Plutonium as an energy source: Quantifying the commercial picture

As civilian inventories of plutonium rise, international interest is focusing on how the stockpiles will be used and managed

by Pierre M. Chantoin and James Finucane

Plutonium is one element formed in the fuel of nuclear reactors during their operation. Although it can be separated, stored, and subsequently reused in recycled fuel for nuclear power plants, plutonium's well-known military use as a weapons material makes this a delicate issue.

This article reviews a number of important aspects concerning the use of plutonium as an energy source in the civilian nuclear sector; it does not address military-related developments. Specific topics that are examined include plutonium's formation in nuclear fuel, its separation during reprocessing, and its re-utilization (recycling) in a special type of nuclear fuel, a mixed oxide (MOX) fuel of uranium and plutonium. Also addressed are the projected accumulation of plutonium in civilian storage worldwide, and the possible role of the IAEA in helping to ensure that these inventories are safely handled, transported, stored, and managed. The temporary accumulation — which is foreseen over about the next 10-to-30 years — is an outgrowth of delayed national programmes to build fast-breeder reactors (FBRs) that would have used the plutonium. Its duration is largely dependent upon the availability of facilities to fabricate MOX fuel for light-water reactors, which are the mainstream nuclear power plants operating and being built today.

Plutonium formed in nuclear fuels

Over the next 15 to 20 years, a significant amount of plutonium will be produced in nuclear power stations worldwide, adding to amounts already in storage. *(See graphs, page 41.)* In 1965, less than one tonne was produced. By 1992, with a greater number of power stations in operation, 50 tonnes were produced (contained in about 9000 tonnes of spent fuel). Since the beginning of commercial nuclear power generation, about 600 tonnes of plutonium have been accumulated in spent fuels. By the years 2005 and 2010, it is expected that about 1000 tonnes and 1500 tonnes, respectively, will have accumulated.* Because one tonne of fissile plutonium theoretically has the energy equivalent of approximately 22 million megawatt-hours of electricity, some countries have chosen to reprocess this spent fuel. The spent fuel is chemically treated (reprocessed) to recover the plutonium and then recycled in MOX fuel for use in reactors. The quality of plutonium recovered from reprocessing of spent fuel mainly depends upon the type of reactor and degree of fuel utilitization (burnup) during operation.

Fuel reprocessing or storage

Reprocessing is a proven technology that is commercially available. *(See table.)* In 1992, the total reprocessing capacity for all types of fuel was an estimated 4015 tonnes of heavy metal (tHM). That capacity represents only about 40% of the fuel discharged from power reactors. All operating reprocessing plants use advanced Purex technology. No major problems are anticipated in dealing with fuels of higher burnup (up to 45 megawatt-days per kilogram heavy metal) or with MOX fuel.

In some countries, reprocessing capacities are being expanded. In France, the UP-2 reprocessing plant is being modified to double its

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* The estimates of plutonium are the results of calculations made with the CYBA computer code operated by the IAEA Division of Nuclear Fuel Cycle and Waste Management. They are based on electricity production and generic models of fuel and reactor management for each type of reactor in use.

	Fuel type	1992	Projections 1995	2000	2005	2010
France	GCR	600	600	0	0	0
	LWR	1200	1600	1600	1600	1600
	FBR	5	5	5	5	5
India	PHWR, RR	200	200	600	600	600
Japan	LWR	100	100	900	900	900
Russia	LWR	400	400	400	400	400
United Kingdom	GCR	1500	1500	1500	1500	1500
	LWR	0	1200	1200	1200	1200
	FBR	10	10	10	10	10
Total		**4015**	**5615**	**6215**	**6215**	**6215**

Notes: Data in tonnes of heavy metal per year. GCR = gas-cooled reactor. LWR = light-water reactor. FBR = fast-breeder reactor. In India, the Tarapur plant is a pressurized heavy water reactor (PHWR), and Trombay is a research reactor (RR). In Russia, the completion of a reprocessing plant having an annual capacity of 1500 tonnes heavy metal has been postponed.

Existing and project capacities worldwide for reprocessing nuclear fuel

annual capacity to 800 tHM. It is now scheduled to restart at the doubled capacity in 1994 or 1995. In the United Kingdom, construction of the Thermal Oxide Reprocessing Plant (THORP) at Sellafield is complete. Operation was to begin in December 1992, but commissioning has been delayed by problems involving the issuance of a site license. In Japan, work on the Rokkashomura reprocessing plant, which has a design capacity of 800 tonnes of heavy metal, began in April 1993 and is scheduled to be completed by the year 2000.

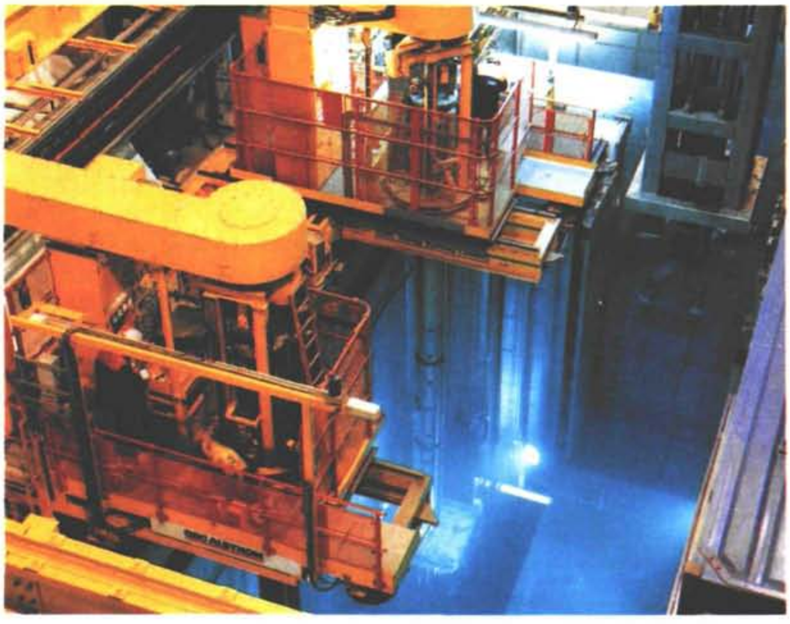
Up to and including 1992, the total amount of commercial spent fuel that has been reprocessed is about 46 000 tHM. By fuel type, this breaks down to 34 000 tonnes from gas-cooled reactors; 11 700 tonnes from light-water reactors; and 40 tonnes from fast-breeder reactors.

Projected reprocessing capacity — which depends on future demand for reprocessing services — is expected to increase up to the end of the century and then level off. (*See table.*) The proven Purex technology is unlikely to be replaced or fundamentally changed, although some modifications and improvements may be introduced. Major developments in reprocessing are likely to be reduction of capital and operating costs; reduction of waste; and increased automation.

Separated plutonium accumulation

At the end of 1992, the total inventories of separated plutonium in the world from civilian nuclear power programmes were estimated at 86 tonnes, based on data reported to the IAEA by its Member States.

Existing facilities	Capacities by fuel type in 1992 GCR	LWR	FBR	Others
Marcoule UP-1 (France)	600			
La Hague UP-2 (France)		400		
La Hague UP-3 (France)		800		
Marcoule APM (France)			5	
Tarapur (India)				150
Trombay (India)				50
Tokai (Japan)		100		
Kyshtym (Russia)		400		
Sellafield (UK)	1500			
Dounreay (UK)			10	
Total	**2100**	**1700**	**15**	**200**



Spent fuel at Sellafield. ***(Credit: BNFL)***

Country	Supplier	Capacity	Status
Belgium	Belgonucleaire	35	in operation
	Belgonucleaire	40	planned
France	Cogema	15	in operation
	Framatome-Cogema	120	under construction
Germany	Siemens	25	temporarily shutdown
	Siemens	120	90% complete
Japan	Power Reactor & Nuclear Fuel Development Corp.	10	in operation
	Power Reactor & Nuclear Fuel Development Corp.	40	planned
United Kingdom	British Nuclear Fuels	8	under construction
	British Nuclear Fuels	100	planned

Notes: Data is in tonnes of heavy metal per year. With respect to capacity, the plutonium content of MOX fuel is assumed to be constant at 4.5%, except for PNC in Japan which fabricates fuel with 2% plutonium.

MOX fabrication capacities in 1992 for light-water reactors

For estimating future plutonium inventories, two scenarios have been examined by the IAEA. *(See box and graph, page 41.)* In the first scenario, which takes into account national reprocessing policies, the rate of plutonium separation continues to exceed the rate of its utilization up to around 2000. By the year 2000, the estimated inventory reaches about 170 tonnes of plutonium. Beyond 2000, the inventory decreases at a rate of 7-to-10 tonnes per year.

The second scenario, based on data reported by IAEA Member States, yields somewhat different results. It assumes that all projected reprocessing and MOX plants will be operated on schedule and at full capacity. In this case, plutonium stockpiles increase until 1997, reaching approximately 120 tonnes. After the year 2000, projected stocks decrease by about 20 tonnes per year.

MOX fuel technology

Experience has shown that plutonium can be used as a raw material for mixed oxide fuel for water-moderated power reactors. Specifically, MOX fuels can be used in light-water reactors (LWRs), which make up the majority of nuclear plants operating worldwide today. Several countries already have plans to use MOX fuel. Facilities for fabricating MOX have been operated successfuly in Belgium, France, Germany, and Japan. Others are being constructed and planned. *(See table.)*

Since its satisfactory performance has been confirmed on test assemblies, MOX fuel is being irradiated to increasingly higher burnups. The economic viability of MOX fuels depends on the balance between uranium and enrichment prices and the costs for fabrication, reprocessing, and waste management and fuel storage.

MOX fuel performance. Tests using MOX fuel have been done for more than 20 years in Belgium, France, Germany, and Japan. They show that MOX can be used safely in existing LWRs with up to 30% of the core loaded with MOX, without the need for significant modification of reactor control systems. Experience shows that there is no major difference between MOX and uranium dioxide fuel in terms of fission product and thermo-mechanical behaviour in the range of fuel burnups experienced up to now. However, differences exist (nature of the fuel, neutron spectrum, and fuel temperature profile). Consequently, further experiments and examination of test assemblies are being done on fuel with a burnup greater than 35 megawatt-days per kilogram heavy metal (MWd/kg HM) to ensure that no adverse effect appears at higher burnups.

In France, Germany, and Japan, research on core configurations is being done to increase the loading of MOX fuel to levels between 50% and 100%. However, these loadings would require either a new generation of water reactors or significant modifications of existing reactor control systems.

In Germany, a broad range of MOX fuel assemblies for boiling-water and pressurized-water reactors has been designed and engineered. At the Hanau facility, MOX fuel assemblies of various types have been fabricated, containing 5.8 tonnes of fissile plutonium. Construction of a new commercial MOX fabrication plant in Hanau has been completed but the start of production has been delayed by political problems. The annual capacity is expected to increase gradually to 120 tonnes by the year 2000. German experience includes irradiation of MOX fuel in 70 000 fuel rods in 490 assemblies loaded in six pressurized-water and three boiling-water reactors. A peak pellet burnup of 53 MWd/kg HM has been achieved.

In France, 16 pressurized-water reactors are licensed to use MOX fuel and 410 MOX fuel assemblies of advanced design have been delivered to seven different reactors. The maximum assembly burnup is around 39 MWd/kg HM with a maximum rod burnup of 47 MWd/kg. All of the assemblies that have completed irradiation cycles have performed to expectations without a single leaking fuel rod. Moreover, the fabrication of more than 60 000 fuel rods, mainly in Belgium during the last several years, has proceeded without problem.

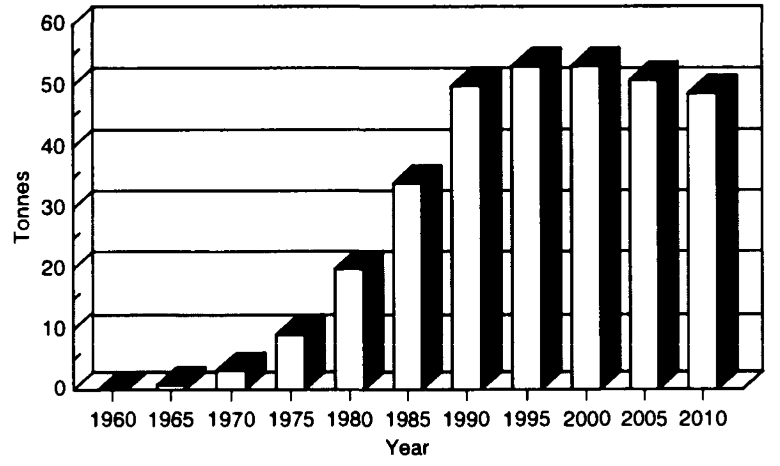
In Japan, recycling of uranium and plutonium in thermal reactors is considered to be the

Projecting plutonium supplies

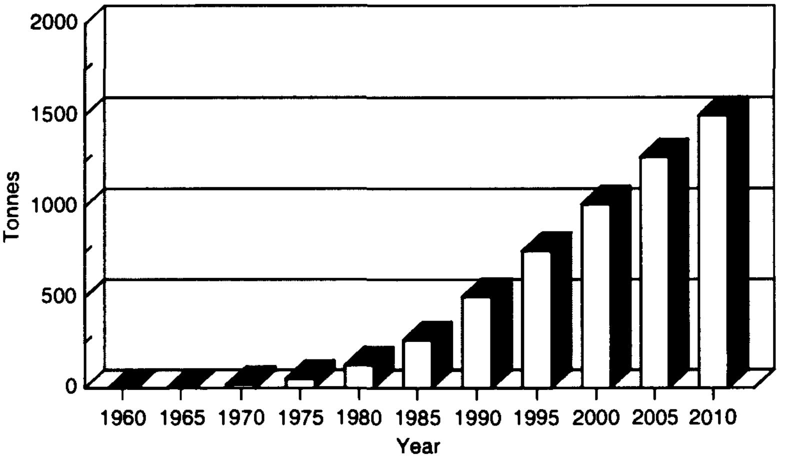
An IAEA analysis on the evolution of plutonium inventories over the coming decades found that estimates are subject to considerable uncertainties. Two scenarios were examined, each based on different assumptions about national nuclear policies and plans. *(See graph below.)*

- In the first scenario, projected stockpiles would gradually decrease after the year 2000. This case took into account national policies for reprocessing and evaluated likely MOX fabrication capacities. In the MOX evaluation, only firm contracts and projects were considered. Expansion of MOX plants in France was not considered. For the United Kingdom, it was assumed that an additional MOX capacity of 50 tonnes would be built but expanded to 100 tonnes only if Germany discontinues its recycling policy. These scenarios did not consider the working inventory of MOX plants (representing about 3 months of normal utilitization, or three to four tonnes plutonium). All these assumptions combine to make this scenario a "high" case. Because one important uncertainty in these projections was Germany's policy, which is currently under review, a sensitivity analysis was carried out in which German policy changed to direct disposal, the Hanau MOX plant did not operate, and Germany stopped reprocessing in 1994. In this case, plutonium production and utilization rates both dropped, but there was no significant effect on the total worldwide accumulation of plutonium.
- In the second scenario, projected stockpiles would disappear after about 10 years. This case considers that reprocessing plants will work at full capacity all the time, and that all proposed MOX plant projects will come on line as currently scheduled. These considerations are subject to a few precautionary remarks: 1) the assumptions of using full reprocessing capacity and timely MOX plant construction are probably optimistic; 2) under existing contracts, the utilization of full capacity of reprocessing plants is not assured beyond the year 2000; and 3) in the event MOX facilities are not ready on time, utilities might wish to delay reprocessing because of problems associated with the buildup of activity of the separated plutonium and with plutonium storage. All these assumptions combine to make this a "low" accumulation case. It is very likely that the actual situation will be somewhere between these two extreme scenarios.

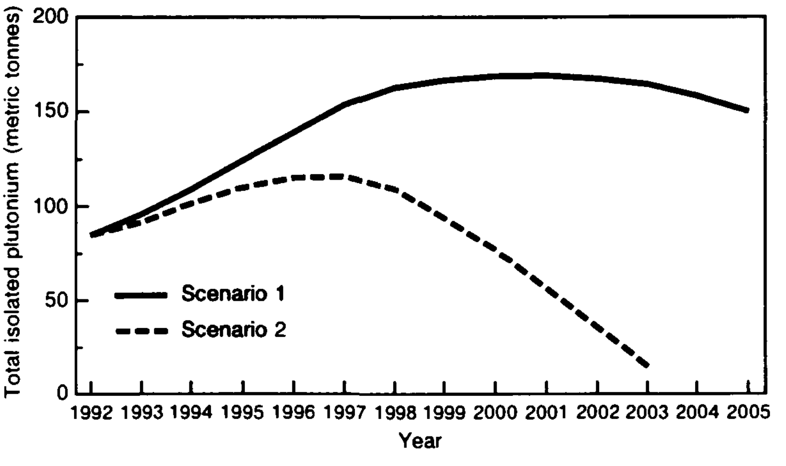
Annual amount of fissile plutonium in spent fuel



Cumulative amount of fissile plutonium in spent fuel



Total projected civilian inventories of plutonium at year's end



best choice until commercial fast-breeder reactors are in place. Japan has decided to have the MOX fuel fabricated in Europe, using Japanese-owned plutonium recovered from reprocessing in Europe. In the future, plutonium from domestic reprocessing will be used at a planned MOX facility in Japan. The plutonium produced will be used for fast reactors and advanced thermal reactors. However, a major part of the plutonium will be recycled in LWRs. Four MOX fuel assemblies loaded in pressurized-water reactors and two in boiling-water reactors have now reached the end of their lives with satisfactory performance. *(See related article on Japan's nuclear fuel cycle policies in this edition.)*

Experience using MOX fabricated in Belgium for pressurized-water reactors now extends up to 70 MWd/kg HM and that for boiling-water reactors up to 49 MWd/kg HM. Fuel performance has fulfilled expectations. More than 100 000 MOX fuel rods have been irradiated in 620 fuel assemblies loaded in three boiling-water and 10 pressurized-water reactors. The only failures recorded since 1980 were the result of debris-induced fretting, which also affected the normal uranium fuel assemblies in the same plant.

MOX fuel development. Mixed oxide fuel is now commercially well established and is playing an important role in the nuclear fuel industry. MOX fuel facilities have been built or planned in Belgium, France, Germany, Japan, Russia, and the United Kingdom. Belgium plans to begin using MOX fuel at its nuclear plants during the mid-1990s. By the year 2000, France plans to have 16 reactors loaded with MOX fuel assemblies. Beginning in 1995, it is planned that the MELOX plant at Marcoule will start fabricating MOX fuel for Electricité de France. In Germany, seven reactors have been loaded with MOX fuel, and by the year 2000 this number is expected to increase to about 20. Most MOX fuel assemblies for these reactors are to be fabricated at Hanau, while the remainder would be supplied by the Belgonucleaire plant in Dessel, Belgium.

In Japan, small-scale programmes are being conducted before large-scale demonstrations and commercial utilization in LWRs. The large-scale demonstration (with one-quarter core loading in one boiling-water and one pressurized-water reactor) is scheduled for the mid-1990s. The commercial utilization of MOX fuel (with one-third core loading in five boiling-water and five pressurized-water reactors) is projected to begin at the end of this decade.

In Russia, owing to the delay in the introduction of fast reactors, plutonium recycling is being studied for thermal reactors. A new plant to manufacture MOX fuel is being built at the Chelyabinsk complex in the southern Urals. This plant, with a capacity of 60 tonnes of heavy metal annually, will fabricate MOX fuel for fast reactors. However, it will also be adapted to produce MOX fuel for the WWER-1000 thermal reactors. *(See related article on Russia's nuclear fuel cycle policies in this edition.)*

Switzerland currently uses MOX fuel in its two units at Beznau, and one or two of the Swiss utilities will begin recycling plutonium in other LWRs in the mid-1990s. The MOX fuel for these loads will be fabricated by Belgonucleaire and by British Nuclear Fuels.

From the research and development point of view, MOX fuel will continue to receive special attention from utilities. Its behaviour during irradiation will be further studied under both normal and abnormal reactor conditions and for extended burnups. This is being done to address any technical and operational problems that might arise (for example, relating to temperature and fission gas release) from the differences between MOX and normal uranium fuels. The studies also will address design evolutions as they occur.

France and Germany have agreed to collaborate in designing a new generation of water reactors to improve plutonium recycling. Due to delays in the development of commercial fast reactors, burning plutonium in thermal reactors presently represents the only outlet for the exploitation of the fissile material recovered during reprocessing.

Safely managing future supplies

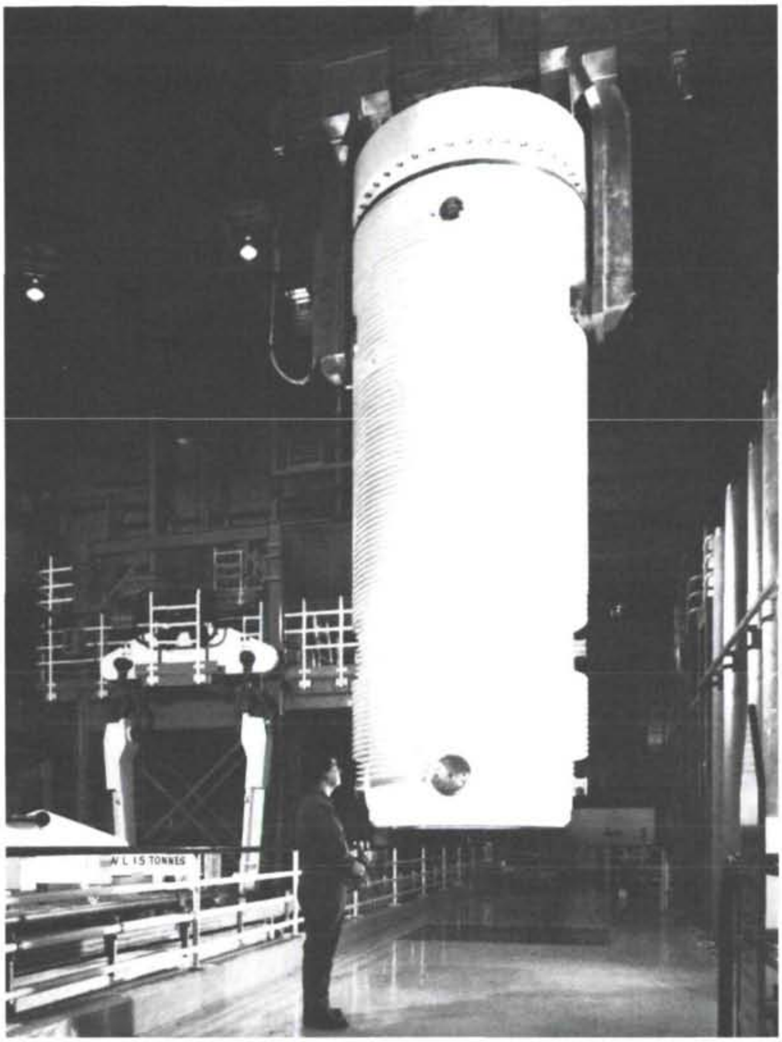
As projected inventories of separated plutonium increase, ways will have to be found to safely store, manage, and use them. Several countries already have good experience in handling, transportation, and storage of plutonium.

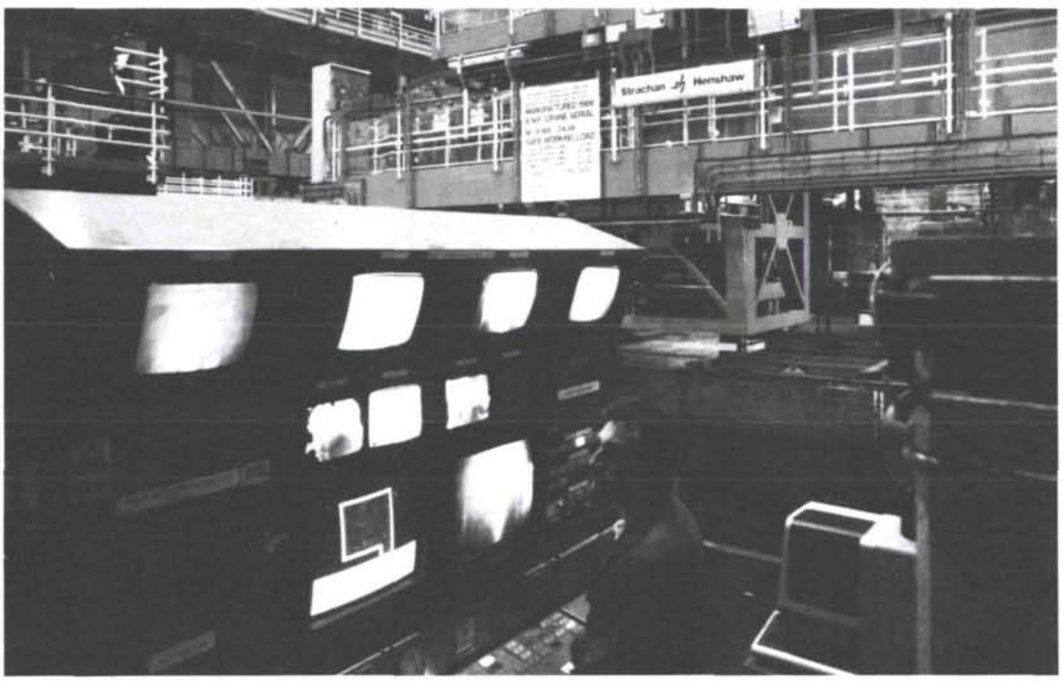
In years ahead, a number of possible roles could emerge for the IAEA to foster greater and more effective international co-operation on plutonium-related issues. National experience could be reviewed, for example, to identify areas for improvements and establish a series of recommendations addressing matters such as physical protection, criticality, and health physics. This information then could be published in safety documents covering quality assurance and safety standards. Additionally, the IAEA could play an enlarged role in providing guidance and supervision to the implementation of international recommendations that may be developed.

Regarding industrial developments, the IAEA could promote exchanges between countries to facilitate the research and development of mixed oxide fuel. One present limitation on the use of MOX fuel lies in the limited capacity for fuel fabrication. Another is the relatively low proportion of MOX fuel loaded in reactor cores. Currently, it is possible to load 30% MOX fuel without changing the core configuration. However, if this amount is to be increased towards 100%, studies show that the core configuration would have to be modified and that the number of control rods would have to be increased.

The IAEA will continue to track plutonium inventories to reduce uncertainties in projecting and evaluating future plutonium stocks to the extent possible. By the year 2000, projected plutonium inventories from civilian reprocessing will increase; they are projected to decrease thereafter. How much plutonium stocks increase — and over what period of time — are subject to considerable uncertainties. These questions are sensitive to assumptions about reprocessing rates, and about capacities and availability dates of the facilities for fabricating mixed oxide fuel. If no new facilities are built beyond those presently projected, it would take about two decades to re-absorb plutonium stockpiles into the fuel cycle.

In light of increasing supplies of plutonium, and its potential use in weapons, interest has grown regarding the development of an international system to safely manage and safeguard civilian inventories. Such a system, in which the IAEA is seen to play a significant role, could well provide the public with assurance that plutonium stockpiles are being appropriately safeguarded and safely handled. ❐





Inside the Sellafield facility in the United Kingdom, where spent fuel is sent for reprocessing. *(Credit: BNFL)*