Inner void spaces (which would be greater for BWR than for PWR fuel) would be filled with powdered bentonite for physical stability during the waste emplacement phase, when the canister must have sufficient strength to prevent releases from operations, including recovery of stuck and/or damaged packages. The canister is not expected to have any other waste-isolating characteristics.
Boreholes	The boreholes, designed to accommodate 340 mm OD canisters, are expected to be ~ 5 km deep with an emplacement zone at the bottom 1-2 km in crystalline basement rock. Borehole casing would be cemented in place and boreholes would be plugged and backfilled following waste emplacement. A single borehole might hold 200-400 canisters, emplaced one at a time or in multi-canister strings. The rock stress conditions would be assessed for borehole stability, and anticipated stress changes due to decay heat as well as long-term chemistry would be evaluated as part of borehole design. Individual boreholes are spaced in an array such that interactions among the holes will be insignificant.

Table 2: Performance Assessment Scenarios

Scenario	Description	Discussion
Transport in Borehole	Hydrologic flow up the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere.	- Canisters in the emplacement zone could deteriorate relatively rapidly leading to high permeability within the zone. - A hydrologic potential gradient could be caused by ambient hydrological conditions, pressurization, and buoyancy of fluid due to radioactive decay heating, or thermochemical reactions that release fluids within the zone.
Transport in disturbed rock around the borehole	Hydrologic flow up the annulus of disturbed rock surrounding the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere.	- Permeability in the disturbed zone around the borehole could be relatively high if grouting during construction is not effective. - Thermal effects could increase the permeability in the vicinity of the emplacement zone. - A hydrologic potential gradient could be caused as above.
Transport in surrounding rock away from the borehole	Hydrologic flow up through the crystalline basement and sedimentary cover transports radionuclides to a shallow aquifer from which they are pumped to the biosphere.	- A hydrogeologically conductive feature, such as interconnected fracture zones would be required to conduct significant quantities of fluid to the aquifer.

Table 3: Performance Assessment: Excluded Processes

Event or Process	Description	Rationale for Exclusion
Criticality inside a Waste Canister	A self-sustaining nuclear chain reaction initiates inside a single waste canister.	The physical constraints with a single PWR assembly in a container would not permit criticality, even in the most reactive geometry.
Criticality outside a Waste Canister	A self-sustaining nuclear chain reaction initiates outside the canisters in the near-field of a single canister or in the far field.	The limited amount of material in a single canister prevents criticality developing from that material alone in the borehole outside the canister. For criticality to develop, material from several canisters would need to be transported to a single location and formed into a critical configuration. Analysis of material transport in the emplacement environment and requirements for criticality indicates that this is not a credible event.
Molecular Diffusion	Chemical diffusion of radionuclides through the host rock matrix and borehole seals results in the migration of contaminants, even in the absence of fluid flow.	Diffusion in crystalline rock and borehole seals is a slow process even on geologic time scales. Given the emplaced waste, diffusion is excluded as a significant process.
Thermal Hydrofracturing	Thermal expansion of fluid fractures the rock near the emplacement zone, increasing the permeability of the surrounding rock and providing a pathway for upward vertical hydrologic flow and radionuclide migration toward the surface.	The average horizontal stress at 4 km depth would be about 96 MPa. Hydrothermal modeling results suggest that comparable thermally induced fluid pressures would not be achieved and that therefore no hydrofracturing would occur by this process.

Sandia conducted a preliminary performance assessment for emplacement of ~150 MTHM in a 2 km waste emplacement zone. Dissolved concentrations were assumed to be limited by thermal-chemical conditions. A withdrawal well was assumed to be pumping water from a location 1000 m above the top of the emplacement zone. The peak dose rate to a "reasonably maximally exposed individual" was estimated to be 1.4×10^{-12} mSv/a and to occur at 8,200 years.

Construction of a 5 km deep borehole is estimated to take 110 days and to cost about US$20 million. With the assumption that each borehole would contain about 400 fuel assemblies; emplacement of the projected 109 300 MTHM inventory would require about 950 boreholes. With a borehole spacing of 200 m, these could, for example, be located in several borehole fields totalling about 30 km^2 and be conducted over 50 years. The construction cost of the boreholes would be about US$19 billion. Very rough estimates of additional costs, (site characterization, licensing, emplacement, monitoring, transportation, etc.) give a total life-cycle cost of US$71 billion (2008 dollars).

A comparative analysis for emplacement of 4 million CANDU fuel bundles, assuming 14,400 fuel bundles in a single borehole, gives about US$5.6 B to construct the boreholes or roughly 70 US$/kgHM. This compares to about 100 US$/kgHM for the PWR case. As the burnup of natural uranium CANDU fuel is about a quarter that of PWR fuel, the estimated borehole construction cost for long-term management of CANDU fuel would be almost three times that

for PWR fuel per unit energy produced. A cost estimate made recently (Kang, 2010) as part of a study of VDH emplacement of Korean used fuel (von Hippel and Hayes, 2010) arrives at an even greater cost differential due to assuming lower-density packing of the CANDU fuel in the borehole. None of this discussion includes consideration of other costs, including the costs of site characterization, emplacement, or transportation. These costs and some optimization of the system for CANDU used fuel would need to be included before a reasonable comparison could be made with the cost of a DGR.

4.3 STATUS

The 2003 MIT study on the future of nuclear power (MIT 2003) recommended that a technical program be undertaken to investigate the VDH concept, siting as the main advantages of VDH relative to mined geological repositories:

(a) a much longer migration pathway from the waste location to the biosphere;

(b) the low water content, low porosity and low permeability of crystalline rock at multi-kilometer depths;

(c) the typically very high salinity of any water that is present (because of its higher density, the saline water could not rise convectively into an overlying layer of fresh water even if heated); and

(d) the ubiquity of potentially suitable sites.

An additional advantage is expected to be a smaller thermal footprint than a mined geological repository, because boreholes placed more than ~200 m apart are unlikely to thermally affect one another.

Recent work reported on the VDH concept has been conducted principally by researchers at MIT and Sandia Laboratories. Following are the principal items of interest reported:

- The main transport mechanism of concern is reaffirmed to be movement of dissolved radionuclides through the highly impervious igneous bedrock. (Jensen and Driscoll 2010)

- The deep water chemistry is affirmed to have a beneficial effect in assuring sequestration of nuclides through providing low solubility under reducing conditions, retardation by adsorption, and inhibition of buoyancy and colloid formation because of its salinity. (Jensen and Driscoll 2010)

- A variety of materials are proposed for various wastes, including one concept in which lead shot is added as backfill. An overview article (Gibb 2010) describes the use of lead shot as filler between the waste containers and the borehole wall. The decay heat from the waste would eventually melt the shot to “create a dense liquid that will displace the aqueous fluid upwards and fill any remaining voids between the containers and wall rock.” As the decay heat diminishes over a few decades the molten alloy solidifies, sealing the containers into the borehole.

Table 4 describes the principal conclusions drawn regarding the Sandia VDH concept, along with our evaluation of their Canadian context.

Table 4: Summary of Sandia Very Deep Borehole Concept

Factor	Sandia Concept (Swift 2010)	Canadian Context
Space requirements	All used fuel from the existing U.S. light water reactors (109 300 MTHM) could be emplaced in about 1000 deep boreholes.	For the same containers and borehole design as the Sandia study, the projected inventory from current Canadian power reactors of 4 million natural uranium used CANDU fuel bundles (80 000 MTHM) would require about 300 boreholes, assuming dense packing of the bundles in the emplacement canisters (4 bundles per layer). If fewer bundles can be packed per canister layer, the number of boreholes required increases proportionally.
Relative cost	Total costs are competitive with mined repositories	Comparative total costs for repository and boreholes have not been estimated. In addition to borehole raw construction costs, total cost will be influenced by transport logisitics and degree of centralization (e.g. need duplication of infrastructure) as well as operational costs.
Performance	Long-term performance is likely to be excellent	As the CANDU fuel is physically and chemically similar to PWR fuel, the reactivity is lower, and the burnup is much lower, the performance assessment for the PWR case should be relatively conservative for CANDU fuel. However, retrievability (a key component of APM) will be very difficult, if not impossible, to implement.

5. KEY QUESTIONS CONCERNING THE REPROCESSING OF CANDU FUEL

The purpose of this section is to summarize the results of the three Annual Reports done to date framed in terms of seven key questions pertinent to the reprocessing of CANDU used fuel. The questions are as follows.

1. What would be the rationale for reprocessing of used CANDU fuel?
2. To what extent does reprocessing reduce the quantity of radionuclides?
3. Are there any emerging technologies that will significantly reduce the quantity of radionuclides in used fuel or its by-products? If so when may these be commercially available?
4. What are the issues that would need to be considered in a decision on reprocessing and who would be the decision makers?
5. What is the likelihood of reprocessing CANDU fuel in the next 30 years: with existing technology and with new technology?
6. What facilities in addition to a DGR would be required to support reprocessing of used CANDU fuel in Canada (e.g. high-level waste vitrification and interim secondary waste storage)? Estimated cost of these facilities?
7. Are there any current or foreseeable scenarios that suggest NWMO should alter its course towards a DGR?

5.1 RATIONALE

The discussion starts by considering question 1.

1. What would be the rationale for reprocessing of used CANDU fuel?

For peaceful applications of nuclear energy, there are two primary reasons for reprocessing of used nuclear fuels from all reactor types including CANDU:

A. To obtain additional nuclear fuels by extracting for recycling the fissile isotopes in the used fuel, thus making the most efficient use of the existing fuel supply.
B. To reduce the radiotoxicity of nuclear fuel waste per unit of energy produced by removing short-lived fission products and long-lived actinides.

Rationale B will be discussed under Questions 2 and 3.

Implementation of reprocessing on the basis of rationale A would imply a shortage of nuclear fuel in the long term most probably as a result of a large expansion of nuclear power causing an exhaustion of conventional uranium resources. In the shorter term it may also be a reflection of the desire of some countries to be less dependent on external supplies of uranium (Japan and India for example).

The key factors that impact Rationale A, nuclear fuel availability, are:

- the rate of expansion of nuclear power
- depletion of conventional uranium deposits and rate of discovery of new ones
- availability of fissionable materials from dismantled weapons
- exploitation of non-conventional uranium sources (phosphates, sea water and others)
- progress in thorium fuel utilization

These factors will now be briefly discussed in turn.

In recent years there has been much discussion of a revival in nuclear reactor construction under the heading “nuclear renaissance”. If the deployment of nuclear power was expanding rapidly then there would be a growing demand for uranium resources which would provide an impetus for reprocessing in order to obtain fissile material for recycling. However, at this time the nuclear renaissance has both a non-uniform geographical distribution and also most likely a non-uniform distribution in time.

Interest in building new nuclear reactors is strongest in Asia. China has an ambitious program to build 24 more power reactors to add to the 12 already operating. Some of the new reactors are already being built. Several more may well be added to this total since the long range energy plan is to have 250 GW(e) of nuclear power by 2030. India is also building new reactors of various types both under arrangements with foreign vendors and also of their own design. South Korea has 20 nuclear power plants supplying about 40% of its electricity. The plan is to increase this to 60% by 2030. Japan is the world’s third largest producer of nuclear power, obtaining 35% of its electricity from 53 reactors. It is now in the process of planning a new nuclear build program.

Russia traditionally has been a strong player in the nuclear area. Nuclear power stagnated as a result of the Chernobyl accident and the fall of the Soviet Union but has bounced back in the last decade due to strong electrical demand. The present plan is to more than double Russian capacity by constructing 24 additional reactors by 2020 for a total of 51 GW(e). However, in the rest of Europe only Finland and France are each constructing one new reactor and these projects have not been going well.

In contrast, North America is showing little activity in new build nuclear. It appears that one new reactor plan of some 30 proposals has succeeded in getting through all the necessary steps for construction in the United States. The reasons given in the media for the delay in US nuclear construction are said to include the economic recession, the difficulty of getting US government loan guarantees, the recent uncertainty in the US nuclear waste management program, the increasing availability of cheap shale gas, and the lack of a carbon tax to make nuclear power economic. In Canada, although a number of new reactors have been proposed in several provinces, the only reasonably firm projected new reactors are the two to be built at the OPG Darlington site. OPG has been preparing the environmental assessment and seeking regulatory approvals for siting. However, the future owner of AECL, the likely vendor, is not yet known and construction cannot proceed until contracts can be negotiated with AECL in its restructured form. This may well take some years.

A nuclear renaissance is under way in Asia but as yet there is comparatively little activity in other parts of the world. About 65 countries have expressed an interest in nuclear power and about 30 of them are discussing plans for new nuclear power stations. (WNA 2010) Many of these countries have no previous nuclear experience (IAEA 2010) and will require development of a national nuclear infrastructure. Others plan to resume nuclear programs after long periods of no activity. Most of these reactors would not likely come on stream until 2020-2030 for the proposals that materialize. Therefore, a second wave of reactor building will probably occur in that decade although its extent cannot be predicted at this time. Uranium mining companies such as Cameco have benefited from Asian orders (Morrissy 2010).

According to the WNA (2010c), 2007 world uranium reserves were estimated at 5.5 million tonnes compared to a 2009 production level of 51,000 tonnes. Therefore, the known reserves of uranium extractable at $130/ kg or less would last for about 100 years at the current rate of consumption. In Canada consumption for domestic use in 2009 was 1,675 tonne compared to production of 10,173 tonne in the same year, the balance being exported.

Uranium mining is supplemented by highly-enriched uranium from dismantled weapons that displaces about "10,600 tonnes of U_3O_8 production from mines each year, and meets about 13% of world reactor requirements" (WNA 2010b). Plutonium from reprocessing is blended with uranium in MOX fuel increasing the availability of fissionable material but only about 2.3% of uranium-235 from reprocessing (called RepU) is used for fresh fuel (IAEA 2009). Annual world uranium consumption is approximately 62,000 tonne from all sources. Therefore, even without having to resort to non-conventional sources like uranium extraction from sea water, there is ample uranium available for decades.

The original MIT study (MIT 2003) stated that there was enough uranium *"to fuel the deployment of 1,000 reactors over the next half-century"*

As reviewed in the 2009 Annual Report, "interest in thorium was more driven by its geographical distribution than by a perceived shortage in uranium supply". For example, India has a lot of thorium but not much uranium and hence, its nuclear self sufficiency would have to be based on thorium. There has been a large thorium fuel R&D program in that country for many years. Canada has also been involved in thorium fuel testing to highlight the fuel cycle flexibility of CANDU reactors and thus, to make them more attractive to foreign buyers.

The example of the thorium cycle in India illustrates the fact that long-term energy self sufficiency may well be an important component of "sustainability" for some nations. France has no domestic uranium resources but owns uranium mines in other countries including Canada. Nevertheless, not having to rely on foreign sources of uranium would appear to be an important factor in France's nuclear strategy. Japan has had a policy of national energy self sufficiency for at least a century. As in the case of France, maximum use of uranium resources is a significant goal of its nuclear program.

The conclusion for the Rationale A component of Question 1 is:

There is not now and will not be for some decades a need to recycle nuclear fuel to make up any shortfall in the availability of nuclear fuel.

5.2 REDUCTION OF RADIONUCLIDES

2. To what extent does reprocessing reduce the quantity of radionuclides?

This question refers to the present status of RP&T. The technology for fuel partitioning and recycling is well known and already in commercial operation in countries such as France, Japan, UK, Russia, and India as reviewed in the 2008 Annual Report. Some CANDU-type[3] fuel has been partitioned in order to extract fissile isotopes for non-civilian purposes in India (Jackson 2003) and probably also in Pakistan. Therefore, the required technology is available for reprocessing CANDU fuel, although it may not exist at the capacity required to handle the large quantity of Canada's used fuel in a reasonable time frame.

Plutonium and uranium-235 are extracted for recycling and the former is incorporated in MOX (mixed oxide) fuels which are burned in reactors in Japan and Europe. One could argue that consuming plutonium in MOX fuel results in destruction of radionuclides contained in the original used fuel. This is true but additional radionuclides are produced by fission and neutron capture in the MOX fuel. Therefore, whether the total quantity of radionuclides is reduced or increased depends on the details of the MOX fuel cycle. Using MOX fuel not only results in increased energy from the uranium comprising the used fuel but it also reduces the stockpiles of stored plutonium from reprocessing thus, reducing the risk of its diversion for illicit purposes.

In today's fuel recycling operations the fission products and MA's are separated out as part of the process and vitrified in glass blocks destined for eventual interment in a DGR. No transmutation occurs and the total quantity of radionuclides (allowing for normal radioactive decay) remains unchanged but they are redistributed into different places. In other words at this time there is now no "T" in RP&T.

A related question concerns the total quantity and form of radioactive and other wastes from each fuel cycle. For the current once-through fuel cycle, this is a relatively easy prediction with a small number of waste streams resulting from mining, milling, fuel fabrication, operation and eventual decommissioning of all facilities in the fuel cycle, with most of the radioactivity contained in the chemically very stable used nuclear fuel. However, for advanced fuel cycles, the waste streams become much more numerous and complex and depend heavily on the actual implementation employed (i.e. they may reduced in one area, but may result in an increase in another area). This generally results in distribution of radioactivity in numerous wastes including highly radioactive and chemically active liquids (e.g. strong acids) that require further complex treatment before storage or long-term management. As such, it is difficult to predict if reprocessing will reduce the total quantity of radioactive or other wastes without undertaking a very detailed analysis of a specific fuel cycle.

The answer to Question 2 is then:

With the possible exception of extracting additional energy via MOX fuels (which in turn creates additional fission products and minor actinides), today's nuclear fuel reprocessing by itself does not result in any net reduction in the quantity of radionuclides. Decades of additional R&D are required to implement the transmutation aspect of RP&T in order to reduce the quantity of long-lived radionuclides.

[3] India developed its own but essentially identical version of the CANDU system after its 1974 nuclear test resulted in a breach of nuclear relations with Canada.

5.3 EMERGING TECHNOLOGIES

3. Are there any emerging technologies that will significantly reduce the quantity of radionuclides in used fuel or its by-products? If so when may these be commercially available?

This question looks to the future whereas the previous question considered the present. Rationale B from section 5.1, improving the waste management aspects of used nuclear fuel, concerns the potential role of the partitioning and transmutation aspects of "RP&T" in mitigating nuclear waste management issues including:

- Segregation of fission products that cause excess heating in a DGR
- Reducing the radioactive "source term" for accidental disruption of a DGR
- Conditioning radionuclide bearing materials to inhibit their migration from a DGR
- Destroying Minor Actinides via advanced fuel cycles including those in fast reactors
- Transmutation of Minor Actinides in Accelerator Driven Systems (ADS)

The first three technologies are available and used now. Today there is a substantial international R&D effort to develop MA burning in fast reactors and transmutation in ADS systems aimed at reducing the long lived radionuclides from used fuel. These programs are supported by intensive R&D in advanced partitioning. Monitoring and reporting on developments in these areas is a large part of the NWMO Watching Brief function as documented in the three Annual Reports.

As indicated above and in the previous two Annual Reports, the extent to which the quantity of radionuclides would be reduced by advanced partitioning and transmutation would depend on the fuel cycle used. A large number of fuel cycle options are under consideration internationally as are the associated advanced partitioning technologies required to make them work. These fuel cycles are being optimized in terms of sustainability (both saving uranium and reducing long-lived radionuclides). However, they cannot be fully implemented using current reactor designs and will require a substantial investment in fast reactors or accelerator based systems.

A recent RAND study (LaTourrette 2010) concluded that:

> *"Some advanced fuel-cycle configurations have the potential to significantly reduce geological repository capacity requirements (though this gain will be partially reduced by an increase in radioactive process wastes) but will have little benefit in terms of reducing a repository's long-term safety and environmental risk".*

It may well be that as stated in the original MIT report (MIT 2003) and unchanged in the update to it (MIT 2009):

> *"We do not believe a convincing case can be made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant safety, environmental, security considerations and economic costs."*

This is consistent with the quote from the same study (section 2.1) urging concentration on once through fuel cycles. While this strategy has much to commend it, there is a key aspect that this perspective misses, namely the importance of sustainability particularly to the people of Europe and Japan. The extensive R&D efforts in advanced partitioning and transmutation in these nations totalling in the order of a few $100M a year are predicated on an effort to fulfill an implied promise to make nuclear energy sustainable both in terms of energy self sufficiency and environmental stewardship.

The response to Question 3 is:

Yes, there are fuel cycle technologies now emerging from R&D programs that are aimed at significantly reducing the amount of long-lived radionuclides arising from used fuel. The basic concepts of these technologies will likely be demonstrated via prototypes within the next two decades. However, the commercial implementation of these technologies will require the establishment of a large and costly infrastructure of fast reactors and ADS devices and may take a century or more to achieve a fully sustainable nuclear energy economy. It is doubtful that these systems would be commercially viable for waste management purposes alone without large government subsidies or large increases in energy prices.

5.4 ISSUES FOR DECISION AND THE DECIDERS

4. *What are the issues that would need to be considered in a decision on reprocessing and who would be the decision makers?*

If a rationale were to be identified for reprocessing of used CANDU fuel then the following factors would have to be considered in a decision to implement it:

a) Reprocessing of used nuclear fuel is currently carried out on a commercial scale in a number of countries such as France, Russia, and the UK. It is also being commercialized in other countries, such as Japan and India. India has just opened its fourth small reprocessing plant (WNN 2011) and China has recently announced its success in developing and implementing reprocessing technology (BBC 2011). In all cases reprocessing is being done within the objective of a sustainable nuclear energy economy rather than as a stand alone waste management strategy. As discussed previously (Jackson 2003), the concentration of fissile materials suitable for recycling in used CANDU fuel is roughly five times less than in the used fuel of the light water reactors used in the countries seeking long term nuclear sustainability. Thus, achieving this sustainability using closed fuel cycles is more difficult for CANDUs.

b) Future developments in other nuclear countries would be an important issue. Europe and Japan have made sustainable nuclear power including advanced closed fuel cycles based on reprocessing a matter of public policy. The existence of such large R&D programs in RP&T influences world and Canadian attitudes. Similarly, the entire US nuclear program including its nuclear waste management component is under review by a Blue Ribbon Commission. Its recommendations on reprocessing would also have an influence on Canada's policy. In the case that reprocessing of used nuclear fuel became the acceptable norm in other countries, it is difficult to imagine that Canada would be able to long resist the adoption of the same standard. Because the federal government

is responsible for Canadian nuclear policy, it would be an important stakeholder in decisions on RP&T.

c) Canada is a member of several treaties and international organizations such as the Nuclear Energy Agency of the OECD and the International Atomic Energy Agency (IAEA). The purpose of these agencies is to exchange information and to prevent the spread of nuclear weapons. In particular, the Non-Proliferation Treaty (NPT) as administered by the IAEA makes the connection between reprocessing and weapons. This has prompted discussion of the concept of international nuclear fuel "banks" where nuclear power countries, especially those new to the technology, could obtain fuel for their reactors and then return the used fuel to the bank in exchange for fresh fuel. The hope is that this system would greatly reduce the possibility of the diversion of civilian nuclear materials to weapons. In order to further NPT objectives, the policy of the Nuclear Suppliers Group (NSG), consisting of the governments of approximately 40 nuclear countries (including Canada), is to discourage the building of new national nuclear fuel cycle facilities, not only reprocessing facilities but also enrichment plants, in countries that don't already have them. Therefore, Canada might have great difficulty in obtaining the NSG's support to build a reprocessing facility if it so desired. More likely in this scenario, Canada might be encouraged to have its fuel reprocessed at existing facilities, in for example France or Russia, with the various separated components returned for recycle and placement in a deep geological repository as appropriate. However, public sensitivity to issues such as export and import of nuclear materials, highly visible transportation in ocean going vessels, etc., may make such offshore solutions extremely difficult to implement in practice. The deciders in this case would be the Federal government along with international organizations. Given the large quantities of CANDU fuel, transportation to these off-shore facilities might also be a major logistical consideration (see the discussion in 5.6)

d) Environmental issues would be another important aspect. Any reprocessing scheme for CANDU fuels would have to be shown to be less damaging to the environment than the current once-through cycle with a DGR alone. Assuring the environmental safety of the latter for 100,000 years or more is already contentious in the public's view. A nuclear fuel cycle based on reprocessing would also require a DGR of its own but likely a rather different one with integrity required over a much shorter time scale if the long-lived radionuclides were destroyed by transmutation. In weighing the relative environmental issues, the complete fuel cycle, cradle to grave, would need to be considered including uranium mining and milling, conversion, transportation, generation, and management of all wastes, including mine/mill tailings and chemical wastes.

e) The Canadian Nuclear Safety Commission (CNSC) would be in charge of assessing the safety issues associated with reprocessing facilities namely leaks, spills, criticality accidents and transportation. If fast reactors and ADS were included then the CNSC would need to recruit a number of experts in these areas from a limited international pool, which would also be in high demand elsewhere.

f) Economics would also be an important issue in any decision on reprocessing and this issue is considered in section 5.6 below. If for some reason it was decided that CANDU fuel would be reprocessed, then the primary deciders on how to accomplish this including the economics would be the owners of the fuel i.e. Canada's nuclear power

utilities and their respective provincial governments. They would have to fund the reprocessing even though it is likely that industry would play an important role.

g) Ultimately the Canadian public will decide whether there should be reprocessing of domestic used fuel. If partitioning and transmutation technology to reduce radionuclides was convincingly demonstrated and publicly accepted elsewhere, there would be strong public pressure stoked by the media to adopt this technology in Canada.

Many of these factors depend on developments in other jurisdictions which must be monitored accordingly.

The answer to question 4 is then:

Technical progress in other countries, treaty obligations, environment, safety, economics and public acceptance are the issues; the deciders would be domestic governments (federal and provincial) and their various agencies and nuclear utilities along with international organizations, all of which will be strongly influenced by the general public.

5.5 TECHNOLOGY STATUS AND PROJECTIONS

5. What is the likelihood of reprocessing CANDU fuel in the next 30 years:

- *With existing technology?*

Reprocessing of CANDU fuel is technically possible with existing technology and is being done in India. The possible reasons for reprocessing CANDU fuel have already been discussed under Questions 1 and 2 and the deciding issues under Question 4. At present there is no technical rationale for reprocessing in Canada, either in response to a shortage of nuclear fuel which today's technology can address or to reduce the quantity of long-lived radionuclides which today's reprocessing technology can't. This last comment refers to today's lack of demonstrated transmutation systems but it would be feasible to separate out the long-lived radionuclides (MAs) before depositing the remaining components in a DGR. This strategy might be adopted if the results of the R&D programs now underway gave sufficient encouragement in the next 30 years that transmutation would be possible in the future.

- *With new technology?*

Emerging technologies have been covered under Question 3. The nature and rate of introduction of new technologies in other countries over the next 30 years may well alter the balance in the deciding issues of Question 4 and hence, requires careful monitoring. It is unlikely that advanced partitioning and transmutation would become commercially demonstrated and be generally available within this timeframe.

The answer to Question 5 is:

If there is no further development of transmutation fuel cycles in the next 30 years then there is a very low likelihood of reprocessing used CANDU fuel. On the other hand, if there is a convincing demonstration and public acceptance of a prototype transmutation system abroad within the next 30 years then reprocessing might be justifiable in order to reserve long-lived isotopes for later transmutation.

5.6 REQUIRED FACILITIES AND THEIR COST

6. What facilities in addition to a DGR would be required to support reprocessing of used CANDU fuel in Canada (e.g., high-level waste vitrification and interim secondary waste storage)? Estimated cost of these facilities?

Estimates of the capital and operating costs of building reprocessing plants in Canada were made in the 2009 Annual Report largely based on work reported at the Global 2009 conference (Rothwell 2009).

The following new facilities would be needed to support a domestic reprocessing enterprise in Canada:

- Two 1,500 tonne /year reprocessing plants including vitrification facilities at a capital cost of at least $15 billion each,
- Facility for fabricating domestic fuel (e.g. MOX) from highly radioactive recycled isotopes,
- Plant to package surplus high level fissile fuels for export,
- Fast reactor or modified CANDU reactor to burn MA,
- Accelerator Driven Systems depending on the fuel cycle used,
- Interim storage facilities to hold used fuel prior to reprocessing,
- A smaller and less costly DGR to hold reprocessing by products.

Extrapolations were made from the costs of existing plants and it was assumed that vitrification plants are included in the capital costs of reprocessing facilities. The estimates made showed that domestic reprocessing would be very costly in the order of $7.5-9.5B/year for 100,000 CANDU bundles per year. Two or more reprocessing plants would have to be built because of the large backlog of CANDU fuel to be reprocessed and because of its low burnup compared to other reactor types. However, no credit was given for the value of the recycled fuel and no attempt was made to consider off shore reprocessing with return of materials to Canada. To address the former issue a comprehensive economic study is needed of the economics of CANDU reprocessing including the value of the fuel recovered comparable to the Harvard report (Bunn 2003) on recycling of LWR fuel.

Interim waste storage costs for CANDU fuel would have to be based on NWMO's estimates of fuel storage costs prior to interment in a DGR and the value of any savings in DGR construction costs arising from RP&T would also need to be included. The costs of other required facilities, such as fuel fabrication plants, fast reactors, ADS, etc, have not been specifically estimated. However, the capital costs are expected to be in the multi-billion dollar range for each facility.

Ottensmeyer has been promoting RP&T of used CANDU fuel followed by fast reactor burning of MAs emphasizing that a large financial payoff is possible from the energy value remaining in the used fuel (Ottensmeyer 2010). To arrive at an estimate the following formula is used:

$$(40{,}298/1{,}390) \times (99.26/0.74) \times (\$9.2B) = \$36T$$

The first term is the ratio in tonnes of the used fuel in storage to the amount used per year, the second term is the ratio of the fissile material left in the fuel to the amount used and the last figure is the dollar value of the electricity generated, all numbers for the year 2008.The original figure of $20T quoted in the paper has been increased to $36T (Ottensmeyer 2010a). This is a

very over simplified calculation that does not take into account the very large investment in construction and operation of advanced fast reactors and other infrastructure (such as reprocessing and fuel fabrication plants) required to take advantage of this energy source.

Another study of reprocessing LWR fuel (Grubert 2009) concluded that:

> *"Reprocessing spent fuel only becomes competitive with direct disposal if uranium prices experience significant increases between $184 and $280 per kilogram[4]. If uranium prices remain at current levels, spent fuel storage costs would need to increase from $400 per kilogram to almost $1,000 per kilogram for reprocessing one additional time in a thermal reactor to have viability. Storage costs would need to exceed $2,500 per kilogram for reprocessing in a closed fuel cycle to have economic advantage."*

The MIT study (MIT 2003) states in a similar vein that:

> *"…given the assumptions about uranium resource availability and new plant deployment rates, the cost of recycle is unfavorable compared to a once-through cycle, but, the cost differential is small relative to the total cost of nuclear power generation."*

Many fuel cycle options require fast reactors. Although Canada is a partner in the Generation IV international collaboration whose objective is a sustainable nuclear power system based on fast reactors, it is unlikely that fast reactors would be built in Canada at least not for many decades into the future. Thermal reactor burning of MA, in CANDUs even with their high neutron fluxes, is probably not economically feasible because of the accumulation of undesirable isotopes such as the long-lived isotope californium-252. (Dyck 2008) (Hyland et al, 2008). However, this possibility should be further investigated since a CANDU-based transmutation process would be very attractive.

The foregoing makes the tacit assumption that Canadian entities would do the reprocessing of CANDU fuels as a domestic activity. However, another scenario is that used CANDU fuel could be sent to reprocessing countries such as France, Russia or Japan and the various components returned to Canada for recycle or placement in a deep geological repository. This possibility would have to be investigated before a decision was made to do reprocessing in Canada. This scenario would require ocean going transport vessels and a careful study of the associated logistics. There are shipping lines (PNTL 2010) that specialize in nuclear transport and other countries have built ships for this purpose. Canada's navy would be capable of protecting those ships on the long ocean voyages involved. The main difficulty would likely be public and political acceptance of transporting large volumes of used nuclear fuel to offshore destinations by sea compared to the transport of the same amount of used fuel overland in many smaller rail/truck loads to a DGR in Canada.

The answer to Question 6 is:

Reprocessing of CANDU fuel as part of a closed fuel cycle would be a costly undertaking needing either a large domestic infrastructure or long-term contracts with offshore reprocessing companies, all predicated on the successful development of MA burning systems based on technology not yet commercially available (such as fast reactors or ADS transmutation systems).

[4] The spot market price of uranium at the end of December 2010 was $62.50 per pound of U_3O_8 or $138 per kg.

5.7 ALTERNATIVE SCENARIOS FOR A DGR

7. *Are there any current or foreseeable scenarios that suggest NWMO should alter its course towards a DGR?*

NWMO's Adaptive Phased Management (APM) approach allows for retrievability of the used fuel from the DGR. This would permit the commencement of reprocessing at a time after filling of the repository has started. Reprocessing, even with advanced partitioning and transmutation, would not eliminate the need for a DGR but might well alter the characteristics of a DGR compared to one for used fuel without reprocessing.

A more radical departure from NWMO's current path would be to use a repository design consisting of very deep boreholes. This would essentially involve abandoning the retrievability policy. There is increasing interest in this technology and support of this concept in the recommendations of the US Blue Ribbon Commission could increase Canadian interest. An economic study of the deep borehole option for Canada in comparison to the current DGR plan is required.

In the absence of a comparative cost study, we find no clear basis at present for deviating from the current APM conceptual design for cost estimating purposes. The DGR concept is consistent with the advanced used fuel/HLW repository programs in Finland, Sweden, and France, which have adopted a DGR concept. As there has been no demonstration of the VDH emplacement operations, it is not obvious that the perceived advantages would be realized in practice. Nor is it clear whether siting would be easier in Canada for a VDH system than for a DGR.

The answer to Question 7 is:

If its feasibility is demonstrated, if it is shown to be cost effective, and if it is shown to offer advantages in establishing long-term safety, then the very deep borehole concept may alter NWMO's plan for a mined deep geological repository. However, the APM approach is flexible enough to take this into account at a future decision point prior to licensing of a used fuel repository.

The key questions and the answers on reprocessing issues are summarized in Table 5.

Table 5: Summary of Reprocessing Issues

Issue	Answer (in Canadian Context)
1. What would be the rationale for reprocessing of used CANDU fuel?	The primary reason would be to obtain additional nuclear fuels for recycling. However, there is not now, and will not be for some decades, a need to recycle nuclear fuel to make up any shortfall in the availability of nuclear fuel.
2. To what extent does reprocessing reduce the quantity of radionuclides?	With the possible exception of extracting additional energy via MOX fuels, today's nuclear fuel reprocessing by itself does not result in any net reduction in the quantity of radionuclides. Decades of additional R&D are required to implement the transmutation aspect of RP&T in order to reduce the quantity of long-lived radionuclides.
3. Are there any emerging technologies that will significantly reduce the quantity of radionuclides in used fuel or its by-products? If so when may these be commercially available?	Yes, there are fuel cycle technologies now emerging from R&D programs that are aimed at significantly reducing the amount of long-lived radionuclides arising from used fuel. The basic concepts of these technologies will likely be demonstrated via prototypes within the next two decades. However, the commercial implementation of these technologies will require the establishment of a large and costly infrastructure of fast reactors and ADS devices and may take a century or more. It is doubtful that these systems would be commercially viable for waste management purposes without large government subsidies or huge increases in energy prices.
4. What are the issues that would need to be considered in a decision on reprocessing and who would be the decision makers?	Technical progress in other countries, treaty obligations, environment, safety, economics and public acceptance are the issues; the deciders would be domestic governments (federal and provincial) and their various agencies and nuclear utilities along with international organizations, all of which will be strongly influenced by the general public.
5. What is the likelihood of reprocessing CANDU fuel in the next 30 years: with existing technology and with new technology?	If there is no further development of transmutation fuel cycles in the next 30 years then there is a very low likelihood of reprocessing used CANDU fuel. On the other hand, if there is a convincing demonstration and public acceptance of a prototype transmutation system abroad within the next 30 years then reprocessing might be justifiable in order to reserve long-lived isotopes for later transmutation.
6. What facilities in addition to a DGR would be required to support reprocessing of used CANDU fuel in Canada (e.g. high-level waste vitrification and interim secondary waste storage)? Estimated cost of these facilities?	Reprocessing of CANDU fuel as part of a closed fuel cycle would be a costly undertaking needing either a large domestic infrastructure or long-term contracts with offshore reprocessing companies, coupled with MA burning systems based on technology not yet commercially available (such as fast reactors or ADS transmutation systems).
7. Are there any current or foreseeable scenarios that suggest NWMO should alter its course towards a DGR?	If its feasibility is demonstrated, if it is shown to be cost effective, and if it is shown to offer advantages in establishing long-term safety, then the very deep borehole concept may alter NWMO's plan for a mined deep geological repository. However, the APM approach is flexible enough to take this into account at a future decision point prior to licensing of a used fuel repository.

6. SUMMARY OF PROGRESS IN 2010

The following summarize the main points in 2010.

- The United States is studying the future of its nuclear power program including its waste management aspects. The recommendations will set the future direction of RP&T in that country.
- Both France and Japan have major decision deadlines in 2012 at which time the future direction of the two leading RP&T programs will be decided.
- The chemistry of partitioning has made great strides since the previous NEA RP&T meeting two years ago in large part because of the European ACSEPT program.
- Real progress is being made on ADS systems in terms of realistic tests and fuel development. The first test of an ADS system was made in Japan this year.
- There has been increased interest and more research in the very deep borehole concept for long-term management of used fuel.
- The main issues pertinent to the reprocessing of used CANDU fuel have been framed in a series of seven questions and answers have been derived from the information presented in all three Annual Reports to date. This framework helps to clarify the reprocessing issues for Canada, as summarized in Table 5.

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