Spent fuel management

by I.L. Rybalchenko and J.P. Colton*

The light-water reactor (LWR) fuel cycle has always been based on the assumption that the spent fuel would stay for between one and three years in storage basins at the reactor before being reprocessed. Only a limited storage capacity is required in the fast breeder reactor (FBR) fuel cycle, since early reprocessing – to recover the new fissile material "bred" in the reactor – is an integral component of the fuel cycle. On the other hand, it was originally intended that spent fuel from Candu heavy-water reactors (HWR) should be stored permanently and not reprocessed.

Delays in implementing the LWR reprocessing step have occurred in some States as questions have arisen about technologies, economics of the nuclear industry, the choice of fuel cycle, and the political aspects of non-proliferation. As a result of the increased need for extended storage of LWR spent fuel and of a review of the eventual recycle of HWR spent fuel, methods for the interim storage of spent fuel and for its eventual recycling are being considered afresh.

Spent fuel arising

The forecasts of spent fuel arisings and of storage and reprocessing capacity on a world-wide and regional basis imply that no major problems are foreseeable until 1990 However, regional or global comparison does not reflect the real situation within an individual country because spent fuel normally cannot be freely distributed among the available storage locations. Much of the storage capacity is at newly constructed reactors, whereas the need exists at reactors which have been operating for some time and have filled their storage pools. Therefore, some countries and utilities will not have enough capacity and some other plans or techniques will have to be adopted – shipments to storage facilities at other reactor sites or to facilities located away from the reactor site, cask storage, double stacking of spent fuel, etc.

Problems are likely to occur between 1990–2000. Data available to the Agency from the International Nuclear Fuel Cycle Evaluation study (INFCE) and the International Spent Fuel Management study (ISFM) is graphed in Figure 1. The graph does not include figures from the CMEA countries. However, for these countries it has also been decided to extend spent fuel storage before commercial reprocessing and to provide additional storage capacities for a period of 10 years. The reason is the delay in the FBR programme deployment for which plutonium from the LWR spent fuel is necessary [1].

The data imply that the problems might be solved in 1990, whereas the data for the year 2000 indicate that major alternatives to storage must be explored. Due to the lack of new reactors, the at-reactor (AR) storage capacity essentially stabilizes while the arisings continue. This implies that the additional needs will have to be accommodated by stores at locations other than at the reactor as well as by reprocessing or disposal. The studies show that even if projected reprocessing plants become operational as scheduled there will be a significant amount of fuel to be stored or disposed of.

Storage and reprocessing technologies vary as fuel from different reactor types has different characteristics. The length of an LWR fuel element is 4–6 metres, whereas Candu fuel is 0.5m long. Each fuel assembly weighs about 700–800kg for pressurized-water reactors (PWRs), 200–300kg for boiling-water reactors (BWRs), and about 25kg for Candu reactors. FBR fuel elements will most likely be 4–5 metres long and weigh 560kg. The current design of large reactor foresees PWR fuel being exposed to a burn-up of 33 000 megawatt days (thermal) per metric tonne (MWd/t) at a specific power of 36 MW/t, BWR fuel to 27 500 MWd/t at a specific power of 22 MW/t, and HWR fuel to 7500 MWd/t with a specific power of 15.2 MW/t. The burn-up for FBR fuel is foreseen to be 50–100 000 MWd/t with a specific power of over 95 MW/t [2].

Irradiation and fissioning within the reactor causes a change in the content of the fuel pins and figure 2 reflects this change [3]. Radioactive decay by the ejection of alpha and beta particles from the nucleus, and the release of gamma rays, generate heat in the spent fuel assemblies. As an example, the heat generated in spent fuel exposed to 25 000 MWd/t of reactor operation at a specific power of 35 MW/t decreases from a thermal power of 100 kW/t after ten days cooling to less than 1 kW/t as the fuel nears 100 days of cooling. The fission gases trapped within the cladding tube present a potential hazard should the cladding develop a hole through which they can escape. The heat, potential air and water contamination from radioactivity, and criticality measures are the primary considerations for the design and construction of any type of storage facility.

Spent fuel storage

Spent fuel has been stored without problems in water pools for long periods: over 20 years with low burn-up fuel and over 10 years with high burn-up fuel [2].

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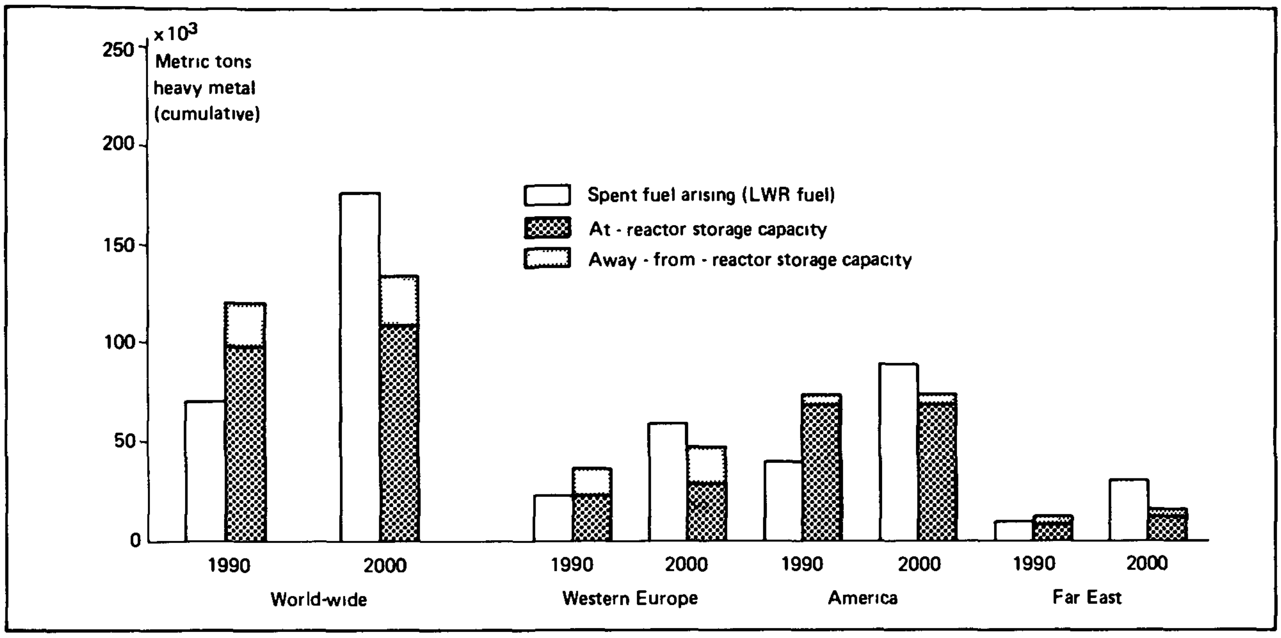

Figure 1. Forecasts of LWR spent fuel arisings and storage capacity up to the year 1000.

A recent survey of pool operators conducted by the Agency revealed that while pools have been operated since 1947 no event has caused a significant release to the environment or exposure to personnel. Underwater storage pools at the reactor not only allow for the cooling and decay time which spent fuel requires before its transport for reprocessing or for disposal, they also allow for the discharge of the entire core of the reactor in case a reactor inspection is necessary. Therefore, under the assumption that the spent fuel would be sent to be reprocessed within 1 to 3 years, space was originally provided for one full core discharge plus 1 to 3 annual reloads (an annual reload is normally 25 to 35% of the total core). The concept of extended storage was not foreseen in the original fuel cycle steps and therefore had not been extensively investigated. However, as the need for longer periods of storage has become apparent many countries have been actively investigating the various techniques for the interim storage of spent fuel.

Because of the delays mentioned earlier it became apparent that additional at-reactor storage might be the most rapid solution to the problem. At first, storage capacity was increased by densification of storage

Figure 2. The change in fuel composition after irradiation in a reactor.

I – Before irradiation
II – After irradiation
A – Thermal reactor with natural uranium fuel
B – Thermal reactor with enriched uranium fuel
C – Fast reactor with plutonium fuel
FP – Fission products.

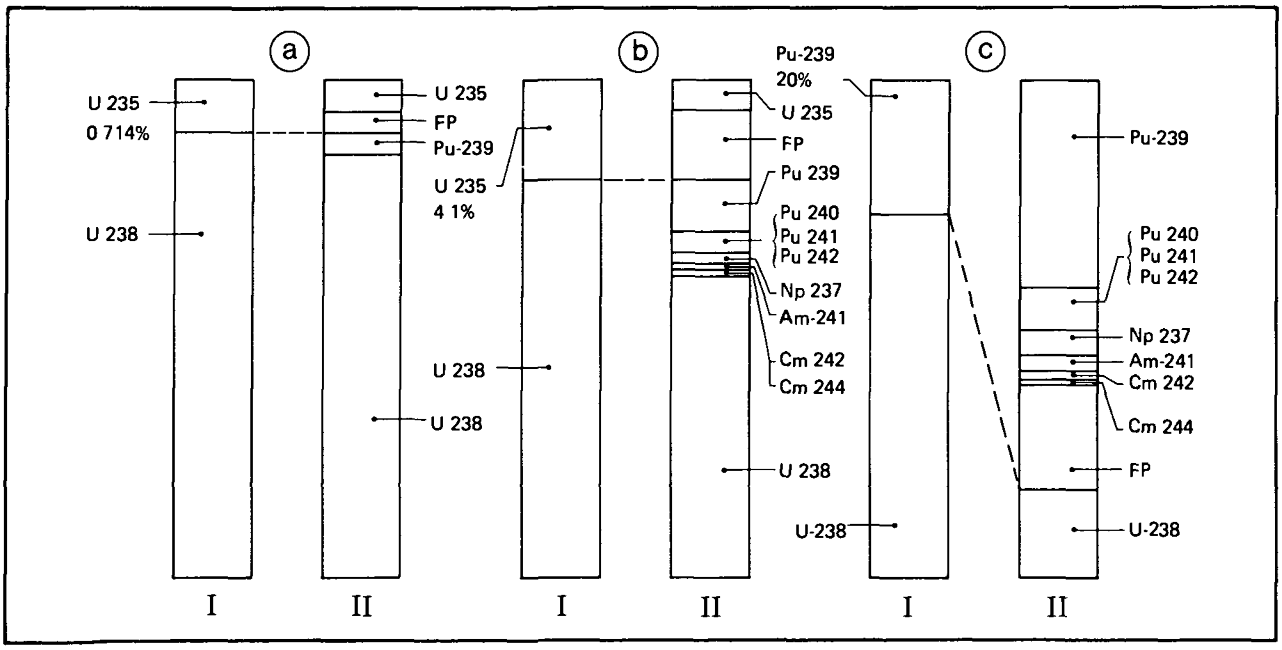

Figure 3a. The vault for dry storage of spent fuel from the gas-cooled reactor at Wylfa, England.

(compaction). filling unused space with additional storage racks, modifying existing racks to allow for closer spacing, and using neutron absorbing material to allow closer spacing.

The second approach to modifying existing AR pools is the double stacking of the fuel elements. As most pools are deep enough to allow the fuel elements to be inserted into the storage racks from the top, adequate space exists for a second tier with entry from the side.

Due to the nature of both HWR and LWR designs it is doubtful that anything other than pool storage would be considered for AR storage. The possibility of further compaction of fuel in water pools by disassembly of the fuel elements and storage of the fuel rods in a close-packed array (see Table 1) [4] is currently being investigated.

For extended storage of spent fuel, dry techniques appear to have a number of advantages over water pools. Therefore if national decisions require more interim storage, it appears that dry storage will be a prime alternative. Various dry storage concepts are being studied and in some limited cases actually being used for the storage of spent fuel. Although dry storage has not been developed or used to the extent that wet storage has, it has been used for some HWR, LWR and GCR fuel. Experience exists with Peach Bottom and Fort St. Vrain fuel in the USA and with the gas-cooled reactor Wylfa in the UK. Another large forced-cooling vault exists for high-level waste cylinders at Marcoule, France.

Currently, tests are being made in the USA with actual LWR fuel assemblies using various dry storage techniques [4,5]. The Canadians are currently investigating the use of dry storage for HWR spent fuel [6]. It would appear that storage in dry facilities might be the last step in the management of Candu spent fuel until a final decision to reprocess or dispose of the fuel is made.

Several different dry storage techniques are now being explored – dry caisson storage, geologic (hardrock) storage, vault storage (using both convection and conduction cooling), concrete cask storage, and transport cask storage. It would appear that only vault storage and storage in transport casks are being seriously considered for interim storage by most of the Member States interested in dry techniques.

The two types of vault storage which are being considered are the convection and the conduction cooling types. Forced air circulation with blowers, ventilation ducts, and filters is being considered, as is passive cooling which uses the natural convection caused by the decay heat in the fuel elements. The basic structure required for radiological and environmental protection appears to be the same for the two types of vaults. The passive approach appears to require less maintenance. Figure 3 shows pictures of two air-cooled vaults which are now operating.

The use of a shipping cask is a recent development utilizing the experience gained from transporting spent

Table 1. Advanced reracking concepts (PWR fuel)

Status	Reracking Concept	Storage density (MTHM/ft²)*
Presently used	Non-poisoned racks	0 39
Presently used	Poisoned racks	0 52
Advanced concept	Core plate storage	0 66
Advanced concept	Shot-filled canister storage	0 78
Advanced concept	Stacked racks	0 78
Advanced concept	Compacted fuel assembly storage	0 94
Advanced concept	Pin storage	1 07

* Metric tons heavy metal per square foot.

fuel elements. The concept developed in the Federal Republic of Germany is based on the fabriction of a transport and a long-term storage unit with larger carrying capacity, lighter cask structure, and lower construction costs.

Reprocessing technology

The main objective of reprocessing is to recover fissile and fertile nuclear materials which were not used in the reactor and also to separate plutonium and transplutonium elements which are formed in the reactor as a result of the nuclear reactions. The radiochemical composition of spent fuel depends on its residence time in the reactor (fuel burn-up) and on its initial composition (Fig.1). Chemical reprocessing of spent fuel was originally developed to recover plutonium. The same technology was later applied to the commercial reprocessing of fuel from nuclear power plants. This technology is based on the *Purex* process using solvent extraction as the main chemical separation method and has been described in detail at many international meetings [8,9,10].

Concentrated solutions of uranyl nitrate, plutonium nitrate, and nitrates of fission products are the result of the Purex process. Uranyl nitrate is converted to uranium trioxide by denitration and calcination. Uranium trioxide can be fluorinated to produce uranium hexafluoride which is recycled to enrichment plants. Plutonium nitrate is converted to ceramic plutonium dioxide for recycle in thermal or in fast breeder reactors.

The radioactive waste solution containing nitrates of fission products is evaporated, then denitrated to reduce its oxides which could be mixed with glass-forming material and vitrified. Vitrification is considered to be the most reliable way of preparing high-level radioactive waste for disposal.

There are basic differences in reprocessing requirements of the different fuel cycles due to the different fuel characteristics. Irradiated fast breeder reactor fuel has a higher plutonium and fission product content than thermal neutron reactor fuel. The higher plutonium concentration produces criticality complications which require a different design. The high burn-up and short cooling times lead to very high radioactivity and specific thermal power in the spent fuel. The small diameter of the pins and the presence of spacer wires also complicate chopping and dissolution operations.

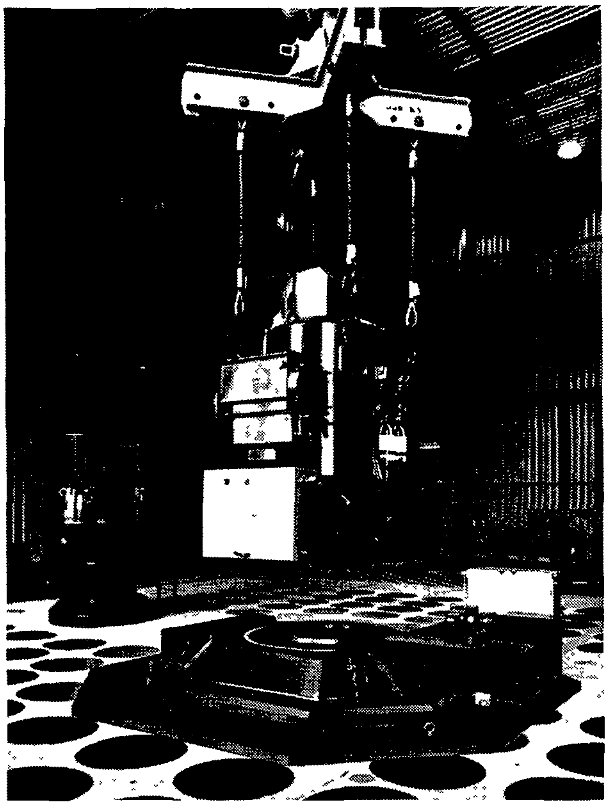

Figure 3b. The vault for storing vitrified waste canisters at Marcoule, France.

The current status and plans for fuel reprocessing of LWR fuel in some countries are described in Table 2. Technical and economic considerations show that a commercial reprocessing plant has an optimum capacity of about 1500 t/yr [8]. At present, the estimated reprocessing capacity needed to deal with the spent fuel generated from existing power reactors could be more than 3000 t/yr. For the year 1990 with an expected installed nuclear power of 400 GWe reprocessing capacities should be about 12 000 t/yr The information available on actual and planned reprocessing capacities shows that only a small amount of spent fuel is being reprocessed now and even by 1990 when some large-scale commercial plants could be operational, a significant proportion of the spent fuel will be in storage.

Delays in reprocessing are connected not only with technical aspects of construction of reprocessing facilities or difficulties in FBR developments but also with the political and institutional problems of non-proliferation. INFCE and other studies suggest that the problems of the back-end of the fuel cycle may be solved by the development of regional or multinational fuel cycle centres

Table 2. LWR fuel reprocessing facilities in some countries

Country	Name of plant/ location	Owner	Status	Present capacity HMt/yr*	Expansion/ planned capacity HMt/yr for the period up to 1990	
Belgium	Dessel-Mol	Government	Reconstruction of former Eurochemic plant		60–300	[12]
France	LaHague/UP2	Cogema	Operational	400	800	[13]
	LaHague/UP3	Cogema	Planned		800	
	LaHague/UP3	Cogema	Planned		800	
Germany, F R of	Karlsruhe	WAK	Operational	16–35		
	Commercial plant	DWK	Planned		350	
India	Tarapur	IAEC	Operational	100		[14]
	Kalpakkam	IAEC	Planned		100	
Japan	Tokai	PNC	Operational	210		
	2nd plant	JNFS	Planned		1 200	[15]
UK	Windscale	BNFL	Operational	400		
	Windscale (Thorp)	BNFL	Planned		1 200	[16]
USA	Barnwell	AGNS	Constructed but not put into operation			[17]

* Tons heavy metal per year

including international facilities for spent fuel storage, reprocessing, plutonium storage, and mixed-oxide (MOX) fuel refabrication.

International activities

The Agency has been active in the area of spent fuel management over the last five years, sponsoring a number of studies and meetings. The study on Regional Fuel Cycle Centres (RFCC), and subsequent consultants' meetings pointed out that not enough experience had been gathered in storing fuel for extended periods of time. The Agency supported and contributed to the International Nuclear Fuel Cycle Evaluation working group dealing with all areas of spent fuel management. Current IAEA-sponsored studies in spent fuel and plutonium storage will undoubtedly bring additional insight to the subject.

The Agency is evaluating the current world experience in the storage of fuel in water pools. A co-ordinated research programme to monitor fuel that has been in storage for a long time both in wet and dry environments has been established. An advisory group met recently to discuss storage alternatives for spent fuel. The programme includes the publishing of a guidebook in 1982 on spent fuel storage and the sponsoring of a seminar in 1983 on the integrated aspects of spent fuel management – storage, transport and reprocessing – and their impact on economics, environment, safety and non-proliferation.

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