IAEA-SM-353/40

OPTIMIZATION OF THE FUEL CYCLE

XA0053571

S.W. KIDD
The Uranium Institute,
London

K. BALU
Bhabha Atomic Research Centre,
Trombay, Mumbai, India

P.G. BOCZAR
Atomic Energy of Canada Ltd,
Chalk River, Ontario, Canada

W.D. KREBS
Siemens AG, Unternehmensbereich KWU,
Erlangen, Germany

Abstract

The nuclear fuel cycle can be optimized subject to a wide range of criteria. Prime amongst these are economics, sustainability of resources, environmental aspects, and proliferation-resistance of the fuel cycle. Other specific national objectives will also be important . These criteria, and their relative importance, will vary from country to country, and with time. There is no single fuel cycle strategy that is optimal for all countries. Within the short term, the industry is attached to dominant thermal reactor technologies , which themselves have two main variants, a cycle closed by reprocessing of spent fuel and subsequent recycling and a once through one where spent fuel is stored in advance of geological disposal. However, even with current technologies, much can be done to optimize the fuel cycles to meet the relevant criteria. In the long term, resource sustainability can be assured for centuries through the use of fast breeder reactors, supporting high-conversion thermal reactors, possibly also utilizing the thorium cycle. These must, however, meet the other key criteria by being both economic and safe.

1. INTRODUCTION

Nuclear power has to demonstrate its worth to a critical world and it is recognized that the industry must maximize its performance in order to satisfy its critics. This requirement leads to the concept of optimizing the fuel cycle, which must be carefully defined.

We must firstly recognize that the nuclear industry has a very long time horizon. In the shorter term, which in nuclear terms extends to decades, the industry is attached to a predominant technology, that of uranium-powered thermal reactors. The key variants are reactor type (LWRs and PHWRs), and whether the spent fuel is recycled to close the cycle, or stored with the intention of final disposal in a deep underground repository. Given known current plans, development of these reactors is likely to be evolutionary rather than revolutionary and such fuel cycles are likely to remain important in fifty years time. Nevertheless, there are many options for optimizing these cycles, using existing reactors and fuel cycle technologies. Moreover, further opportunities for optimizing the fuel cycle in this time frame may arise from developments in fuel cycle technologies, such as enrichment, new advanced recycling processes, remote handling and fuel fabrication, reactor operations, advanced fuels, and waste management.

Over the longer term, the possibilities for optimizing the fuel cycle are potentially more extensive. Most of these options involve a much greater use of the resource base for nuclear power and typically involve fast breeder reactors and the introduction of new reactor fuels such as thorium. However, the caveat is that fuel cycle decisions taken today can impact the options available in the longer term. There is a finite resource of fissile material that can be used to initiate fast reactors or thorium fuel cycles. The rate of introduction of these new fuel cycles, and their ability to meet energy requirements in the future, will depend on the extent and availability of fissile material when it is needed. Fuel cycle decisions taken today, can either open or close doors in the future.

Optimization itself is not a value-free term. What is an optimal solution for one party may not be so for another. In particular, different countries may simultaneously have very different energy policy requirements, based on many factors, including access to, and diversity, cost and security of energy resources; the state of industrial development; availability and cost of fuel cycle technologies, both domestically and off-shore (such as enrichment and reprocessing); back-end considerations, including total inventories of spent fuel and high-level waste; and government policy on energy and industrial development. We must also recognize that over time, concepts of what is optimal may alter substantially, according to what are regarded as the relevant criteria. This is highly relevant in the case of nuclear power, as it is such a long-term business. Reactors take several years to plan and construct, but also then operate for 40 years and beyond. Given the pace of change in the modern world, it seems highly likely that what is regarded as an optimal solution during the development of a reactor program will not necessarily prove to be the case throughout the whole lifetime of a plant. Changes to operating practices may sometimes be made along the way, but the world can frequently become stuck with choices which eventually prove to be sub-optimal.

Given the historical difficulty in predicting the availability and cost of energy resources and fuel cycle technologies, and the large uncertainties and variability in many of the factors, a superior nuclear energy strategy must include fuel cycle flexibility. This will enable a country, or utility, to optimize its fuel cycle strategy based on its own unique circumstances, and to change that strategy when those change.

It is also important to note that the fuel cycle must be seen as a whole in the discussion of optimization. It is possible to seek best solutions for each stage or element in isolation, without considering the effect on the whole. This is poor practice, given the important inter-relationships between the stages, where the knock-on effects of choices have to be evaluated. This "whole" includes consideration of not only the entire fuel cycle, but also of the entire national, or even regional energy environment. It is in this context that Korea, for instance, is considering exploiting the synergism between their PWRs and CANDU reactors through the DUPIC fuel cycle.

It is useful to firstly explore some of the possible concepts of optimization of the nuclear fuel cycle before briefly examining their application in a historical context. The analysis can then be brought up to date by examining how technology and practices can relate to the alternative concepts, in both the short and long terms, before reaching some conclusions on how the nuclear industry may proceed.

2. ALTERNATIVE CONCEPTS OF OPTIMIZATION

There are a wide variety of potential criteria for optimizing the nuclear fuel cycle. Some fuel cycle options may possibly optimize all of the criteria simultaneously; the more common situation involves a trade-off between conflicting criteria. The four most important criteria are arguably economics, sustainability and security of energy resources, environmental, and proliferation resistance, although this list is by no means exhaustive. Safety is not included in the list of potential criteria, as all fuel cycle options must meet the highest levels of safety, and there is usually little to differentiate between different fuel cycle options on the basis of safety.

For the electricity utility today operating an existing nuclear power plant, economic optimization means minimizing the costs of producing electricity, based on a high degree of plant reliability, operational flexibility and maximum fuel utilization. This will include the costs of spent fuel management and eventual plant decommissioning. The restructuring of electricity markets which is taking place throughout the world means that nuclear plants must compete directly with other modes of generation. Only if plants can prove cost effectiveness will they survive.

With regard to possible new plants, they must again prove their economic viability against their rivals. Although some countries still adhere to the concept of national energy planning, the invisible hand of the liberalized market is gradually taking over decision-making in the energy world. Optimization of the fuel cycle therefore fundamentally implies selecting options which constrain costs. Another important point is that the time horizon of private financial markets is relatively short, so there is an incentive to minimize costs which come early in a project and obtain a financial return as quickly as possible. Utilities are also very conservative, risk-adverse, and reluctant to make changes to proven methods unless the benefit is compelling. This favors evolutionary improvements to plant design, and well-proven fuel cycle options based on existing technologies and facilities, rather than attempting anything very innovative, which may experience cost over-runs and delays to the arrival of the revenue stream from electricity sales.

Even if the time horizon is opened up to allow fundamental technology shifts, there is likely to remain a strong economic criterion to be satisfied. Selected options will have to make economic sense, but considering a longer period allows the inclusion of a wider range of costs and benefits. For example, it is likely that external costs of energy supply programs will increasingly be incorporated in decisions, in particular the key environmental factors. In this regard, it is important to note that nuclear power internalizes the costs arising from ensuring safety and radioactive waste management and decommissioning of facilities. This means that these costs are included in the price of electricity generated by nuclear power. On the other hand, the costs arising from the adverse environmental and health impacts of other electricity generating options remain to be fully internalized. If this happens, it will serve to increase the cost competitiveness of nuclear power compared to fossil fuel burning for electricity generation.

The resource optimization criterion includes several factors: the cost, availability, and sustainability of the world's natural resources; local or national energy-resource independence and security of supply (whether natural or enriched uranium); diversity of energy resources (including non-nuclear). Some contend that nuclear power is now repeating the mistakes of the exploitation of other energy resources, such as coal, oil and gas, where market-controlled exploitation has taken place with little regard for its sustainability into the longer term. In an extreme view, optimization of the nuclear fuel cycle considering only the resource optimization criteria would only take place when the maximum amount of energy is extracted from each kilogram of uranium. Based on current operational fuel cycles, this is clearly not taking place, which implies that over the longer term, the process must have a strictly limited life. Uranium reserves may currently appear extensive, but an upsurge in nuclear power based on current fuel cycles may have a limited life of only fifty years or so.

Some adherents of the sustainability view of optimization would claim that theirs is the only credible longer term perspective and that it fits in well with the latest intellectual thinking about energy. For the developing countries in particular, it is clear that the pattern of energy exploitation followed the early industrialized countries cannot be repeated, as it is not sustainable in terms of known resources. It is also not sustainable in environmental terms, given concerns about the build-up of greenhouse gases in the atmosphere, due to the burning of fossil fuels. It is not seen as justifiable, however, to have the economic development of the world's poorer countries constrained by a problem which has arisen owing to misuse of resources by another set of countries. In addition, countries with relatively weak energy resource endowments feel the need to protect what they do possess, for fear of undermining the security of their economic development and of incurring substantial foreign exchange costs through energy imports. Recent international economic turmoil has provided support for this view. So far as nuclear power is concerned, it can offer the world certain advantages in environmental terms, but with a move to alternative fuel cycles in the longer term, may also be able to offer an unsurpassed level of sustainability, towards the level of those energy resources which are deemed renewable.

Nuclear fuel cycles have been subjected to a significant degree of outside scrutiny, which has produced a mass of information on the safety of reactors and other operating plants within the fuel cycle and the environmental aspects of spent fuel management. Evidence in these very difficult areas is, however, seldom clear-cut and decisions on what to prefer frequently require value judgments about what is inferior or superior. In these areas, it is notoriously difficult to be scientific, as so much is determined by people's perceptions of risk, which is often not based on objective reality.

Two examples illustrate the difficulty in establishing environmental criteria in an objective manner. One often-quoted waste management measure-of-merit is the volume of spent fuel or high level radioactive waste. In fact, it is well established that in a geological repository, such as that envisioned by Canada or Sweden, it is the decay-heat loading of the spent fuel or high level waste, rather than the volume, that is the main determinant in the size and cost of the repository. Hence, for example, the higher volume of spent natural uranium CANDU fuel is offset by its much lower decay heat, that allows a higher packing density in the repository compared to spent LWR fuel. As a consequence, the disposal costs and repository areas are similar for spent LWR and CANDU fuels. Another example is the focus on the radioactive source term, or the "radio-toxicity" of the spent fuel. Again, for geological disposal in a repository following the Canadian or Swedish concept, the contribution from the actinides in spent fuel to the long-term radiological dose is negligible. In a properly engineered repository, in a reducing environment, the actinides are virtually insoluble. Hence, one must be careful to consider the total risk and environmental impact of fuel cycle options, rather than focusing on only one narrow aspect.

The identification of non-proliferation optimization criteria is even more controversial. In the context of reactor and fuel cycle choices and future technological development in the civil nuclear power sector, the nuclear non-proliferation regime has been able to provide the necessary assurances, irrespective of the nuclear technology chosen, and should be able to do so in the future. In other words, nuclear fuel cycles and their facilities can be safeguarded. Nonetheless, concerns over proliferation aspects of fuel cycles has played a major role in shaping the nuclear industry today. The rejection of the reprocessing and recycling option in the United States is the most obvious illustration of this; and this policy continues to influence fuel cycle choices in other countries. On the other hand, the successful implementation of reprocessing and MOX fuel fabrication technology in Europe demonstrates that safeguards can be applied to fuel cycles involving the separation of fissile material to minimize proliferation risk. Controversy even extends today to spent fuel disposal, where some argue that once the spent fuel has cooled, either prior to or after final disposal, it may prove to be an easier source of plutonium for any party possessing the appropriate separation technology.

There are novel fuel cycles which contain a high level of proliferation resistance of which the DUPIC (Direct Use of Spent PWR fuel In CANDU) is an example. The high degree of proliferation resistance stems from several characteristics, including that there is no purposeful separation of isotopes (nor can the processes be easily tampered with to effect such a separation), the plutonium concentration is dilute (making it much more difficult for the removal of a significant quantity) and all stages of the process, as well as the final DUPIC fuel bundles, are highly radioactive (making physical access to the material, and its removal, extremely difficult). Between DUPIC and conventional reprocessing a range of other recycling technologies can be envisioned that have various degrees of proliferation resistance. The proliferation resistance of conventional reprocessing can be increased by not separating the plutonium and uranium to the same extent, and by leaving some fission products. In the so-called "TANDEM" cycle, uranium and plutonium from spent PWR fuel are co-precipitated for use as CANDU fuel; some fission products could be left as well to further enhance the proliferation resistance of this fuel cycle.

To understand the application of the various optimization criteria, it is worthwhile delving back briefly into history. Although the nuclear era is only half a century old, there have already been significant changes in perceptions of how nuclear power should develop, with the important lesson for us today that the future pattern is unlikely to be any different. Fuel cycle options which are readily criticized as irrelevant today may quickly become accepted once circumstances change.

3. SOME HISTORY

In the early days of the commercial nuclear power industry, it was always believed that owing to the scarcity of the world's uranium resources, the uranium-based fuel cycle would be a short-lived phenomenon. Optimization at that time therefore involved moving towards a fast-breeder reactor cycle to maximize utilization of scarce resources. This would initially involve the closing of the fuel cycle by the reprocessing of spent fuel to extract usable uranium and plutonium in order to commence the commercial development of fast breeder reactors. The use of MOX fuel in thermal reactors was considered as only an intermediate stage in the process. At the time, it was believed that the economic and sustainability concepts of fuel cycle optimization would coincide in the future, on the basis that the cheapest long term choice was also the sustainable one. The conception was that uranium would become very expensive as its scarcity increased, adversely affecting the economics of nuclear power.

There are many reasons why this has not happened, but in particular the much slower than expected growth of nuclear power and the discovery of extensive additional world uranium resources. Uranium today is no longer regarded as a scarce resource in most countries as there are abundant supplies available to fuel current nuclear technology for many decades. The introduction into the fuel cycle of uranium formerly tied up in nuclear weapons has strengthened this view.

Fast reactor development has also been much slower than was anticipated. Part of this may be attributed to lower perceived necessity for their introduction, but the technical and economic challenges have also proved demanding. The public hysteria which has been created concerning the use of plutonium as a fuel may also have had an impact.

The position today is that for many countries, there is a direct conflict between the economic and sustainability concepts of optimization. In many countries, the pressures to constrain costs of generation in increasingly competitive electricity markets imply that fuel cycle options which contradict the sustainability criterion will be selected. The time horizon taken by investors is a major constraint - independent power producers (IPPs) typically look ahead only a decade, thus either ruling out nuclear power or greatly limiting possible fuel cycle options.

There are exceptions to this. In India, with poor uranium resources and concerns about the energy security and foreign exchange costs of acquiring alternative supplies, a closed fuel cycle is seen as an essential step towards more resource-efficient fuel cycles based on fast breeder reactors, and high conversion heavy-water-moderated thermal reactors using thorium. The Russian Federation regard their uranium and plutonium resources as important national assets, irrespective of perceived abundance of uranium on world markets. They are resources not to be squandered by adopting options which may appear to be low cost with only a short term perspective.

Otherwise plants must prove their economic viability on a short term basis, or they are threatened with closure. Some of the solutions to achieving this may involve increasing the utilization of the uranium raw material through either high fuel burnups in LWRs or via reprocessing and eventual recycling of spent fuel. This will, however go only a small way towards hitting the sustainability criterion, as only a small part of the potential energy will be extracted from the raw material.

It is useful at this point to examine how technology and practices are seeking to address the various optimization criteria, initially in the shorter term when the current main fuel cycles are effectively fixed and then in the longer term, when there is a potential for a much greater range of solutions.

4. OPTIMIZATION IN THE SHORT TERM

As described in the previous section, the economic criterion is likely to dominate, subject to satisfaction of base requirements on safety, environment and non-proliferation. The prime means of achieving this will be to get reactors running as much as possible for as long as possible, in other words having high load factors over extended operating lives.

Considerable achievements in improving load factors have already been achieved with operating reactors, but there remain laggards performing well below the best in the industry. In LWRs, longer operating cycles, beyond the usual 12 months, are one route towards raising load factors, as are short, efficiently managed outage periods. Longer operating cycles do, however, have the disadvantage of increasing fuel cycle costs - it is always a matter of satisfying various conflicting objectives. Given the age structure of existing reactors, plant-life management and reactor refurbishment is becoming an increasing issue, involving in some cases, replacements of key components such as steam generators and, in others, the modernization of instrumentation and other components. Power uprating is also becoming increasingly common and this may greatly assist the economics of power production.

Economic optimization involves the minimization of all cost components. Operating and maintenance costs began to run out of control in some nuclear plants in the past, but are now strictly controlled. Another important area for attention is fuel costs and performance, with utilities tailoring their procurement practices to fit in with a perceived abundance of uranium and gradually moving towards higher fuel burnups for LWRs (which cut costs at both the front and back end). Fuel managers experiment with new fuel designs incorporating different enrichment levels in order to minimize costs for a given electricity output, with the trend towards higher average enrichment levels. This however, pushes LWR fuel technology towards its performance limits, which may bring some new technical problems. Back-end policies are still effectively decided on a national basis, but there are some signs that economic criteria will be more influential here when reprocessing contracts come up for renewal. Nuclear generators are increasingly having to sell their sole product in a competitive market and must seek low-cost solutions in every area.

Despite the low level of new plant orders in Western countries, considerable progress is still being achieved with evolutionary plant designs based on existing reactor types. Again the motivation is primarily economic, with a focus on nuclear power's relatively high capital cost, as nuclear power's previous financial advantage over similar base load electricity generation options has clearly been substantially eroded by low fossil fuel prices, and in particular, by increases in the thermal efficiency of the latest combined-cycle gas plants. The competitiveness of new nuclear plants can also benefit greatly from increased thermodynamic efficiencies, achieved through higher coolant temperatures. This in turn may require further advances in fuel technology. New designs aim to provide utilities with a high degree of fuel cycle flexibility, to fit in with their own unique circumstances Many aim at achieving economies of scale with unit sizes from 1000 to 1800 MWe - these will, however, only suit major electrical grids. It is also hoped that standardization of key nuclear plant designs will improve economics, as should the practice of having several reactors based on one site, where integrated operating and maintenance can be realized.

On the sustainability criterion, while present fuel cycles are clearly far from optimal, significant improvements in resource utilization can still be achieved using existing technology. Reprocessing and recycling of the recovered fissile material from LWR spent fuel back into LWRs can improve the overall uranium utilization by about 30%. Recycling the recovered uranium and plutonium from reprocessed spent LWR fuel into CANDU reactors would further improve the overall uranium utilization. Exploiting such fuel cycles and the natural synergism between LWRs and CANDU reactors can ensure sustainability for at least 50 years without a leap in technology (and perhaps much longer), until more resource-conserving fuel cycles are employed. The availability of environmentally friendly nuclear power is particularly important in developing countries, where much of the growth in energy and electricity demand is forecast in the next century.

Although future spent fuel reprocessing will become fundamentally an economic decision, there now exists new experimental technologies as an alternative to the PUREX process. Some hold out the possibility of being significantly cheaper, while not separating the uranium and plutonium to the same extent (which is attractive from the non-proliferation point of view). The DUPIC option that has previously been discussed in the context of its high degree of proliferation resistance, also has the potential of being simpler, and hence cheaper than conventional reprocessing.

There are some current fuel cycle features apart from recycling which also contribute to sustainability, albeit only slightly. Increased fuel burnups in LWRs economize on the uranium resource, while surplus world enrichment capacity is being used to re-enrich part of the enormous depleted uranium inventory and reconstitute it as low-enriched uranium (LEU). If the move to laser enrichment takes place, lower tails assays requiring a smaller uranium feed are likely.

With regard to the safety and environmental criterion for optimization, it may be accepted that there is little a priori reason to prefer either a once-through cycle or one closed by the recycling of reprocessed spent fuel, assuming that the facilities are operating properly. The arguments are quite finely balanced and hard to resolve in favor of one side or another. Moreover, from the resource utilization perspective, spent fuel disposal is not necessarily "final", as the public usually demands monitoring and retrievability. In an energy-scarce future, the fissile material in a repository could be recovered, if cost effective. What is certain is that there will be continued importance placed on safety and environmental considerations in an attempt to minimize the perception that these are key disadvantages of nuclear power. Those in the industry recognize that in fact, these are really the key advantages of the industry; the challenge is to convince the public that the industry is safe and environmentally sound, and that it should be the option of choice in meeting the challenges of global warming. The increased importance placed on safety and environmental impact will inevitably cost money, and although attempts will be made to reduce the regulatory burden where it is deemed inappropriate, it will remain as a significant cost. Some possible developments, such as higher fuel burnups for LWRs and lower enrichment plant tails assays, may reduce the amount of waste generated, but the prime motive will be economic. The key issue to be resolved for both the once-through and the recycle options, is convincing the public of the soundness of geological disposal for spent fuel and high level waste, without which confidence in the industry may diminish.

For non-proliferation criteria, shorter term optimization involves the application of strict safeguards throughout current fuel cycles. In reality, there is again little to choose between once-through and closed cycles. As noted above, advanced recycling technologies may be developed that not only reduce costs, but also reduce proliferation risk.

It is insightful to leave this discussion on the short-term optimization of the nuclear fuel cycle with an example that illustrates the simultaneous optimization of several criteria – the use of slightly enriched uranium (SEU) in CANDU reactors. The optimal enrichment that minimizes the fuel cycle costs in CANDU reactors is between 0.9% and 1.0%. Operational considerations may easily be met with enrichment at this level with no changes to the reactor, while fuel-cycle costs are reduced by 20 to 30% compared to natural uranium fueling. This cost saving is partly due to an improvement in uranium utilization (natural uranium requirements per unit of electricity generated are reduced by about 25%) and partly by spent fuel disposal costs being reduced relative to natural uranium by as much as 30%. SEU may also be used to up-rate the reactor power, which may provide a large economic benefit for both new and operating plants. Finally, the use of recycled uranium from reprocessed spent LWR fuel offers access to a potentially very economical supply of enrichment at the optimal enrichment level. Hence, SEU allows the optimization of several important criteria. The fact that it is not yet utilized by utilities underscores their conservative nature, which are generally focused on maintaining current plant operation

5. OPTIMIZATION IN THE LONG TERM

Optimizing the fuel cycle in the longer term essentially involves a significant improvement in the resource sustainability criterion which fails to be met by existing operational fuel cycles, together with satisfaction of the economic, safety, environmental and non-proliferation aspects. There are essentially two alternatives here, either the widespread introduction of technologies which make much more use of a scarce resource or an extension of fuel cycles to utilize new resources. The former is most likely to be satisfied by fast breeder reactors, while introduction of a thorium-based fuel cycle in current reactor types provides an example of the latter. However, as noted earlier, the caveat is that both cycles require fissile material for their initiation (and for fissile topping in the case of thorium cycles), and that resource is finite with reactor technologies currently in use. The rate of introduction of these new fuel cycles, and their ability to meet future energy requirements, will depend on the availability of fissile material when it is needed.

Despite good operational experiences with experimental and prototype fast reactors, their widespread introduction has been delayed and is now unlikely for several decades. The twin motives for their eventual introduction are likely to be the significant increase in the extraction of the potential energy from fuel together with the utilization of the plutonium and depleted uranium inventories which will have built up by that time. Owing to the breeding capability, the quantity of economically viable nuclear fuels may also increase significantly with fast reactors, taking in account currently uneconomic uranium deposits and also those of thorium.

One attractive option is a mixture of fast breeder reactors and lower-cost high-conversion thermal reactors utilizing thorium fuel, with the former supplying both initial and topping fissile requirements of the latter. While there is only limited knowledge of the extent of thorium resources in the world, the discovery of large deposits with high grade ores in several locations suggests that they are extensive. In principle, thorium-based fuels can be used in all current reactor types. Even though thorium does not contain a fissile component, ^{233}U is produced in-reactor through neutron capture in ^{232}Th, and subsequent beta-decay of ^{233}Th and ^{233}Pa. The concentration of ^{233}U in the spent fuel is about 5 times that of ^{239}Pu in spent natural uranium UO_2 fuel. This isotope of uranium is a very valuable fissile material because of the high number of neutrons produced per neutron absorbed (η) in a thermal neutron spectrum. The full exploitation of the energy potential from thorium requires recycling, which will not be economically justified for many years. Since commercial thorium fuel recycling facilities have not been built, there is an opportunity to develop a new, cheaper, proliferation-resistant technology for recycling.

This bridge between the thorium recycle options of the future and current uranium-based fuel cycles is the once-through thorium (OTT) cycle. This may prove attractive to countries having abundant thorium reserves, but are lacking in uranium. For example, two general approaches have been devised for OTT cycles in CANDU reactors. The first is a “mixed-core” approach, in which a large number of channels fueled with “driver” fuel would provide the external source of neutrons for a fewer number of channels fueled with ThO_2. This is the conventional OTT, and theoretically, values of enrichments, burnups, and relative feed rates can be chosen that may make this fuel cycle competitive (both in terms of resource utilization and economics) compared with natural uranium fuel. A “mixed-fuel bundle” approach is an alternative strategy for introducing the OTT cycle, which has the benefit of a particularly simple fuel management strategy. The “mixed-fuel bundle” contains ThO_2 in the central elements of a CANDU fuel bundle, and SEU in the outer 2 rings of elements.

Such a transition between the large installed thermal reactor system and one employing fast breeder reactors may take many years. The key resource sustainability and waste management advantages of FBRs will have to be balanced against their likely high initial capital costs but also their need for a demonstrated safety record. In bridging this gap between current and long term fuel cycles, policy makers will have to consider whether specific decisions preclude future fuel cycles options. One such fuel option that would close doors to future fuel cycle flexibility is the annihilation of plutonium (in for example, an inert matrix). While satisfying one fuel cycle criteria (proliferation resistance), this option would irrevocably reduce resource sustainability, by eliminating a future potential fissile material for initiating fast breeder or thorium fueled reactors.

6. CONCLUSIONS

In a climate where competition is gradually being introduced into electricity markets in many countries of the world and where there is an abundance of the uranium raw material, it is natural that the economic criterion is dominating moves towards optimizing the fuel cycle. It is essential that currently operating nuclear plants demonstrate their ability to prosper in this new environment. Some economic-based measures have either positive or negative implications for the other criteria but standards on safety, environment and non-proliferation must be enhanced rather than compromised. The next generation of evolutionary reactor designs should be able to make enhancements towards optimization on each of the criteria, but their introduction is heavily dependent on the current generation of plants demonstrating their worth. The incorporation of the advantageous environmental characteristics of nuclear power in future new generating capacity decisions would make new nuclear capacity more likely. The key to a shift to effectively infinitely resource sustainable fast breeder reactors is the acceptance of plutonium as a safe and economic fuel. This is still some way off, but is a reasonable objective for the industry in the medium term.