FUEL CYCLE TECHNOLOGIES - THE NEXT 50 YEARS[1]

L.N. CHAMBERLAIN, S.E. ION, J. PATTERSON
BNFL, Risley, Warrington, United Kingdom

Abstract

World energy demands are set to increase through the next Millennium. As fossil fuel reserves fall and environmental concerns increase there is likely to be a growing dependence on nuclear and renewable sources for electricity generation. This paper considers some of the desirable attributes of the nuclear fuel cycle in the year 2050 and emphasises the importance of considering the whole of the fuel cycle in an integrated way - the concept of the 'holistic' fuel cycle. We then consider how some sectors of the fuel cycle will develop, through a number of multinational contributions covering: enrichment, fuel, aqueous reprocessing, non-aqueous reprocessing, P&T, MOX, direct disposal, waste. Finally, we summarise some of the key technical and institutional challenges that lie ahead if nuclear power is going to play its part in ensuring that planet Earth is a safe and hospitable place to live.

1. INTRODUCTION

All credible predictions suggest that World energy demand will grow through the next Millennium. Such demand needs to be balanced against environmental constraints and the availability of raw materials; meeting the World's energy needs in this sustainable manner is a huge challenge to mankind.

Many reviews of World energy demand have been published [1]. Electricity generation makes a significant impact [2], not just because power generation has a great influence on the environment, but also because increasing industrialisation and quality of life in the developing nations leads to much increased electricity demand. Almost 17% of total demand is produced by nuclear power stations today. In view of the reducing reserves and environmental effects of fossil fuels, it is expected that there will be increasing reliance upon nuclear and renewable generation. It is projected that maintaining nuclear at 15% of the World electricity generation would require some 1000 GWe of capacity by 2050 (compared to 350 GWe today); achieving the World Energy Council projections for energy mix suggest the need for about 2500 GWe on the same timescale [2].

It therefore seems inevitable that fuel cycle services will also be required in 2050. The nature of these services will change as the reactor mix changes and as differing technologies mature and fade in response to customer demand, regulatory challenge, public perception and political pressure. The fuel cycle facilities of tomorrow are driven by the need to achieve:

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[1] with contributions from:

S. BJURSTRÖM, Swedish Nuclear Fuel and Waste Management Co.(SKB), Stockholm, Sweden
N. CAMARCAT, CEA, Paris, France
K. HESKETH, BNFL, Risley, Warrington, United Kingdom
R. G. G. HOLMES, BNFL, Risley, Warrington, United Kingdom
V. B. IVANOV, RIAR, Russian Federation
M. KATSURAGAWA, PNC, Japan
J. PALEIT, Urenco, Marlow Bucks, United Kingdom
P. PRADEL, COGEMA, Vélizy, France
R. SCHENKEL, Joint Research Centre, European Institute for Transuranium Elements (ITU), European Union, Karlsruhe, Germany
A. SCHILLMOLLER, GE, United States of America

- demonstrably high levels of safety;
- minimum overall fuel cycle costs;
- minimum overall environmental impact, including minimum waste generation;
- maximum utilisation of natural resources;
- minimum proliferation risk and maximum safeguards visibility;
- public support;
- diversity and security of energy supply.

These requirements, which are not necessarily in any priority order, are comprehensively discussed elsewhere [3]. However, it is appropriate to re-emphasise one particular concept - the 'holistic' fuel cycle.

The 'holistic' fuel cycle considers the complete fuel cycle as a whole, rather than as a number of individual stages. Figure 1 illustrates how the concept integrates the various options for fuel manufacture, reactors, reprocessing, waste management and decommissioning to optimise the whole fuel cycle within the requirements of the total nuclear system [4]. Minimising total cost, maximising safety whilst reducing waste generation are all key factors and are consistent with the requirements listed above. The holistic fuel cycle is a long-term, maybe idealistic target - but it is a target worth striving for. To achieve it will require more flexible processes, greater synergies between existing systems and those planned for the future, more emphasis on co-ordination between the sectors and a greater role for international collaboration.

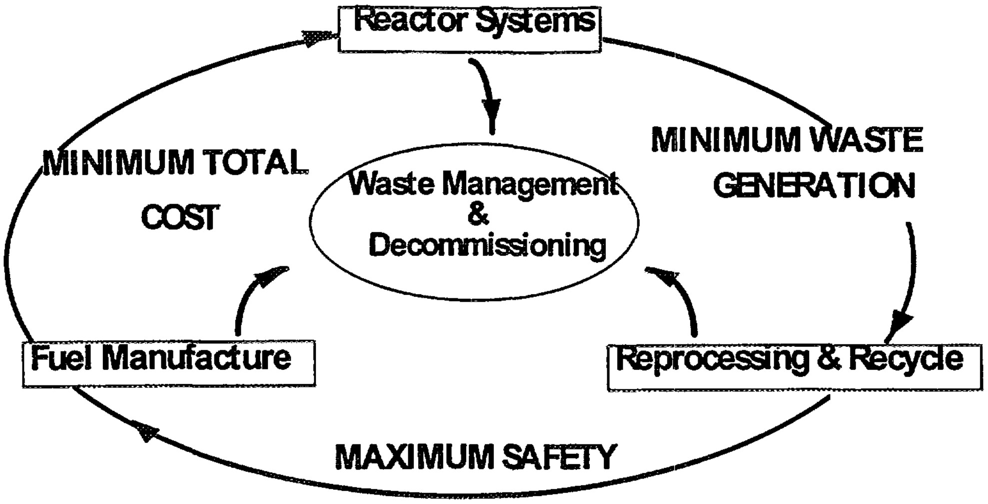

FIG. 1. The Holistic Fuel Cycle [4]

The purpose of this paper is to provide an international perspective on some of the emerging fuel cycle technologies that may be expected to see commercial realisation in the period 2015-2050.

2. FUEL CYCLE TECHNOLOGIES TO 2050

2.1. Centrifuge enrichment

J. Paleit, Urenco, UK

There are currently four primary enrichment suppliers in the long-term enrichment market - the United States Enrichment Corporate (USEC) which operates two plants utilising the gas diffusion process in the USA, Cogema/Eurodif which operates one diffusion plant in France, Urenco which operates plants utilising the gas centrifuge process in Germany, the Netherlands and the UK, and Tenex which operates four gas centrifuge plants in Russia. Small enrichment plants are also operating in China and Japan. The total capacity of these plants is some 55 million separative work units (SWU) per year or sufficient to cover the annual enrichment requirements of over 500 reactors of 1000 MWe capacity. This may be compared to an annual demand for enrichment services of around 38 millionSWU/a over the next ten years.

The enrichment services provided by the gas diffusion plant operators cover some two thirds of demand today with the plants at 70% of their nominal capacity. This level is close to their commercial maximum at today's market prices since above this level power costs for the diffusion plants rise considerably. A diffusion plant requires some 2300-2500 kWh/SWU.

By 2015 the diffusion plants in the USA will have reached the end of their lifetime following 55 years in operation. Even today they struggle to meet current licence standards and maintenance costs are high. In France the diffusion plant will be approaching 35 years in 2015 and be facing replacement.

The most modern enrichment technology today is the gas centrifuge, particularly that developed in Europe by Urenco. A number of design generations have been introduced over almost 25 years with modular installation of units having continuously improving efficiency and competitiveness. Costs are closely controlled and there is further technical potential already being developed.

The Tenex gas centrifuge plants are of an early design similar to that introduced by Urenco in the early 1970's. It is questionable whether this capacity can be maintained in operation in 5, 10 or 15 years time. Further the economics becomes more difficult as market economy principles are introduced. New centrifuge technology will require considerable R&D investment.

Looking ahead the first technology question will be what process will replace the gaseous diffusion plants by about 2015? Currently laser separation is being pursued as a possibility at laboratory scale (AVLIS or SILVA in the US and France respectively, MLIS in South Africa also with French investment). In Australia USEC is an investor in the SILEX process. A number of other routes, eg jet nozzle, helikon process and crisla, have been pursued in the past but not commercially proven on an industrial scale.

Experience has shown that new technology is fraught with development complexities, technical uncertainties and high cost. It will be for governments as well as the enrichment industry itself to determine how much capital is invested in new technology. This will also depend on the future growth of the nuclear power industry worldwide. One alternative to new technology is further exploitation of the gas centrifuge. This also has the advantage in its ability to re-enrich reprocessed uranium which is already offered as a routine service.

Looking beyond the period 2015-2020 towards 2050 is inevitably more speculative but the above comments also apply. In summary it is likely that technological development in the enrichment industry will be evolutionary rather than revolutionary in the next 50 years.

2.2. Laser enrichment

A. Schillmoller, GE, US

The traditional enrichment of virgin uranium through the centrifuge and diffusion processes has historically provided as much as 95% of the Western World's enriched uranium supply with non-traditional sources providing the balance. However, it is now clearly apparent that the ageing diffusion plants are approaching technological and economic obsolescence. These plants and technology must surely be replaced by 2025. The United States, France, and Japan have announced programs that may lead to the deployment of laser enrichment technologies. The most advanced of these programs, AVLIS and SILVA, enrich uranium in the form of a metal alloy, in contrast to the Russian and Urenco advanced centrifuge programs which handle gaseous uranium hexafluoride. The deployment of laser enrichment has major implications for both the uranium conversion and fuel fabrication segments of the industry where the potential receipt of uranium in both a metal and UF_6 form may lead to significant restructuring.

USEC has announced the scheduled operation of the first AVLIS laser enrichment facility for 2005. Cogema has not yet announced a deployment date for SILVA or MLIS, but by 2025 the Pierrelatte facilities will be approaching 50 years old and due for replacement. Since AVLIS and SILVA process uranium in the form of a metal alloy, UF_6 may no longer be traded universally for either natural feed or enriched uranium product. This may necessitate both a new front end product for laser enrichment and also a new back end product for delivery to the fuel fabricators. The enricher faces the choice of delivery of uranium to the fabricator in the form of metal, UF_6, or oxide. It is anticipated that some form of extraction process will be required to remove all contaminants from the uranium alloy. This may be done at either the enrichment facility, at a central reconversion plant, or at the individual fabricators. The enrichment enterprise also faces the decision of reconversion technology, plant(s) size and location. Economics, safety, and environmental considerations will enter into the decision. A probable outcome is that existing solvent extraction (Purex) technology will be used to process the uranium alloy and that the resultant uranyl nitrate will be converted to uranium oxide at central reconversion plant(s).

Therefore by 2015, the fuel fabricator may be facing a new reality. Enriched uranium product may be available in the form of UF_6, uranium alloy, and oxide. The fabricator will face the decision of maintaining duplicate facilities and technologies to deal with the various uranium forms or working with others to rationalise the diverse forms of uranium feed. The maintenance of duplicate capabilities and facilities by the individual fabricator will entail the worst of both worlds. To avoid this problem, we believe that it is logical that central reconversion facilities will be constructed by the enrichers and that the fabricators will consolidate UF_6 processing capacity by shutting down the older wet ADU processes.

The fabricator will consider four broad criteria in determining the acceptability of uranium for processing: (1) ALARA, (2) Quality, (3) Fuel Performance, and (4) Cost. Laser enrichment provides a safe, environmentally sound and acceptable industrial process for transporting and manufacturing enriched uranium dioxide. Current technology involves the shipment and processing of UF_6 gas into UO_2 powder and pellets. The atomic vapour laser process will ship and process a uranium metal alloy in the form of ingots. The environmental and industrial safety problems of shipping and handling UF_6 gas cylinders are eliminated and leakage to the environment will no longer be a concern. The difficulty and hazards of processing fluoride gases, hydrofluoric acid and solid fluoride wastes are also avoided.

Compared to gaseous diffusion and gas centrifuge technology, the laser enrichment process is safer, reduces total energy cost and protects the environment.

2.3. Fuel

K. Hesketh, BNFL, UK

The long-term evolution of fuel product and manufacturing technologies will largely be dictated by the mix of reactors that will exist. The nature of this reactor mix has been, and will continue to be debated in detail elsewhere. One vision of a nuclear industry revived by growing global electricity demand whilst fossil fuel reserves fall and global warming is kept in check is:

- Existing LWRs will be shutdown, or at least be middle-aged by 2015. New-build will be APWR or ABWR, with further enhanced designs being considered after 2020.

- Helium-cooled graphite moderated high temperature reactors are commercialised having advantages of high thermal efficiency, intrinsic safety of high melting point fuel, single phase coolant and no need for metallic cladding.

- Fast breeder reactors also become available, driven by increasing uranium prices, flexibility to keep plutonium stocks in balance and recognition that they generate far fewer minor actinides per GWye.

- Reprocessing will be accepted, but must compete economically with interim storage. Plutonium becomes a scarce resource.

So existing and advanced LWRs will be operating in 2015, whilst further advanced thermal reactors, high temperature reactors and fast breeder reactors will co-exist by 2050.

Against this possible background, let us consider now some of the issues relating to fuel.

The economics of thermal reactor fuel will depend upon both the 'front end' and the 'back end'. In the 'front end', the economics improve with burn-up to about 55-60GWd/t. Beyond this level, the separative work function rises steeply and the corresponding irradiation times imply a greater discounting penalty, both of which restrict the likely economic burn-up. In the 'back-end', both reprocessing and direct disposal costs are likely to increase with burn-up. When all these effects are taken into account, the economic optimum burn-up of thermal reactor fuels are not much different from today's technological capabilities - up to about 60GWd/t.

As to the future technical limitations on fuel burn-up, it is considered that for a reprocessing cycle, the likely range will again be about 55-60GWd/t. Extending burn-ups beyond this range may not be optimal because of increased difficulty and expense of reprocessing more active fuels, decreasing fissile quality of plutonium (particularly if considered for re-use in thermal reactors) and low U-235 assay. Therefore, minor developments in fuel design and cladding are all that will be required.

For the once-through cycle, much increased 'back-end' costs may drive burn-ups towards 80 or even 100GWd/t. However, current cladding has little prospect of achieving such levels of burn-up and a radical alternative - such as ceramic cladding will be required. Furthermore, the much higher power peaking factors associated with high burn-ups will take the fuel too close to its fundamental limits, such as melting point. A new fuel design will therefore be required.

High temperature reactor fuel will use coated particles - uranium dioxide or MOX inside a silica or silicon carbide shell, possibly pressed into blocks incorporating graphite or maybe as a pebble bed. Fission gas retention should be good and there is no requirement for cladding, hence there should be few barriers to achieving very high burn-ups and setting the economic standards against which the LWRs will have to compete.

There are several other fuel cycle options that are likely to be relevant in the period 2015-2050:

- Use of recycled uranium. Current enrichment processes enrich U-236 (a neutron absorber) and U-232 (with strong gamma emissions from its daughter products making fuel fabrication difficult) as well as U-235. Selective enrichment of U-235, for example by laser isotope enrichment, would allow use of recycled uranium of lower assay. However, fuel from recycled uranium can only remain a small proportion of world's fuel supply, though it might be a useful strategic resource if uranium prices increase dramatically.

- New reprocessing technologies may chose not to separate U and Pu to present levels of purity with consequential effects on fuel manufacture. Examples may be pyroprocessing followed by vibro-manufacture (Section 2.5) or concentrating Pu to about 20% in uranium and finishing to fuel by a gel route.

- Thorium-based fuel cycles may form a minor part of the overall nuclear capacity, though current views are that the theoretical advantages are insufficient to achieve dominance over uranium/MOX cycles and that the claimed non-proliferation benefits may not gain full public acceptance.

- MOX recycle in LWRs will be accepted, partly through disposition programmes, though its use will be relatively small scale. Reprocessing and reuse in LWRs, or high temperature reactors, prior to optimising its value in fast reactors is likely. Ultimately MOX will need to be disposed of, whether or not it is recycled further.

It is therefore concluded that advances in fuel technologies over the next 50 years will be driven by the prevailing reactor mix, by economics and by the need to integrate fuel manufacturing with adjacent segments of the fuel cycle, for example, the output from reprocessing plants.

2.4. Aqueous reprocessing

N. Camarcat, CEA, France
P. Pradel, COGEMA, France

The World's current reprocessing technology is the 50-year old PUREX process, with associated waste treatment operations. The conservatively-designed PUREX process achieves a high recovery efficiency and meets defined end-product specifications. Incremental improvements, for example in the performance of the extraction cycles, will lead to lower activity levels in effluents and improved operating practices will lead to reduced waste volumes.

However, in addition to technologies targeted at cost reduction and enhanced safety, a future objective is to reduce the total potential radiotoxicity of the waste to be disposed of. This can be achieved by reducing waste volumes and, particularly in the longer term, by reducing the toxicity of the wastes for disposal through further separation and treatment of their actinide content. The SPIN (SeParation-INcineration) programme in France is a good example of a national programme aimed at such a flexible and complete scheme for HLW management. The SPIN programme involves two sub-programmes:

PURETEX, for the short and medium term, endeavours to reduce the volume and activity of reprocessing waste from 1.5m^3 to 0.5m^3/tHM (against 1.7 m^3/tHM for direct disposal in the once-through cycle). The optimisation involves volume reduction, decreased activity in wastes and discharges, and improved matrix confinement properties.

For liquid waste, preference is given to evaporation processes over precipitation processes and the activity of discharges to the environment is reduced by sorting the effluents at source. CEA is also developing incineration or the mineralisation of organic compounds. For solid waste, the search for techniques best suited to each type of waste such as incineration of burnable waste, compaction of compressible waste, fusion of metallic waste and mineralisation of oxidisable waste are under investigation.

A large part of the PURETEX programme is connected with industrial projects of COGEMA:

- A new waste management scheme for low and medium active effluents at La Hague, has led to the elimination of coprecipitation and the associated bitumen wastes;
- The replacement of waste grouting for hulls and end fittings by a more efficient process of compaction;
- The construction of a facility for processing by-products and alpha wastes.

ACTINEX, for the long-term, is oriented towards the reduction of the ultimate waste quantity and toxicity. ACTINEX will assess the various separation and transmutation strategies, their advantages, their feasibility, and their use in novel nuclear schemes (including recycling of minor actinides in fission reactors and hybrid systems).

It is first necessary to assess the way to reduce the potential radiotoxicity of the spent fuel containing uranium, plutonium, fission products and minor actinides where the main contributors to the radiotoxicity include americium, curium and neptunium isotopes (since plutonium has been separated by classical PUREX process). Separation of americium and curium is difficult. Specific processes such as the DIAMEX or the SESAME process using innovative schemes of solvent extraction with new organic molecules are under development. Fundamental research also goes on for selected fission-product separation, especially for technetium, zirconium and caesium.

Aqueous reprocessing technologies are continuously under development and can be adapted to a large range of environmental choices. For the mid- and long-term, advanced fuel cycles will represent opportunities to take technology towards a more flexible and complete scheme for HLW management. R&D programmes are in progress to assure this objective and to confer benefits in fissile material utilisation and in environmental concerns over current conservatively-designed cycles.

2.5. Non-aqueous reprocessing

V.B. Ivanov, RIAR, Russian Federation

Non-aqueous methods are possible new technologies for the fuel cycle. Indeed fuel reprocessing plants constructed after 2015 may be based on such flowsheets. The non-aqueous processes tend to be shorter and simpler (fewer operations) as well as ensuring the containment of hazardous components within the system and the ready compatibility between reprocessing and fuel manufacture. They also tend to demonstrate the desirable attributes listed in Section 1 (above).

Several examples of the development and application of non-aqueous processes already exist. Here we will consider the molten salt, fluoride volatility and DUPIC technologies.

Pyroelectrochemical reprocessing using molten salts includes the following main stages:

- dissolution of the irradiated fuel in molten salts (mainly molten alkali chlorides at 450-700°C);
- decontaminating the fuel by electrolysis or other methods;
- minimal treatment of the products (such as removal of salts and crushing, melting or liquid metal vacuum extraction) prior to remanufacture of the fuel.

This approach has been applied to oxide fuel (RIAR, Russia), metal fuel (Argonne National Laboratory, US) and nitride fuel (JAERI, Japan) with suitable modifications. Benefits include:

- high chemical stability
- high dissolution capacity (more than 30 wt %)
- no neutron moderator
- improved proliferation resistance
- generally performed in one compact device, leading to lower production costs
- minimised HLW volume through concentration of fission products from the molten salts
- final products are ready for fuel manufacture
- suitable for wide range of fuel types without the need to alter equipment

Though the technology was developed for FBR fuel (eg for oxide fuel at RIAR or metal fuel at Argonne) there is sufficient experimental data to demonstrate the applicability for LWR fuel. Indeed, these processes have been tested on a semi-industrial level and are ready for commercialisation.

A second non-aqueous technology is fluoride volatility. This well-known process has some safety drawbacks as a large portion of the radioactive materials is transferred into the gaseous phase. However, techniques are available which can allow only the uranium to be extracted (as UF_6) from the irradiated fuel, keeping all other products solid. If necessary, a pyrochemical treatment can extract the plutonium dioxide from the fluorination residues (the CENTAUR process). This process is particularly suitable for reprocessing long-cooled fuel in order to extract good quality uranium suitable for further enrichment.

In future, there may be limited application of methods for direct repeated irradiation of fuel. The DUPIC (Direct Use of PWR fuel in CANDU) programme in South Korea is an example. Though this method has yet to be demonstrated on a large scale, feasibility studies are encouraging. Similar principles can be used for internal recycle of FBR fuel especially for fuel containing minor actinides for transmutation.

All these technologies have been experimentally proven to differing degrees. They can be modified depending on the reactor types used in future and will permit the reduction in recycle duration by integrating reprocessing and fuel manufacture.

2.6. MOX

M. Katsuragawa, PNC, Japan

Plutonium utilisation in existing LWRs as MOX fuel has now reached commercial maturity in France, Germany, Switzerland and Belgium. Japanese utilities will also start to use MOX by next century. It is estimated in the year 2005, about 400t of LWR MOX fuel will be loaded annually in these countries. This trend will be continued and progressively accelerated by increasing the number of licensable LWR plants and the loading level of MOX fuel from the present partial core to full cores. Furthermore, one option for the disposal of surplus weapons Pu, amounting to more than 100t, is burning as MOX in existing LWRs.

To promote LWR MOX utilisation, there are several issues to be addressed; improved economics, higher burnup and recycling of Pu from reprocessed LWR MOX spent fuels.

The cost of MOX fuel fabrication is four to five times higher than for conventional uranium oxide fuels [5]. With the increase of MOX utilisation and thus the expanding fabrication capability of industrial MOX plants, PNC estimates that MOX fabrication costs should be reduced to less than three times that for uranium oxide fuel. This will be achieved in fully automatic MOX plants by modifying and simplifying fabrication processes and developing more integrated equipment. Burnup increases to 55 GWd/t and beyond is another important factor for economic improvement. However, multi-recycling of Pu by reprocessing of LWR MOX spent fuels produces degraded Pu which contains more radioactive minor actinides to be transmuted and lower fissile content, requiring more protective shielding of the MOX fuel fabrication process. This will negate the efforts to save cost.

Around the year 2020 to 2030, the Pu stockpile from reprocessing will be adjusted by consuming it as LWR MOX and then the FBR will be introduced to consume recycle Pu from spent LWR MOX and provide sufficient flexibility to adjust the Pu production and consumption.

Industrial fabrication of FBR MOX fuel with higher quantities but less fissile Pu content is the next target. The fabrication technologies proven for LWR MOX fuel can be applied to FBR MOX. However, there will be strong incentives to improve safety, economics, proliferation resistance and waste minimisation by implementation of advanced technologies. The main candidates for advanced fuel technology are likely to be based on current MOX fuel recycle, because LWR MOX will still continue to be utilised in parallel with FBR MOX after around 2030.

The concept of advanced MOX fuel fabrication is closely linked to advanced reprocessing such as advanced PUREX and pyrochemical reprocessing, which aim for coextraction of Pu/U with low decontamination factors. This requires fabrication technology able to treat Pu/U/MAs in a simplified remote process without an increase in costs. One effective way to reduce MOX fuel fabrication costs drastically is the integration of recycling capability, ie the integration of fuel fabrication, reprocessing and waste treatment in one plant. Sphere-packing or vibro-packing fuel fabrication are attractive candidates; both have already been demonstrated in Switzerland and Russia and used in the UK.

International discussion and collaboration for the review and implementation of R&D for advanced fuel technologies is strongly recommended. The selection of advanced recycle technologies should be discussed widely to consider the circumstances when LWR MOX spent fuel is available for reprocessing and when the FBR fuel cycle is overtaking the LWR MOX fuel cycle; parallel LWR/FBR reprocessing plants are likely to be essential.

2.7. Partitioning and transmutation

R. Schenkel, ITU, EU

The safe disposal of highly active wastes dominates the nuclear debate in several countries, despite the fact that long term modelling calculations [6] demonstrate that the resulting maximum risk is much less than most of the risks commonly accepted by society. To further reduce the potential long-term hazard of such wastes, partitioning and transmutation (P&T) research is being performed in several countries [7,8,9] with the objective of separating the actinides and long-lived fission products then reducing their toxicity by transmutation.

Current use of MOX fuel in thermal reactors can be considered as a simple example of successful P&T for plutonium. Other toxic elements include neptunium, americium and possibly curium and technetium. Ongoing R&D activities concentrate on three major areas : partitioning, advanced fuel fabrication and transmutation.

New chemical separation processes with high separation and decontamination factors are under investigation. Extractants under test are CMPO, TRPO, DIPDA or Diamides [10]. Non-aqueous pyrochemical processes appear to be better than aqueous processes in the context of recycling and P&T applications in fast reactors; the main reasons are given in Section 2.5 (above).

It is clear that a fast neutron flux is essential for efficient burning of even numbered actinides and some odd numbered isotopes such as Np-237 and Am-241 [11]. Only systems with intensive high energy neutron spectra, like fast reactors or accelerator driven subcritical systems with their potential for very high neutron fluxes can effectively transmute minor actinides and long lived fission products.

How might P&T develop in future? Nuclear energy, around 2020, is expected to be provided by predominantly LWRs, some based on advanced designs. There are indications that the uranium price could increase, due to shortage of easily accessible ores, in the period from about 2020 to 2050. In such a situation, fast reactors or thorium fuelled reactor systems may become economic alternatives, [3]. This transition period of coexistence of thermal and fast reactors could be long; it may in fact be a good choice at different stages in different countries. As far as P&T is concerned, such a development could lead to the following scenarios for countries that have chosen the recycling option:

- In the medium term, the introduction of P&T could be in harmony with thermal reactor fuel cycles, i.e. predominantly based on aqueous partitioning and heterogeneous recycling in a fast spectrum waste burner. The CAPRA project could be considered a prototype for the fast burning not only of excess plutonium, but also for minor actinides. Accelerator Driven Systems fuelled by metal alloy, oxide or even nitrides could play a similar role, in particular with regard to long lived fission products.

- In the long term, the introduction of P&T could follow future reactor development. Accordingly there could be fast burners with metal, oxide or nitride fuel with minor actinide enriched cores and/or systems with self recycled fast neutron systems, i.e. in a "mixed park" concept or like for example the Integrated Fast Reactor. Fuel could be recycled on-site using pyrochemical and electrorefining technologies. In the steady state, with a conversion factor of about 1, the reactor would consume most of its own long lived waste and would only require the addition of fertile uranium or thorium as a source of fissile material.

2.8. Direct disposal

S. Bjurström, SKB, Sweden

Today, over 100,000t of used fuel is stored at nuclear power plants and interim storage facilities around the world. The world's reactors discharge another 10,000t of used fuel annually, of which around 3000t is recycled by reprocessing. Independent of the development of existing and future technologies for utilisation of this huge energy resource there is a need for storage over long periods and for permanent disposal solutions. The direct disposal technologies developed today can play an important role; a deep repository planned for direct disposal of spent fuel can retain this flexibility over long time periods with minimum burden on the future and maximum safety.

Direct disposal systems are based on deep geological disposal and the utilisation of several technical barriers to ensure safety and isolation. The advantage of such geological repositories are that many countries have suitable geology for a repository and thus the possibility of taking care of their own waste. Clay, salt, sediments and granites may all be very good host mediums for a repository. Such a repository is not technically complicated though demonstration of the safety can be complex.

The particular risk of direct disposal of used fuel is that one must deal with the properties of the fuel as they are. The potential hazard of fuel placed in a repository is related to effects "after intake" where the radioactive elements may reach the biosphere by water flows through the repository. For this, the ability of the fuel to be dissolved into groundwater obviously plays an important role. Fission products in the fuel like caesium can be dissolved and reach the surrounding environment. However, the lifetime of those products is relatively short - some hundred years. For the long lived actinides, the potential risks will remain for much longer - many ten thousands of years before it has the same toxicity as the once-mined uranium. But, and this is very important, those products in a stable chemical form are almost impossible to dissolve and hence the source term will be very small and it is almost impossible to calculate any releases.

Spent fuel and also the vitrified waste from reprocessing must be isolated in a qualified way for several hundred years to take care of the short-lived activity. For longer periods the placement in a deep geological formation is the most important factor. There is however no reason not apply strict regulation and utilise today's good and available technology. The relatively small volumes means that much can be done within reasonable economic limits, as illustrated by the system developed in Sweden. Here safety and the isolation of fuel is based on:

- the fuel, almost impossible to dissolve in water;
- copper canister, to encapsulate the fuel in a very corrosion resistant material;
- emplacement into watertight swelling bentonite clay;
- the bedrock offering "lasting" conditions and also acting as efficient filter.

Disposal of encapsulated fuel is planned to start between 2008-2012 and continue for several decades. The technology for encapsulation is already developed on an industrial scale for a copper canister with a steel insert. A pilot plant is under construction and an application to build a commercial facility in connection with the existing interim storage is planned to be submitted some years after the turn of the century.

The deep repository is expected to be built in Sweden in a location where the geology is suitable and where there is support from the local population. The facility consists of a medium sized surface industry and underground tunnelling system at 400-500m depth where encapsulated fuel will be placed. Public acceptance is a crucial issue. Discussions are in progress with 5-10 municipalities which may be suitable for initial feasibility studies. Subsequently, investigative drilling in two locations will take place prior to selecting one for detailed characterisation in tunnels. Subject to acceptance of that particular municipality and satisfactory test results, the first phase of the repository will be constructed there.

In summary, direct disposal systems in deep repositories can offer a solution for safe storage of fuel over long periods. Such storage can - with proper preparation - be turned into a permanent solution at any time as decided by future decisionmakers. At all times there will be flexibility to accommodate new conditions and requirements and to retain the possibility to reuse the fuel (although demanding more or less work).

2.9. Waste

R. G. G. Holmes, BNFL, UK

One of the most complex and challenging areas of the fuel cycle is that of waste management and disposal. Waste management and disposal includes reducing the generation and diversity of wastes (waste minimisation), its retrieval, treatment, storage and ultimate disposal. Wastes include stored historic wastes generated during the early years of the nuclear industry, arisings from current plant, many of which will continue into the period 2015 to 2050, waste from decommissioning and management of redundant plant or sites and waste from advanced fuel cycle options.

The technical challenges in the waste management area include:

- Treating the large volume of historic waste.
- Devising acceptable schemes for disposing of solid wastes.
- Reducing current discharges whilst tackling the historic waste problems.
- Producing cost effective strategies that are sensitive to environmental issues.

Treating large volumes of historic waste will certainly tax the abilities of the nuclear industry. It is, however, unlikely that these tasks will demand new technological solutions, but rather they will demand skilful integration and deployment of demonstrated technologies to provide robust facilities to treat waste for disposal, with minimal discharges.

In the timeframe 2015 to 2050 it is unlikely that partition and transmutation of nuclides in waste, except utilisation of recovered actinides and ex-military material in MOX fuel, will be demonstrated and justified on economic or environmental grounds.

The main technical option is for land disposal of the current wasteforms (e.g. grouted or vitrified wastes); here the challenge is to provide a robust safety argument to support the disposal option, relying heavily on predictive tools and models underpinned with a strong scientific understanding of the local geology and problems associated with disposal.

Since disposal is currently viewed as a national or regional responsibility, past attempts to adopt an international approach by, for example deep sea dumping, have not been accepted. An international land-based repository is technically feasible in view of the relatively small total volume of higher categories of waste involved and may offer advantages where the effects of some radionuclides are not driven by inventory. Such an international approach might also offer the opportunity to utilise the best available geologies (for example, avoiding areas of seismic activity) and also offer a flexible solution for countries which cannot afford or may not need their own internal facility. Regional or international repositories seem almost inevitable.

A major issue in waste and indeed the nuclear industry is that of public perception. With the advent of freely and rapidly available information we can expect a more informed public. This is likely to result in:

- A more balanced public perception of nuclear energy in the context of competitive energy sources.

- A less emotive view of the nuclear industry with lower emphasis on our military beginnings.

- A greater understanding and less fear of the implications of radioactivity.

To play its part, the industry must put safety as its highest priority. We must also understand the public position and agenda and work with the public to address their concerns, putting our case in easily understandable terms.

Advanced fuel cycle processes will produce less waste for discharge and disposal. The concepts that are being adopted by all process industries will be applied to the nuclear industry, that is eliminating waste of all types at the process definition stage, using gentle and benign reagents, recycling and reusing material generated by processes. These activities must be pursued to balance the increased effect of treating historic wastes.

The size and scope of the challenge however demands international collaboration between existing and emerging players in nuclear energy. Standards and options require a level of international endorsement whilst the consequences and benefits of the nuclear industry transcend national boundaries. To ensure research programmes are cost effective, international collaboration in technology development, benchmarking and sharing experiences are essential in the development of advanced fuel cycles.

3. KEY ISSUES

In the foregoing technical contributions, we have shared a vision of some of the fuel cycle technologies that may reach commercial maturity in the period 2015-2050. Though our coverage is by no means comprehensive, many issues have emerged - some technical, some institutional:

Technical

- Role of laser isotope separation when set against the evolution of advanced centrifuge technology;
- What burn-up will LWR's achieve?
- When might Fast Reactors or Thorium fuels be implemented?
- Can the advantages of non-aqueous reprocessing overturn 50 years of experience with the PUREX process?
- Is MOX reprocessing viable? What technologies may be needed to refabricate the fuel for use in FBRs?
- What are the optimum transmutation schemes and can accelerator driven subcritical systems become a reality? On what timescale?
- To what extent does transmutation reduce overall dose and is such a reduction cost-effective?
- Is it realistic to consider retrievable deep geological repositories?
- How do we balance the need to clean up historic wastes whilst reducing discharges?

Institutional

- How can we promote discussion and collaboration as a means of optimising the fuel cycle?
- How can we work together to minimise the overall cost of the fuel cycle, yet maintain commercial competition, especially in a market that historically has looked at only one sector at a time?
- How much will governments be prepared to invest in new technology?
- How do we reach agreement on international repositories?
- How do we learn to understand and communicate with the public?
- How can we retain facilities and competence in preparation for the dawning of the FBR age?

This leads to the final point; the need to retain facilities, resources, training and competence means that we can't just switch the nuclear industry 'on' and 'off'. In about 20 years we will know for sure how serious is the threat of global warming. Nuclear appears to be the most significant contributor to retarding or even reversing planetary damage; addressing some of these issues will keep nuclear switched 'on'.

REFERENCES

[1] for example, HOUGHTON J., Energy for Tomorrow's World - the Realities, the Real Options and the Agenda for Achievement, World Energy Council Commission (1993), Kogan Page.

[2] EYRE B.L., Prospects and Challenges for Nuclear Power in the 21st Century, Proc KAIF/ANS Conf. (1997), 45-59.

[3] MENELEY D., et al, IAEA-SM-343/KIP-3, these Proceedings.

[4] ION S.E., Alternatives for High and Intermediate Level Waste Management, Proc 4th Conf of the European Commission on the Management and Disposal of Radioactive Waste, Luxembourg (1996).

[5] Special report from COGEMA, The Nuclear Fuel and COGEMA (March 1994).

[6] Performance Assessment of Geological Isolation Systems for Radioactive Wastes (PAGIS), Summary, Commission of the European Community, EUR 11775 EN (1988).

[7] M. VIALA, M. SALVATORES, The SPIN Program, in Global 1995, International Conference on Evaluation of Emerging Fuel Cycle Systems, p. 118 ff.

[8] T. MUKAIYAMA et al, Partitioning and Transmutation Program "OMEGA" at JAERI and T. YOKOO et al, Performances of Minor Actinides Recycling LMRs in Global 1995, International Conference on Evaluation of Emerging Fuel Cycle Systems, Vol. 1, p. 110 ff and Vol. 2, p. 1570 ff. (1995).

[9] O.V. SKIBA et al, Nuclear Fuel Cycle based on "Dry" Methods for Fuel Reprocessing and Fuel Manufacture Automated Processes, Global 1993, Future Nuclear Systems, Vol. 1,p. 934.

[10] J.P. GLATZ, J.F. BABELOT, G. NICOLAOU, L. KOCH, Theoretically and Experimentally Derived Criteria for Partitioning and Transmutation of Radionuclides in Existing Reactors NEA Report N° 13 (1995), p. 489.

[11] H. RIEF, J. MAGILL, H. WIDER, Accelerator Driven Systems - Some Safety and Fuel Cycle Considerations, NATO Advanced Research Workshop on Advanced Nuclear Systems Consuming Excess Plutonium, 13 - 16.10.96, Moscow (1996).