Survey of developments in nuclear fuel cycle

by Igor Rybalchenko and Leonard Konstantinov

Nuclear power cannot be developed without proper development of the resource base and the whole nuclear fuel cycle technology. A number of different nuclear fuel cycle strategies has been adopted for various reasons, but basically two types of nuclear power reactors have been developed on a large commercial scale:

- Reactors based on natural uranium fuel, graphite or heavy-water moderated, and gas-cooled or water-cooled;
- Reactors based on slightly enriched uranium fuel, water or graphite moderated, and water-cooled.

Both types of power reactors, with some slight modifications, are well established and many countries have a long, positive operating experience.

To meet requirements of growing nuclear power programmes, adequate technology for the whole of the nuclear fuel cycle has been developed in a number of countries during the past 20 to 30 years. This technology has proved to be reliable, safe, and economically feasible for many countries.

In recent years, as expectations of nuclear power growth have not materialized, projected demands for nuclear raw materials and fuel have decreased, leading to overproduction in some countries and a significant fall in the uranium market price. This was a result of reduced electricity demand, financial problems, and political and public constraints in some countries.

It is expected, however, that steady growth of nuclear power in general will improve the situation of the nuclear industry in many countries and the demand for nuclear materials and fuel cycle services will be stabilized. Following is a review of developments in the nuclear fuel cycle and IAEA activities in this area.

Uranium resources and supply

The condition of the uranium industry has continued to deteriorate in the last few years, although the decreased level of uranium production in 1983 (around 38 000 tonnes in WOCA*) has tended to reduce the level of overproduction. Average uranium contract prices in the United States improved to US $70 per kilogram for imported uranium and US $100 per kilogram for domestic uranium. The spot market price per kilogram uranium, meanwhile, improved from about US $44 in August-September 1982, to US $60 in the fall of 1983, but it fell again later.

Major cutbacks in exploration and mine development activities have occurred in many countries, although a few projects have continued to operate on low-cost deposits, especially in Canada and Australia. Future expectations of uranium demand see an increase of requirements from 31 500 tonnes in 1983 to 45 000 tonnes in 1990 and 55 000 tonnes in 1995.

In light of this projection and the lead-times for uranium mining projects, uranium exploration activities will need to pick up if the long-term demand is to be satisfied.*

Figure 1 provides a summary of the supply and demand situation as noted in *Uranium Resources, Production and Demand,* a joint project of IAEA and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development. Steps continue to be taken to make this biennial report more complete and to assure more uniform reporting of data. To support this effort, two manuals have been prepared: one covers estimation of production capability and the other covers estimation of ore reserves.

In addition to current information on uranium resources and production officially reported by the concerned countries, the report contains an updated estimate of speculative resources for some 182 countries (See Table 1). Previous estimates were made in 1976–77.

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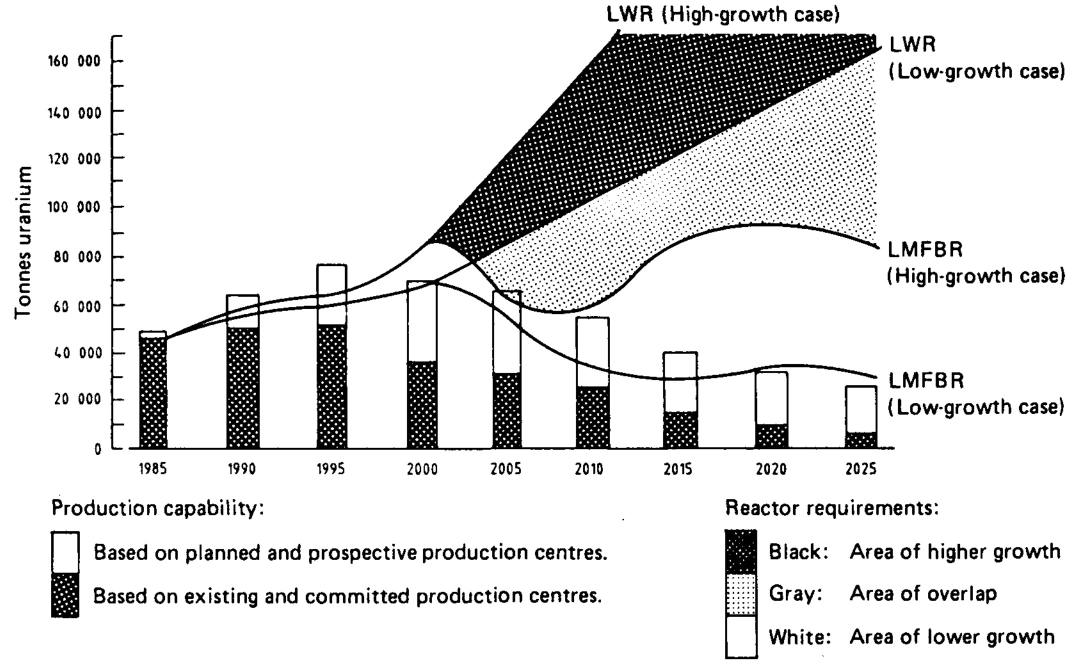
* World Outside the Centrally-Planned Economies Area.

* IAEA activities in this area have focused on updating information on nuclear materials resources and supply (mainly uranium) and on collecting, evaluating and reporting on uranium geology, exploration, and production. IAEA Technical Reports published include *Uranium Evaluation and Mining Techniques* (1980), *Uranium in the Pine Creek Geosyncline* (1980), *Uranium Deposits in Latin America* (1981), *Uranium Exploration Case Histories* (1981), *Vein Type and Similar Uranium Deposits in Rocks Younger than Proterozoic* (1982), *Uranium Exploration in Wet Tropical Environments* (1983), and *Geology and Metallogenesis of Uranium Deposits of South America* (1984). In addition, a Technical Report was issued on *Remote Sensing in Uranium Exploration* (1981) and a Manual on *Borehole Logging for Uranium Exploration* (1982).

Fig. 1. Annual reactor uranium requirements and uranium production capability from known resources* (1985–2025)



* Supported by known resources (Reasonably assured resources and estimated additional resources) recoverable at costs of US $130 per kilogram of uranium, or less.

Table 1. Speculative resources of uranium (millions of tonnes)

	Number of countries	Full range Low	Full range High	Most-likely range Low	Most-likely range High
Africa	50	1.3	4.6	2.6	3.5
America, North	3	1.8	2.9	2.1	2.4
America, South and Central	40	0.7	1.8	1.0	1.3
Asia and Far East*	37	0.3	1.6	0.5	0.8
Australia and Oceania	17	2.0	4.0	3.0	3.5
Western Europe	22	0.3	1.1	0.4	0.6
Total WOCA**	169	6.4	16.0	9.6	12.1
CPEA***	13	3.3	8.4	5.2	6.5

* Excluding People's Republic of China and eastern part of USSR.

** World Outside the Centrally-Planned Economies Area.

*** The potential shown for the Centrally-Planned Economies Area is estimated total potential and includes an element for "reasonably assured resources" and "estimated additional resources" although those data were not available to the Steering Group.

Regarding uranium exploration techniques, IAEA currently is preparing a manual on geochemical prospecting, and arrangements have been made to prepare references for gamma-ray assay of geological materials. Geochemical Analysis System (GAS) computer programs for large computers have been obtained and prepared for distribution in 1984. A related system (MICROGAS) for microcomputers also was made available in 1984.

Work also is continuing on the computerized International Uranium Geology Information System (INTURGEO), which stores information on uranium geology and deposits and national uranium statistics, with information being compiled on uranium occurrences in Africa, Asia, North America, and South America. Mapping and other graphics software were developed to assist data presentation, and the design of the system was made available to interested Member States.

Processing and production of nuclear materials

In the field of nuclear materials processing and production*, the technology of uranium extraction has reached a state of maturity. There have been no major

* IAEA activities in this area have centered on the collection, evaluation, and dissemination of information on the technology of uranium ore processing and the production of nuclear fuel and reactor materials, on the compilation of basic data on nuclear fuel cycle facilities throughout the world, and on providing technical advice to Member States on nuclear fuel technology.

technical innovations in the past few years but hydrometallurgical processes continue to be refined to improve their efficiency and flexibility and to lower their costs and their environmental impact.

Advances have been made in the industrial use of pressure leaching and in the use of pulsed columns for the concentration and purification of uranium liquors by solvent extraction. The use of Caro's acid (H_2SO_5) as an oxidant seems to be quite promising.

The recovery of uranium from phosphoric acid is marginally economic at the present time. Improvements are needed to make these recovery processes more competitive. Efforts are being made to develop new extractants, and particularly solid extractants that would reduce the requirements for pre- and post-treatment of the acid.

Several countries are developing processes for the recovery of uranium from coal and from natural waters, including seawater. It appears that these processes are not being developed to compete in price with uranium from conventional resources, but to put a ceiling on this price and to provide long-term security of supply for those countries with large nuclear power programmes and with very limited indigenous uranium resources.

Many developing countries are establishing, or have expressed their intention to establish, a national uranium ore processing industry.

Uranium enrichment. The situation with uranium enrichment is similar to that of natural uranium – overcapacity and oversupply. The existing capacity is about 42.6 million separative work units (SWU) per year while the estimated demand for 1985 is 25 million SWU/year. Existing and planned capacity can therefore meet future requirements for enriched fuel for many years.

The large-scale enrichment of uranium by the gaseous diffusion process has been carried out for 40 years and is an established and well-developed technology. It is, however, a very expensive process and is now facing competition from newer processes, notably the gas centrifuge separation process. Gaseous diffusion plants in several countries are still the major source of enriched uranium but several gas centrifuge plants are already in operation.

The US gaseous diffusion plants are the base-load plants for most of the world although the American share of the foreign market has dropped to 35% from 100% about 10 years ago. Improvement projects completed in 1983 brought US plant capacity to 27.3 million SWU/year while power requirements were reduced by some 23%.

The first two units of the gas centrifuge enrichment plant under construction at Portsmouth, Ohio, are scheduled for start-up in 1988–89 with a capacity of 2.2 million SWU/year. With 20 years of development and 2000 machine-years of experience, the performance and reliability of gas centrifuges are well established.

In Europe the Eurodif plant is now in operation and the Tricastin gaseous diffusion plant is complete and operating at the planned capacity of 10.8 million SWU/year. This is a significant achievement that places Eurodif as a major enrichment supplier and gives Europe considerable independence in the supply of enrichment services.

The Urenco tripartite project also has progressed well with centrifuge plants in operation in the Netherlands and in the United Kingdom, and a third plant planned in the Federal Republic of Germany. Urenco plans to expand its capacity to 2 million SWU/year in the late 1980s. This tripartite arrangement has worked well and provides a model for a successful multinational nuclear project involving government and industry.

Efforts to improve existing enrichment technology and to develop new technologies have continued at a high level. The gas centrifuge process, while well proven, still shows considerable promise for further improvement.

The USA has made considerable progress in developing improved machines with 50% increased capacity that will be used in subsequent units of the centrifuge plant. These centrifuges are over 25 feet long and operate at supercritical speeds. In Japan, increased attention is being paid to centrifuge manufacturing. Japan will need 9.5 million SWU/year by 2000 and plans to provide a minimum of 3 million SWU/year from local plants.

Other technologies are considered to have the potential for future commercial use. The French chemical enrichment process, Chemex, has been developed to the stage of pilot plant operation. The separation nozzle process developed in the Federal Republic of Germany also has shown considerable progress. A pilot plant is under construction in Brazil and a demonstration plant of 300 000 SWU capacity is planned.

Very small nozzles are involved, for which special manufacturing techniques have been developed. The nozzles are assembled as chips in tubes to form stages. Work on laser technology also continues, and when successful it is expected to provide the most economic process of enrichment.

Nuclear fuel fabrication

The major part of the world's operating power reactors (about 90%) are water-cooled and have uranium dioxide as a fuel. Eleven countries have been fabricating nuclear fuel for commercial use for quite a long time (see Table 2).

A number of other States are developing manufacturing technology and conducting various R&D projects. Manufacturing processes employed are quite similar for most plants, although special requirements exist for the various types of fuel.

Practically all fuel assemblies of existing power reactors consist of uranium dioxide fuel rods in zirconium alloy cladding. The geometry of rods and fuel assemblies

Table 2. Commercial fuel manufacturing plants

Country	Plant	Capacity (tonnes/year)	Fuel types fabricated
Belgium	FBFC, Dessel	400	PWR & BWR
Canada	CGE	600	HWR
	W Canada	500	HWR
	C-E Canada	230	HWR
F.R. Germany	RBU	850	PWR, BWR & HWR
	Exxon, Lingen	200	PWR, BWR
France	FBFC, Romans	600	PWR
	CFC, Pierrelatte	500	PWR
Great Britain	BNFL	100	BWR & PWR
Italy	Agip Nucleare	200	BWR & PWR
India	DAE	135	HWR & BWR
Japan	JNF	480	BWR
	MNF	460	PWR
	NFI	50	BWR & PWR
Sweden	ASEA-ATOM	330	BWR & PWR
USSR	State Committee	700	PWR & BWR
USA	B & W	375	PWR
	C-E	265	PWR
	ENC	600	BWR & PWR
	GE	1100	BWR
	W	800	PWR

varies, but physical and mechanical features are somewhat similar. Different manufacturers may have different organizational and technical approaches to quality assurance and control (QA & QC) procedures. Besides that, a number of developing countries are entering the suppliers group and are constructing their own nuclear fuel fabrication facilities. Among them are Argentina, Brazil, Republic of Korea and Romania.

Experience with fuel fabrication shows very few fuel failures and continued improvement in fuel reliability. Problems of hydridization, uranium dioxide densification, fretting, and pellet-cladding interaction have been studied in detail. Improvements have been made by changes to specifications, and improved quality control and fabrication techniques.

Strict QA and QC procedures have contributed significantly to the high reliability of today's fuel, with past experience leading to today's satisfactory stage of reliability for fuel behaviour in operating conditions. Efforts of utilities, industry, and research to develop remedies against initial defects have been largely successful.

Average failure rates on the order of 0.01% failed rods per reactor year can be achieved for prevailing current mode of operation and current discharge burnups. R&D work is being done on improvements in fuel utilization (extended burnup), load-following-mode of operation, use of plutonium in thermal reactors, and the possibility of reconstruction of failed fuel assemblies.

The trend to improve fuel utilization in water-cooled reactors could be achieved by two parallel ways – change in fuel management strategies, or improvement of mechanical and metallurgical properties of the fuel. R&D efforts are being focused on such problems as fission gas release, water corrosion of zirconium cladding, dimensional stability, pellet-cladding interaction, and increased use of burnable poisons. Most of these problems are not new, but prior to licensing it is necessary to check the behaviour of the fuel by experiments under expected conditions. Computer models and codes in fuel behaviour analysis have proved to be useful for the development of the new designs.

Implementing improvements does not present insurmountable difficulties. Due to the nature of the work, however – length of irradiation time, necessity to check carefully safety aspects, delays related to industrial procurements – the full benefit of improvements in fuel utilization is not expected before the next decade.

Innovations in fuel technology would require additional or new QA and QC measures, which should also prove to guarantee higher safety standards for fuel operation.*

* IAEA activity in the nuclear fuel fabrication area includes the collection, evaluation, and exchange of information on water-reactor fuel element fabrication, with particular emphasis given to better fuel utilization (extension of burnup) and to fuel element performance behaviour and reliability.

Through the International Working Group on Water-Reactor Fuel Performance and Technology (IWGFPT) and its specialists' meetings, a review was made of internal fuel-rod chemistry, fuel behaviour under power ramping and power cycling conditions, fuel element performance and fission gas release modelling, pellet-cladding interaction in water reactors, high burnup in water-reactor fuels, and coolant/cladding interaction. Technical documents were issued on post-irradiation examination techniques and the utilization of particle fuels in different reactor concepts.

A regional seminar on heavy-water reactor fuel fabrication and control was organized in 1983, and another seminar on remote handling equipment for nuclear fuel cycle facilities was held in 1984.

A guidebook on Quality Control of Water-Reactor Fuel was issued in 1983, and a seminar on the same subject was held in 1984.

Three co-ordinated research programmes are in different phases of development: D-COM (Development of Computer Models for Fuel Element Behaviour in Water Reactors), CCI (Investigation of Fuel Element Cladding Interaction with Water Coolent in Power Reactors), and ED-WARF (Examination and Documentation Methodology for Water Reactor Fuels).

Spent fuel management

Significant experience also has been gained in the back-end of nuclear fuel cycle (storage, transport, and reprocessing). Currently, a large portion of irradiated nuclear fuel is being stored in water pools at reactors, while a smaller part of spent fuel is in storage pools at reprocessing plants or in away-from-reactor (AFR) storage sites (see Table 3). The first commercial dry-storage facility for oxide fuel has been commissioned recently in Gorleben, Federal Republic of Germany.

Only a small quantity of the spent fuel produced has been reprocessed. Even with full operation of reprocessing plants, a large portion of spent fuel will not be reprocessed for some time and will have to be stored. For example, through 1990, no more than 6500 MtU of oxide fuel can be reprocessed in Europe and an inventory of some 10 800 MtU of unreprocessed fuel will accumulate by that time.

Expansion of on-site storage and reprocessing capacities, as well as the provision of centralized storage facilities, should prevent spent-fuel storage problems in the near future. But at the same time, long-term storage of irradiated nuclear fuel requires reliable behaviour of fuel (especially fuel cladding integrity), even after its discharge from the reactor. Although the storage environment is less hostile than in the reactor circuit, storage time is significantly longer. Additional R&D work to prove the reliability and safety of storage during extended periods of time is needed.

In the transport field, a new industry has been established for the movement of fuel from power stations to reprocessing plants or storage sites. Dry and wet transport systems were developed with transport being carried out by road, rail, and sea, according to international regulations. For a period of about 30 years, no incident leading to significant exposures to personnel or the public during transportation of spent fuel has been registered.

In the area of reprocessing, a proven chemical process based on Purex solvent-extraction separation technology has been established. Experience gained with reprocessing both metallic and oxide fuel has confirmed the reliability and safety of this technology. The environmental impact of reprocessing is negligible. Operational reprocessing plants are mainly in a few European countries and in India and Japan, and their capacities, existing and planned, are substantially less than actual spent fuel arisings.

Countries with limited uranium resources consider that spent fuel reprocessing and fissile material (plutonium and uranium) recycling in water-cooled reactors could reduce their dependence on imported uranium. The

Table 3. Spent fuel storage facilities away-from-reactor (AFR)

Country	Name of plant/ location	Owner	Status	Start-up	Fuel type	Present design capacity	Present storage	Planned capacity (year)
						(tonnes of heavy metal)		
Belgium	Dessel-Mol	Eurochemic	Standby		PWR			
		State*	Planned		PWR			380 (1987)*
Canada	Whiteshell	AECL	Operating	1974	OCR	11.1	10.2	**
France	La Hague	COGEMA	Operating	1967	GCR	400		
				1975	LWR	4000		+2000 (1983)
								+2000 (1987)
Germany F.R.	Ahaus	DWK/STEAG	Planned	1985	LWR			1500
	Gorleben	DWK	Construction	1983	LWR			1500
Sweden	Simpevarp	SNFSC	Construction	1985	LWR			3000 (1985)
UK	DNPD, Thurso	UKAEA	Operating	1960	MTR U/Al	***		
	Windscale B30	BNFL	Operating	1960	MAGNOX	1500		
	Windscale B27	BNFL	Operating	1968	LWR	2300		
	Windscale Pond 4	BNFL	Licensing	1980	AGR	550		
	Windscale Pond 5	BNFL	Construction	1983	MAGNOX			1000 (1983)
					AGR			510 (1984)
	Windscale THORP	BNFL	Planned	1987	LWR, AGR			1500 (1987)
USA	West Valley	State of New York	Operating	1966	LWR	250	165	
	Morris	GE	Operating	1971	LWR	700	350	
	Barnwell	AGNS	Planned		LWR			400

* depends on decision of Parliament.
** dry storage as requested.
*** 700 assemblies.

plutonium-fuelled fast breeder reactors are seen as the best prospect for a substantial and enduring contribution to global energy supplies.*

International co-operation

Multinational co-operation in the nuclear field is becoming more important, placing added value on IAEA's role as the only organization capable of collecting and evaluating information, and of providing support to a large number of Member States in the field of nuclear materials and fuel cycle technology.

From 1980–84, the IAEA assisted in the implementation of technical co-operation projects on uranium exploration in 41 countries of Africa, Asia, Europe and South America. The number of supported projects varied between 30 to 40 per year, out of which 6 to 10 have been large-scale projects financed by the United Nations Development Programme (UNDP). The annual total budget of these projects is in the order of US $2 000 000.

In the area of nuclear fuel during recent years, assistance has been provided to countries including Egypt, Indonesia, the Republic of Korea, Mexico, and Romania. Quality assurance and quality control is one of the most important subjects in the technical assistance programme.

At present, the IAEA is supporting the work of the Committee on Assurances of Supply in regard to nuclear materials, fuels, and fuel cycle services. The assured supply of reactor fuel is very important for many developing countries.

Despite the fact that a number of countries are developing their own production capacities, many countries still will be dependent on other countries. To assure a reliable fuel supply, many countries are interested in diversifying their source of supply. In this situation, fuel supply assurance, standardization of fuel fabrication technology, and quality control programmes are needed to a large extent. All this can be achieved only through extensive co-operation.

The IAEA will continue its programmes in the nuclear fuel cycle area with emphasis on improvements of fuel cycle technology and fuel performance and safety. The programme's importance will increase as more countries embark upon utilization of nuclear energy for electricity generation and other peaceful uses and need assurances for the supply of nuclear materials, fuel, and fuel cycle services.

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* Agency activities in this area are concentrated on technical matters of management of spent fuel from various types of reactors. Collection and evaluation of information continued on short-, medium- and long-term storage options as well as on transportation, reprocessing, and recycling technologies.

The results of the world survey on storage of water-reactor spent fuel in water pools was published in 1982 as a Technical Report, Series No. 218.

A guidebook on spent fuel storage has been published recently as a Technical Report, Series No. 240. It contains the following items: wet and dry spent-fuel storage technology, transport of spent fuel, economics of spent fuel storage, institutional arrangements, international safeguards, evaluation criteria, and multinational co-operation. Work is continuing to summarize world experience in the field of spent-fuel dry storage.