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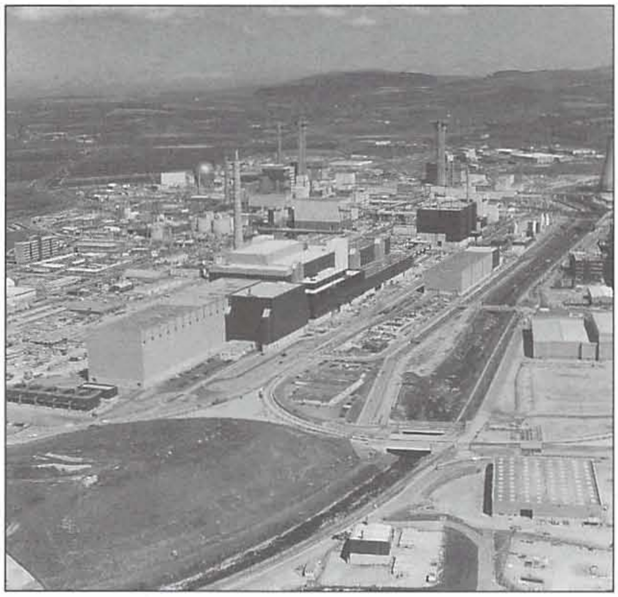
The International Civilian Reprocessing Business

BY FRANS BERKHOUT

It is a curious irony that just as the separation of plutonium for military purposes is drawing to a close, the separation of plutonium in civilian programmes is undergoing unprecedented expansion. Far from being another 'peace dividend,' commercial reprocessing is an artefact of beliefs and technological commitments made several decades ago. Whereas a few years ago it appeared that commercial reprocessing faced a slow but certain death because it was too costly and unpopular, the context has changed over the past couple of years. This article provides an explanation of the scope of and justifications for civilian reprocessing, and provides an analysis of the changes now occurring in the international reprocessing business.



▲ *The Thermal Oxide Reprocessing Plant (THORP) at Sellafield, England, commissioned in 1994.*

Reprocessing defined

The vast majority of power reactors today are fuelled with enriched uranium. The energetic, or fissile, uranium (uranium-235) is irradiated and fissioned in the reactor to generate heat. Over a period of three to five years, the fissile content of the fuel is gradually depleted. This depleted or spent fuel routinely needs to be replaced with fresh fuel. Hot and highly radioactive spent fuel is therefore discharged from the reactor. The heat and radioactivity are generated by the decay of new radioactive materials produced during nuclear power production.

Following discharge from the reactor, the spent fuel must be stored securely, usually under water, to allow it to cool. There are two alternative routes for spent fuel management over the longer term. Either the fuel can continue to be stored, and perhaps eventually disposed of as a waste (direct disposal), or the fuel can be chemically processed to separate out its constituent parts (the "closed" cycle). Reprocessing is the chemical separation of plutonium (0.2 to 1 percent by weight) and uranium (95–96 percent) from the fission products and other long-lived wastes (3–4 percent) contained in spent nuclear fuel. Cumulatively, about one-third of spent fuel discharged from power reactors has been reprocessed to date; the remainder has been placed in long-term storage pending final disposal.

Justifications for reprocessing

To tell the story of how civilian reprocessing has evolved it is necessary to

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E D I T O R I A L

International Implications of US Reprocessing

BY LYDIA POPOVA

In the fall of 1995, the environmental community in Russia learned about the letter sent by Defense Nuclear Facilities Safety Board Chairman John Conway to Secretary of Energy Hazel O'Leary in support of reprocessing as a method of spent fuel management. The start up of reprocessing at the Savannah River site in February 1996 was perceived by the Russian community as a confirmation of the US government's intention to reconsider the policy on reprocessing adopted under President Jimmy Carter. It

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know not only about the technological and industrial context, but also about the assumptions and beliefs which have powered the whole enterprise. Nuclear reprocessing is the quintessential 'big' technology. For instance, the Thermal Oxide Reprocessing Plant (THORP) at Sellafield in the United Kingdom took 20 years from planning to execution. The total capital cost of the plant was about $4 billion. Big technologies require strong rationales. Over time, as conditions and perceptions change, these rationales are also forced to change.

Justifications for civilian reprocessing fall roughly into three time periods. During the early period stretching from the 1960s to the mid-1970s, reprocessing was considered the only viable management option for most spent fuel types. Plutonium recycling in fast neutron ("breeder") reactors was regarded as an essential feature of the long-term growth of nuclear power, providing energy security in an age of energy scarcity. Recycling plutonium in this way would unlock the energy potential of the more abundant uranium-238 which does not fission in significant amount in conventional reactors.

In the second period, from the mid-1970s to the late-1980s, the economic and strategic case for reprocessing gradually unravelled. Nuclear power grew more slowly than expected and uranium, far from being scarce, turned out to be relatively abundant. Low uranium prices undermined the economic case for plutonium whose real cost increased greatly due to escalations in the price of reprocessing. Meanwhile, although huge amounts of public money was spent on research and development, breeder reactor commercialisation remained a distant dream, primarily because of the great technical difficulties involved. During this period, the proliferation risks of the 'plutonium economy' became a serious international issue. Since the mid-1970s, the United States has had a *de facto* policy opposing civilian reprocessing. Justifications for reprocessing therefore turned less and less on the value of plutonium as a fuel and more on the claim that reprocessing yielded environmental benefits over the alternative spent fuel management route: storage-direct disposal.

In the current period, storage-direct disposal has become the preferred spent fuel management route in most countries. Reprocessing survives primarily due to the inertia of industrial and commercial commitments made during the 1970s and 1980s. In the future, the industry is likely to be limited to a shrinking 'core' of reprocessor countries: France, the United Kingdom, Japan, Russia, and perhaps India. Despite this clear declining trend, the economic, security and environmental rationales for reprocessing are now being recast.

The evolution of civilian reprocessing

Civilian reprocessing has remained the preserve of the few, with nuclear weapon states establishing an early commercial advantage which they have never given up. Today there are just four major commercial reprocessing facilities in the world: La Hague and Marcoule in France; Windscale/Sellafield in the United

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FRANCE

BY MYCLE SCHNEIDER AND MATHIEU PAVAGEAU

In France, plutonium separation began as a part of the nuclear weapons research program developed after World War II. Three plutonium producing reactors were put into operation between 1956 and 1958 at the Marcoule site. UP1,[1] the first full-scale reprocessing plant was completed there in 1958. Cogéma, a subsidiary of the Commissariat à l'Energie Atomique (CEA) set up in 1976, inherited technologies and facilities developed for the weapons program. Cogéma is the operator of the French reprocessing program, with contracts from both the military and the French electric utility, Electricité de France (EDF). Cogéma operates two large scale reprocessing plants at La Hague, UP2 and UP3, which together produced roughly 80 percent of all separated plutonium in the world in 1995. The nominal annual capacity of each is 800 metric tons of heavy metal, equivalent to an annual production of separated plutonium of about 8,000 kg. UP2 was started up in 1966, originally to reprocess Magnox fuel. Its nominal capacity varied and was finally put at 400 tons per year. From 1976 onwards a new head end enabled the plant to reprocess oxide fuels of light water reactors (LWRs). Since 1994, after significant modification and expansion, the plant operates under the name UP2-800 to indicate its new nominal annual capacity. UP3 came on line in 1990.

The French plutonium industry's development over the past 20 years has depended on important contracts from foreign clients. More than half of the spent LWR fuel processed at La Hague has been of foreign origin. UP2 reprocessed foreign fuel up to 1990 and has since been entirely devoted to French fuel (with the exception of a batch of German MOX fuel processed for demonstration purposes). UP3, financed by foreign clients, is due to reprocess only foreign fuel until around the year 2000. In 1977 and 1978, 30 foreign customers in seven countries funded the construction of UP3 and in return received contracts for UP3's planned reprocessing capacity during the first ten years of its operation. Today, Cogéma provides nuclear fuel services to electric utilities from Germany, Japan, Belgium, the Netherlands, and Switzerland. SGN, an engineering subsidiary of Cogéma, is providing the know-how for the construction of the Rokkasho-mura reprocessing plant in Japan, based on the design of the plants at La Hague.

Despite its long-declared policy to reprocess all spent fuel unloaded from reactors, France is unable to do so. The present capacity of the reprocessing plants at La Hague is completely committed to EDF and foreign clients and Cogéma can now reprocess 850 metric tons out of some 1200 metric tons of spent fuel unloaded annually from French reactors. The spent fuel which is not reprocessed is put into storage. In 1996 it became clear for the first time that EDF did not intend anymore to achieve the all-reprocessing goal. A fierce conflict is now taking place back stage within the nuclear establishment over the definition of a future spent fuel management strategy in France. In 1992 already EDF decided—without any publicity—"not to take into account anymore, in deduction of the provision for reprocessing, of the value of plutonium which will come out of reprocessing, given the uncertainties of its future use."[2]

Further, EDF is having second thoughts about the use of mixed-oxide (MOX) fuel due to its high cost relative to uranium fuel. Today sixteen reactors are licensed for MOX fuel use (30 percent of the core), of which nine were loaded with MOX by the end of 1996. EDF will have to expand its MOX program and ask for a MOX license for an additional 12 reactors. According to information obtained by WISE-Paris, the Minister of Industry has recently ordered EDF to increase the number of reactors to be "moxed" to ten in the next year. France already has very large stockpiles of plutonium, which will increase over the coming years since MOX throughputs are limited and plutonium production is not decreasing accordingly. Official figures for stockpiles of unirradiated plutonium in France in various forms (separated, fresh MOX, etc.) amounted to 55,300 kg as of December 1995 of which 25,700 kg belonged to foreign countries.[3] Thus, France is aggravating both problems: spent fuel and separated plutonium stocks.

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1 UP stands for "usine de plutonium" (plutonium factory).

2 EDF, *Rapport annuel 1994*, Paris, 1995. Translation by the author

3 Ministère de l'Industrie, *L'énergie nucléaire en 110 questions*, Ed. Le Cherche Midi, Octobre 1996

BRITAIN

BY FRANS BERKHOUT

After France, Britain is the second largest reprocessor of power reactor spent fuel in the world. This activity is located at the Windscale/Sellafield site in the north-west of England.[1] Civilian reprocessing began at Windscale in 1964, and is set to continue until at least 2010. See below for the historical rate of plutonium separation at Sellafield.

Thermal reactor fuel reprocessing

Magnox power-reactor fuel has been reprocessed at the Building 205 (B205) plant at Windscale/Sellafield in northwest England since 1964. The plant has served a critical role in the British Magnox reactor programme, while servicing fuel from Japanese and Italian Magnox reactors as well. All Magnox fuel has routinely been transported to Sellafield. By the end of 1995 some 26,800 metric tons of fuel had been processed at B205 from which a total of about 59 metric tons of plutonium had been separated. Magnox fuel reprocessing is expected to continue until 2015, about five years after the shut down of the last Magnox reactor in Britain. By then nearly 90 metric tons of plutonium will have been separated at B205.

Oxide fuel reprocessing began at Windscale in 1969 when a small Head-End Plant (HEP) at which oxide fuel was prepared for feed into the B205 plant was brought into operation. In all 110 metric tons of fuel were processed through HEP/B205 before an accident caused the permanent closure of B204 in 1973. About 400 kg of plutonium was extracted.

Large scale oxide fuel reprocessing began with the commissioning in 1994 of the Thermal Oxide Reprocessing Plant (THORP) (capacity, 700 metric tons fuel per year). About 70 percent of the first ten years' production at THORP will be dedicated to foreign fuel. 'Baseload' and 'options' contracts for 6600 metric tons of fuel are due to be processed by 2005. Contracts beyond 2005 are less secure. The British utility, British Energy holds contracts for about 2600 metric tons of fuel, while additional contracts for 700 metric tons of fuel were signed by German utilities in 1990. These contracts would secure production at THORP until 2010.

Fast reactor fuel reprocessing

Fast reactor and materials test reactor (MTR) fuel has been reprocessed at Dounreay in northern Scotland since July 1958. Two facilities have been operated by the UK Atomic Energy Authority (UKAEA): D1204 for MTR fuel; and D1206 for fast reactor fuel. D1204 is a small facility which has processed fuel from British and non-British research reactors. D1206 began operation in 1961 and processed highly-enriched uranium fuel from the Demonstration Fast Reactor (DFR, shutdown 1977) and MOX fuel from the Prototype Fast Reactor (PFR, shutdown 1994). Both reactors were located at Dounreay. By the end of 1995 about 21 metric tons of PFR fuel had been reprocessed at Dounreay, containing some 4.5 metric tons of plutonium. In the absence of new MTR reprocessing contracts, the D1206 plant is therefore expected to be closed down in 1997–98.

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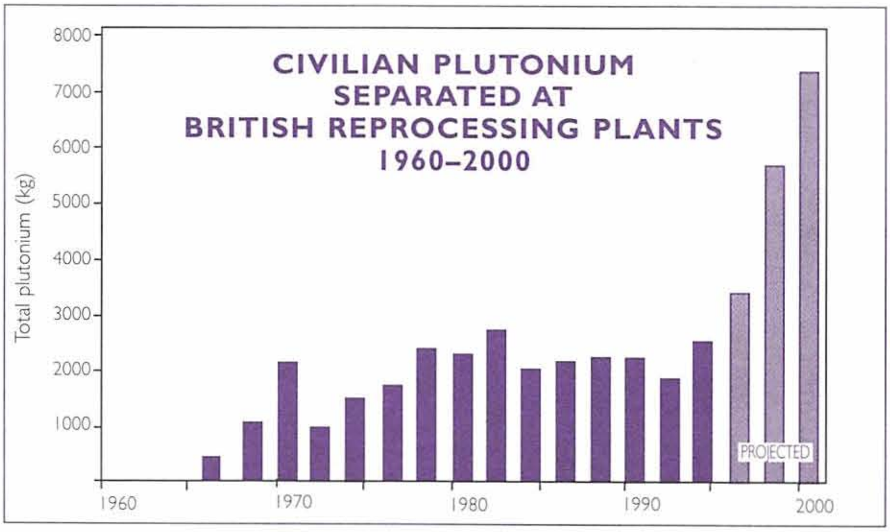
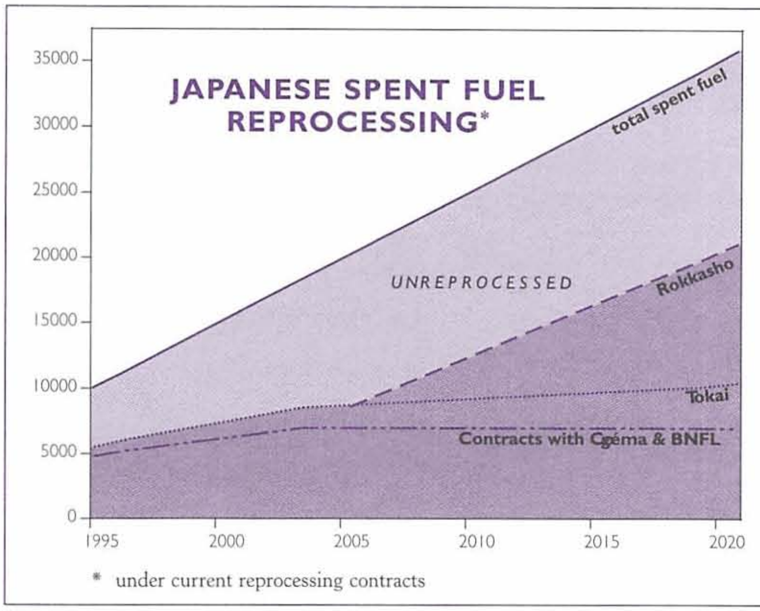


[1] The name of the facility dealing with civilian activities was changed in the early 1980s from Windscale to Sellafield.

JAPAN

BY JINZABURO TAKAGI



Japan's nuclear fuel cycle policy is to reprocess all spent fuel and consume all the extracted plutonium as reactor fuel. Based on this policy, the government-owned Power Reactor and Nuclear Fuel Development Corporation (PNC) built and started the Tokai reprocessing plant in 1977. Japanese utilities also signed contracts with Cogema and BNFL for reprocessing of about 7000 metric tons of spent fuel at the La Hague and Sellafield plants. In addition, Japan Nuclear Fuel Limited (JNFL) is now constructing a commercial-scale plant at Rokkasho, Aomori prefecture, which will enter commercial operation in mid-2000 according to the official plan.

Actual developments in Japan, however, show that this policy, intended to constitute the basis of a nuclear back-end policy, deviates largely from reality. According to government statistics, the cumulative amount of spent fuel discharged from light water reactors (LWRs) was 10,400 metric tons as of the end of FY 1994 (March 31, 1995), and the current rate of discharge is about 1000 metric tons annually. The Tokai plant is operating at pilot plant capacity, and had reprocessed a total of 864 metric tons by the end of FY 1995.

Given the limited capacity of the Tokai plant together with Japan's policy that no new contracts be made with overseas reprocessors, Japan cannot reprocess all of its accumulated spent fuel. Even if the Rokkasho plant starts full commercial operation in the mid-2000s as planned, the plant's reprocessing capacity of 800 metric tons and storage capacity of 3000 metric tons of heavy metal will absorb only a small portion of the accumulated spent fuel along with that which will be discharged annually.

Furthermore, the soaring cost estimate of the Rokkasho plant makes the future of its construction very uncertain. JNFL's latest estimation of the construction costs is 1.88 trillion yen (about $17 billion), including the liquid high-level waste vitrification facility—up to 7 times more than the costs of its European counterparts. It is possible that construction work will be postponed after the completion of a spent fuel storage pool, expected in 1997.

When viewed from the plutonium demand side, the central government and utilities face a serious surplus problem. Japan's ambitious plutonium program has been suffering from technical, economic and political difficulties. Strong concerns over security and safety, both international and domestic, were aroused when the Akatsuki-maru ship carried 1.5 metric tons of plutonium from France to Japan. In 1995, Japanese utilities forced the government to scrap the MOX-fueled Ohma advanced thermal reactor (ATR) project on economic grounds. A sodium leakage accident at the fast breeder reactor (FBR) Monju on December 8, 1995 dealt a severe blow to the government plutonium program. Japan's entire FBR program has since been postponed, perhaps indefinitely.

The government plans to consume most of the plutonium separated in Europe as MOX fuel in LWRs, in order to maintain the pledged "no-(plutonium) stockpile policy." But, the MOX use program could also be substantially deferred due to the opposition of local governments. In that case Japan's already large separated plutonium surplus in Europe of 8.7 metric tons (as of the end of 1994) would increase to 20–25 metric tons by the turn of the century.

Japanese reprocessing policy now faces a curious contradiction. On the one hand, Japan is confronted with a shortage of spent fuel reprocessing capacity. On the other hand, it is suffering from an increasing surplus of plutonium. The reprocessing-based nuclear fuel cycle/back-end policy is becoming more and more controversial and is losing its justification. The only way to get out of this difficulty is a thorough reconsideration of the reprocessing policy to prevent a further build up of surplus separated plutonium.

Jinzaburo Takagi is the executive director of the Citizens' Nuclear Information Center in Tokyo.

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Kingdom; and Chelyabinsk-65/Ozersk in Russia. Over 95 percent of civilian reprocessing to date has been carried out at these four sites. These facilities are the nodes of a global fuel management system in which spent fuel is sent from reactors to reprocessing plants, and the separated constitutents (uranium, plutonium and waste) are typically by contract returned to the owner of the fuel. A number of smaller facilities have also operated. The map on p. 9 shows selected reprocessing plants. Commercial plants are marked with stars.

> MOX disposition programs for military uranium and plutonium will strengthen the industry by building up commercial infrastructures and subsidising commercial MOX activities.

In order to understand the future prospects for reprocessing, it is useful to understand the development of the industry up until now.

Reprocessing technology and the assumption that irradiated (or spent) fuel should be chemically treated were an inheritance from atomic bomb programs. In the UK and France reprocessing plants at Windscale and Marcoule originally devoted to weapons plutonium production have been used to process fuel from civilian Magnox power reactors as well. Metal fuel from these early gas-cooled reactors corroded quickly when stored under water. Rapid reprocessing was therefore a safety and environmental requirement for these reactor systems in the absence of dry storage facilities. Essentially all Magnox spent fuel has been reprocessed. Reactor shutdowns in France, Spain, Japan and the UK will bring Magnox fuel reprocessing to an end in around 2010. To date about 40,000 metric tons of Magnox fuel have been reprocessed, some 80 percent of this at the B205 plant at Windscale/Sellafield.

Oxide fuel used in advanced gas-cooled reactors (AGRs) and light-water reactors (LWRs) can be stored safely for longer periods of time. These reactor systems are therefore more independent of reprocessing. Moreover, dedicated commercial reprocessing facilities had to be constructed to handle oxide fuel. The build-up of oxide fuel reprocessing has therefore been slower.

Oxide fuel reprocessing began at the Nuclear Fuel Services facility at West Valley (NY) and at the small Eurochemic plant in Belgium, both in 1966. A Head End Plant (HEP) which prepared oxide fuel for the separation stages at B205 began operating at Windscale in 1969. None of these facilities operated for long. The West Valley plant was shut down for commercial reasons in 1972, the Windscale plant was closed following an accident in 1973, and the Eurochemic plant was closed in 1975 following the withdrawal of German and French partners.

These early failures coincided with a renewed interest in civilian reprocessing. The energy crisis of 1973–74 meant nuclear power was given a higher priority in energy policy. It was argued that over the longer term nuclear power would be based on plutonium-fuelled fast reactors because the anticipated growth in nuclear capacity would not be met by existing uranium resources. For a brief period, reprocessing and the commercialisation of fast reactors became guiding objectives of energy policy in many countries.

This window of opportunity was exploited by British Nuclear Fuels Ltd. (BNFL) and Cogéma, the state-owned British and French reprocessing companies. They launched ambitious projects to expand reprocessing at Sellafield and La Hague. The plants at these sites would service both domestic and foreign requirements, and during 1978 and 1979 binding contracts were signed with European and Japanese utilities. Over 60 percent of the first ten years-worth of capacity at these two sites was sold to foreign utilities who funded up front the capital cost of UP3 and THORP. UP3 began operating in 1990, while UP2-800 and THORP were both commissioned in 1994.

Reprocessing programs were launched in a number of other countries, notably in Germany and Japan. Both countries began operating pilot reprocessing plants in the 1970s (WAK at Karlsruhe in Germany, and Tokai-mura in Japan), and developed plans for major commercial facilities. The German program survived until 1989 when it was canceled because of its cost and political unpopularity. Japanese reprocessing has developed more slowly than originally planned, partly due to hostile international responses to its plutonium program. Construction of a commercial facility at Rokkasho-mura began in 1992 with a design substantially based on French technology.

The 1970s also saw the creation of a separate spent fuel management regime lead by the Soviet Union. The fuel cycle for Soviet-built reactors was centrally controlled, partly as a non-proliferation measure, by the Ministry of Atomic Power and Industry (MAPI). Spent fuel from the smaller 440 series LWRs (VVER-440) in the former Soviet Union, Eastern Europe and Finland was routinely sent to Chelyabinsk-65/Ozersk for reprocessing. Under intergovernmental agreements, this 'take-back' arrangement was provided free of charge. Plutonium separated from the fuel remained the property of MAPI (later Minatom) and was stored for anticipated future use in fast reactors.

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THE ECONOMICS OF REPROCESSING

The relative economics of reprocessing-waste disposal and interim storage-direct disposal has been the focus of much debate over the past ten years. Many approaches have been used and to a certain extent the approach taken will determine the outcome of the assessment. Most prominent recently have been the full-scale systems studies of the OECD Nuclear Energy Agency (1994)[1] and the German Energiewirtschaftlichen Institut (EWI) (1995).[2] Neither of these studies is definitive because there are always uncertainties and national specificities, but they represent the current possible spectrum of views.

These studies model the total fuel cycle costs of a reprocessing-recycling system based on thermal recycling of plutonium and compare this to the total costs of an open fuel cycle with direct disposal. The range of results produced by these studies is very wide, but all are agreed that under current economic conditions the reprocessing-recycle option is the more costly. The debate is over the width of the gap. Table 1 provides results of two recent studies at either end of the range of estimates: the 1994 OECD study as interpreted by Cogema in a recent presentation; and a 1993 study by the Vereinigung Deutscher Elektrizitätswerke (VDEW). The OECD figures appear to show only a marginal difference between the relative costs of the two options, whereas the VDEW study shows that for German conditions the reprocessing-recycle option is over twice as expensive as storage-direct disposal. The main differences are the assumed cost of reprocessing and waste management, and the treatment of credits/penalties for recycling recovered uranium and plutonium. The EWI study showed a cost difference between the two options of about 25 percent.

More limited assessments have used the 'free plutonium' concept in which the cost of separating the plutonium in reprocessing is discounted.[4] This picture is closer to the reality faced by utilities today, since many regard reprocessing as a sunk cost to which they are committed through binding contracts with reprocessors. It also explains why penalties are attributed to plutonium recycling in the VDEW study. Under the 'free plutonium' scenario the economics of MOX is a question of balancing the savings made in avoided fresh uranium ore purchases and avoided uranium enrichment with the additional costs of plutonium fuel fabrication. Production of MOX is more expensive than production of LEU fuel because of the added safety and security precautions needed in handling plutonium.

Assuming current and expected prices for uranium, enrichment and fuel fabrication, MOX fuel will be more expensive than LEU fuel. Even assuming the full-scale operation of large new MOX fabrication plants (Hanau, Melox), MOX fuel would cost about twice as much as LEU fuel. If reprocessing costs are all attributed to the cost of MOX fuel (uranium credits are discounted), then MOX fuel would appear to be as much as six times as expensive as LEU fuel.[5] Rather than being an asset, plutonium must be seen as a liability. Even if uranium resources are conserved, it is unlikely that an economic case could be made for the large premium that would be paid with thermal plutonium recycling. All minerals are potentially valuable, but only those which are economical are exploited.

—FRANS BERKHOUT

See endnotes on page 16.

TABLE 1: COST COMPARISON
between reprocessing-recycle and storage-direct disposal options: back-end costs only (undiscounted costs, mills/kWh)[3]

	OECD/Cogema (1994)		VDEW (1993)[1]	
	Closed	*Open*	*Closed*	*Open*
Fuel transport	0.20*	0.20	0.38	0.12
Fuel storage	–	0.62	–	1.06
Reprocessing	2.40	–	4.16	–
Spent fuel packaging	–	1.0	–	1.86[2]
Waste storage and packaging	–	–	2.32	0.46
Waste disposal	0.22	0.38	2.32	2.32
Subtotal	*2.82*	*2.20*	*9.14*	*5.92*
Uranium credit[3]	-0.36	–	+0.46	–
Plutonium credit[3]	-0.14	–	+1.62	–
Subtotal	*-0.50*	–	*+2.08*	–
Total	**2.32**	**2.20**	**11.26**	**5.92**

* To convert any of the numbers in this table into $/metric ton of fuel, multiply by 356.4.

1 Assumes a reactor efficiency of 0.33, a fuel irradiation of 45 GWd/t.

2 Assumes fuel conditioning plant throughput of 450 tHM per year.

3 A negative entry implies a cost saving and hence a positive value attributed to recovered products.

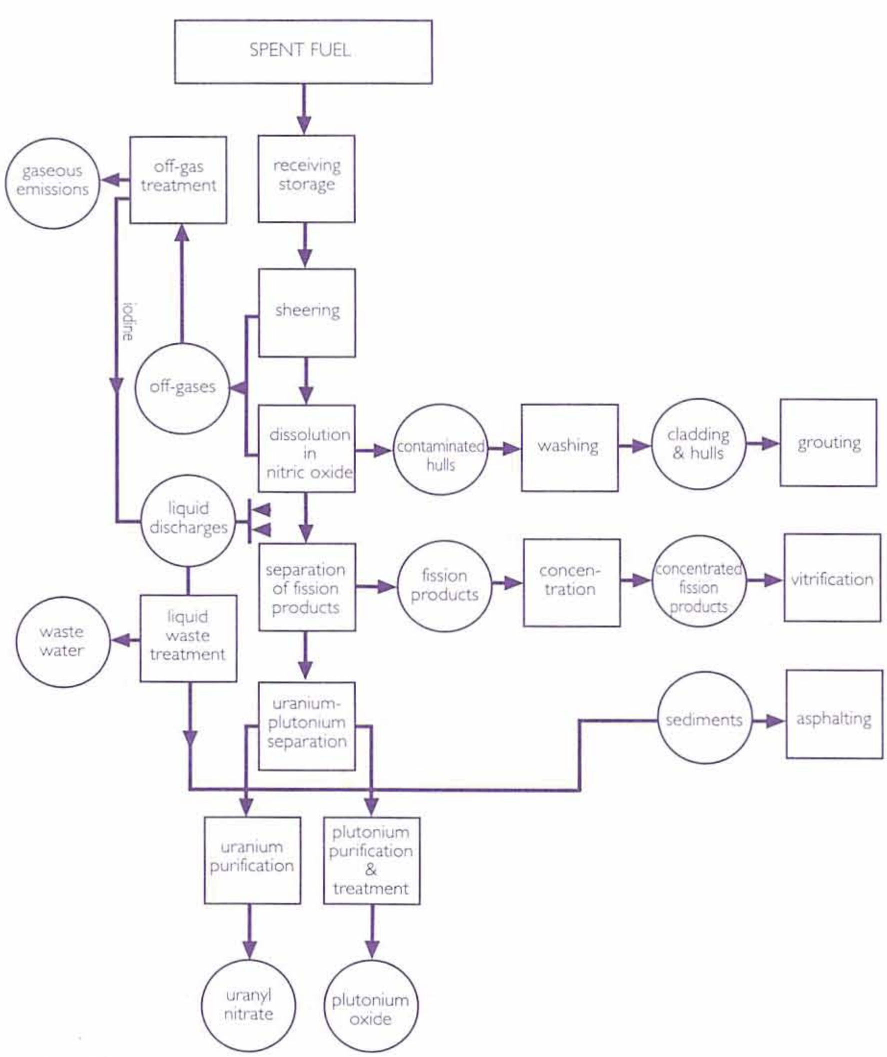
Reprocessing: Where and How

Reprocessing is generally regarded as a key link between civilian nuclear power and nuclear weapons production, since plutonium must be separated from irradiated fuel to be usable in nuclear weapons. In the past thirty years, nuclear industries have undertaken large-scale "commercial" reprocessing, in the vain hope that plutonium can be an economical energy resource (for more information on the use of plutonium as an energy source, see Issue #1 of *Energy & Security*). The map on the opposite page shows the location of major reprocessing facilities, both commercial and military. Design capacities are shown for commercial plants. Military and commercial reprocessing use basically the same process of plutonium separation; it is the type of spent fuel used that differentiates one from the other.

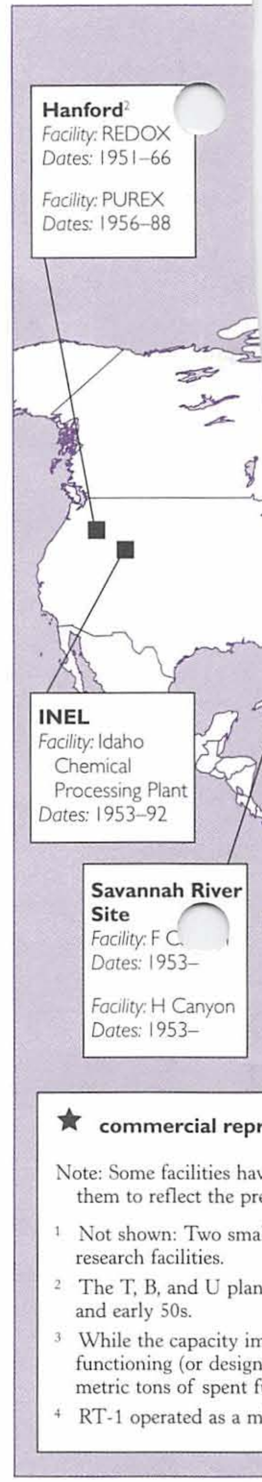
In a reactor, uranium-238 in the fuel rods is converted into fissile plutonium-239 as a result of neutron absorption and subsequent nuclear reactions. Gradually, some of the plutonium-239 is converted into non-fissile plutonium-240 upon absorption of another neutron. As the reactor continues to operate, more uranium-238 is converted into plutonium-239, leading to more plutonium-240 as well. Higher plutonium isotopes, notably plutonium-241 and plutonium-242, also build up with longer irradiation time.

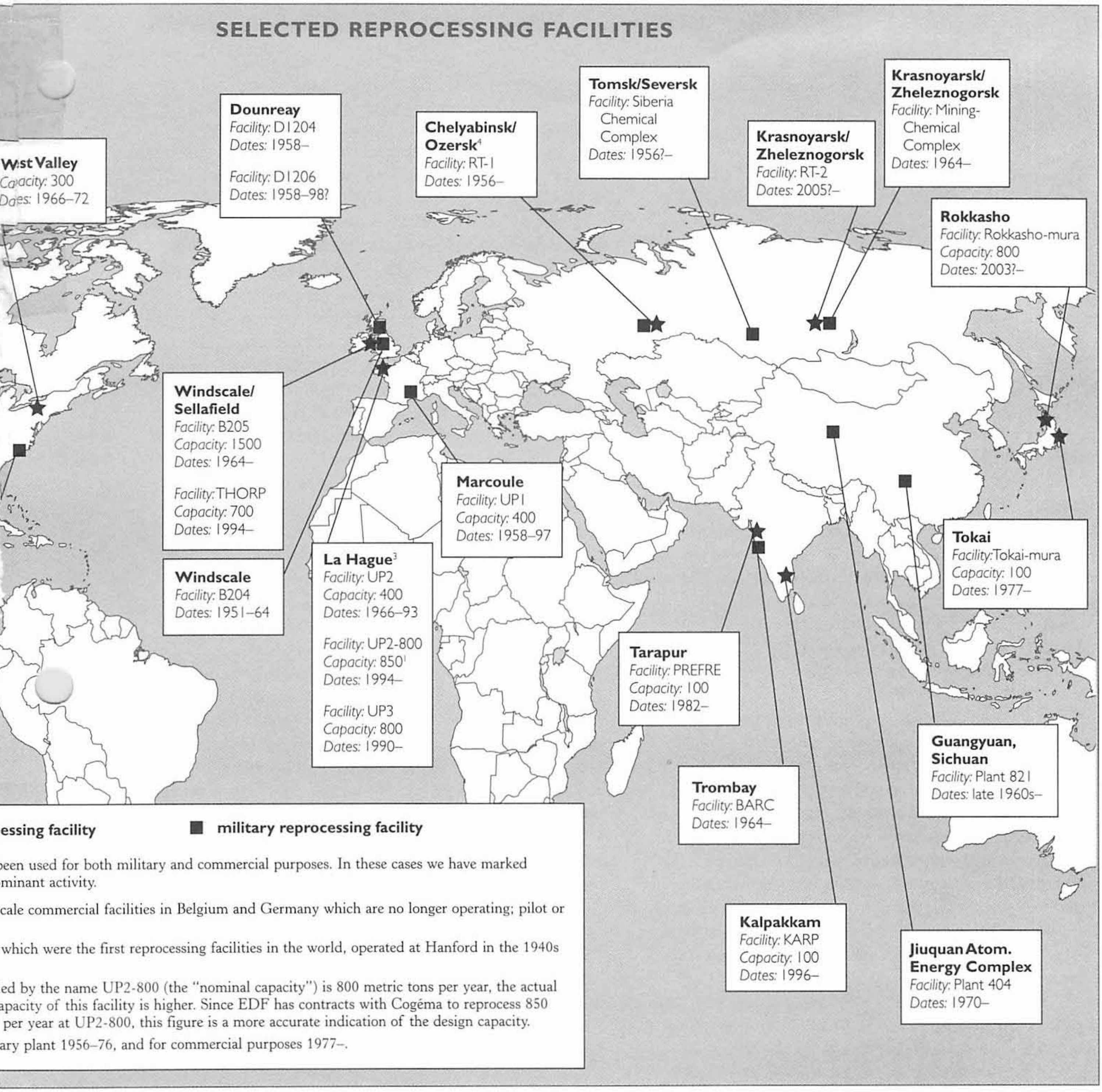
Spent fuel in civilian plants is typically "high burn-up" spent fuel—that is, it has been irradiated for extended periods in the reactors so as to generate a large amount of energy. Spent fuel from light water reactors (the most common type of civilian reactor) typically contains approximately 0.7 percent plutonium-239 and plutonium-241 (the fissile isotopes), and 0.2 percent non-fissile plutonium isotopes. Uranium irradiated for the extraction of plutonium for weapons is "low burn-up" fuel, which has been irradiated to minimize production of plutonium-240 and other undesirable higher plutonium isotopes. Spent fuel from military reactors contains a small fraction of a percentage of plutonium, almost all of it plutonium-239. Plutonium with less than 6–7 percent plutonium-240 content is considered "weapons grade," but it is possible to make a nuclear bomb with plutonium

THE PUREX PROCESS



Adapted from Cogéma publication *Le Retraitement des Combustibles.*





from high burn-up commercial reactor fuel as well.

Plutonium in spent fuel cannot be used until it is recovered through reprocessing. The most common kind of reprocessing is called the "Purex" process, which stands for Plutonium-URanium EXtraction (see diagram). All reprocessing facilities which are currently operating use the Purex process. Other reprocessing techniques have been used in the past, including the Butex (for diBUTyl carbitol EXtraction) process, the Redox (for REDuction OXidation) process, and the original bismuth phosphate process used to build the first US atom bomb. The US is also developing a new reprocessing method, commonly known as "pyroprocessing" which is an electrolytic method of separating spent fuel into three different streams (see article, p. 13).

COMPILED BY ANITA SETH

RUSSIA

BY ANATOLI DIAKOV

Reprocessing of spent nuclear fuel (SNF) from civilian nuclear reactors in Russia was started in 1977 when the RT-1 plant at the Mayak complex was brought into operation. The plant reprocesses spent fuel from VVER-440 and BN-600 civilian power reactors; naval propulsion reactors of icebreakers and submarines; and research reactors. The installed capacity of the plant is 400 metric tons of SNF per year. Uranium which is separated through reprocessing goes to the production of fuel for RBMK-1000 reactors (2.4 percent enriched). Separated plutonium in oxide form is put into storage; at the present time it exceeds 30 metric tons.

Most of the liquid low- and medium-level waste resulting from reprocessing is sent to storage tanks, pools, and reservoirs without treatment. High-level waste is stored in tanks. The total amount of high-level waste at the Mayak complex resulting from the reprocessing of fuel from production and commercial reactors is about 389 million curies. It is stored at the present time in the forms of solution (11,200 cubic meters, 258 million curies) and pulp (18,650 cubic meters, 131 million curies).

Vitrification of liquid high-level waste began in February 1991 with the introduction of the EP-500 furnace. The furnace can process 500 liters of high-level waste per hour and produces phosphate glass. Although designed to have a lifespan of 3 years, the furnace is still in operation, although its productivity has significantly diminished. Over the course of its operation, the furnace has vitrified 280 million curies of high-level waste. Currently, two additional furnaces of the same design are under construction, one of which could be completed within a year if funding is sufficient.

The construction of a "cold" crucible furnace[1] with a projected capacity of 100 liters of solution per hour is near completion. This facility will produce borosilicate glass. It is believed that with the introduction of this new facility, vitrification of high-level waste which contains large amounts of silicon, molybdenum, iron, sulfur, and other components will be possible. This waste could not be vitrified in the EP-500 furnace, and therefore has been accumulating in metal tanks.

In 1995, about 200 tons of SNF were reprocessed at RT-1, and about 150 tons was reprocessed in 1996. The plant has reprocessing contracts with both foreign and domestic nuclear power plants. Among the suppliers of SNF are two Finnish VVER-440 reactors (about 25 tons per year), four Hungarian reactors (about 50 tons per year), the Kolsk nuclear power station, and two reactors at the Novovoronezh station. Some spent fuel from Ukrainian reactors is also reprocessed.

Recently there have been disagreements between the plant and the Finnish power stations. Because of the rising prices of fuel and electricity, Mayak wants to raise the contract price of reprocessing to $800 per kilogram of uranium. According to unofficial sources the price is now about $400–500 per kilogram. The Finnish side is unwilling to agree to this rise in contract prices, and stopped reprocessing at the end of 1996. Another difficulty in foreign contracts lies in new Russian laws, according to which separated and vitrified radioactive waste must be returned to the country from which the spent fuel originates. The Finns object to Russian insistence on returning the waste. A similar situation exists with Hungary, which is also unwilling to take back waste.

It was once assumed that spent fuel from VVER-1000 reactors would be reprocessed at the RT-2 station at Zheleznogorsk (formerly called Krasnoyarsk-26). However, construction on this station is only in the primary stages, and in recent years has stopped for financial reasons. It is not realistic to count on domestic sources of financing, and attempts to attract foreign investment are are unlikely to be successful because of negative attitudes abroad toward reprocessing spent fuel. In light of these circumstances, Mayak is examining the possibility of reprocessing spent fuel from VVER-1000 reactors at RT-1. However, significant investment would be required to build a facility for preparation of VVER-1000 spent fuel.

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[1] A furnace in which a layer of solid glass separates the cooled crucible wall from the glass melt.

EDITORIAL

FROM PAGE 1

was a cause for celebration for the Russian Ministry of Atomic Power and Industry (Minatom) and a great disappointment for environmentalists and those concerned about the proliferation of nuclear weapons.

Seeing Americans promote reprocessing creates great concern and confusion in Russia because it encourages individuals in Minatom in their support for reprocessing. Minatom officials use many deceptive arguments to defend the Russian reprocessing program. They claim that reprocessing is the best method for management of spent nuclear fuel. This is not true, as reprocessing is currently based on the outdated PUREX technology, which produces large volumes of hard-to-handle liquid radioactive waste. It is now well-known that alternatives exist, and many countries have decided to explore them.

> Reprocessing should not be supported either in the U.S. or in Russia, if for no other reason than the signal it sends to other countries.

Minatom also claims that reprocessing is economical because it recovers plutonium, which can be used to fuel reactors, including a new generation of breeder reactors. But currently it is much cheaper and safer to use enriched uranium as a reactor fuel. Moreover, since the end of the Cold War there is a surplus of uranium, which can be used to fuel reactors if necessary—so much that Russia is sending some of it to the US.

Construction of a new reprocessing plant in Russia, RT-2, which was started in early 1980s and then halted due to public opposition and financial difficulties, cannot be resumed without foreign investment. Minatom officials hoped to find customers for reprocessing at RT-2 by offering them favourable terms. But even under these terms Germany and Switzerland have decided not to send spent fuel from their reactors and not to invest into the construction of RT-2.

Breeder technology is too expensive and has not been proven safe. Reprocessing becomes even more expensive if environmental and health standards are followed properly by industry. In addition, uranium that is extracted during reprocessing is contaminated by isotopes uranium-232 and 236, limiting its potential for re-use. This makes the concept of a closed nuclear fuel cycle quite vulnerable. Extracted plutonium creates more environmental, health and proliferation problems than can be justified by its economic advantages.

In the mid-1970s, the US government rejected commercial reprocessing primarily for non-proliferation reasons. Now the Department of Energy says that it will do a limited amount of reprocessing for environmental reasons, but will not reprocess any kind of spent fuel either from commercial or military reactors. Since it was first announced under President Bush, and then continued by President Clinton, this rejection would not appear to be based on political grounds.

In a true market economy reprocessing becomes uncompetitive. Nevertheless, reprocessing is promoted not only in Russia, which is making its first steps in the market, but attempts are also made to promote it in the U.S., which is often referred to as an example of a model market economy. Clearly, initiatives for reprocessing in both countries come from experts who inherited the same Cold War mentality, as there does not appear to be any logical technical or economic reason for promotion of reprocessing. Those who seek to win jobs and political support at Tomsk, Krasnoyarsk and Chelyabinsk in Russia are relying on the same unnecessary and dangerous technology that supports US government jobs in South Carolina.

Both our countries bear the environmental and health burden of the Cold War legacy. We believe that our scientists can find truly safe and environmentally friendly technologies to handle spent fuel, if they work together. If politicians in our countries really want to help their people, funds and resources should be directed to these efforts, not to the use of the PUREX process.

Nuclear experts claim that no viable technical alternatives to reprocessing currently exist for types of spent fuel with very thin cladding, which pose problems for safe storage. Minatom officials and experts now refer to the renewed operation of the reprocessing plant in Savannah River Site as a confirmation of this claim. We believe that nuclear engineers both in the United States and in Russia are smart enough to develop an alternative to reprocessing to stabilize the spent fuel which would produce less waste, cost less, and which would not create unnecessary and dangerous stocks of fissile materials.

The costs to humankind of pursuing a regime of non-proliferation are great in terms of material, financial and intellectual resources. Even the Non-Proliferation Treaty cannot guarantee that other nations will not join the five declared nuclear powers. Reprocessing, a technology for separation of plutonium that can be used in weapons, is a standing temptation for governments who seek nuclear weapons.

Reprocessing should not be supported either in the US or in Russia, if for no other reason than the signal it sends to other countries who look to us for technical guidance. Would our governments have all states follow their example?

Lydia Popova is the director of the Center for Nuclear Ecology and Energy Policy of the Socio-Ecological Union in Moscow.

INDIA

BY FRANS BERKHOUT AND SURENDRA GADEKAR

India has long had a policy of developing a closed fuel cycle with plutonium recycling in fast reactors. It has done this on the basis of a power reactor program based on natural uranium-fuelled CANDU reactors. The long-term aim of the Indian program is to be able to utilise India's large thorium-232 reserves in the production of nuclear electricity.[1] As noted in a 1982 report: "There was early realisation that the reactor system had to be capable of utilising the limited uranium resources to the maximum extent possible and no matter how good the reactor system was, the potential for power generation [in India] from uranium resources alone was not going to be very high."[2]

Today three reprocessing plants are operated by the Indian Department of Atomic Energy (DAE) with a total design capacity of about 230 metric tons, none of which are safeguarded. The first Indian reprocessing plant at the Bhabha Atomic Research Centre (BARC) at Trombay began operating in 1964 and has processed fuel from the Cirus and Dhruva research reactors. It was decommissioned in 1973 due to excessive corrosion, then refurbished and put back into service in 1982. A total of about 400 kg of plutonium is estimated to have been separated at the small BARC facility, and is reported to have been used in the Indian nuclear weapons program.[3] The plutonium used in the "peaceful nuclear device" exploded in Rasjasthan in 1974 was reprocessed at BARC.

> Three reprocessing plants are operated by the Indian Department of Atomic Energy with a total design capacity of about 230 metric tons, none of which are safeguarded.

A second reprocessing plant dedicated to reprocessing CANDU power reactor fuel, the Power Reactor Fuel Reprocessing (PREFRE) facility, was brought into operation at Tarapur in 1982. The design capacity of PREFRE is 100 metric tons of fuel per year. However, production at the plant has been constrained by logistical and technical problems. Furthermore, India has sought to avoid building plutonium stockpiles. In 1995, there was a serious leak of radioactivity at the Waste Immobilization Plant associated with the Tarapur plant. In the spotlight of public scrutiny caused by the leak, it was revealed that due to a "shortage of funds," the equipment for the waste immobilization plant was corroded from lying out in the open.

To date, fuel from just two nuclear stations, the Rajasthan Atomic Power Station (RAPS) and the Madras Atomic Power Station (MAPS) has been reprocessed at PREFRE. Estimating the amount of fuel that has been reprocessed at PREFRE is extremely difficult since no data have been published by the Indian authorities. Estimates are therefore based on assumptions about the way in which the RAPS and MAPS reactors have operated, and how much fuel could have been dispatched to Tarapur.

A maximum of about 310 metric tons of cooled spent fuel from these two reactors is estimated to have been reprocessed, yielding a maximum of 900 kg of plutonium by the end of 1995. A more realistic estimate, taking account of plutonium requirements of the Fast Breeder Test Reactor (FTBR) at Kalpakkam, suggests that 300–400 kg of plutonium had been separated at PREFRE by the end of 1995.

In March 1996 cold commissioning (operation without actual spent fuel) began at the Kalpakkam Reprocessing Plant (KARP) located at the Indira Gandhi Centre for Atomic Research (IGCAR) near Madras. 'Hot' commissioning, with the introduction of fuel, was planned for the end of 1996. Originally, this site was planned to have 1,000 tons of reprocessing capacity by the year 2000, but these plans are now in limbo.[4] The facility is currently designed to process fuel from the MAPS reactors and has a design capacity of 100 metric tons of CANDU fuel per year, for an annual output of about 350 kg of plutonium.

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1 Under irradiation thorium-232 is transformed into uranium-233 which is fissile, and can be used in both thermal and fast reactors. Thorium has not been used in any nuclear program on a commercial scale as yet because of many significant technical and economic issues connected with its use.

2 N. B. Prasad Committee's report on Rajasthan Atomic Power Station (1982)

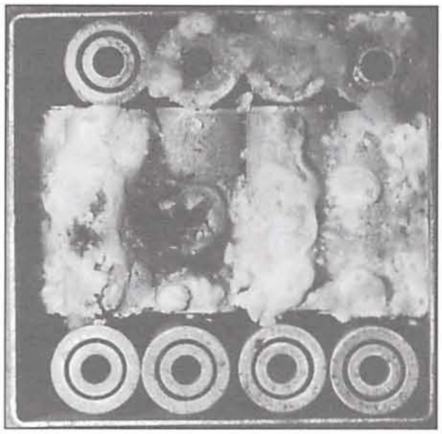
3 See David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: Inventories, Capabilities and Policies*, SIPRI/Oxford University Press, 1997, pp. 180–83.

4 P. K. Iyengar in *Nuclear Power: Policy and Prospects* ed. P. M. S. Jones (John Wiley and Sons) 1987, p. 283.

UNITED STATES

BY BRIAN COSTNER

Through World War II and the Cold War, the United States separated some 100 metric tons of plutonium. Plutonium separation, or reprocessing, occurred primarily at the Hanford Reservation in Washington and the Savannah River Site (SRS) in South Carolina. Additional reprocessing took place at smaller national laboratories, particularly Los Alamos in New Mexico. At the Idaho National Engineering Laboratory (INEL), reprocessing was used to separate highly enriched uranium from fission products in used naval reactor fuel.



▲*Corroded reactor target slugs, Reactor Disassembly Basin, Savannah River Site*

Each of these facilities is federally owned. The only private reprocessing in the US was conducted at the West Valley plant in New York. That plant was closed in 1972 and the separated plutonium was turned over to the federal government, while responsibility for clean-up of the facility is being shared by New York state and the federal government. Stabilizing, containing, and monitoring all the radioactive wastes and environmental contamination created by 50 years of reprocessing in the US could cast taxpayers about $1 billion for every ton of plutonium produced, according to Department of Energy (DOE) estimates.

President Reagan's Energy Secretary, John Herrington, publicly declared that the US had produced a plutonium surplus even before the Cold War came to an end. Once it did end and arms reduction agreements were signed, President Bush's Energy Secretary, Admiral James Watkins, announced that reprocessing operations would be phased out. The phase out, however, has run into political hurdles at all but the Hanford Reservation, which locked the doors on its last reprocessing plant in early 1996. Supported largely by the desire to protect jobs, reprocessing projects at SRS and INEL have actually been gaining momentum, rather than being brought to a timely and safe end.

SRS is home to the last two reprocessing plants in the US based on decades-old PUREX technology. These mammoth concrete structures, built in the 1950s, were slated to be shut down by the turn of the century. This date, based on the time necessary to complete reprocessing of various on-site irradiated fuels and other nuclear materials left over from Cold War operations, has been extended to about 2002 because of delays caused by safety concerns. Additionally, SRS managers and local community officials are proposing to extend operations as much as 30 years by bringing in wastes from other DOE facilities, and possibly commercial reactors, for reprocessing at SRS.

At INEL, the reprocessing plant operated during the Cold War has been placed in standby and is not expected to operate again. However, a new, smaller reprocessing plant using a new technology which is not yet commercial has been brought on-line. This technology, often referred to as pyroprocessing or electrorefining, was developed as a part of the US breeder reactor program, which was canceled in 1995 because of continuing nonproliferation, technical, and economic concerns. The reprocessing component of the program, however, was kept alive and renamed a waste management operation. This is especially troubling to nonproliferation proponents because this new reprocessor can be constructed in a much smaller space than the old-style plants and as a waste management technology its design characteristics may not be fully protected.

The next year will be a critical juncture in the fate of reprocessing in the US as key decisions are made about whether to move forward with the planned shut down of reprocessing plants or to expand their role. Two opposing views dominate the current discussion. The view most consistent with longstanding US policy is that since there is no longer a military need to separate plutonium, it is time to shut down the remaining reprocessing capacity and implement better techniques for managing spent fuels and other nuclear materials. People supporting a different view propose the federal government's current and future spent fuel management needs as a rationale for extending reprocessing in the US, with the hope that such an approach will ultimately be tied to a revitalization of the nuclear power industry.

Brian Costner is the director of the Energy Research Foundation in Columbia, South Carolina.

CIVILIAN REPROCESSING

FROM PAGE 7

The situation today

Two civilian reprocessing regimes today exist side-by-side: the European-Japanese system, and the Russian system.

The European-Japanese system, centred on plants at La Hague and Sellafield, is nearly complete. Magnox fuel reprocessing continues steadily at Sellafield at a rate of about 1000 metric tons per year, while total oxide fuel throughput in France and Britain will reach about 2350 metric tons in 1998 when THORP reaches full capacity. The three plants handle fuel from about 150 reactors operating in nine countries (including the UK and France). Added to these principal facilities is a small Japanese plant at Tokai, with a capacity of about 100 metric tons per year.

This system is due to be supplemented by an 800 metric ton per year facility at Rokkasho-mura in Japan in 2003. However, Japanese plutonium policy is being reassessed following an accident at the Monju fast reactor in December 1995. The capital cost of the Rokkasho plant (1.88 trillion yen, or about $17 billion) is causing utilities to look again at fuel management strategy. There is a good chance that the plant will not be completed.

Two further elements have been added to the European-Japanese regime. The failure of fast reactors forced utilities in the early 1980s to consider alternative ways of disposing of plutonium. Although a far less efficient way of using plutonium, recycling in conventional 'thermal' reactors has been adopted by utilities in Belgium, France, Germany, Switzerland and Japan as a way of avoiding the costs and difficulties of storing plutonium. To enable plutonium recycling in thermal reactors, mixed-oxide (MOX) fabrication plants have been built in Belgium (Dessel P0, operating on a significant scale since 1986), France (Melox, operating since 1995) and the United Kingdom (SMP, which will begin operation in 1997). Utilities have also needed to licence their reactors to take MOX fuel. Although technically feasible, the introduction of plutonium fuel into reactors has proven politically controversial in several countries, including Germany and Japan. The MOX fabrication and fuelling bottlenecks continue to be an obstacle to the European-Japanese reprocessing-recycle regime.

Survival of this industrial system beyond 2005 will depend on new demand for reprocessing services. Utilities have increasingly turned their backs on reprocessing in favour of the cheaper and less problematic fuel storage-direct disposal route. Sustained future demand for reprocessing is likely in the UK (Magnox fuel), France and Japan. Elsewhere extended fuel storage capacities will be made available. One open question is whether the rapidly industrialising Asian economies will come to depend more on nuclear power. This could feed through to a demand for reprocessing.

The Russian reprocessing system has been adversely affected by the collapse of the Soviet Union. From 1990 to 1994 throughput at the RT-1 plant was around 100 metric tons per year. There has been a slight upturn in 1995 and 1996 due to contracts with Finnish, Hungarian, and Ukrainian clients. However, almost all of the non-Russian clients reprocessing at Chelyabinsk are now pursuing spent fuel storage policies, while Russian reactor operators are failing to pay their bills. The future of the plant appears to depend on the faint possibility that new foreign clients can be attracted.

TABLE 2: WORLD CIVILIAN PLUTONIUM INVENTORIES

Inventory		Total plutonium (metric tons)
Military plutonium		250*
Civilian plutonium		990
Spent fuel	*800*	
Separated plutonium in store	*141*	
Recycled plutonium	*49*	
Total		1240

* An older estimate of 270 metric tons (which assumed a Russian weapons inventory of 150 metric tons, rather than 130 metric tons) was published in Issue #1 of *Energy & Security*.

Summary of fuel reprocessing: 1960–1995

In 1995, 17 metric tons of plutonium were separated at civilian reprocessing plants. Of this somewhat less than 8 metric tons were fabricated into MOX fuel; the remainder was placed into storage. One of the enduring legacies of civilian reprocessing is that most of the materials (plutonium and uranium) recovered from spent fuel have remained in store. Almost three-quarters of the plutonium separated to date remains in store. The largest civilian inventories are in the UK (49 metric tons), France (55 metric tons), and Russia (about 30 metric tons). Table 2 provides a summary of world inventories of plutonium at the end of 1995, at which time a total of 190 metric tons of plutonium had been separated at civilian reprocessing plants.

The Changing Context of Reprocessing

Although commercially the picture does not look rosy for reprocessing, a number of perverse developments have emerged over the past few years which are

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REPROCESSING AND THE ENVIRONMENT

Environmental justifications began being made for reprocessing during the 1970s when questions were raised about the strategic rationale for reprocessing. Given the poor record of radioactive emissions (gaseous and liquid) from reprocessing plants, this has been a difficult argument to sustain. Here we review only the general environmental comparison between the storage-direct disposal route and reprocessing-waste disposal. Two principal claims have been made:

- lower volumes of waste would be produced in reprocessing, and
- the toxicity of reprocessing waste streams was lower than that of spent fuel.

Lower waste volumes

European reprocessing companies have invested heavily in reducing the volume of low and intermediate wastes associated with reprocessing, leading to a three-fold reduction over the past 15 years.[6] However, even today the total volume of conditioned and packaged reprocessing waste is about 20 m^3/tHM, while the volume of conditioned and packaged spent fuel is about 2 m^3/tHM.[7] Although the volume of vitrified high-level waste from reprocessing is lower than the volume of spent fuel, intermediate-level wastes must also be disposed of in a repository adding considerably to total repository waste volumes resulting from reprocessing. Cogema and BNFL have announced further waste volume reductions in the future. However their figures still ignore low level wastes which account for about half of total reprocessing waste management and disposal costs.

What advantages do smaller volumes bring? They clearly reduce storage and transport costs, but the benefits in terms of repository safety are less clear. The design and performance of a repository is primarily dependent on the heat output of the waste placed inside it. Although glassified HLW has a slightly reduced heat rate because it does not contain plutonium, this will not affect waste storage or repository design. Moreover, the decay heat associated with actinides in spent MOX fuel is significantly higher than for spent uranium fuel.

Lower toxicity

A general index of radiotoxicity is often used by reprocessors to argue that the removal of plutonium from the high level waste stream significantly improves long term safety of the repository. However, safety assessments for a variety of repository designs and geological environments show that spent fuel can, in principle, be disposed of as safely as vitrified high-active reprocessing waste. The German repository concept assumes, for instance, that spent fuel and vitrified HLW will be disposed of in the same repository. Spent fuel is at least as good a matrix for fission and actinide products as glass, and new research into ceramic waste forms suggests that it may be better.[8]

Repository safety assessments show that long-term safety depends on the mobilisation of radioactivity. Studies of plutonium mobilisation suggest that it will not move far out of the near-field of the repository under most conditions. Removing plutonium does not therefore bring great improvements to long-term safety which is determined more by the prevalence of nuclides like neptunium-237, technetium-99 and iodine-129. These occur in the same amounts in spent fuel and reprocessing waste.

—FRANS BERKHOUT

See endnotes on page 16.

CIVILIAN REPROCESSING

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changing the way in which reprocessing is viewed by utilities and governments.

The first of these is the mounting problem utilities have in many countries with the extension of spent fuel storage capacity. This issue is linked to the long delays and uncertainties which surround radioactive waste repository programs. Understandably, publics living near to reactors do not like the idea of reactor sites becoming long-term spent fuel stores. In addition, environmental organisations who see spent fuel storage as the Achilles heel of the industry reason that if they can block spent fuel stores they may be able to force nuclear reactors to shut down. However the response of the utilities in Germany and elsewhere has been to restart negotiations with reprocessors as the only way out.

The second development is the reinvention of fast reactor programmes as 'partitioning and transmutation' programs. Partitioning refers to the separation in advanced reprocessing plants of radioactive materials besides plutonium and uranium which represent a long-term hazard. These materials would then be 'transmuted' through irradiation in either reactors or in accelerator-based converters. This would break them down into shorter-lived species which could be stored and disposed of as short-lived low-level wastes. These programs are being justified as a way of resolving the

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CIVILIAN REPROCESSING

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problem of long-term burial, and some advocates of a plutonium economy see them as a golden opportunity.

The third development is nuclear weapons dismantlement, and the recovery of plutonium and enriched uranium from warheads. From one perspective this represents a threat to reprocessors. The availability of large new stocks of plutonium and uranium further undermines the rationale for separating more in civilian reprocessing, especially given the large civilian stocks which already exist. However, there are two potential benefits for reprocessors, who are also the major producers of MOX fuel. Recycling in commercial reactors has become the preferred option for weapons plutonium and uranium disposition in Russia, and is also being considered seriously in the US. MOX disposition programs for military uranium and plutonium will strengthen the industry by building up commercial infrastructures and subsidising commercial MOX activities. Weapons plutonium MOX programs also have the advantage of appearing to turn 'swords into ploughshares', so legitimising the activity.

Conclusions

A global civilian reprocessing industry has been built up since the mid-1960s. Today this system services the fuel management requirements of about one-third of the world's reactors. In future the importance of reprocessing as a fuel management is likely to decline. However, the resilience of an industry whose underlying rationale and economic viability have been undermined over the past twenty years should not be underestimated. This is a supply-dominated, rather than a demand-led industry. The future of reprocessing will finally be determined by whether or not political agreement can be reached on the main alternative spent fuel management route: interim storage followed by direct disposal.

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[1] OECD Nuclear Energy Agency, *The Economics of the Nuclear Fuel Cycle*, Paris, 1994

[2] I. Hensing and W Schultz, *Economic Comparison of Nuclear Fuel Cycle Options*, Energiewirtschaftlichen Instituts, Cologne, 1995.

[3] Cogema, *Reprocessing-Recycling: the Industrial Stakes*, presentation to the Konrad-Adenauer-Stiftung, Bonn, 9 May 1995.

[4] OECD Nuclear Energy Agency, *Plutonium Fuel: An Assessment*, Paris, 1989.

[5] The cost of an LEU fuel assembly delivered to a nuclear reactor lies somewhere between $1000-1500/kgU. Typical MOX fuel fabrication and transport costs are about $2000-3000/kgMOX. 4 kg of LEU spent fuel need to be reprocessed to separate the plutonium required for 1 kgMOX. European reprocessing prices are now set at about $1000/kgHM, therefore the reprocessing cost associated with 1 kgMOX is about $4000.

[6] Cogema, 'Reprocessing-Recycling: the Industrial Stakes', presentation, Bonn, May 1995.

[7] G. Kessler, 'Direct disposal Versus Multiple Recycling of Plutonium', paper presented at the German RSK/Japanese NSC Meeting, Tokyo, November 1992.

[8] W. Lutze and E.C. Ewing (eds), *Radioactive Waste Forms for the Future*, North Holland, Amsterdam, 1988.

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