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CANDU FUEL:
Evolution towards Optimal Performance

Fuel Recycling in CANDU – the Global Benefits

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Abstract

The increased recognition of Greenhouse-Gas Free electric generation has provided a new impetus for nuclear power. This will raise the profile of long-term fuel cycle sustainability. This paper provides an update survey of the future potential for fuel recycling, considering current prospects for nuclear power.

The paper outlines the basis for considering fuel reprocessing and recycling, and the gaps to be addressed in order to meet expectations for a closed fuel cycle. The paper notes CANDU's role in using existing inventories of reprocessed materials, and future roles to demonstrate and use advancements in recycling technology.

1. Introduction

COP 21 in Paris in 2015 was a game-changer, establishing a consensus for urgent action on climate change over the next few decades. Globally, the response to the Paris COP 21 agreement includes the intention to replace fossil-fuelled electricity supply with GHG-free capacity, and indeed to expand the proportion of energy use delivered by electricity, to reduce fossil fuel use in transportation, heating, etc. Nuclear power provides a unique baseload, widely sited GHG-free energy option. The potential exists for major increases in nuclear capacity over the next decades. To succeed in meeting the need, the nuclear power industry will have to address the challenges of economics and security, and meet public expectations for environmental responsibility, including managing wastes.

Management of the fuel cycle is a fundamental part of this challenge. So far, the great majority of present nuclear capacity is based on the once-through Uranium fuel cycle. This has the advantage of simplicity and low front-end fuelling costs. But in an expanding nuclear world, this cycle is vulnerable to increases in resource costs and scarcity, and escalating costs and public concerns over long-term waste management. Will fuel recycling play a more prominent role in a low-GHG world? This paper surveys and summarizes trends in fuel recycling, and considers the impact on CANDU® technology in particular.

2. Background – The context for fuel recycling

2.1 Development of nuclear generating capacity

Nuclear power can play a unique and expanding role in base-load GHG-free supply - provided that economics and public acceptance challenges are met. Currently nuclear generating capacity is about 370GW, supplying about 2400 TW/year of electricity, about 11% of global total electricity consumption (Ref 1, World Nuclear Association, 2014 statistics). Various scenarios forecast increased capacity in future. For example, the World Energy Council forecasts a doubling of total world electricity demand from ~20,000 TWh in 2012 to more than 40,000 TWh in 2040 (Reference 1).

Various scenarios have been put forward for nuclear energy supply evolution, for example the OECD International Energy Agency "2DC" scenario based on limiting global warming to the COP 21 2 degrees C target (Ref. 2). This calls for nuclear generation to increase to 17% of world demand by 2050. This would imply an installed capacity of more than triple todays capacity, or more than 1000 GW in the next 2-3 decades. The ability to deliver this is already being demonstrated, in particular in China, where the current rate of domestic nuclear capacity addition is in the range of 8GW/year. Energy scenarios are always interpretations based on a set of assumptions and perspectives, however this projection represents a credible nuclear scenario and therefore "fuel cycle challenge".

Canada is part of this challenge. To meet its COP 21 commitments, Canada's electricity sector will be under pressure to move to a virtually GHG-free level over the next decades, and may also expand to replace fossil-fuelled transportation and heating etc. with electricity. The result could be a demand for additional high-reliability nuclear generating capacity as large, or larger than, Canada's currently-operating CANDU fleet.

2.2 Development of nuclear fuel supplies

The supply and management of fuel for the current fleet of nuclear reactors has enabled fuel costs that are a modest fraction of electricity costs. The price of uranium has varied greatly over the years, as new sources of supply are developed to meet demand, and as existing stocks are used (either from material inventories or from fissile materials released from military programs). At the time of writing, uranium prices are depressed, but new demand will require added supply capacity, with long-term impact on price and availability. Resource demand scenarios can be constructed, based on some key assumptions such as:

- The current fleet of operating reactors (largely LWR's) will largely continue operating through the crucial climate period to 2050 (based on current success in life extensions)

- Rapid expansion of production capacity by new build in this time frame will need to use existing technologies with incremental adaptations (based on the time-consuming requirements to develop new technologies and deliver at scale), meaning initial build out based mainly on LWR's and PHWR's
- In the longer-term, nuclear power plants under construction or in planning today will be available to continue operating to close to the end of this century. A significant fraction of the nuclear fleet for 2050 and beyond is thus already defined

Some key fuel resource statistics are noted in Table 1: (Reference 3)

Table 1: Current fuel resource parameters (LWR-based fleet, once-through fuel cycle)

Current global nuclear fleet generating capacity	>370 MW	
Current Uranium requirement (U3O8)	78,000 Mt/year	
Current Uranium supply capacity (U3O8, 2013)	~70,000 Mt/year	
Uranium resource estimate at <=US$130/lb	5.9 M tonnes	
Resource availability in years at 1000 GW capacity	28 years	
Resource availability at 500 GW capacity	56 years	

Uranium is a relatively common element; in principle, there is much extractable uranium still to be identified – however, extraction costs would tend to increase as supply is expanded, despite the development of improvements in technology; as with most resource extraction industries, it is the cheapest supplies that are exploited first.

Based on these assumptions, fuel cycle development involves two timescales:

- Short-term: What can be done at significant industrial scale in the next few decades
- Longer-term: What can be developed to address a long-term widespread use of nuclear power

In the short-term, the overall demand for fuel resources will grow, depending on the scenario. For a total capacity of 1000 GW by 2040, the global requirement would grow to the range of 240,000 tonnes/year. This is significantly beyond current supply capability and would exhaust existing assured resources within a few decades. Given uranium's prevalence, this should not mean a supply crisis, but a reasonable scenario would involve uranium price rising to the "reference" resource projection level of $130/lb or significantly higher – in the range of 5 times the lowest prices of early 2016. Strong nuclear growth could put further pressure on price and supply reliability beyond this. Can fuel recycling make a difference to fuel cost?

2.3 **Public acceptance and waste management**

The operation of the current nuclear fleet has built up an inventory of used nuclear fuel. In most jurisdictions this inventory is under short term pool storage, or medium term dry storage, awaiting longer-term management. Spent fuel is securely stored today, and credible engineering solutions for geological disposal have been developed. However, there is still great public and activist questioning of spent fuel (or any other) long-term nuclear waste facilities, driven by the perception that there must be a guarantee that no radioactivity from spent fuel reaches the public for vast timescales (the "million-year problem") and by reluctance to agree as host communities. Successful examples of progress in Sweden and Finland are counterbalanced by the high-profile failure to make progress on the proposed Yucca Mountain fuel disposal site in the USA. In Canada, the NWMO have proceeded to carefully build a public engagement for a retrievable fuel storage facility, but the crucial test of public acceptance is still to come. This results in uncertainty about the cost, timing and success of geological once-through spent fuel disposal. Can fuel recycling help?

2.4 **Reprocessing inventories**

Historically, a significant portion of the accumulated spent fuel inventory has already been reprocessed to separate plutonium, uranium and miscellaneous waste streams. Table 2 gives some statistics on spent fuel today (source: WNA).

Table 2 Spent Fuel Statistics

Total inventory of commercial power reactor spent fuel (tHM) in storage (WNA)	~240,000 tonnes	
Quantity of spent fuel already re-processed (tHM)	~90,000 tonnes	
Current spent fuel production (tHM/year)	~7,000 tonnes/y	
Currently active LWR reprocessing capacity (France, Russia)	2100 tonnes/year	

Significant inventories have been built up of fuel resources arising from reprocessing, including separated Plutonium and Reprocessed (or Recovered) Uranium, which have value as fuel components in appropriate circumstances. As part of the pioneering French comprehensive nuclear power program, LWR fuel reprocessing has been incorporated fully into the power generation system. France obtains typically more than 70% of its electricity from its LWR program, reprocessing its fuel, and obtaining plutonium and repU which provide the materials for about 20% of the French fuel supply (Reference 4).

Major additions to global reprocessing output in the next 2-3 decades will likely be limited. The complexity, cost, and public policy challenges mean that introducing a new reprocessing plant, even with currently available technology, is a time-consuming and uncertain development. Important exceptions include Russia, where a closed fuel cycle is pursued as government policy, and China, where LWR fuel reprocessing is recognized as an essential part of the national nuclear strategy, and an 800 tonnes/year facility is in preparation (Reference 5). R&D is progressing on more innovative reprocessing technologies, but industrial scale application of advanced technologies will take many years of development. Therefore, making use of the existing inventory of reprocessed material will be an important short-term consideration.

A separate alternative to the further development of the uranium fuel cycle is the use of thorium as a fertile source of future fissile materials. Thorium has advantages, in a future where fuel reprocessing technology is more widely established. Thorium is even more widespread than uranium, and possibly could be a more economical raw material; and its use as fuel does not lead to the creation of plutonium or other transuranic isotopes that are the source of long lived radioactivity in used uranium fuels. This drastically reduces the long-term challenge of final waste disposal. However, thorium use at full scale implies a requirement for reprocessing, so will still need a significant level of R, D&D before full-scale industrial application.

3 The Challenge for Fuel Recycling

3.1 Fuel recycling today

Reprocessing of Uranium oxide fuel (the standard in LWR's and PHWR's) using current PUREX technology is a challenging technology; raising capital to put in place a reprocessing facility would require strong assurances of utility purchase of the outputs – and this would require a cost advantage over conventional uranium fuel, or an explicit recognition of a waste management benefit.

The ultimate fuel cycle goal is to re-use and recycle close to 100% of the fuel materials, including U-238 and Th-232. For uranium, this is not practical in thermal reactors, as an outcome of the interaction of their neutron spectrum with the fission and absorption characteristics of U and Pu isotopes. Fast neutron-spectrum reactor characteristics allow more complete fissioning of plutonium and other actinides, and more complete use of U-238. Most recently, a Russian proposal to use co-processed Plutonium and Uranium as the base for recycled fuel (REMIX, see Reference 6) asserts that recycle up to 5 times in thermal reactors such as LWR's or CANDU's is possible. This would involve a build up of long-lived actinides that would present a further challenge. Near-breeder thorium cycles for PHWR's have been shown to be achievable in principle, with little change to reactor design, but would require further fuel and reprocessing R&D.

Currently fast reactors remain an expensive and less-proven technology. Over the short term period of the next 3 decades, the contribution of fast reactors to global nuclear generating capacity will likely be limited. Even in the longer term, a combined system including both thermal reactors and fast reactors would represent a cost-effective optimum. Given the limited expectation for large-scale FR use in the next 3 decades, the full recycle of all Pu is a longer-term objective.

Fuel recycling can be applied to minimize the long-term high level waste burden. Reducing both long-term heat load and long-term radioactive source term reduce geological disposal costs, and may add to public and decision-maker confidence in disposal. Long-term radioactivity, beyond about 500 years, is dominated by plutonium isotopes, then by the minor actinides, americium, neptunium and curium. It follows that if reprocessing can either separate out, or recycle, actinides as well as plutonium, then the long-term waste disposal burden is drastically reduced. Today, this capability has been extensively studied but is not in industrial-scale use.

3.2 **Factors to evaluate the case for fuel cycle development**

As noted, the case for recycling, as the alternative to the once-through cycle, is based on the importance assigned to key factors, on the comparative costs of recycling and on key factors including:

- Cost, competitiveness and scarcity of fuel supply
- Cost and public acceptance for long-term waste disposal
- Security of materials against diversion

Resource cost: as noted above, in an expanding nuclear scenario, uranium costs could be expected to rise over time; fuel recycling becomes economically attractive if the recycled material enables a lower net fuel cost than from fresh uranium. The challenge for recycling is to develop and put in place technologies and improvements to reduce the cost of production of plutonium for MOX, and (particularly for PHWR's) recovered uranium with significant U235 content. If the back-end cost of spent fuel management is included as part of fuel supply cost, then the advantages of recycling, by reducing quantities or radiotoxicity of spent fuel, can be factored into this economic comparison. A number of cost models have been developed to evaluate the target range for reprocessing, including evaluation of spent fuel management costs.

Economic competitiveness is sensitive to the large future uncertainties in spent fuel management and reprocessing costs. For example, in spent fuel management and long-term disposal, the timing of implementation of a disposal facility greatly affects the "present value" of that cost via application of a discount rate to the time value of money. For example, the total overnight cost of Canadian spent fuel disposal is estimated by the Nuclear Waste Management Organization (NWMO) to be $21.2B (ref. NWMO) while the present value of this cost as of June 2015 is estimated to be $7.7B. One good example (Reference 6) from 2008, building on NWMO economic estimates, evaluates a sample cost for CANDU PHWR reprocessing, remote fabrication and final fuel disposal, providing breakeven for a uranium cost of less than $180/lb; if this approach was applied to reprocessing of spent LWR fuel, with its higher fissile content, economics would be further improved. This represents an example of a target figure and an evaluation model that can be updated and applied to potential reprocessing technology proposals.

Spent fuel long-term disposal is a key public policy concern regarding the use of nuclear power – the perceived "million-year problem". From an engineering point of view, the industry has invested great time and money to addressing this, and geological disposal models have been developed which address the management challenge. From a public perception viewpoint, there is persistent scepticism about the viability of any solution which, to all appearances, has to be in place for many hundreds of thousands of years. Two points are often noted in considering the role of recycling:

- The original source material of uranium is radioactive, with a billion-year timescale. There is an understandable logic in identifying when spent fuel materials reach a state similar to that of the originating, naturally occurring material.
- No matter how effectively recycling is implemented, there will always be some residual long-lived radioactive material which must be dealt with in a multi-thousand year timeframe. This would still be equally true even if nuclear power production stopped tomorrow. So the challenge of long-term waste management must be addressed, no matter what.

The impact of public perception on spent fuel management is a significant intangible affecting cost, and even achievability. For example, estimates for the cost of the Canadian disposal solution, would be greatly affected if, as in the U.S., a large capital cost facility was abandoned after massive capital investment. This aspect is a cost risk that is significant for governments as they establish waste management policy. Any innovations in fuel recycling that substantially reduce the long-term waste burden, reduce this risk.

Safeguards: Unprocessed spent fuel as currently stored is currently seen as acceptably safeguarded. Spent fuel, even if diverted, would require massive infrastructure and cost to militarize. One challenge for recycling is to ensure that sufficient security continues to exist to protect strategic materials, e.g. Plutonium, from being diverted. On the one hand, this strongly favours the disposition of any stockpiles of strategic materials; on the other, it favours the development of reprocessing and fuel re-constitution processes that maintain strategic materials in blended form such that they cannot be militarized.

3.3 **Short-term challenge**

- The nuclear power challenge and opportunity is to grow in response to the urgent drive to reduce GHG's in the next 3-4 decades. In the context of major facility construction, where typical planning timescales are 10 years-plus, and construction times may be equally as long, the short-term challenge is to use technology broadly available today. This still opens up a wide scope, in particular the opportunity to make use of, and demonstrate, recycling of the large inventories of already-reprocessed materials available today.

3.4 **Longer-term challenge**

- Part of the challenge for nuclear today, is to demonstrate that over the longer-term it can meet economic, sustainability and environmental stewardship expectations. So, in parallel with an industrial scale expansion of nuclear capacity in the short-term, development activities demonstrating this capability may be fundamentally important. The longer term will benefit from development and market-readiness demonstration in the short-term, fuel cycle sustainability. There is tremendous value over the next three decades, in demonstrating innovative, more economical and secure reprocessing technologies and long-lived actinide disposition, using current power reactors.

4 Fuel Recycling and CANDU

CANDU PHWR technology has unique characteristics that lead towards particular roles and capabilities with regards to fuel recycling:

- High degree of neutron efficiency providing flexibility to deal with varying fuel reactivity and parasitic absorption from trace materials, and allowing operation with lower levels of fissile enrichment of fuel
- On power fuelling allowing individual test bundles to be readily introduced and withdrawn
- Short, simple fuel assembly, relatively easily manufactured and handled, particularly for higher-radioactivity materials
- Core characteristics readily adaptable to different fuel parameters

These characteristics enable CANDU reactors to play a unique fuel cycle role in both the short term and the longer-term, including both demonstration and full-scale application.

4.1 Extending resources

In the standard open fuel cycle, CANDU reactors generate about 30% more energy per tonne of mined uranium than LWR's, so are the most effective use of fuel resources in today's commercial reactor types.
Typically, recovered uranium from LWR reprocessing plants has in the range of 0.9% U235 content – too low for re-use in LWR's without a cumbersome re-enrichment step, but suitable for use in CANDU units, for example diluted with low-cost depleted uranium to form "Natural Uranium Equivalent" (NUE) fuel (see Ref.8). The NUE initiative for the Qinshan CANDU units in China, is to use a blend of RepU and Depleted Uranium to create a low cost, recycled fuel with natural uranium characteristics. Development and demonstration irradiation has been completed, and preparation for full core implementation is being completed.
Existing stockpiles of reprocessed uranium are a significant fuel resource for CANDU. They would form a sufficient resource for the range of 15 GW of capacity for 30 years. A reprocessing plant such as that under consideration by China at 800t/year, could generate sufficient Recovered Uranium for 8 to 12 PHWR units.
In addition to this, the Plutonium produced from reprocessing has the ability to provide more power through PHWR units than in other reactor types. This acts as an immediately available alternative to complement strategic stockpiling of plutonium for future fast reactor use, and ensures that these stockpiles are kept to a minimum. For example, the UK civilian Plutonium stockpile, generated by reprocessing fuel from the Magnox and AGR fleet, can provide fuel for a 3GW PHWR fleet for about 30 years (Reference 9).

4.2 Minimizing wastes

The most notable public perception concern over nuclear waste management, is the long half life of certain wastes. While engineering solutions have been developed to manage these wastes, there may be future benefit in minimizing the extent of these wastes, which will both reduce costs and escalation risk, and address public concern over environmental stewardship. While drastic reductions in plutonium content are best achieved using a combination of thermal and fast neutron spectrum reactors, the CANDU system offers a very neutron-efficient system for recycling plutonium initially. In the short term, this is a practically achievable way to reduce Pu content; in the long term, because of their neutron efficiency, CANDU PHWR units provide the best complement to fast reactors in an overall system that recycles and eliminates the vast majority of plutonium isotopes. Similarly, CANDU units offer a very practical and short-term achievable vehicle to recycle and eliminate large portions of the actinide stockpiles.

4.3 Technology demonstration

As well as the presently proven, but expensive and difficult technologies, primarily the PUREX process used extensively in France and elsewhere, reprocessing technology options include a number of promising approaches that are still at the lab- or demonstration scale. In the present investment climate, and without a proven market demand, development work to bridge the gap between lab-scale and industrial scale application is challenging to carry out. Demonstrating the operational performance of innovative reprocessing technologies may be most readily done using CANDU fuel in operating reactors – on-power refuelling lends operating flexibility to test fuel in small, readily-handled batches, and the lower fissile requirement lessens the material specification demand. Demonstration irradiations can be achieved with low impact on the plant safety case. The recent demonstration of NUE fuel performance in the Qinshan Phase 3 CANDU units in China is a good example of this.

4.4 Path to introduce thorium

With the minor exception of U-233 daughter products, the irradiation of thorium does not produce long-lived heavy element isotopes. By re-using the U-233 produced, either in-situ or by recycling, thorium cycles can avoid significant inventories of long-lived waste. For thorium, the CANDU system offers two advantages. First, CANDU's neutron efficiency means that it can, with adaptation, be operated in a virtually self-sufficient thorium cycle, thus extracting energy from a very high proportion of the original thorium resource; secondly, the on-power refuelling, simple bundle design and reactor operation flexibility of CANDU's mean that these reactors form the ideal test-bed for developing thorium-based fuel capabilities and technologies.

5 Development steps

Wider use of recycled and alternative fuels for the current reactor designs has been slow to develop. But the current revitalization of interest in nuclear innovation opens up discussion of the range of possible reprocessing strategies and objectives. A number of reprocessing options are being researched which may lead to improvements in cost and environmental footprint, and may enable more efficient and secure recycling.

In some cases, technologies that do not completely separate waste streams are being developed. This has a security benefit in eliminating separated plutonium, and also enables simpler and more economical reprocessing steps. However, the use of the mixed U-Pu-Actinide product becomes more complicated, and may involve greater challenges in handling high-radioactivity material.

Typically, advancements in reprocessing methods are being carried out with a view to their eventual use in fast reactors. But CANDU units have advantages that mean these developments may provide major benefits when applied in CANDU's. Because of CANDU's high neutron efficiency, the reactors can handle added neutron absorption burdens from trace materials such as fission-products or actinides which are part of the reprocessed fuel stream. And the benefits of the simpler fuel bundle in CANDU reactors can be important, as fabrication of higher-activity fuel would be much simpler than for LWR fuel assemblies. At present, application of advancements in reprocessing technology to CANDU is a "missing link" in the evolution of fuel recycling and waste reduction, and is an area with great scope for investigation.

Some notable reprocessing developments include:

- Development and adaptation of PUREX: Adaptations of the PUREX approach have been developed in France, USA and elsewhere, to enable combined Pu-U outputs that still contain substantial fissile material proportions (for example, COEX approach to generate Pu-U output streams, e.g. Ref 4). Inclusion of actinides in this recycle output stream enables reduction of long-term actinide waste burden, and can simplify the waste-handling associated with reprocessing.

- Pyrochemical processing improvements: A prominent approach under continuing study is fluoride-based separation. High-temperature spent-fuel processing with fluorine or fluorine/hydrogen gas streams creates fluorides with differing volatility depending on the valency of the fluoride. Typically this enables separate U and Pu streams, or more recently recognizes that co-streaming of U and Pu can be achieved. Reference 10 outlines some recent development of this process to create a U-Pu-Np stream with some trace fission product content. Ref. 6 outlines the effectiveness of CANDU in using the outputs of the process, and gives an indicative economic analysis that shows potential overall cost-effectiveness close to the $130/lb long-term "reference" Uranium price. Actinide fluoride streams are also created, and so this process can also support actinide burning. This type of process is more compact, and uses materials more resilient in high-radiation environments, than PUREX. It also produces lower volumes of reprocessing waste, compared to PUREX.

- REMIX: As noted earlier, most recently Russia has moved to a reprocessing approach which delivers successive rounds of recycling of VVER fuel, capable of achieving up up to 5 recycling stages, titled REMIX (Ref. 5). This involves co-processing Pu and U outputs to provide a mixed oxide product directly to fuel fabrication. The approach is indicated to use a range of reprocessing techniques in series.

- Dry reprocessing options: The DUPIC process jointly developed between Korea, Canada and the USA (e.g. Ref 11) is a process with an extremely simple approach, based on recycling spent LWR fuel in CANDU reactors with limited processing. Spent LWR fuel is processed through high-temperature oxidation/reduction steps to remove most fission products and leave a U-Pu-Actinide material with some residual FP content, but that is suitable for re-use in PHWR reactors. Typically the fissile content would be in the range 0.9% U235 and 0.6% Plutonium isotopes. DUPIC has been studied primarily as a single recycling step, but in view of the recent REMIX study (see above) a series of DUPC steps could be envisaged with significantly increased energy output from the originating LWR fuel.

Including and beyond the above examples, there is a wide suite of activities to improve reprocessing, based on a number of world research centres, and with policy support from a number of government entities. Canada has played an important role in this over the years, and is well-placed to continue to be a strong participant, with benefits to our role in the global nuclear industry.

6 Final remarks

In principle, nuclear fuel reprocessing and recycling are the natural fit to society's expectations, for all industries, to make the best use of resources and minimize long-lived wastes. In practice, reprocessing is a challenging technology. With the potential for uranium supply price to increase, and continuing uncertainty in the full (including social) costs of geological disposal, there is a strong incentive to continue developing innovative reprocessing technologies so they can be available as an alternative to the once-through cycle. Development of options such as those mentioned above may reduce the cost and deployment challenge, and may enable effective recycling of the full range of actinide isotopes. Success is most likely to be reached by exploring a healthy range of reprocessing strategies and options.

In parallel, there is long-term potential in the development of thorium fuel cycles, subject to the challenge of achieving economical reprocessing technology. Again, this provides an alternative option for scenarios where the uranium cycle becomes costly or long-term disposal is seen as a drawback.

The uncertainty in development outcomes means that it would be difficult for the private sector to actively fund development by itself. This is in parallel to some development of innovative reactors, where a number of promising private sector initiatives, e.g. in SMR's, are actively under way, with the benefit of public-private partnering arrangements. The most encouraging progress in reprocessing technology is occurring where government policy support, and appropriate funding, provides a fertile ground for successful demonstration of value, for example in France, China and Russia.

Bottom line: Given the climate change imperative, and the prospects for nuclear power expansion, it is essential that further development of the closed nuclear fuel cycle is strongly supported, to provide the fullest possible menu of policy options for the future. Application of CANDU technology has a powerful potential role to play, that has not been fully explored yet, and could benefit from closer attention from policy-makers and researchers. Ongoing activities that seem to continue to merit priority, from this survey:

- Give priority to making full use of existing reprocessed material stockpiles, to minimize waste, extend resources and build technology capability for the long-term
- Active, open, engagement by governments with society to establish agreed frameworks and acceptance criteria for long-term disposal of fuel waste
- Governments and industry to facilitate R&D to improve reprocessing cost-effectiveness, safeguard-ability and waste-minimization
- Develop technologies to enable thorium recycling
- Be ready to implement fuel recycling when/where supported by society

7 References:

1) World Energy Council: “World energy Scenarios: Composing Energy Futures to 2050” published 2013
2) OECD International Energy Agency: “Energy Technology Perspectives; 2015”
3) WNA: Uranium Market Update, February 2015
4) Commissariat d’Energie Atomique (CEA): Report on Sustainable Radioactive Management” December 2012
5) WNA Country Report: China’s Fuel Cycle: April 2016
6) IAEA-CN-226-106: “Multiple Recycle of REMIX Fuel Based on Reprocessed Uranium and Plutonium Mixture in Thermal Reactors” by Y.S. Fedorov et al; IAEA International Conference on Spent Fuel Management, Vienna, June 2015
7) Nuclear Waste Management Organization, NWMO Discussion Paper: Reprocessing versus Direct Disposal of Spent CANDU Nuclear Fuel: A Possible Application of Fluoride Volatility, D. Rozon and D. Lister, January 2008
8) ICONE-21 June 2013, Chengdu, China “Natural Uranium (NUE) Fuel: Full Core Use of Recovered Uranium and Depleted Uranium in CANDU Reactors” by C. Cottrell et al
9) 7th Annual International Conference on Sustainable Development through Nuclear Research and Education Pitesti, Romania, May 2014, “An overview of the Enhanced CANDU 6 capabilities for Plutonium Stockpile Disposition and Advanced Fuel Cycles” by J.Saroudis
10) OECD-NEA 11th meeting on partitioning and transmutation, San Francisco, November 2010 “Current Progress in R&D on Pyrochemical Partitioning Technology in the Czech Republic, J. Uhlíř Nuclear Research Institute Řež
11) Global '95 Conference (Sept 1995, Versailles), “Burn Spent PWR Fuel Agaiin CANDU Reactors by DUPIC”, Lee, J. S et al