Nuclear fuel cycles: Adjusting to new realities

Changing political and economic conditions have re-opened global debate about nuclear fuel reprocessing and recycling options

by B. A. Semenov and N.Oi

Since the 1970s, when nuclear power stood among the fastest developing sources of energy, the technology has been making significant contributions to electricity supplies in many countries. Nuclear power's share of total worldwide electricity generation today stands at just over 17%, and it surpasses 25% in 15 countries.

In the 1990s, nuclear power will continue to be a major source of electricity worldwide. However, its rate of growth has slowed and is projected to remain modest through the decade. At the same time, supplies of uranium and plutonium — the fuel sources for nuclear power plants — are projected to increase considerably, with growing surpluses expected.

The changing situation has influenced the strategies and approaches of industries characterizing the nuclear marketplace. So, too, have economic, environmental, and political considerations affecting the world's overall energy and electricity development. At the international level, debate is focusing increasingly on a number of industrial operations and processes associated with what is commonly called the nuclear "fuel cycle". *(See box.)* These activities include uranium mining; fuel enrichment and fabrication; reprocessing, and subsequent recycling, of spent (used) fuel; and the management of nuclear wastes and spent fuel.

Given the changing conditions affecting nuclear power development, it is useful to look at how these fuel-cycle activities are adapting to the new set of circumstances. This article presents a brief overview of developments, and describes a number of international activities being undertaken by the IAEA through its programme covering the nuclear fuel cycle.

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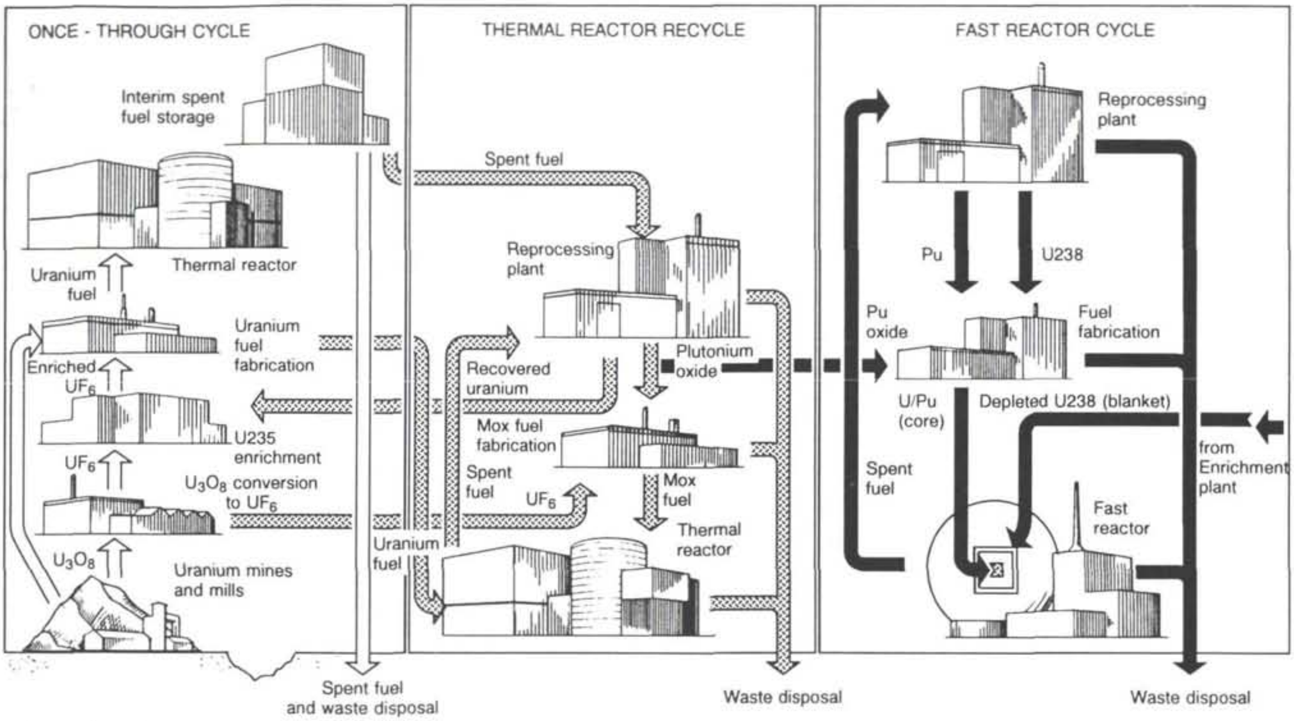
Evolution of the nuclear fuel cycle

The concept of a nuclear fuel cycle is an old one, almost dating back to the conception of controlled nuclear fission to generate electricity. At the time of the development of the first nuclear power plants, it was generally taken for granted that fuel from power reactors would be reprocessed and that the recovered uranium and plutonium would be recycled.

In those days, uranium ore was a scarce and expensive commodity and it was naturally assumed that economically available supplies would not meet the demands required by a widespread use of nuclear power. Consequently, the extraction of all the potential energy content of uranium, not just from uranium-235, seemed to be essential. Such a complete exploitation of uranium resources requires reprocessing of the spent fuel and the extraction of plutonium for burning in specially designed "fast" reactors. The approach became more attractive with the concept of fast breeder reactors, which could produce more fuel than they consumed. For such reasons, many countries during the 1960s attached high priority to the development of fast reactors, and it was anticipated that they would be widely deployed in the 1980s.

Until the early 1970s then, the nuclear fuel cycle was pictured as an orderly sequence of processes. It began with uranium mining, milling, and conversion, was followed by fuel enrichment, fuel fabrication, and power generation, and was finally completed by reprocessing, recycling of plutonium and uranium to fast reactors, and final disposal of waste streams from reprocessing plants. In essence, closure of the fuel cycle meant the effective use of plutonium

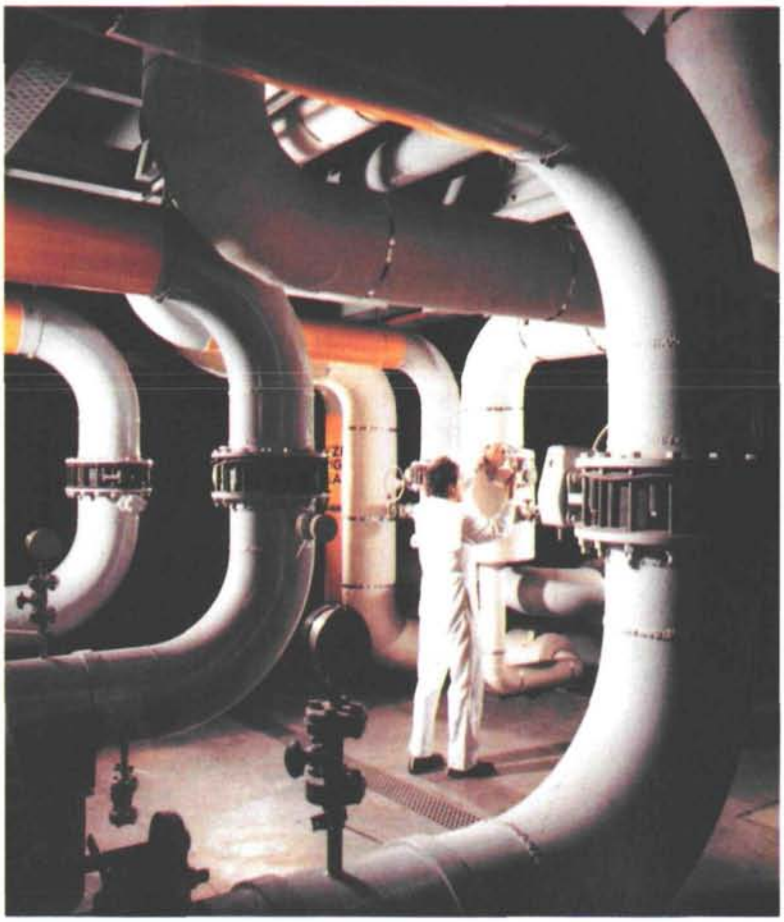


U_3O_8 = yellowcake
UF_6 = uranium hexafluoride
MOX = mixed oxide fuel (uranium/plutonium)

Nuclear fuel cycles

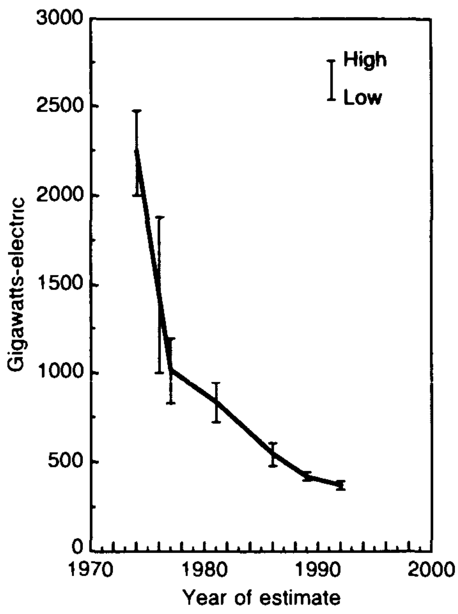
Three different types of fuel cycle are commonly identified for nuclear power generation, depending on whether fuel is recycled and on the type of reactor used for electricity production.

- **The "once-through" fuel cycle**. In this cycle, the spent fuel is not reprocessed but kept in storage until it is eventually disposed of as waste.
- **The thermal reactor cycle.** In this cycle, the spent fuel is reprocessed and the uranium and plutonium are separated from the fission products. Both the uranium and the plutonium can be recycled in new fuel elements. It also is possible to recyle only the uranium and to store the plutonium, and vice versa.
- **The fast breeder reactor cycle.** In this cycle, the spent fuel is similarly reprocessed and the uranium and plutonium fabricated into new fuel elements. However, they are recycled to fast breeder reactors, in which there is a central core of uranium/plutonium fuel surrounded by a blanket of depleted uranium (uranium from which most of the uranium-235 atoms have been removed during the process of enrichment) or to burner reactors. This depleted uranium consists mostly of uranium-238 atoms, some of which are converted to plutonium during irradiation. By suitable operation, fast breeder reactors thus can produce slightly more fuel than they consume, hence the name "breeder".



Inside a centrifuge plant for enriching uranium. ***(Credit: BNFL)***

Projections of installed nuclear capacity in market economies at the year 2000



Source IAEA Reference Data Series, editions for 1981 to 1992

generated in thermal reactors to fuel fast breeder reactors.

Why the concept has been modified

The situation has changed dramatically during the last 20 years. No closed fuel cycle of the type originally envisaged to be operational in the 1980s exists today. Although the closure of the nuclear fuel cycle has been experimentally demonstrated in France, Japan, Russia and the United Kingdom, it has not been been demonstrated yet on a commercial scale.

Current thinking is divided into two schools. One believes that plutonium as an energy source has no economic value and spent fuel should be disposed of in a safe way (the "once-through" option). The other essentially adheres to the traditional nuclear fuel cycle (closed cycle option). The difference of opinions stems mainly from the predictions of nuclear electricity growth and the predicted availability of economical supplies of uranium, although it is coloured by political and environmental issues as well.

It should be noted that plutonium can be used in fast reactors for more efficient energy production, with the added advantage that the inventory of transplutonium elements inherent in the once-through option can be reduced. In the closed cycle option, the burning of plutonium in the form of mixed-oxide (MOX) fuels in light-water reactors (LWRs) is only a temporary expedient until fast reactors are available.

Nuclear power projections and fuel supplies

Over the past 20 years, the projections for nuclear electricity production in the year 2000 have been revised dramatically. In 1980, when the International Nuclear Fuel Cycle Evaluation (INFCE) studies were performed, nuclear electricity production in the year 2000 was predicted to be between 850 and 1200 gigawatts-electric (GWe) in countries having market economies.* This stands in stark contrast to the most recent IAEA estimate, which projects that nuclear generating capacity worldwide in the year 2000 will lie between 372 to 382 GWe. *(See graph.)* At the end of 1992, the world's net nuclear capacity stood at 330 GWe.

Concerning uranium market conditions, developments can be traced back through past publications of *Uranium Resources, Production, and Demand*. Commonly called the "Red Book", it has been a joint publication of the IAEA and Nuclear Energy Agency of the Organization for Economic Co-operation and Development (NEA/OECD) since 1965. The Red Book has adopted a cost category of US $80 per kilogram uranium (kg/U) since the 1977 edition to identify reasonably assured resources, although the real dollar value has decreased by 50% in the meantime.

During the INFCE evaluation in 1980, reasonably assured resources at $80 per kg/U amounted to 1.85 million tonnes uranium. In 1991, they were estimated at 1.5 million tonnes uranium. *(See graph.)* Disregarding minor details, the estimated resources have remained roughly at the same level since 1975. The resource estimates correspond to about 30 years of future requirements, based on the needs assumed for the year 2000.

The price of uranium has fallen steadily from its level in 1980 (US $40 per pound) to its current level on the spot market of less than US $8 per pound. Many producers are on standby awaiting the recovery of the uranium price that is forecast for the 1995-2000 period. Because of current low prices, uranium production in Western countries in 1991 declined to 27 000 tonnes. This amount was lower than the amount of uranium required by the world's nuclear reactors in 1991, which was 44 500 tonnes. The underproduction was covered by materials held in stock and inventories that included imports from China and

* At the time, these countries were grouped under a category known as WOCA, which stands for World Outside Centrally Planned Economic Areas.

the former Soviet Union. *(See the article on uranium market conditions in this edition.)*

Under the closed fuel cycle concept, plutonium was expected to gradually take the place of enriched uranium as the primary nuclear fuel. This has not happened, however. The earlier expectation that the value of uranium and plutonium recovered from reprocessing would be greater than the cost of reprocessing has diminished.

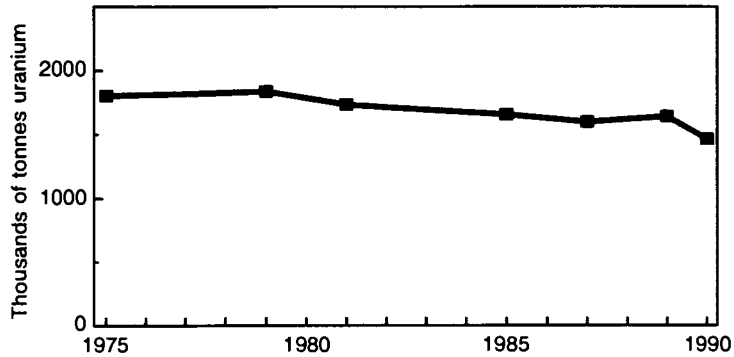
The future of nuclear fuel cycle options

At the present time, the two options for the nuclear fuel cycle are hotly debated by their proponents. It seems that the once-through option combines pessimistic predictions about the future of nuclear energy with optimistic predictions about the availability of economical uranium resources. In our view, however, this option has an inherent problem. The spent fuel, or vitrified plutonium mixed with fission products, that is disposed of in geological repositories will become potential plutonium mines after thousands of years. This is because most of the fission products will decay more rapidly than plutonium.

The closed fuel cycle option is supported by the long-term outlook for nuclear energy. It is estimated that the world population of 5.5 billion will increase yearly at the rate of 100 million. By the year 2010, it has been estimated that about four times as much electrical energy as is currently consumed will be needed. Such a drastic increase cannot be supplied without jeopardizing the environment unless there is a greater commitment to nuclear energy. Also, it is likely that stronger commercial competition in reprocessing and MOX fuel fabrication will develop over the next 20 years, resulting in substantial price reductions. With the inevitable price escalation of uranium, there will be more justification on economic grounds for using plutonium to fuel fast reactors, and thus for closing the fuel cycle.

Nevertheless, the closed fuel cycle option has several attendant difficulties. Among the most important may be national policies and regulations governing licensing and their effect on the economics of future fast reactors. Detailed regulatory considerations developed over decades for current water reactors undoubtedly will be adapted to fast reactors. This would cause long delays and impose heavy economic burdens.

Some modifications to the two basic fuel-cycle options can be considered. One is to proceed to extra-high burnup levels of fuels in present light-water reactors to produce plutonium of isotopic composition that is easier to verify and safeguard. Another is to revisit the thorium/uranium cycle that is free of the stigma associated with plutonium.



Notes: Reasonably assured resources are defined as those within a cost category of less than US $80 per kilogram uranium. Data is for countries formerly grouped in the category known as WOCA (World Outside Centrally Planned Economic Areas)
Source: Uranium Resources, Production, and Demand (Red Book), jointly published by the IAEA and NEA/OECD

Estimates of reasonably assured uranium resources since 1975

The future development of the nuclear fuel cycle will probably differ from one country to another. Those who can afford expensive natural resources may decide for political and other reasons to curtail their nuclear energy programmes and adopt the once-through option. Others will surely expand their nuclear programmes and strive to implement the closed cycle option. It may take another 20 years to visualize how the trend will take shape.

International co-operation and the IAEA's programmes

The IAEA's programmes for the nuclear fuel cycle are adjusting to the changing and unpredictable circumstances governing nuclear power development. The programmes fundamentally are designed to help countries enhance the safety, reliability, and economic viability of their nuclear fuel cycles, while minimizing environmental and health impacts.

Nuclear fuel cycle programmes have been an integral part of the IAEA's activities since its inception. Although the resources allocated to these programmes is only a small fraction of the Agency's overall budget, countries have been able to accomplish a great deal. The activities fall into four areas: uranium resources; reactor fuel performance and technology; spent fuel management; and nuclear fuel cycle evaluation. Additionally, important work is being done through sub-programmes related to structural materials used in the nuclear industry. Throughout the nuclear fuel cycle, facilities have been plagued over the years with problems associated with some types of materials subjected to irradiation. Degradation of their mechanical and physical properties have led to the failure of components and costly downtime of reactors. The corrosion of metals and alloys continues to pose serious difficulties. These and other technical matters are being addressed internationally with the Agency's involvement and support.

Uranium resources. As previously noted, the price of uranium is an important factor in the nuclear fuel cycle because it directly relates to the economic incentives for fast reactors and plutonium utilization. A comprehensive and reliable resource database is essential to planners and decision-makers, and the previously mentioned Red Book is widely regarded as meeting that purpose. Recently, the book has become more comprehensive and useful with the addition of data, previously unavailable, from former republics of the Soviet Union and other countries. An ongoing effort is the harmonization of these data with current database requirements and information needs.

The Agency has been a center of information on uranium geology, exploration, mining, ore processing, and the analysis of supply and demand for many years. Current work further covers the closure of uranium mining and milling projects from the point of view of safety, environmental protection, economics, and licensing. Emphasis also is placed on supporting technical co-operation projects in countries seeking assistance in developing their peaceful nuclear programmes and fuel-cycle capabilities.

Fuel performance and technology. Fuel cladding is the first barrier to fission product release into the environment from a reactor. After experiencing an "epidemic" of fuel failures in the 1970s, current water reactor fuel performs very well with very few fuel failures. Continuing demands for improved fuel performance, however, may jeopardize fuel reliability. In particular, there is a strong incentive to extend the burnup of fuel more than ever to reduce the amount of discharged spent fuel. At the same time, there is always the incentive for utilities to have "zero fuel failure" in order to keep the power plant clean. Consequently vendors, utilities, and licensing authorities carefully monitor fuel performance and are interested in exchanging information, even though the fuel technology is regarded as mature, especially in Western countries.

An International Working Group on Nuclear Fuel Performance and Technology (IWGFPT), which was established in 1977, continues to guide the IAEA's work in the area of fuel design, fabrication, and performance. It now consists of 25 Member States and three international organizations and acts as a forum for contact between developed and developing countries.

Spent fuel management. It is estimated that more than 100 000 tonnes of spent fuel from power reactors will be stored in facilities throughout the world by the year 2000. Less than a half of the amount generated annually will be reprocessed by then and the rest will be stored for a long time before final disposal in geological repositories or before being sent for reprocessing. Because of the delay in the deployment of the fast reactors, countries with reprocessing capacity are also storing large amounts of spent fuel and thus long-term storage is becoming more and more important. Large amounts of fuel are now being stored in wet condition in pools, or in dry conditions in casks, vaults, or canisters. Although spent fuel storage so far has not posed any serious safety problems, it is recognized that associated technological, licensing, and economic problems continue to be an area for useful international co-operation. *(See related article in this edition.)*

The IAEA's Regular Advisory Group on Spent Fuel Management was established in 1984. The Group meets every second year to provide technical advice on the Agency's programme and serves as a vehicle for information exchange on the backend of the nuclear fuel cycle, particularly the storage of spent fuel. Presently, the Advisory Group is composed of representatives from 12 countries and the NEA/OECD.

One of the more important activities is the preparation of international standards for spent fuel storage. The IAEA is preparing safety guides on design and operation of spent fuel storage facilities, as well as a document on safety practices.

Additionally, the Agency is now preparing an Irradiated Fuel Management Advisory Programme (IFMAP) that addresses issues related to both power and research reactors. Its purpose is to offer guidance and training primarily to specialists in developing countries.

Nuclear fuel cycle evaluation. A number of IAEA activities cover the entire nuclear fuel cycle. An example is a study of the environmental and health impacts of nuclear fuel cycle facilities under normal and accident conditions. This is part of the international effort called "DECADES" on the comparative assessment of health and environmental impacts of nuclear power and other energy systems.

Another important activity concerns plutonium. It is estimated that 86 tonnes of separated civilian plutonium have accumulated in the world and the inventory is projected to keep increasing until the end of the century. This inventory results from the mismatch of production and utilization. An important new role for the Agency has been envisaged with respect to the international management of plutonium and supporting activities. These activities may include a role concerning plutonium from the military sector that is recovered from dismantled warheads.

Solidifying global co-operation

In terms of developments affecting nuclear power and its fuel cycle, the coming years will be challenging times for the international community. As national policies and approaches unfold, they will continue to influence both the scope and direction of global co-operation, and by extension the IAEA's work in various areas.

The IAEA's programmes covering nuclear fuel cycle activities are an integral part of the Agency's international services, and they will continue to adjust to changing conditions and interests of Member States. As instruments for global co-operation, the programmes will help to enhance the safety, reliability, and economic viability, and to minimize the environmental and health impacts, of national nuclear fuel cycle activities. ❒

Aerial view of the UP-3 reprocessing plant in La Hague, which was inaugurated in early 1992. *Below:* UP-3's interim storage pool. *(Credit: Cogema)*