

Watching Brief on Reprocessing, Partitioning and Transmutation (RP&T) and Alternative Waste Management Technology – Annual Report 2009

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December 2009

David Jackson and Kenneth Dormuth

David P. Jackson & Associates Ltd.

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ABSTRACT

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Abstract

This is the 2009 Annual Report of the NWMO watching brief on Reprocessing, Partitioning, and Transmutation (RP&T) and Alternative Waste Management Technologies.

In this report the situation following the virtual cancellation of the US Yucca Mountain project, which includes the potential for a US RP&T program, is discussed. In Europe, nuclear power has been recognized as a sustainable energy option and a comprehensive R&D plan has been developed including a commitment to closed fuel cycles.

The resurgence of interest in thorium fuels is briefly reviewed, but there has been little progress in developing the commercial scale RP&T necessary for the deployment of these fuels.

Recent work in estimating the costs of aqueous reprocessing of used LWR fuels is applied to assess the costs and feasibility of reprocessing of CANDU fuels with the conclusion that it would be prohibitively expensive and, based on recent experience in Japan, would require decades to implement. Volume reduction for CANDU used fuel would depend on the reprocessing system used but plausibility arguments indicate that it might be difficult to achieve.

Sandia Laboratories has produced a preliminary evaluation of very deep borehole disposal of used fuel from the U.S. reactors, indicating excellent long-term safety. The study also indicates that construction costs for very deep borehole disposal of light water reactor fuel would be competitive with a mined repository. However, we estimate that the cost of constructing very deep boreholes for disposal of existing CANDU fuel waste in Canada would be significantly greater than that for light water reactor fuel on a per-kilowatt-hour basis. Further work would be required to adequately compare the total life-cycle costs for very deep borehole disposal of Canada's used fuel with the current concept of Adaptive Phased Management. 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.

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1. INTRODUCTION

This is the second of a series of Annual Reports in fulfilment of the mandate of the Nuclear Waste Management Organization (NWMO) to provide an annual watching brief on international developments in reprocessing, partitioning and transmutation (RP&T) of used nuclear fuel, and alternative technologies for long-term management of nuclear fuel waste. The first 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 October 2008. This report concentrates on selected topics in RP&T:

- 1) the US situation arising from the virtual cancellation of the Yucca Mountain facility;
- 2) the new European Union policy on nuclear power,
- 3) the apparent revival of interest in thorium fuels;
- 4) an update on reprocessing costs; and
- 5) some new information on alternative waste management technology.

The Global 2009 and Top Fuel 2009 conferences held in Paris in September 2009 had several presentations relevant to the foregoing topics which are cited in this report.

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

- a) the metal fuel cladding materials that hold the fuel pellets;
- b) uranium-238, which forms most of the fuel mass;
- c) fissile isotopes such as uranium-235 and plutonium-239, which can be recycled in fresh reactor fuels;
- d) the Fission Products (FP) and other radioactive isotopes formed by neutron activation, which are generally for disposal; and
- e) the Minor Actinides that have long half lives and are responsible for the long lived radioactivity of spent fuel.

Broadly speaking **transmutation** involves forcing the Minor Actinides to fission in an intense flux of high energy neutrons provided by a Fast Reactor (FR) and/or an Accelerator Driven System (ADS) with the purpose of destroying them prior to Geological Disposal (GD). These activities are grouped together under the abbreviation RP&T.

As stated in the first Annual Report, 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 technology development 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. However, NWMO's APM (Adaptive Phased Management) concept was developed based on a once through fuel cycle (as currently practiced by all Canadian nuclear utilities) and includes placement of used fuel in a deep geological repository (DGR). The discussion of RP&T is solely for information purposes. RP&T would still require a DGR for the long-term management of the residual high-level radioactive wastes from reprocessing.

2. MAJOR DEVELOPMENTS IN INTERNATIONAL RP&T PROGRAMS

2.1 UNITED STATES

The US nuclear power program was been thrown into confusion by the virtual cancellation in early 2009 of the Yucca Mountain Project to develop a DGR for US nuclear fuel waste.

At Global 2009, offline conversations with the US delegates attending the meeting showed that they were of the opinion that the Yucca Mountain repository was dead. The reasons given were:

- As a result of the 2008 Congressional election Senator Harry Reid of Nevada, a long time opponent of Yucca Mountain, became majority leader in the US Senate and used his considerable influence to curtail funding for it.
- There appears to be a strong lobby in the US nuclear technical community in favour of reprocessing which was encouraged by the previous US administration's move toward it.

P. Finck (Finck, 2009) stated in the opening plenary of Global 2009 that he expected there would be interim storage at several sites such as possibly Idaho National Laboratory until "at least mid-century". He also noted that the Department of Energy (DOE) was repositioning its fission research program as a basic science program to examine such issues as long term options for fuel cycles. D. Klein of the USNRC (Klein 2009) also echoed this theme by noting that present license extensions for current US nuclear plants envisaged them operating for total lifetimes of 40 to 60 years but much more R&D would be needed to see if the operating lifetime of a current reactor could be pushed to 80 years or more.

In the long term the possibilities of reprocessing and/or selecting another site to replace Yucca Mountain would be pursued but interim storage seems the only possibility in the short and medium term.

The key question is: what is the US plan for dealing with its spent fuel if Yucca Mountain is not available? The transcript of the September, 2009 meeting of the US Nuclear Waste Technology Review Board (NWTRB, 2009) addresses the post-Yucca outlook for nuclear power in the US. Some of the points covered were as follows.

- It is important to make sure that Yucca Mountain is fully documented for future referral so that the \$13.5 billion expenditure to date is not totally wasted. The licensing case for the project as submitted to the NRC (Nuclear Regulatory Commission) consisted of 8,600 pages with another approximately million pages of supporting references. Hence, substantial resources would be needed by the NRC to review it and make informed judgment on its validity and by the appropriate departments in the DOE to provide answers. This exchange was still ongoing in September 2009 but probably could not be continued in the 2010 fiscal year because resources were not appropriated by the US Congress.
- The US government introduced an incentive plan for reactor construction in 2005 and, while many license applications for new reactor construction have been made to the NRC, construction has not started on any of the proposed reactors. Increased reactor costs and lower electricity demand were cited as the main problems.

- Fears were expressed by some members of the panel that additional nuclear power would take so long to implement that it would not play a significant role in reducing climate change.
- Utility executives are not inclined to proceed with new reactor construction until there is a clear and definite plan for waste management. This would cause further delays in nuclear new build projects.
- Some Board members took the view that RP&T was something for the future and therefore, the nuclear industry and the government should concentrate now on building LWRs.
- The utilities felt that an important factor was that a RP&T based nuclear economy could mean that spent nuclear fuel would remain at reactor stations for long times while the RP&T system was being established. This was unacceptable in terms of risks to surrounding populations and centralized storage would be necessary.
- Comments were made to the effect that RP&T would produce new waste streams with differing concentrations, isotopic compositions and chemical properties that might make it necessary to have specially selected DGRs of appropriate geology to accommodate them.
- A new MIT study on the future of nuclear power updating its 2003 report (MIT, 2003) is almost completed and promises to be as controversial as the first one.

US Energy Secretary Chu is expected to soon appoint a Blue Ribbon Commission to study and make recommendations on a plan for US nuclear waste. The US situation on nuclear waste will likely not be clarified until this process is completed.

2.2 EUROPEAN COMMUNITY

In contrast to the US, in early 2007 the European Commission published its energy policy in which nuclear energy became a Strategic Energy Technology (SET), joining wind, solar, CCS (Carbon Capture and Storage), grid improvement and biofuels in this group. This development was very significant for nuclear energy in Europe because for the first time its value in reducing GHG emissions, thereby contributing to low carbon electricity, was officially recognized. While France, for example, generates a high percentage of its electricity from nuclear power, in some European countries such as Germany phase outs of nuclear plants had been legislated and in others such as the Italy, nuclear development had been stalled for decades. In large measure the countries negative to nuclear power had been influenced by political action on the part of Green parties especially following the Chernobyl accident. Therefore, it is remarkable that the European Community, composed of countries both positive and negative toward nuclear energy, could come to agreement on a future role for nuclear power. Europeans at the Global 2009 were confident that this development meant that fission R&D was now assured of stable long-term funding.

In a parallel initiative, the European Nuclear Energy Forum has been established to discuss the issues associated with nuclear power. It consists of Members of the European Parliament,

CEO's of nuclear companies, academics and NGOs. This group faces a challenge since only 44% of Europeans were in favour of nuclear energy.

Following the energy policy document, the Sustainable Nuclear Energy Technology Platform (SNETP) was launched in late 2007 (European Commission, 2007). The aims of SNETP are:

- *“maintain the safety and competitiveness of today’s technologies*
- *develop a new generation of more sustainable reactor technologies— so-called Generation IV fast neutron reactors with closed fuel cycles, and*
- *develop new applications of nuclear power such as the industrial scale production of hydrogen, desalination or other industrial process heat applications.”*

SNETP also supports broader goals of the European Community in terms of further developing nuclear energy as a key part of the European energy portfolio, contributing to the security of energy supply and economic competitiveness, and reducing GHG emissions. The specifics of the R&D program of SNETP are set out in its SRA (Strategic Research Agenda) as given in 2009 (SNETP, 2009).

Of particular relevance to this report is the objective of developing closed fuel cycles, which involves R&D programs in RP&T. A whole chapter in the SRA is devoted to fuel cycle initiatives, and, in particular, R&D for improving the sustainability of the nuclear fuel cycles. This plan has the overall objectives of both maximizing the use of natural resources (uranium or thorium) and minimizing the resulting nuclear waste. The SRA notes that the front end of the fuel cycle (mining, refining, conversion, enrichment and fuel manufacturing) is best left to industry while the back end, including RP&T, is emphasized in the R&D to be undertaken. The SRA states in bold type:

“Therefore, it must be underlined that “breeder” reactors, in practice Fast Neutron Reactors (FNRs), are the only solution which can lead to the long term sustainable development of nuclear energy, with regard to the “optimum use of natural resources”

The SRA then continues to elaborate its plan based on the above principle including developing high conversion ratio advanced Generation III reactors, higher burn up fuels and RP&T for plutonium and uranium recycling.

The short objectives of the plan stress: advanced reprocessing of LWR and advanced fuels for Minor Actinide separation using aqueous and pyroprocessing methods and dissolution of minor-actinide-bearing MOX and carbide fuels for FNRs. It anticipates that decisions on developing demonstration facilities should be taken by 2012. In the longer term R&D will be aimed at establishing RP&T as a task for the nuclear industry.

3. THORIUM FUEL CYCLE

3.1 RATIONALE FOR THORIUM

Thorium is estimated to be three to four times more abundant than uranium based on the half life of thorium-232 (~14 billion years) compared to that of uranium-238 (~4.5 billion years). It is available in several countries, some of which don't have much uranium (see Table 1).

Table 1: Uranium and Thorium Reserves in Selected Countries (tonne)

Country	Uranium <\$130/kg U	Thorium <\$80kg Th
Australia	1,243,000	489,000
Kazakhstan	817,000	
Russia	546,000	75,000
South Africa	435,000	18,000
Canada	423,000	44,000
USA	342,000	400,000
Brazil	278,000	302,000
India	73,000	319,000
Other	1,312,000	963,000
Total	5,469,000	2,610,000

The somewhat lower total for thorium is because there has been little serious prospecting for it compared to uranium and the dollar value per kilogram used in constructing the table is lower. A lot of thorium is found in the monazite sands on beaches in India and Brazil. In principle thorium could form the basis of a nuclear fuel cycle at a future time when economically extractable uranium was exhausted. Vance (2009) examined the need for uranium to 2030 with the results shown in Figure 1.

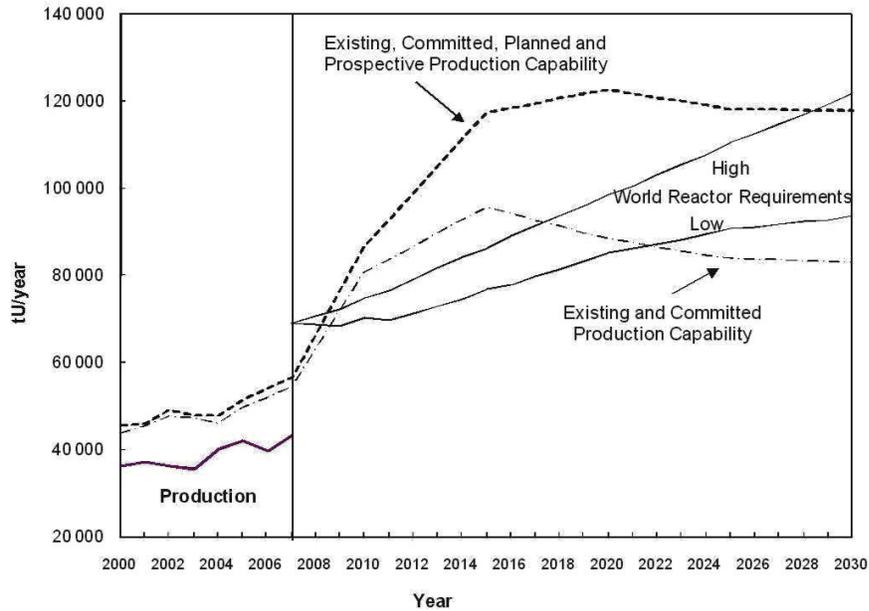


Figure 1: Projected Uranium Production and Demand to 2030

Source: (Vance 2009) and (NEA/IAEA 2008)

Vance uses the latest edition of the well-known “Red Book” (NEA/IAEA, 2008) as the basis for his paper. At present world annual consumption of 66,500 tU, there are enough proven uranium reserves to last for about 80 years (see Table 1). If one extends this to “Prognosticated and Speculative Resources”, the duration of resources is about 300 years. The contentious issue is the requirements of uranium for projected growth scenarios. When the Red Book is compiled the contributing countries are asked to provide a projection of their nuclear plant uranium requirements to 2030. Using this data and noting the current level of nuclear electricity production is 370 GWe, a low (38%) growth scenario of 509 GWe and a high (80%) growth scenario of 663 GWe by 2030 is projected in Figure 1.

On one hand Vance comments on the difficulties of bringing new production on line and on the other hand the growth in reserves due to the positive signals given to uranium exploration and new production by increased demand. Therefore, when the exhaustion of uranium will occur depends on many factors other than simply the rate of growth of nuclear power.

The potential limitation on expansion of fission energy due to a possibly restricted supply of uranium was a concern in the early days of nuclear power. While the most attention has been devoted to solving this problem through uranium-plutonium breeder fuel cycles based on FNRs, research was also devoted to developing thorium fuel cycles in the 1970’s and 1980’s. This remains the case in Europe as the SRA states (SNETP, 2009):

“..it should be noted that there are no short or medium term industrial prospects in Europe for the deployment of the thorium cycle and thus, it will not be an R&D priority. However, thorium could become an attractive option in the long term and a minimum level of basic studies on this cycle should be maintained at the European level”

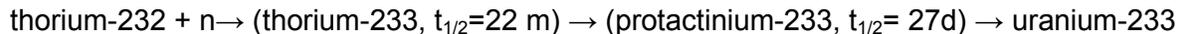
Thorium R&D is conducted at a relatively small level in the US and Russia but little is done in Japan. However, thorium R&D has continued in India and Canada for reasons discussed below.

Recently there has been a revival of interest in thorium as a long-term alternative to uranium presumably (Jacoby, 2009) because of a projected large expansion in nuclear power in response to increasing climate change concerns as evidenced by commercial firms and lobby groups such as (Thor Energy, 2009) now renamed (Lightbridge, 2009), (Thorium Energy, 2009), (Thorium Electronuclear, 2009), (Thorium Energy Alliance, 2009), and (Thorium1, 2009). Thorium fuels are also considered in the Gen-IV program.

Because of this increased interest it is timely to briefly review the current situation on thorium concentrating on the aspects of thorium in relation to RP&T and waste management.

3.2 THORIUM FUELS

The basic thorium reaction with thermal neutrons is:



In this reaction the fertile thorium-232 is converted to fissile uranium-233 which can be burned in the fuel in a once through fuel cycle or can be extracted by specialized reprocessing. Since thorium-232 doesn't fission, a "seed" of fissionable material is needed to start the reactions. This can be uranium-233 from previously irradiated thorium fuel but more often is proposed to be MEU (medium enriched uranium ~ 12 - 20% uranium-235) denoted as a (Th, U) fuel cycle. Another possibility is a plutonium-239 seed either from reprocessing of irradiated uranium fuel (reactor grade), or from dismantled nuclear weapons (weapons grade), to drive a (Th, Pu) cycle.

Many of the key features of the thorium fuel cycle are related to the above reaction as follows:

- All the thorium-232 nuclei can be used to breed uranium-233 and thus, contribute to the fuel cycle in contrast to 0.7% of the natural uranium in the form of uranium-235.
- Thorium-232 has increased thermal neutron absorption to form uranium-233 than uranium-238 to form plutonium-239 but this situation is reversed for fast neutrons.
- The average number of fission neutrons emitted by a uranium-233 per absorbed neutron is greater than 2.0 for most of the thermal neutron spectrum and hence, thermal breeding is possible whereas uranium-238 to plutonium-239 is only feasible at high neutron energies.

In terms of resistance to weapons proliferation the following aspects are characteristics of thorium:

- Uranium-232 is formed by (n, 2n) reactions with thorium-232, protactinium-232 and uranium-233. The uranium-232 has high activity with half life 74 years with gamma emitters in its decay chain. Thus, uranium-232 makes it difficult to obtain separated uranium-233 for weapons in the same way that plutonium-238 makes weapons production from reactor grade plutonium difficult.

- Thorium fuels are more attractive for burning plutonium for eventual placement in a DGR to avoid its misuse in weapons because in contrast to (U, Pu) cycles, no additional plutonium-239 is produced in (Th, Pu) fuel cycles.
- Relatively high levels of enrichment, up to 20% in uranium-235, will be required for driver fuels and there are no civilian enrichment facilities operating to that level which could also make fuel fabrication difficult.
- Nevertheless, uranium-233 is fissile and could in principle be used to produce a weapon. The presence of uranium-232 and other active isotopes is an added protection that makes diversion difficult but it is not absolute guarantee against the misuse of uranium-233 in weapons.

As regards proliferation resistance, an oft-cited advantage of thorium fuels, a comprehensive study of the proliferation attractiveness of various nuclear materials (Bathke, 2009) came to the following conclusion:

"Do other advanced fuel cycles (e.g., thorium based cycles) produce products that are potentially attractive for use in a nuclear weapon or nuclear explosive device? Yes, the thorium fuel cycle produces two potentially attractive materials: plutonium-239 and uranium-233. In general, dilution with uranium-238, thorium-232, or even another inert material increases the bare critical mass and thus reduces the attractiveness of the material. With greater than 80% uranium-238 or 70% thorium-232 (perhaps less with other materials), the material is of "low" attractiveness. Except for dilution of uranium-233 with uranium-235 and uranium-238, the material can still be made attractive by purification but this takes time and some degree of technical capability."

The following favourable material properties of thorium oxides have made the use of thorium fuels practical:

- The stability of thorium oxide is much better than that of uranium oxide; it does not oxidize like uranium dioxide which can become higher oxides relatively easily. Thorium oxide has a higher thermal conductivity and lower coefficient of thermal expansion than uranium oxide.
- Thorium oxide shows superior performance in reactor environments in terms of a much lower level of radiation damage than uranium oxide type fuels with an order of magnitude less fission product release.

In the past few years there have been several comprehensive reviews of thorium as a nuclear fuel, for example (IAEA, 2002), (IAEA, 2003) and (IAEA, 2005).

Historically thorium fuels were demonstrated in many reactor types beginning in the early 1960's and ending in the late 1980's. Thorium fuel was tested in LWRs, both PWRs and BWRs, HTGRs (High Temperature Gas Reactors) and MSR (Molten Salt Reactors). The fuels tested were in various configurations as coated fuel particles, pellets, pebbles, and graphite fuel elements.

For the tests at Fort St. Vrain HTGR, 1976 -1989, almost 25 tons of thorium fuel was manufactured; the fuel ran to maximum burnup of 170,000 MWd/ton compared to comparable figures of 45,000 MWd/ton for LWRs and 7,000 MWd/ton for CANDU reactors.

One of the more interesting experiments was at the Shippingport reactor which was configured as a LWBR (Light Water Breeder Reactor) based on a concept of Alvin Radkowsky (Galperin, 1997). The LWBR was a standard BWR type reactor but with thorium fuel pins arranged in a breeding blanket consisting of 50 tons of Zircaloy clad thorium surrounding driver fuel pins variously containing both plutonium-239 and uranium-235. In this heterogeneous seed/blanket arrangement uranium-233 was allowed to build up in the blanket pins over several years while the driver pins could be replaced independently more frequently. An analysis of fuel rods indicated that significantly more fissile material was present at the end of the core life than at the beginning, providing evidence that breeding had occurred. Similar tests were also done at the Indian Point reactor.

Other tests were performed in Germany and the UK again showing that thorium could be used in reactors of various types. It should be emphasized that thorium fuels for these experiments were prepared in test batches and commercial production was never established.

Interest in thorium fuels waned in 1980's with the decline of interest in nuclear power due in part to the Chernobyl accident and the realization that with the much slower pace of nuclear development the existing uranium resources would last much longer than originally anticipated.

In the intervening years, interest in thorium was more driven by its geographical distribution than by a perceived shortage in uranium supply. As shown in Table 1, India has much more thorium than uranium and thus, energy self sufficiency in that country could be based on thorium but not uranium. Therefore, a large thorium research program has been conducted in India for many years (Anantharaman 2008) and (Kamath 2009) and the use of thorium fuel is planned for the new AHWR (Advanced Heavy water Reactor). It will be interesting to see whether the opening of nuclear relations between India and the US through the so-called 123 Agreement in 2007 and the recent nuclear agreement with Canada, both giving India much better access to imported uranium, will to some extent reduce Indian interest in thorium.

Canada has also done thorium fuel research for many years at AECL's Chalk River Laboratories. The primary motivation is the efficient neutron economy of CANDU reactors which made them an excellent platform for a thorium fuel cycle. Demonstration of this capability would make CANDUs more attractive for potential buyers, especially in countries with significant thorium deposits (Hyland 2009), (Ovanes 2009)

3.3 REPROCESSING OF THORIUM FUELS

A solvent extraction method, THOREX, analogous to the basic PUREX process for uranium/plutonium fuels was developed in the 1950's (Benedict et al, 1981) However, the refractory nature of thorium oxide noted in the previous section causes difficulties. Dissolution of these fuels is very slow and incomplete. Therefore, another method was required and it was found that a mixture of nitric and hydrofluoric acids worked, but not as well as for uranium oxides, for the dissolution of thorium oxide. This mixture was highly corrosive for the materials containing the process. Eventually, it was found that the corrosion problem could be largely but not completely managed by adding aluminum nitrate to the solution of acids. This is the fundamental difference between the THOREX and PUREX processes. After the dissolution stage, an organic solvent TBP is used to extract the thorium and uranium fractions although the fractionation is less effective for thorium than for uranium.

Versions of THOREX were used for reprocessing of the Indian Point thorium test fuel (6% uranium, 94% thorium) to separate out the uranium, leaving the thorium and fission products in solution. Another large scale thorium oxide reprocessing program using THOREX to separate uranium-233 was conducted at Hanford (1966) and Savannah River (1970). The objective was to produce high purity uranium-233 from low burnup fuel. Although the amounts of uranium and fission products in the fuel were much lower than those expected in a reactor, the results were promising for THOREX.

While reprocessing of thorium fuels was done in the past, in recent times it appears that reprocessing has only been applied to small batches of test fuels, notably in India (Anantharaman, 2008).

In the reprocessing of thorium fuels, considerably higher concentrations of uranium-233, as well as seed uranium-235 and plutonium-239, may be present than in equivalent uranium fuels, particularly in high burnup situations. With substantial amounts of uranium-232 present in addition to fission products, high levels of radioactivity would have to be tolerated in the reprocessing plant necessitating remote handling. Another very important issue would be criticality control. Avoiding such accidents would require considerable care in the design of a reprocessing plant dedicated to thorium fuels. Similarly, fabrication of new fuel from reprocessed materials would be more difficult because of the presence of uranium-232.

A true three stream process would likely be necessary for thorium fuel reprocessing. In general, partitioning of the uranium, thorium and plutonium would be required depending of course on the initial composition of the fuel. In particular, if high enrichment levels of uranium-235 or plutonium-239 were used in a homogeneous fuel configuration, then it might well be important to recycle unburned components for economic reasons alone. However, a three stream process has not been demonstrated yet for thorium fuels.

Wilson (1999) noted *“Reprocessing thorium fuels would demand more development than has sometimes been recognized. Even supposing the familiar principles of solvent extraction to be adopted, existing methods could not be applied without modification, especially if essentially complete separation of thorium, uranium and plutonium were required.”*

Even thorium advocates who are generally optimistic about most aspects of the thorium fuel cycle have concluded that *“Closing the thorium cycle would be necessary to achieve substantial improvement of resource utilisation and waste characteristics, and this would require significant R&D efforts”*. (Lefvert and Asphjell, 2009)

In spite of the necessity for reprocessing in the thorium fuel cycles, it appears that there are no large scale R&D efforts underway in RP&T for thorium fuels.

Thorium fuel cycles will produce various streams of high level nuclear waste (HLW) that will have to be managed. The volume of thorium fuel to be reprocessed will generally be smaller per unit of energy produced than uranium fuels due to their much higher burn ups. If uranium or plutonium is used for the seed elements there will be smaller amounts per unit energy produced of Minor Actinides (MA) and Fission Products (FP) than for uranium fuels simply because the seed fuels, the main producers of MA and FP, play a smaller role in overall energy production. However, the fuel may have different chemical, radiological & thermal properties that could affect design of a repository. Thus, the APM strategy would need to have the capability of adjusting to thorium fuels if and when they are used in the distant future.

4. REPROCESSING

The issue of the sustainability of nuclear power has been pursued by many countries. As shown in Section 2 of this report closing the nuclear fuel cycle has been accepted as a goal by the European Community. It is possible then that interest in reprocessing used CANDU fuel may increase. Currently the producers of used CANDU fuel in Canada have no intention to reprocess their used nuclear fuel primarily because of its high costs. Therefore, it is important to refine these costs as better information becomes available in order to test the current position. A very crude estimate of the costs of reprocessing CANDU fuel was made for NWMO in a background paper on the implications of RP&T (Jackson 2005). More information has since become available and will be used in this section to make more refined estimates. All costs in this section are in expressed in US dollars.

4.1 COSTS OF EXISTING PLANTS

The reprocessing options report (IAEA, 2008) notes several estimates of unit costs for aqueous reprocessing (PUREX) of LWR fuels. These were derived from reports from the Boston Consulting Group (BCG, 2006), MIT (MIT 2003), Harvard (Bunn 2003) and from the Gen-IV activities (GIF 2002). The unit costs are largely consistent the range of \$500-\$1,000 per kgHM (per kgHM Heavy Metal and not per kg of uranium to account for plutonium content). A scoping survey (Jackson 2005) produced a rough estimate of \$1,000 per kgHM (2004 \$) for the spot price of reprocessing services.

The costs of existing and past reprocessing plants are also an important parameter in estimating the capital cost of reprocessing. Table 2 shows the capital costs for reprocessing plants with capacities in the 1,000 tHM/year (metric ton of Heavy Metal per year) range.

Table 2: Reprocessing plants: Actual Throughput and Capital Costs (2008\$)

Location	Facility	Throughput (tonne)	Capital Cost (\$B)
France	UP3	800	7.6
France	UP2-800	900	9.0
Japan	Rokkasho	800	25.0
UK	THORP	600	6.25

Source: Rothwell (2009)

Table 2 shows actual throughput. For example, the UP3 plant has an annual capacity of 1,700 tHM but has run at 900-1,000 tHM for some years because this level reflects the available feedstock and allows for maintenance.

An approximate construction cost of \$10 M per tHM/year throughput was assumed by Rothwell (2009) on the basis of the data in Table 2 ignoring the capital cost of Rokkasho as anomalous. (Note, however, that a recent GAO report states the opinion that the Rokkasho costs are low compared to a new facility which the report estimates as costing \$44 billion (GAO 2008)). At this

point the costs of reprocessing fuel could be divided into the repayment of the capital cost of building the facility and the operating costs per unit of fuel reprocessed.

Using the above approximation, a plant with 1,500 tHM/year (80% capacity factor) with throughput of 1,000 tHM/year would have a total capital cost of \$15B. Amortizing this capital cost over 20 years and adding operating costs gives total reprocessing costs as shown in Table 3.

Table 3: Estimated total reprocessing costs (\$) per kilogram HM throughput

Discount Rate	Capital Amortization	Operating \$500/kgHM	Operating \$1000/kgHM	Operating \$2000/kgHM
5%	\$1,188	\$1,688	\$2,188	\$3,188
10%	\$1,737	\$2,237	\$2,737	\$3,737

Rothwell rigorously analyzed all reprocessing costs using the Gen-IV costing methodology. His analysis was also aimed at clarifying earlier work by Haire (2003). He incorporates IDC (interest during construction) and other parameters that result in more accurate cost estimates than the overly simplified Overnight Cost approach used in Table 3. The result of Rothwell's work is a Levelized Unit Product Cost (LUPC) for the same plant parameters with the additional assumption of a six year construction period.

Table 4: Rothwell (2009) Total Reprocessing Costs (\$) per kilogram HM throughput

Discount Rate	Capital	Operating	DD Fund	Total
5%	\$1,170	\$1,846	\$161	\$3,177
10%	\$2,015	\$1,846	\$125	\$3,985

Rothwell also includes a contribution for a decommissioning fund (DD) but this doesn't materially affect the calculations. It is interesting to note that at the 5% rate the IDC is only 16.7% of the Overnight Cost but this rises to 37.2% for the 10% rate.

It would seem then that both the simple approach and Rothwell agree fairly well and probably are reasonably adjacent to the actual costs of building and operating a reprocessing plant. Note that except for Rokkasho the capital costs of the facilities in Table have been retired and excess capacity for these plants would be sold commercially at a spot rate similar or less than the operating cost.

4.2 ESTIMATES FOR REPROCESSING CANDU FUEL

In order to apply the foregoing estimates to CANDU fuel it will be assumed that reprocessing costs are proportional to the mass of heavy metal. Making that assumption, one can then apply reprocessing costs for LWR fuel to CANDU fuel. Certainly CANDU fuel differs from LWR fuel, not only in configuration and its much lower burnup, but also in that it has natural uranium-235 content compared to the 3.5-5.0% enrichment of LWR fuel. These factors make the isotope

content of spent CANDU fuel somewhat different than used LWR fuel. Perhaps, it might be possible to design reprocessing plants that take into account these differences in order to reduce the costs of reprocessing CANDU fuel, but it is not apparent if and how this might be done.

It should also be noted that there is a fivefold increase in the amount of irradiated heavy metal used to produce a given amount of energy for CANDU fuel compared to LWR fuel. In a very simplified picture when natural uranium (0.7%) is enriched in uranium-235 to 3.5% for use in an LWR, five times as much natural uranium must be processed but four parts of this uranium is left at the enrichment plant as depleted uranium tailings and never sees the reactor. Roughly speaking, in a CANDU reactor all of the original mass (five parts) is irradiated in the reactor for the same amount of energy production. In fact, it can be shown that a CANDU system makes more efficient use of uranium than an LWR. However, for reprocessing purposes, a CANDU reactor produces five times as much irradiated heavy metal to be reprocessed. In addition, the remaining U-235 fissile content (0.23%) is less than the U-235 content of depleted uranium resulting from the LWR enrichment (0.25%) making the recovery of U-235 even less attractive. (Jackson 2003), (Jackson and Dormuth, 2008)

In this section, we are assuming a standard CANDU fuel bundle based on a 37-element Bruce reactor bundle. The total mass of the bundle is about 24 kg of which approx 20 kg is uranium (22 kg as UO₂) and 2 kg is the zirconium alloy cladding in which the uranium fuel pellets are encased. As in LWR reprocessing, we assume the zirconium alloy cladding is stripped off and disposed of separately. That leaves 20 kg of heavy metal per bundle to be preprocessed. Selecting values for easy scaling for future use, we assume a historical backlog of 4 million used fuel bundles already in storage by the time reprocessing would be introduced and a nominal annual production of 100,000 bundles, we can then make the estimates shown in Table 5 using the Rothwell numbers from Table 4. (Garamszeghy 2009)

Table 5: CANDU Reprocessing Costs (\$)

Discount Rate	Per kg HM	Per Bundle (20 kg HM)	Backlog 4M bundles	Per year 100,000 bundles
5%	\$3,177	\$63,540	\$254 B	\$6.35 B
10%	\$3,985	\$79,970	\$320 B	\$8.00 B

These reprocessing costs are very large and completely rule out any economic incentive for reprocessing used CANDU fuel. Note that at least two 1,500 tHM/year plants would be needed to handle just the on-going production of 100,000 bundles per year (2,000 tHM/yr). Several more plants would be required to handle the backlog in a reasonable time (a 20 year processing time would result in the need to handle 200,000 bundles per year from the backlog). No credit is given in these numbers for the value of the uranium-235 and plutonium-239 extracted and to properly take these credits into account for CANDU fuel reprocessing would require a full analysis of the type done by the Harvard group (Bunn 2003) for LWR fuel. Nevertheless, under the current assumptions, there is clear indication that reprocessing of used CANDU fuel is not practical from an economic standpoint.

If in spite of these costs, it were decided to move forward to implementation of the reprocessing of CANDU fuels, the Rokkasho plant experience in Japan should give one pause. The total expenditure to 2008 was 2.2 trillion yen or about \$25 B (Asahi Shimbun, 2008). After 22 years of construction and testing it is still not in operation. (Drain 2009).

4.3 WASTE VOLUME IMPACTS

Figure 2 (adapted from (AECL 1994)) schematically compares direct disposal with reprocessing. Part (a) illustrates a “once through” or open fuel cycle and part (b) a reprocessing or closed fuel cycle.

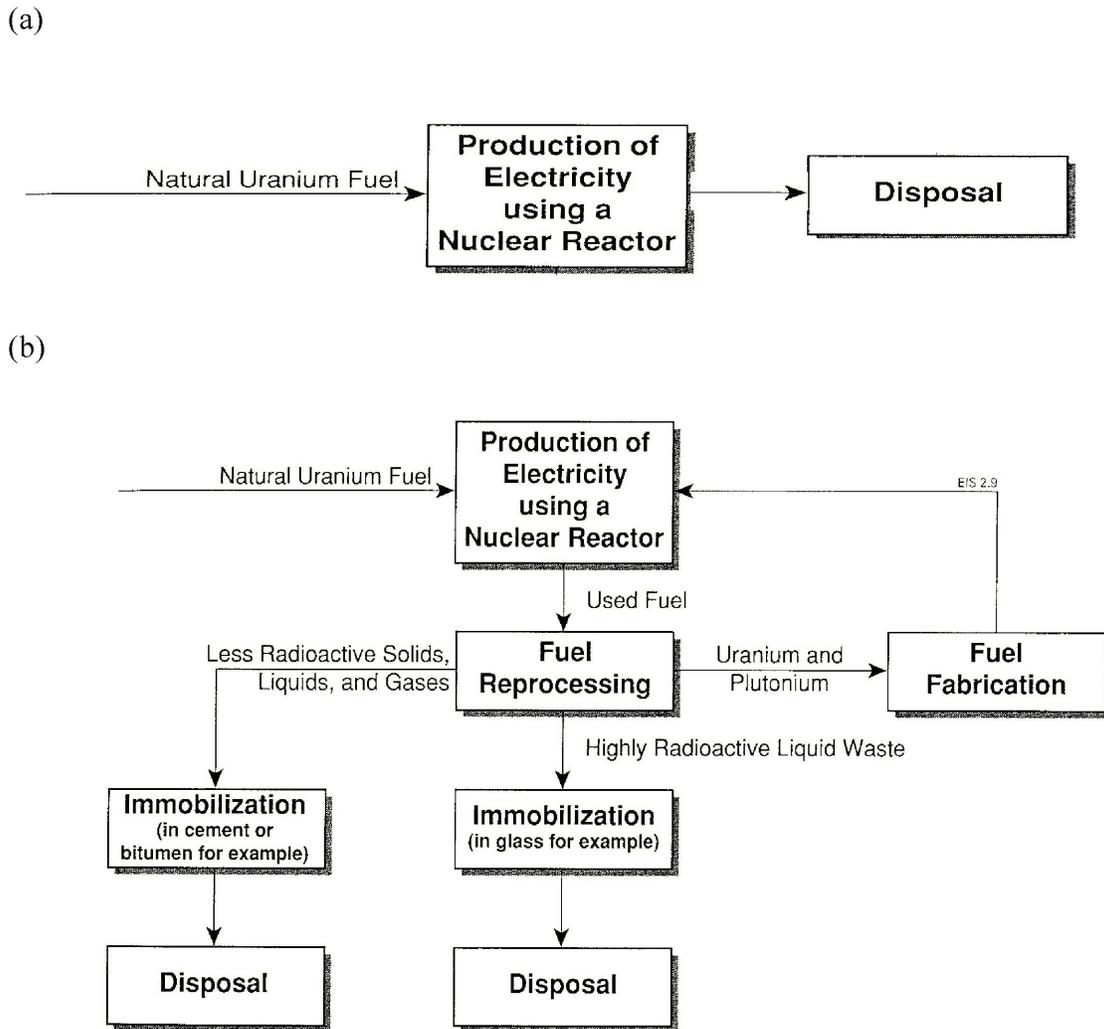


Figure 2: Schematic Comparison of Direct Disposal and Reprocessing

This figure indicates the complexities that may arise from a reprocessing or closed fuel cycle compared to an open or once through fuel cycle. In reprocessing, there are several more waste streams some of which require as yet undeveloped fast reactors in order to transmute them and reduce the overall volume of the waste. Many of these streams may be inherently less stable than intact used fuel, for example concentrated liquids that may be highly acidic.

Whether a reduction of the volume of the waste can be achieved through reprocessing depends on the system used. In fact for HLW (High Level Waste) comparisons based simply on volume can be misleading. The heat generated by HLW and the mobility of different components in the geosphere and biosphere are more important factors than volume, both in terms of safety and costs. For example, I-129 is often found to dominate the estimated dose from a used fuel repository, but does not significantly determine the volume of the used fuel. The heat-generating nuclides as well are a small component of the volume of waste, but may be instrumental in determining the land-area and excavation volume required for disposal. Of course, uranium mine/mill tailings are by far the largest volume of long-lived radioactive waste per unit energy common to all nuclear fuel cycles. It may be possible that recycling could greatly lower the waste volume of this "front end" of the fuel cycle.

If the plutonium is recycled, the post-emplacment heat generated by reprocessing waste would be significantly lower than that in spent fuel from which it came, and should lead to the volume and land area of a repository being lower per unit of useful energy generated. However, long-term radiological risk would not necessarily be improved as it would likely be dominated by mobile nuclides, which may not be recycled or transmuted. The associated intermediate-level waste from reprocessing would likely contain many of these nuclides, which would not improve safety of ILW (Intermediate Level Waste) repositories. Many of the waste components would remain on or near the surface for a long time and, in some cases, in a relatively mobile form, while they remain part of the reprocessing/recycling streams. They would remain accessible to the environment much longer than would be necessary for direct disposal.

Achieving the often cited benefit of a closed fuel cycle to reduce the volume of used fuel / high-level waste for long-term management in a DGR or similar facility would require the large scale deployment of advanced fast neutron reactors. While three fast reactors are operating and at least two more are under construction, these reactors are primarily experimental and are being used to develop the technology required for special processes and techniques to fabricate the fuel for fast reactors. For example, remote fuel fabrication and handling processes are required due to the high radiation fields from the minor actinides in the recycled fuel. However, full commercial deployment of closed fuel cycles using fast reactors is many decades away.

5. ALTERNATIVE TECHNOLOGIES: DISPOSAL IN VERY DEEP BOREHOLES

The very deep borehole concept for long-term management of nuclear waste consists of placing the waste packages nominally 3-6 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 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.

Sandia Laboratories recently published a preliminary evaluation of this concept for disposal of spent fuel assemblies from the U.S. nuclear power reactors (Brady *et al*, 2009). The report evaluation includes very deep borehole design, cost and schedule, and performance assessment.

5.1 DESIGN

The waste is assumed to be placed in the bottom ~2 km of a ~5 km deep borehole drilled through overlying rock into crystalline basement rock. This basement rock is relatively common within a suitable distance of the surface in North America, which suggests that disposal locations could be sited so as to minimize requirements for transportation of the spent fuel from source. Although retrievability would be maintained during placement operations, retrievability of waste after borehole sealing is assumed not to be required.

Table 6 gives a summary discussion of the very deep borehole design.

Table 6: 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 a disposal 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 in a disposal array that interactions among the holes will be insignificant.
Seals	The key requirements of the seal system design are that it be constructible using existing technology and have high durability. Canister strings will be separated by an approximately 1 m interval of compacted bentonite. Compacted bentonite will also be used at the top of the waste disposal zone, above the canister strings. After canister emplacement, the upper 1500 m of borehole casing will be removed and the borehole from the waste disposal zone to the surface will be sealed with a combination of bentonite, asphalt, and concrete. The borehole will be sealed with asphalt from 500 m to 250 m depth and a concrete plug from 250 m to surface.

5.2 COST AND SCHEDULE

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; disposal 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 km² and be conducted over 50 years. The construction cost of the boreholes would be about US\$19 billion, or 170 000 US\$/MTHM. Very rough estimates of additional costs, (site characterization, licensing, disposal, monitoring, transportation, etc.) give a total life-cycle cost of US\$71 billion (2008 dollars).

5.3 PERFORMANCE ASSESSMENT

5.3.1 Scenario Analysis

A consideration of a comprehensive list of the features, events and processes that might influence the performance of disposal system led to the definition of the principal scenarios tabulated in Table 7. Table 8 summarizes the most significant processes excluded from the scenarios and the rationale for their exclusion.

Table 7: 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.	<ul style="list-style-type: none"> - Canisters in the disposal 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.	<ul style="list-style-type: none"> - 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 disposal 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.	<ul style="list-style-type: none"> - A hydrogeologically conductive feature, such as interconnected fracture zones would be required to conduct significant quantities of fluid to the aquifer.

Table 8: 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 disposal 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 disposal 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.

5.3.2 Safety Analysis

A preliminary performance assessment was conducted, using various bounding and conservative assumptions, for the first two scenarios involving transport in a single borehole and transport in the disturbed rock surrounding the borehole. The assessed configuration was for disposal of ~150 MTHM in 400 LWR spent fuel assemblies in a 2 km waste disposal 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 disposal zone.

On the basis of mathematical modelling a transport time of 8,000 years was taken as the time for the bulk of the dissolved radionuclide mass to be captured by the withdrawal well at a constant pumping rate necessary to supply 1,000 people. Thermally driven flow enables transport of radionuclides up the borehole for a period of 200 years, after which this upward transport is assumed to cease. Thus the period for thermally driven flow is short relative to the travel time up the sealed borehole, which results in ¹²⁹I being the only radionuclide with a non-

zero concentration as it is the only radionuclide that is not chemically retarded. The peak dose rate to a “reasonably maximally exposed individual” is estimated to be 1.4×10^{-12} mSv/a and to occur at 8,200 years.

5.4 CANADIAN CONTEXT

Figure 3 shows a CANDU fuel bundle, which is about 50 cm long, 10 cm OD, has a total mass of about 25 kg, and contains about 20 kg of uranium in the form of UO_2 fuel pellets in zirconium tubes welded together.

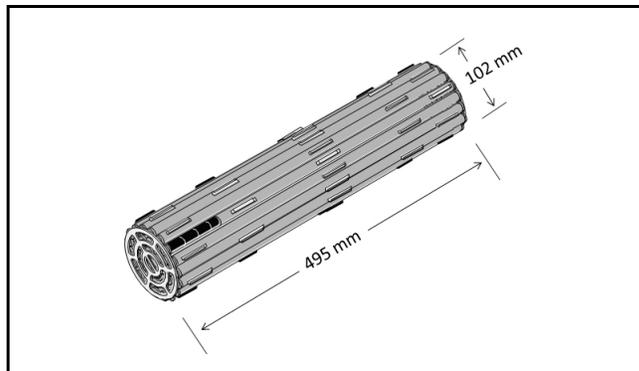


Figure 3: CANDU Fuel Bundle

The 318 mm ID canister could in principle hold up to 4 fuel bundles on a layer. As room would be required for support materials, at most 9 layers could be placed in a single 5 m long canister. Of course, this is not necessarily an optimal canister design for CANDU fuel, but this assumption does have the advantage of allowing a relatively straightforward comparison with the Sandia study.

A canister so employed would contain 36 fuel bundles having a total mass of about 900 kg of used fuel, compared to the PWR element canister with nominally 666 kg total fuel mass. The assumed 2 km long disposal zone could hold up to 400 canisters containing a total of 14,400 fuel bundles, or about 288 MTHM of used fuel. Emplacement of the projected inventory from current Canadian power reactors (Garamszeghy 2009) of 4 million natural uranium used CANDU fuel bundles (80,000 MTHM) would therefore require about 278 boreholes. With an assumption of 200 m spacing, these could be located in fields totalling an area of about 9 km².

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.

In 2008 dollars, the study estimates that each deep borehole would cost US\$20 million to construct, giving about US\$5.6 B to construct the boreholes for the 4 million bundles, or roughly US\$70 /kgHM. This compares to US\$100 /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 disposal of CANDU fuel would be almost three times that for PWR fuel per unit energy produced.

None of this discussion includes consideration of other costs, including site characterization, emplacement costs, or transportation. These would need to be included before a definitive cost comparison could be made with other technologies. It should be noted however, that any conclusions drawn regarding the cost-effectiveness of this method for LWR fuel would not necessarily be valid for the Canadian situation, as the costs of construction would be significantly greater for CANDU fuel on a unit energy basis.

6. SUMMARY

In 2009, the new US administration essentially stopped the Yucca Mountain Project to establish a DGR for used nuclear fuel in the United States. The fundamental issue is now what will the new plan be for dealing with spent fuel? Various options for long-term management of used nuclear fuel are under consideration including a closed fuel cycle which would require RP&T. Another possibility would be a new DGR site. However, it would appear that interim storage for some decades is the only possibility while one or both of these options are put in place. A Blue Ribbon Commission is expected to be established shortly and will make recommendations for a new US spent fuel management plan.

In contrast, there is much less uncertainty in the European program for dealing with spent nuclear fuel. In 2007 the European Commission acknowledged in its energy policy document that nuclear power was one of a few effective methods of mitigating the production of GHG and therefore, merited support as a sustainable energy system. This has reversed many years of nuclear phase out policies and a generally negative attitude toward nuclear energy in many European countries. In 2009, a nuclear R&D plan was published which prominently features closed nuclear fuel cycles and so involves a substantial component of research on RP&T. A European Nuclear Energy Forum was also formed to promote nuclear power since there is still considerable anti-nuclear sentiment in some European countries.

There has been a resurgence of interest in thorium fuels in some nations over the last few years primarily due to concerns that uranium resources alone may not be sufficient to fuel the nuclear renaissance. There are advantages in using fertile thorium to bred fissionable uranium-233: thorium is three to four times more prevalent in the earth's crust than uranium; there may be non-proliferation advantages in a thorium fuel cycle; and, thorium fuels may be better in reactor applications because of their better neutronics properties and physical properties. There were several large scale tests of thorium fuels in the early days of nuclear power and irradiations of tests fuels have continued in India, with large thorium resources and in Canada due to the excellent neutronics of CANDU reactors. However, it is concluded that much more R&D is required on the RP&T of thorium fuel cycles to make thorium fuels a realistic commercial possibility.

Work reported at the Global 2009 conference allows up to date estimation of the costs of reprocessing LWR fuel. For aqueous PUREX type plants this analysis gave rather high costs in the order of \$3,000 to \$4,000 per kilogram of heavy metal reprocessed. This range of values was applied to CANDU fuels by scaling to the amount of heavy metal present in them. The results gave very high total costs to reprocess the present inventory of used CANDU fuel bundles and an assumed level of annual bundle production. The estimated costs coupled with the recent lengthy and expensive experience in building the Japanese plant at Rokkasho show that reprocessing of CANDU fuels would not be economic. The prospect of using reprocessing to recover additional fissile/fertile material from the used fuel and thereby reduce the eventual

volume for a repository, would also require the wide-scale deployment of advanced fast reactors (capable of burning the recovered actinides) as well as the construction of other support facilities, such as fuel manufacturing plants. The technology for these facilities is still in its infancy and is many decades from commercial deployment.

A preliminary Sandia Laboratories study of the very deep borehole disposal concept for used light water reactor fuel indicates this 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 from 3-5 km deep in basement rock. 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 lower burnup of CANDU fuel and costs comparisons with other technologies 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.

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