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Whither the Nuclear Fuel Cycle?

Drs. Evelyne Bertel and Peter Wilmer

The government context that serves as a backdrop to energy policy making at the turn of the millennium is characterised by trends towards deregulation of the electricity markets and increasing awareness of sustainable development goals. Both trends are affecting nuclear energy and its fuel cycle, offering new opportunities and raising new challenges for the future. Industrial practices and research and development programmes supported by governments and/or industry are responding to evolving market and social requirements. Ongoing R&D programmes in the field of nuclear reactors and the fuel cycle are contributing to the enhancement of the technical, safety and economic performance of nuclear systems in operation and under development. Scientific and technological progress follow either evolutionary or innovative routes, but always aim at improving overall efficiency throughout the nuclear energy chain.

Today, nuclear energy contributes to energy supply in more than 30 countries, including 16 OECD countries. More than 10 000 reactor years of commercial operation experience, including 8000 reactor years in OECD countries, have been accumulated. At the end of 2001, some 438 nuclear power plants were in operation in the world, representing an installed capacity of 353 GWe, supplying some 6% of total primary energy consumption and around 15% of total electricity generation. Some 80% of the total nuclear capacity is operated in OECD countries, where the nuclear energy share is higher than worldwide, corresponding to nearly one quarter of total electricity generation [1].

The fuel cycle technologies supporting the current generation of reactors are mature and established within a widespread industrial and commercial framework. There are, however, significant differences in the states of deployment and market conditions at the various steps of the fuel cycle. The technical and economic evolution of the nuclear fuel cycle will depend on the future growth rate of nuclear energy, and on national and utility choices between options for each fuel cycle step.

The nuclear fuel cycle *(Figure 1)* includes a series of steps, each having a specific function and particular characteristics. It covers all the activities needed to produce nuclear electricity, or eventually other energy products, from raw material extraction to disposal of radioactive waste. The evolution of the nuclear fuel cycle industries so far has been driven mainly by economic optimisation at each step while complying with increasingly stringent regulations on safety and radiation protection. In the future, emphasis will be placed on integrated

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optimisation of nuclear systems, i.e. reactors and fuel cycles, from a sustainable development viewpoint.

In economic terms, the nuclear fuel cycle represents only some 20% of the total levelised cost of nuclear electricity generation but, once a nuclear power plant is in operation, the fuel cycle is key to maintaining the competitiveness of the plant. Furthermore, large benefits arise for the plant operator from enhanced fuel cycle performance that allow shorter re-fuelling time and longer in-reactor periods, leading to higher availability factors *(Figure 2)*. In the United States, for example, availability factors have increased dramatically recently, largely because of better fuel performance, thereby enhancing the competitiveness of nuclear units.

Industry and operators have made continuing efforts to reduce fuel cycle costs over the last decades. This is illustrated, for example, by a decrease of more than 40% between 1985 and 1994 in the levelised fuel cycle cost for a PWR operated once-through [2]. *Figure 3* shows that most of the cost reduction resulted from a decrease in fuel cycle unit costs and enhanced fuel cycle process efficiency, with fuel performance improvement, in particular higher average burn up, accounting for less than 10% of the savings.

The nuclear fuel cycle includes two main parts: the front-end, from the mine to the reactor, and the back-end, from the reactor to the waste repository. The industrial structure and market conditions are rather different for the two parts, with a diversified, although imperfect, international market at the front-end and a back-end dominated by domestic, often government-owned, service suppliers.

The front-end of the fuel cycle starts with the extraction of the raw fissionable material, i.e. today, natural uranium. Uranium mining and milling activities are based upon mature technologies with very low risk level, although environmental impacts are a concern for mining in particular and need to be addressed in due course to avoid long-lasting damage to aquifers and soils [3]. Modern uranium mining practices, in particular in OECD countries, reflect very strict radiation protection standards and are subject to regulatory controls. Measures to reduce the levels of risk to workers, the general public and the environment are common practice in mining facilities in operation today.

It should be emphasised that, although collective effective dose to the public from uranium mining and milling activities represents nearly half of the total collective effective dose from the entire fuel cycle, it remains very low. As shown in *Figure 4*, based upon the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the global average dose received by the public is mainly due to natural background. The share of the entire nuclear energy chain in global average annual doses to population is 0.3%, with uranium mining and milling activities contributing half of that, i.e. 0.15% [4].

Supply of fissile materials for nuclear energy is not a concern. The short-term market is well supplied and supplemented by materials released from military use. Uranium resources are sufficient to meet expected demand in the short and medium term. Known conventional uranium resources, i.e., Reasonably Assured Resources plus Estimated Additional Resources recoverable at costs <US$130/kgU are estimated at 3.93 million tU as of 1 January 2001 [5]. They

represent more than 60 years of present consumption and additional resources, that are known to exist, can be better identified with adequate exploration efforts.

It is known that uranium is abundant in the earth's crust and in sea water. Conventional resources, including known and speculative resources, are estimated at 16 million tU or 250 years of present consumption. Beyond conventional resources, uranium recoverable as by-product from phosphates (~22 million tU) and from sea water (~4000 million tU) could provide supply for centuries. Obviously, the finding and economic exploitation of unknown and/or unconventional resources will require exploration effort and technology progress.

Alternatively, nuclear fuel supply may continue to be sought from various sources other than newly mined uranium, including recycled materials and thorium. The resource base can be extended by about 30% through reprocessing and recycling fissile material as MOX in LWRs, a technology already used to a significant extent in Europe and being deployed in Japan. With the introduction of breeders, which are among nuclear energy systems considered in the perspective of a possible nuclear energy renaissance, it is possible to multiply by 60 or more the energy produced from a given amount of uranium and to reduce significantly the amount of highly radioactive waste for disposal.

For light water reactors, which represent nearly 90% of the world installed capacity, the cost of uranium enrichment represents some 6% of the total nuclear electricity generation cost. Current enrichment technologies, i.e., gaseous diffusion or centrifuge, are capital intensive; gaseous diffusion plants have high operating costs because of their large electricity requirements. Furthermore, uranium enrichment processes are sensitive in the light of their potential use for non-civil applications. Therefore, only a few companies are offering enrichment services and the number of enrichment plants in operation is very small.

In spite of the barriers to entering enrichment supply activities, there is excess capacity in operation today, mainly because future demand was significantly overestimated in the mid-70s and it was not economic at that time to build small, modular plants. The availability of surplus capacity, reaching around 20 million SWU in the world by the turn of the century, has driven prices down continuously since the mid-80s and reduced incentives for innovative R&D in the field.

However, some enrichment plants in operation were commissioned more than 25 years ago and they will need to be replaced by modern, high-performance technologies within a decade or so. Since R&D on laser isotope separation has been scaled down drastically, and even abandoned in countries such as France and the USA, the next generation of enrichment plants is likely to be based on centrifuge technology [6].

The accumulation of depleted uranium (world stocks are estimated at around 1.2 million tonnes) could be an incentive to revive laser isotope separation, as this process could be used to re-enrich depleted uranium, thereby saving natural uranium resources. On the other hand, if it were to be determined that depleted uranium has no economic use, technical solutions for its safe interim storage and eventual final disposal exist and can be implemented [7].

Fuel fabrication accounts for only 3% of the total nuclear electricity cost but, in spite of this very small share, the influence of fuel design and fabrication on the overall economy of nuclear power can be very significant. At present, many fuel vendors are working in an extremely competitive market where fabrication capacity is well in excess of current and anticipated future requirements. For example, LWR fuel manufacturing capacity is nearly 50% above estimated annual requirements [6].

Improvement in fuel utilisation, resulting from better design and enhanced characteristics of fuel assemblies, not only reduces fuel cycle costs but also contributes to a higher availability factor of power plants, thereby decreasing total electricity generation cost per kWh. Overall economic optimisation, however, requires a comprehensive integration of fuel performance improvement within the entire fuel cycle strategy.

Scientific and technical progress is aiming at increasing possible discharge burn-up and improving fuel performance, while maintaining an excellent reliability of the fuel assemblies. Depending on the specific economic, technical and regulatory conditions that may vary from country to country and reactor to reactor, the fuel cycle cost can be influenced to various extents by improvement in the fuel utilisation and by the discharge burn-up increase. This is illustrated in *Figure 5*, based upon the experience in design improvement of the Siemens PWR fuel assembly.

The back-end of the fuel cycle, covering all steps after unloading of the spent fuel from the reactor, has a number of strategic implications related to radiation protection, safety, resource management and safeguards. In most countries, technology and option choices for the back-end of the fuel cycle are overseen, and in some countries decided, by governments rather than being left to the initiative of utilities and industry.

A number of approaches have been developed for interim storage of spent fuel, each adapted to national policy and choices for the long term, i.e. once-through or recycling options. Extensive experience has been accumulated on wet storage in cooling pools and dry storage in casks. It indicates that the technologies available for both approaches are suitable for storage over extended periods, probably up to one century. New developments in the front-end of the fuel cycle, including trends to higher burn-up and use of mixed oxide fuel (MOX), will affect spent fuel management, but they are not expected to pose problems for long-term interim storage, provided that adequate technology adaptation is implemented.

In choosing between the once-through/open and recycling/closed fuel cycle options, policy makers take into account a number of criteria that often are country-specific. Nevertheless, the main driving factors in most cases are similar and linked to policy issues such as natural resource management, availability of domestic energy resources and security of supply. For example, the reprocessing and recycling option has been chosen already by some countries, such as France and Japan, which do not enjoy large fossil fuel resources, mainly to increase the energy recovery rate from natural uranium. In the present economic context, however, costs and cash flow are becoming increasingly important factors.

Current uranium prices and resource estimates support economic choices in favour of pursuing the once-though option even if a significant growth of nuclear energy production is anticipated. On the other hand, in a sustainable development perspective, recycling is an attractive option for improving the efficiency of natural resource management and reducing radioactive waste accumulation. Furthermore, in a scenario of nuclear energy revival, including the development of nuclear systems for producing process heat, district heating, desalinated water and hydrogen, the demand for fissile materials may eventually exceed the quantities of uranium economically recoverable.

From the standpoint of radiological impact, although the uncertainties associated with public-exposure estimates are large, relevant findings can be drawn from authoritative studies. For example, an NEA report published in 2000 concluded that public exposures in both the open and closed fuel cycle options are low compared to the pertinent regulatory limits and insignificantly low compared with exposures from natural background radiation [8]. In this context, the differences between the two fuel cycles are not significant.

The economic comparison of recycling versus once-through cycle depends on the expected prices of natural uranium and fuel cycle services as well as country- and technology-specific financial and social conditions. The 1994 NEA study on the economics of the fuel cycle [2] concluded that the small fuel cycle cost advantage, in the idealised reference case of direct disposal versus reprocessing for a standard PWR, was insignificant taking into account uncertainties and country specific variability in costs and other assumptions, e.g., discount rate.

Strategic policy issues have driven choices for or against reprocessing and recycling of fissile materials in the past and will continue to play a major role in the development and deployment of advanced fuel cycles, such as, for example, multiple recycling schemes with partitioning and transmutation of minor actinides. An increasingly important factor, in addition to enhanced uranium resource management, is the reduction of radioactive waste volumes and toxicity achieved by reprocessing and recycling, and the associated benefits in a sustainable development perspective.

At present, without fast breeder reactors, recycling is implemented only through re-use of plutonium extracted from spent LWR fuel in mixed uranium-plutonium (MOX) fuel for LWRs. With the reprocessing capacities in operation, about 3500 tHM of spent fuel, i.e. one third of the amounts discharged, can be reprocessed each year. The current technical and regulatory limits in MOX fuel use – up to ~30% of a reactor core can be loaded with MOX fuel – are resulting in an imbalance between separation and utilisation of plutonium. The stockpile of separated civil plutonium was estimated at about 200 tonnes at the turn of the century.

Recycling of plutonium in LWR-MOX reduces the eventual radiotoxicity of spent fuel by a factor of three if spent MOX fuel is disposed of after one use, i.e. not recycled. Multiple reprocessing and recycling can reduce waste radiotoxicity even further. Theoretically, separating the plutonium and uranium from the fission products and minor actinides several times could lead to a decrease in the long-term radiotoxicity of waste to be disposed of by a factor of 10. However, this reduction can be obtained only after many decades and if process losses are very small.

Current reprocessing practices already contribute significantly to reducing the volumes of radioactive waste. While each tonne of spent fuel represents around 1.5 m^3 of high-level waste (HLW), less than half of a cubic metre, including 0.115 m^3 of vitrified HLW and 0.35m^3 of intermediate-level waste (ILW), remains after reprocessing, and further compacting can be achieved before disposal [2, 6].

Irrespective of the fuel cycle option chosen, the need for a final repository of radioactive waste remains. Advanced fuel cycle schemes could, in principle, reduce drastically the radiotoxicity waste as compared to the once-through option but cannot eliminate totally the need for ultimate disposal of some waste. *Figure 6* shows the evolution in time of the radiotoxicity of waste for different fuel cycle options and indicates that in all cases a need for long-term repositories remains.

The challenge raised by long-lived radioactive waste disposal is not unique to nuclear energy. Other types of toxic waste, such as heavy metals, will remain in the biosphere indefinitely, while ultimately radioactive waste will decay to background level. Furthermore, the volumes of radioactive waste are small, typically less than 1% of the overall toxic waste in countries with a large nuclear energy industry and, while the overall cost of radioactive waste management and disposal is rather high in absolute terms, it does not add significantly to the cost of nuclear electricity [9].

Most countries are developing radioactive waste management programmes aiming at geological disposal of long-lived radioactive waste. This approach was selected after considerable debate and comprehensive analyses taking into account technical, economic and socio-political aspects. Although repository siting programmes have been delayed in many countries, the consensus view remains that geologic disposal is technically feasible and offers a strategy responsive to fundamental ethical and environmental considerations [10].

The present debate on radioactive waste management focuses more on social and ethical implications than on technical feasibility. Confidence in the feasibility of secure and safe deep geological disposal is built upon extensive studies and characterisation and quantitative modelling of natural and engineered barriers of repository systems. Recent developments, in Finland and the United States in particular, show considerable progress towards the implementation of HLW repositories.

On the other hand, the relevance of reversibility and the advantages of long-term storage over final disposal are gaining importance in the light of the emergence of possible alternative options, such as partitioning and transmutation (P&T) of minor actinides. However, while reducing the long-term hazard of radioactive waste from nuclear energy is a core goal for sustainable development, it should be stressed that the full potential of transmutation can be obtained only if a P&T system is utilised for a minimum time period of about a century [11].

Furthermore, the development and industrial deployment of nuclear systems that could achieve, through partitioning and transmutation, the desired radiotoxicity reduction will require extensive R&D. The key challenge for policy makers in this regard is that it is not possible to assess satisfactorily, with the information available today, the benefits from P&T in reducing the burdens and long-term legacy of long-lived radioactive waste. It is difficult in this context to estimate whether the benefits from P&T systems could outweigh the investments necessary for demonstrating their viability and performance.

Although the fuel cycle industry has reached commercial maturity for most of its steps, a range of developments are going on, or projected, that will need R&D programmes aimed at adapting present technologies or developing new innovative approaches within the framework of a nuclear energy renaissance. Beyond the reactors in operation or under construction, a new generation of nuclear energy systems is expected to be designed and developed to meet future requirements.

Several national and international endeavours aiming at the development and eventually the deployment of a new generation of nuclear energy systems illustrate the core role of fuel cycle technologies in meeting the economic, social and environmental objectives of sustainable development. For example, fuel cycle options are integrated in the Generation IV International Forum (GIF) Roadmap [12]. The purpose of the GIF Roadmap is to identify nuclear energy systems that offer the greatest potential for: economic competitiveness; more sustainable use of natural resources and reduced environmental burdens; improved proliferation resistance and physical protection; and enhanced safety and reliability *(Figure 7)*.

The nuclear energy systems selected for further R&D within the GIF Roadmap include a wide range of innovative technologies *(Figure 8)* that raise a number of challenges in the fuel cycle area. Key issues to be addressed in R&D programmes designed for assessing the viability and demonstrating the performance of fuel cycles for Generation IV systems include spent fuel management and repository concepts for once-through cycles and advanced reprocessing technologies for recycling options. In addition, for some very innovative concepts, specific testing of fuel and materials needs to be carried out for assessing fuel cycle viability.

Conclusion

The present fuel cycle industry has reached technical and commercial maturity. Front-end fuel cycle activities are operated in a competitive market context where economic drivers lead to continuing progress towards enhanced efficiency and lower prices. Some adaptation will be needed, however, to replace ageing facilities, in particular enrichment plants.

The role of governments remains predominant in the back-end of the fuel cycle. However, choices between once-through and recycling options are increasingly affected by economic considerations. The implementation of HLW repositories, although not a technical issue, is a political challenge. Major progress achieved recently in Finland and the United States is encouraging in this regard.

The development of a new generation of nuclear systems raises challenges for the fuel cycle, in particular for very innovative systems. Some of the concepts considered within GIF rely on fuels and fuel cycles that need extensive R&D before reaching viability. The R&D programmes proposed place emphasis on integrated system optimisation and stress the importance of fuel cycle issues to achieve sustainability goals in particular.

The need for R&D in the field of fuel cycle will not decrease in the future, but rather increase. Recognising that government R&D funding is limited and that the industry is striving for competitiveness, international co-operation, for example under the umbrella of joint NEA projects, will be essential for the efficient allocation of scarce resources. The opportunities for R&D cost saving through generic cross-cutting R&D programmes [13] and the synergy resulting from multi-country endeavours are key elements for the viability and performance of a new generation of integrated nuclear energy systems.

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Figure 1. **Schematic representation of the nuclear fuel cycle**

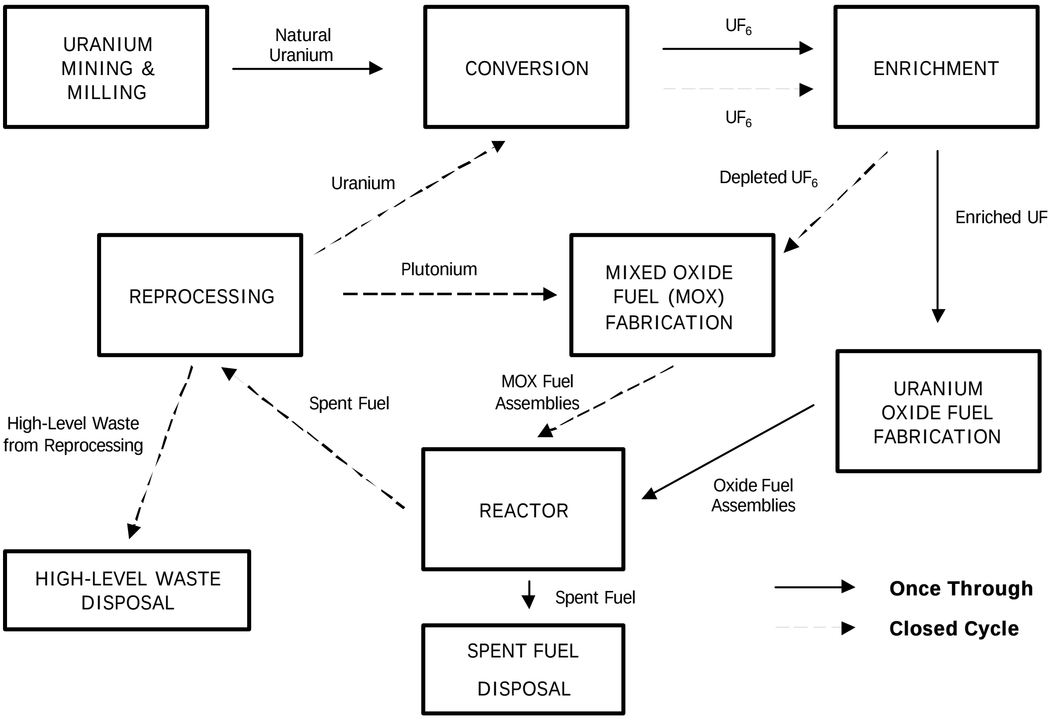

Figure 2. **Evolution of average availability factor of nuclear power plants in the world**

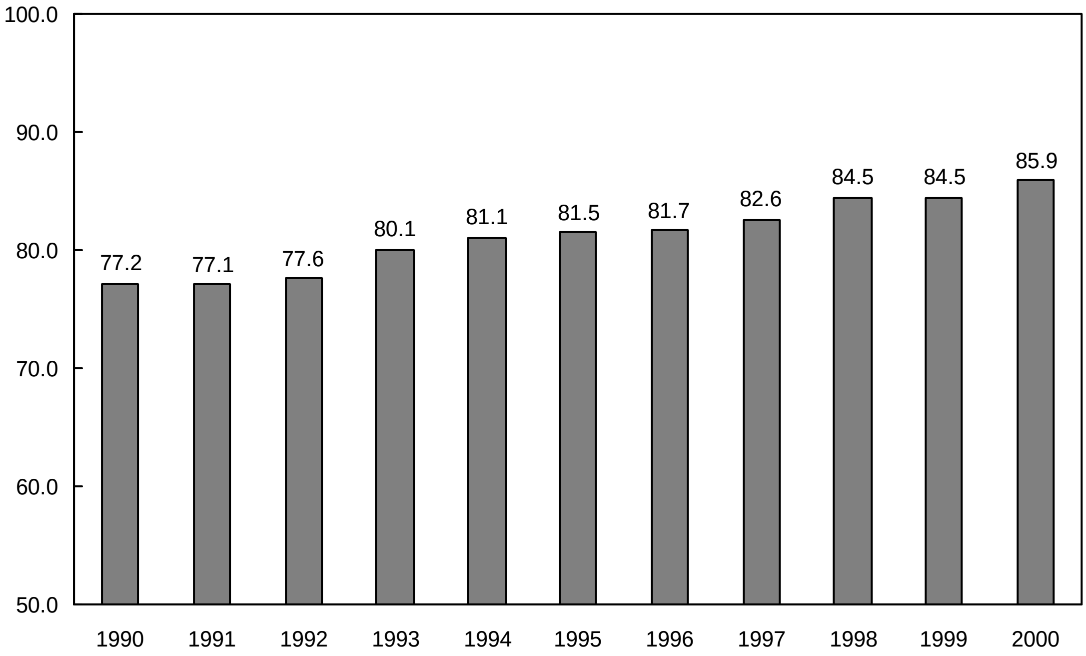

Figure 3. **Evolution of fuel cycle cost for a PWR once through at 5% discount rate (Usmills/kWh)**

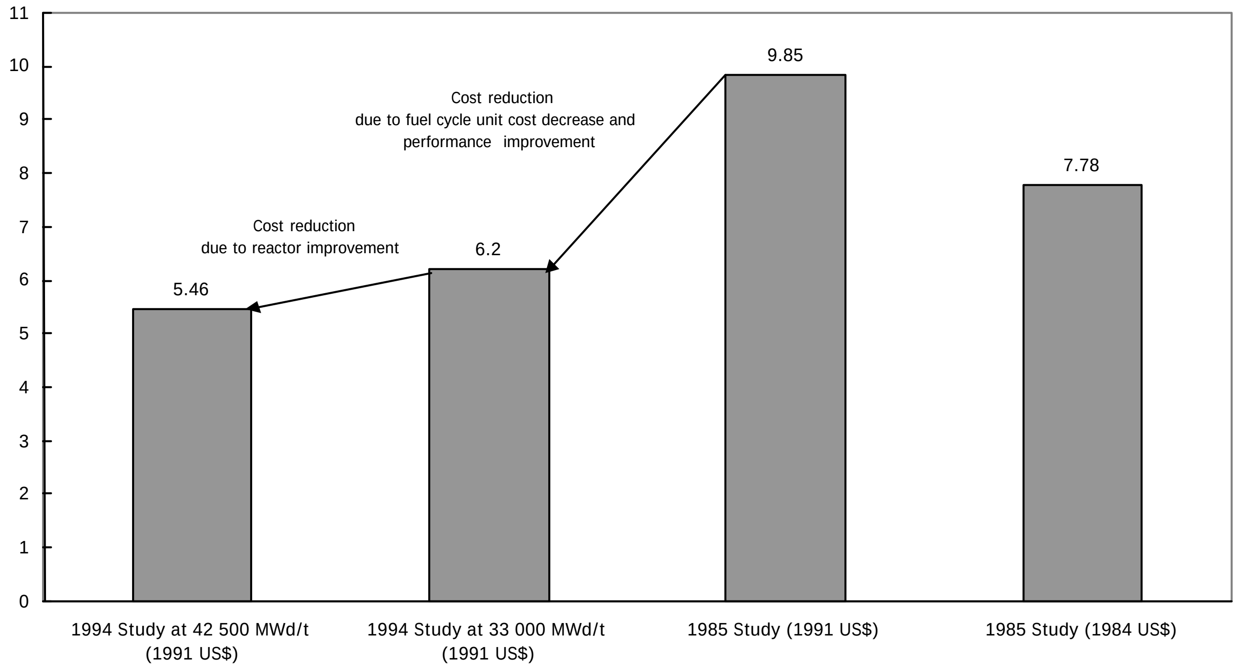

Figure 4 **Estimated shares of global annual doses to population**

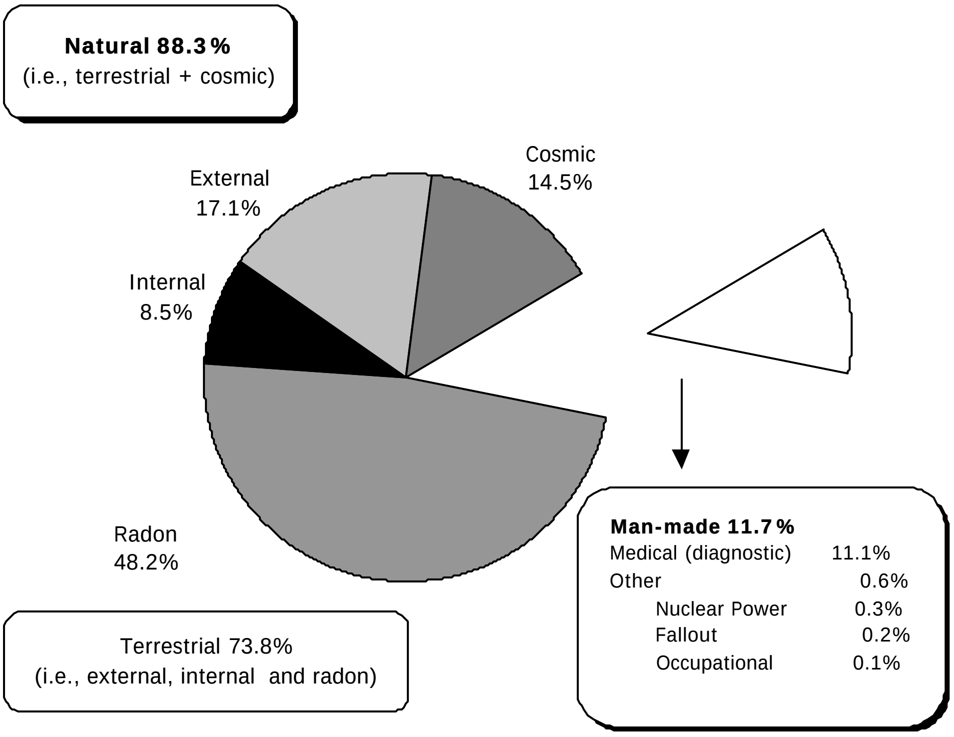

Figure 5. **Impact of fuel design and fabrication on enrichment and U requirements**

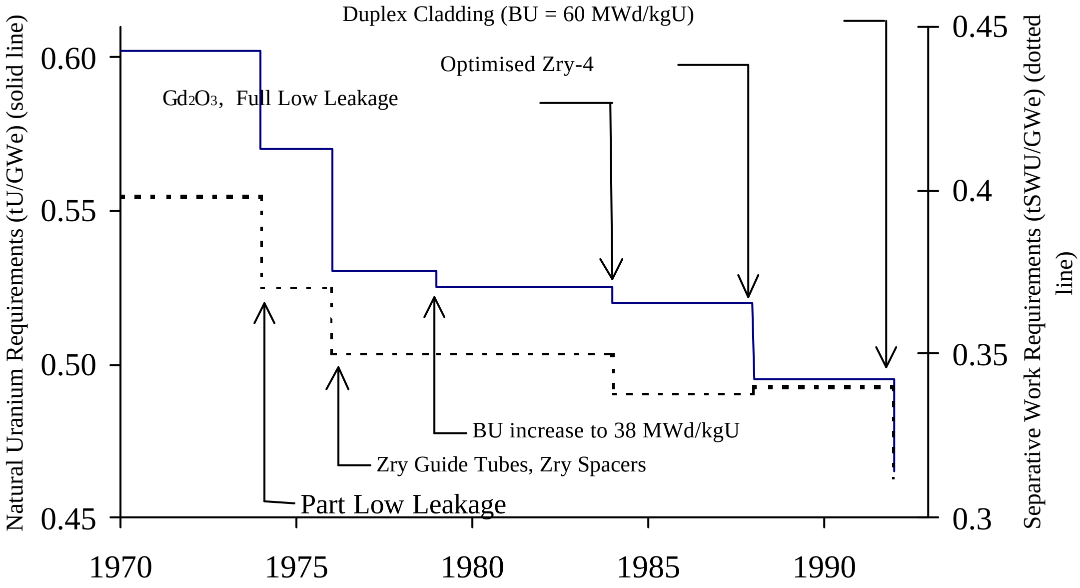

Figure 6. **Radiotoxicity of waste from different fuel cycles in comparison with that of natural uranium (per TWh)**

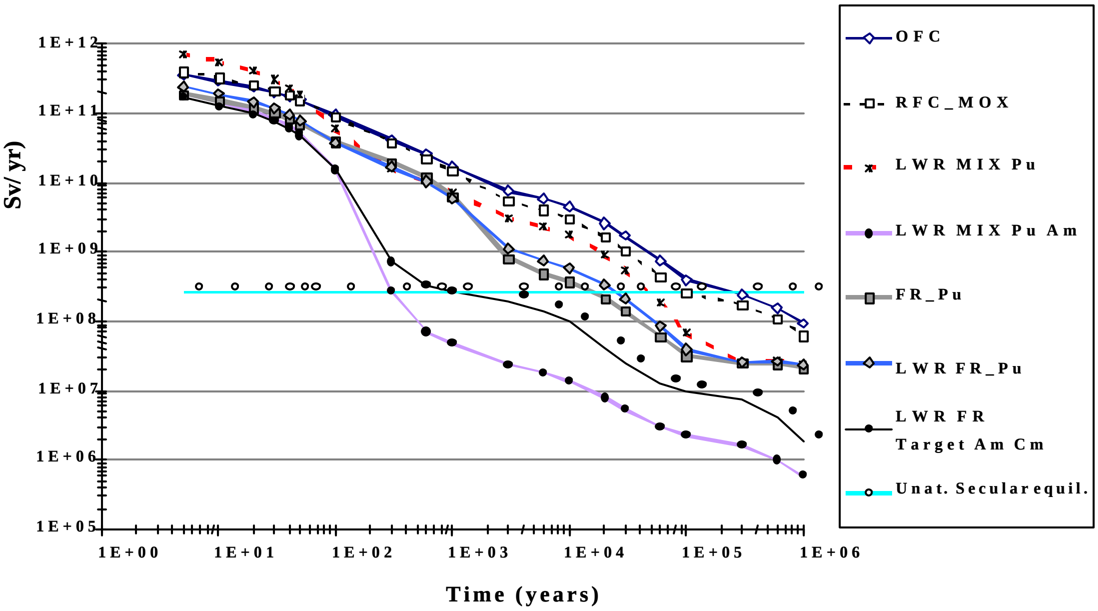

Figure 7. **GIF ROADMAP GOALS**

- Economics
  - Lover life-cycle cost than alternatives
  - Financial risk similar to alternatives
- Sustainability
  - Better use of natural resources
  - Reduced environmental burden
- Proliferation Resistance & Physical Protection
  - Minimise life-cycle susceptibility to diversion of weapon-usable materials
  - Minimise vulnerability to theft, acts of terror or sabotage
- Safety & Reliability
  - Excel in safety & reliability
  - Very low likelihood and degree of core damage
  - Eliminate the need for off-site emergency response

Figure 8. **EVOLUTION OF NUCLEAR ENERGY SYSTEMS**

CURRENT GENERATION	→	GEN III+	→	GEN IV
BWR PHWR PWR		ABWR Ad. CANDU APWR IPSR		SCWR
AGR		MHTGR		VHTR GFR
LMFBR				LMR-Na LMR-Pb alloy
				MSR