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Spent Nuclear Fuel Reprocessing in France

Mycle Schneider and Yves Marignac

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Acronyms

ACRO	Association pour le Contrôle de la Radioactivité dans l’Ouest (citizens’ organization for the control of radioactivity in the West of France)
ANDRA	Agence Nationale de gestion des Déchets Radioactifs (National Agency for Radioactive Waste Management), France
AREVA NC	Nuclear Cycle branch of AREVA, French nuclear-energy equipment, materials and services conglomerate
CdC	Cour des Comptes (Government Accounting Office), France
CDP	Charpin-Dessus-Pellat Report to the Prime Minister on the past and future economics of nuclear power in France, 2000
CEA	Commissariat à l’Énergie Atomique (Atomic Energy Commission of France)
CEPN	Centre d’étude sur l’Evaluation de la Protection dans le domaine Nucléaire (Nuclear Safety Evaluation Centre), France
CGT	Confédération Générale du Travail (General Confederation of Labour)
COGEMA	Compagnie Générale des Matières Nucléaires (now part of AREVA NC, originally the production division of the CEA)
CPDP	Commission Particulière du Débat Public (commission established to organize the debate on a particular project, supervised by the Commission Nationale du Débat Public, the French independent authority responsible for organizing national public debates on projects of significant social and environmental impact)
CSPI	Commission Spéciale et Permanente d'Information près de l'établissement de La Hague, (information commission for the La Hague reprocessing plant)
CSSN	Conseil Supérieur de la Sûreté Nucléaire (Superior Council for Nuclear Safety, now dissolved), France
DGEMP	Direction Générale de l’Energie et des Matières Premières (French Government’s General Directorate of Energy and Primary Materials)
EDF	Electricité de France (French National Utility)
FRF	French Francs

GGR	Gas-Graphite Reactor
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Office for Installations and Reactor Safety), Germany
HLW	High-Level Waste
HPA	Health Protection Agency (UK)
IAEA	International Atomic Energy Agency
ILW	Intermediate-Level Waste
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Institute for Radiation Protection and Nuclear Safety), France
LEU	Low Enriched Uranium, contains less than 20 percent U-235
LL-ILW	Long-Lived Intermediate-Level Waste
LLW	Low-Level Waste
LWR	Light Water Reactor
MINEFI	Ministère de l’Economie, des Finances et de l’Industrie (French Ministry of the Economy, Finance and Industry, now MINEFE)
MOX	Mixed uranium-plutonium oxide fuel
OECD	Organization for Economic Co-operation and Development
OSPAR	Commission for the Protection of the Marine Environment of the North-east Atlantic
PWR	Pressurized Water Reactor
SL-ILW	Short-Lived Intermediate Level Wastes
SL-LLW	Short-Lived Low Level Wastes
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UOX	Uranium Oxide fuel
VLLW	Very Low-Level Wastes

About the IPFM

The International Panel on Fissile Materials (IPFM) was founded in January 2006. It is an independent group of arms-control and nonproliferation experts from both nuclear weapon and non-nuclear weapon states.

The mission of IPFM is to analyze the technical basis for practical and achievable policy initiatives to secure, consolidate, and reduce stockpiles of highly enriched uranium and plutonium. These fissile materials are the key ingredients in nuclear weapons, and their control is critical to nuclear weapons disarmament, to halting the proliferation of nuclear weapons, and to ensuring that terrorists do not acquire nuclear weapons. IPFM research and reports are shared with international organizations, national governments and nongovernmental groups.

The Panel is co-chaired by Professor R. Rajaraman of the Jawaharlal Nehru University of New Delhi, India and Professor Frank von Hippel of Princeton University. Its members include nuclear experts from sixteen countries: Brazil, China, France, Germany, India, Japan, the Netherlands, Mexico, Norway, Pakistan, South Korea, Russia, South Africa, Sweden, the United Kingdom and the United States.

Princeton University's Program on Science and Global Security provides administrative and research support for IPFM.

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Summary

France initiated a spent nuclear fuel reprocessing program to provide plutonium for its nuclear weapons program in Marcoule in 1958. Later, the vision of the rapid introduction of plutonium-fuelled fast-neutron breeder reactors drove the large-scale separation of plutonium for civilian purposes, starting with the opening of the La Hague plant in 1966, financed under the military and civilian budgets of the Atomic Energy Commission (Commissariat à l'Énergie Atomique, CEA). This effort initially was supported broadly by neighboring European countries who contributed to the French fast breeder project and, along with Japan, signed up for French reprocessing services in the 1970s.

Military plutonium separation by France produced an estimated total of about 6 tons of weapon grade plutonium and ceased in 1993. But civilian reprocessing continues. Virtually all other European countries, apart from the United Kingdom, have abandoned reprocessing and the U.K. plans to end its reprocessing within the next decade. France's last foreign reprocessing customer for commercial fuel is the Netherlands, which has only a single small 34-year-old power-reactor, and Italy, which ceased generating nuclear electricity after the 1986 Chernobyl reactor accident in the Ukraine.

This report looks at the reprocessing experience at France's Marcoule and La Hague sites. Since commercial reprocessing ended at the Marcoule site in 1997 and its operational history of reprocessing gas-graphite reactor fuel is not very relevant to today's commercial light water reactor (LWR) reprocessing, the report focuses primarily on the La Hague site.

Since its inception, France's reprocessing industry has benefited from strong financial, technical and political support. The French experience therefore constitutes a case of reprocessing under optimal conditions. Since reprocessing of spent nuclear fuel does not "close the nuclear fuel cycle", as is often claimed, but involves at each stage the production of significant waste streams, we treat it as an open "fuel chain" and assess the record of French reprocessing in terms of waste management, radioactive discharges, radiological and health impacts as well as cost.

Marcoule. France's first reprocessing plant was the Usine de Plutonium 1 (UP1, Plutonium Factory 1) at Marcoule. Thirteen thousand tons* of reactor fuel from gas-graphite plutonium production and power reactors was reprocessed there between 1958 and late 1997. Today the site hosts a huge decommissioning and clean-up effort. In 2003, the clean up, including waste management, was estimated to eventually cost about €6 billion ($6 billion) and is currently expected last till 2040. In 2005, these costs and liabilities were transferred from the government-owned nuclear-services conglomerate, AREVA NC, to the CEA.

La Hague. Between 1966 and 1987, about five thousand tons of gas graphite reactor (GGR) fuel and, between 1976 and the end of 2006, about 23,000 tons of light water reactor fuel (LWR) fuel were reprocessed in the UP2 and UP3 plants at La Hague. Small batches of breeder reactor and LWR mixed uranium-plutonium oxide (MOX) fuel also have been reprocessed. Over the last few years the two reprocessing lines together have processed about 1,100 tons annually.

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* "Tons" stands for metric tons throughout this report.

Until around 2004, close to half of the LWR spent-fuel throughput at La Hague was foreign-owned. Almost all of the foreign spent fuel under contract has been reprocessed, however, and only minor new contracts have been signed. The 600 tons of foreign spent fuel remaining at La Hague could be reprocessed in a few months.

France's national utility, Electricité de France (EDF), has a large backlog of about 12,000 tons of spent fuel, of which two thirds are stored at La Hague – the equivalent of over ten years' throughput at the current rate of reprocessing. Since 1987, France has also built up a large backlog of over 50 tons of its own unirradiated plutonium in various forms, of which more than half is stored as separated plutonium at La Hague. Plutonium is being used in MOX fuel in twenty 900-MWe LWRs that are operating with up to 30% MOX fuel in their cores. In addition, AREVA's foreign clients currently store more than 30 tons of separated plutonium in France.

Economic Costs of Reprocessing in France. In 2000, an official report commissioned by the French Prime Minister concluded that the choice of reprocessing instead of direct disposal of spent nuclear fuel for the entire French nuclear program would result in an increase in average generation cost of about 5.5 percent or $0.5 billion per installed GWe over a 40-year reactor life or an 85 percent increase of the total spent fuel and waste management ('back-end') costs.

Current projected costs by the industry and the Ministry of Industry show that, in addition to a number of other favorable assumptions, the investment and operating costs of a future reprocessing plant would need to be half the costs for the current La Hague facilities in order for reprocessing to cost no more than direct disposal.

Since 1995, EDF has assigned in its accounts a zero value to its stocks of separated plutonium, as well as to its stocks of reprocessed uranium. With the liberalization of the electricity sector, the economic burden of reprocessing is increasingly weighing on the French utility EDF. Cost issues constitute the main stumbling block for a new long-term agreement with AREVA following the reprocessing / MOX fabrication contract that ended in 2007.

Waste Volumes. A major argument made for reprocessing is that it dramatically reduces the volume of radioactive waste. A number of serious biases have been found, however, in official comparisons made by EDF, AREVA and the National Agency for Radioactive Waste Management (ANDRA, the organization responsible for radioactive waste disposal in France). These include:

- Exclusion of decommissioning and clean-up wastes stemming from the post-operational period of reprocessing plants;
- Exclusion of radioactive discharges to the environment from reprocessing. Their retention and conditioning would greatly increase solid waste volumes;
- A focus on high-level waste (HLW) and long-lived intermediate-level waste (LL-ILW), leaving aside the large volumes of low-level waste (LLW) and very low-level wastes (VLLW) generated by reprocessing;
- Comparison of the volumes of spent fuel assemblies packaged for direct disposal with those of unpackaged wastes from reprocessing, which overlooks for instance the fact that packaging reprocessing waste is expected to increase its volume by a factor of 3 to 7; and

- Failure to include the significantly larger final disposal volumes required for spent MOX fuel, because of its high heat generation, unless it is stored on the surface for some 150 years instead of the 50 years for low-enriched uranium spent fuel.

We find that, with past and current operating practices, there is no clear advantage for the reprocessing option either in terms of waste volumes or repository area. Depending upon assumptions, the underground volume required for spent MOX fuel and vitrified waste can be smaller or larger than that for direct disposal of spent LWR fuel.

Radiological impact. The global collective dose over 100,000 years – due primarily to annual releases to the atmosphere from La Hague of the low-level but long-lived emitters, krypton-85 (half-life of 11 years), carbon-14 (5,700 years) and iodine-129 (16 million years) – have been recently recalculated at 3,600 man Sieverts. Continuing discharges at this level for the remaining years of La Hague's operation *theoretically* could cause over 3000 additional cancer deaths over 100,000 years.

Security risks. Reprocessing also has significant impacts in terms of safety and security. These issues are only touched upon in the present report for the case of transportation security risks. The recycle into MOX fuel of European power-reactor plutonium separated at La Hague results in an average of about two truck shipments of separated plutonium per week from La Hague to the MELOX MOX fabrication plant at Marcoule, over 1000 km away.

I. Introduction

Plutonium separation began in France as part of the nuclear weapon program that was launched immediately after the Second World War.[1] Large-scale production of plutonium for military purposes was started in 1958 and ceased between 1991 and 1993, producing an estimated total of 4.3 to 7.8 tons of weapon-grade plutonium, with a mean estimate of 6 tons, which after consumption in tests and losses in process waste has left a stock on the order of 5 tons, none of which has been officially declared as excess.[2]

Plutonium separation grew to its current huge scale, however, because of the dream of plutonium fuelled fast-neutron breeder reactors. This type of reactor was expected to generate more plutonium over time than it consumed, effectively generating more chain-reacting fuel than it used. In order to start up a commercial size fast breeder reactor it takes about 7 tons of plutonium, roughly the annual production of 20 large LWRs. Plutonium fuelled reactors were to replace uranium-fueled power plants within a few decades.

While the first plutonium separation plant started operation in 1958 in Marcoule, mainly for military purposes, the first experimental breeder Rapsodie was commissioned in 1967 followed by the 233 MWe (net) Phénix reactor in December 1973. The breeder reactors were justified by exaggerated projections of the growth of nuclear power and thus by an expected scarcity of uranium. In 1974, French planners officially forecast that France's national electricity consumption would be 1000 TWh in the year 2000, some 2.3 times the actual consumption rate in 2000.

The decision to build the commercial-scale (1,250 MWe) European Superphénix fast breeder reactor was taken in 1976.[3] At that time the French Atomic Energy Commission (CEA) forecast 540 Superphénix-type reactors operating in the world by year 2000 — about 20 in France alone. In reality, as of year 2000, there was not a single commercial size plutonium-fuelled breeder reactor in the world. Superphénix operated with an average capacity factor of six percent for ten years, before being shut down on Christmas Eve 1996. The red-green government that came in as of 1997, decided to keep it shut down permanently. Many within the national electricity utility, Electricité de France (EDF) management welcomed that decision.[4] But this was never made public. Two reactor cores, one partially irradiated and one fresh, containing together 12 to 14 tons of plutonium, remain in interim storage at the reactor site.

Even before Superphénix was connected to the grid in 1986, the commercial failure of the fast breeder reactor had become obvious. The forecasted huge growth of nuclear capacity around the world had not materialized and natural uranium was abundant and cheap. The savings from the higher uranium efficiency of the breeder reactors were therefore much smaller than expected. At the same time reprocessing and breeder reactors had turned out to be costly and fast breeder technology was experiencing a long list of technical problems. Due to the short period that it actually operated, the average cost of the electricity generated by Superphénix was at least ten times higher than from light water reactors. How much higher will not be known until the plant is dismantled.

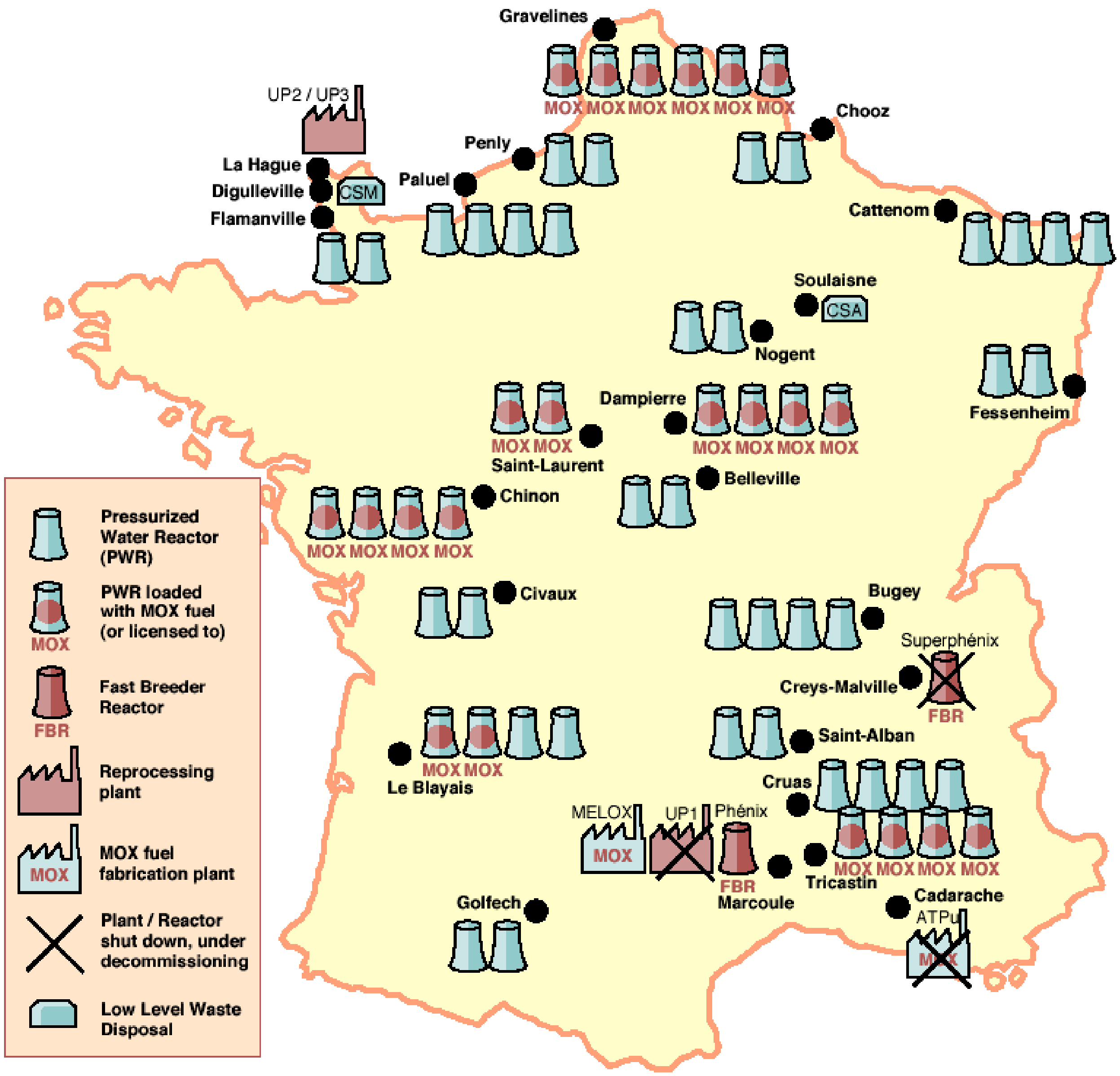

Figure 1. Main plutonium-related facilities in France, as of 31 December 2007.[5]

With the suspension of the breeder program, it would have been natural to abandon the commercial separation of plutonium. At the time, however, the extra costs of recycling separated plutonium in LWR fuel was estimated to be relatively small -- some FRF 2.3 billion (€ 350 million) over a ten-year period.[6] The fuel division of France's national electricity utility, EDF, therefore concluded in 1989 that "putting into question that option [reprocessing] does not have an economic basis and would have other significant international repercussions harmful for the entire nuclear sector."[7]

In 1989, France's government-owned fuel-cycle company, COGEMA, which subsequently was absorbed into AREVA, had just opened a new large reprocessing plant (UP3) at La Hague, almost entirely pre-financed by foreign clients. Germany's utilities had just cancelled their

Wackersdorf reprocessing plant project and had instead signed a new series of reprocessing contracts with France. EDF's decision to give up reprocessing at that point would indeed have sent a shock wave through the international nuclear community.

As of 2007, France operates 58 pressurized water reactors[8] and one 233-MWe fast breeder reactor, which is to be shut down in 2008. EDF's official strategy is to continue reprocessing 850 tons of EDF fuel annually at La Hague, out of a total of about 1,200 tons of spent fuel discharged per year. That leaves a significant share of France's spent fuel unreprocessed, but the rate of plutonium separation corresponds approximately to the current MOX fuel fabrication capacity available to EDF.

The two reprocessing sites, La Hague and Marcoule, contain over 90 percent of France's radioactive waste inventory. Their inventories include spent fuel, separated plutonium, large quantities of liquid and vitrified high level waste, and various types of intermediate, transuranic and low level radioactive wastes. A significant fraction of these wastes remains unconditioned. Conditioning techniques have been under development for decades. In view of changing standards, much of the waste that was conditioned between the 1950s and the 1970s will have to be reconditioned.

II. The Economics of Reprocessing

For many years, the only available cost assessments of French reprocessing were studies based on the methodology used in OECD Nuclear Energy Agency (NEA) reports.[9] This methodology was developed primarily under the auspices of the French Ministry of Industry for comparing nuclear power to other electricity sources.[10] It excludes a great deal of the complexity associated with the reprocessing option, especially the issues and costs associated with waste management. (This is discussed further in the next section.)

A 1982 report prepared by a CEA nuclear engineer for the Superior Council for Nuclear Safety (Conseil Supérieur de la Sûreté Nucléaire or CSSN, then a consultative body for the French government) concluded, however, that "interim storage (40 to 100 years, or more) of light water reactor spent fuel followed by geological disposal (non-reprocessing option) is infinitely less costly than the reprocessing option."[11] The report added that "recycling plutonium in light water reactors is an economic aberration, and only provides theoretical savings of 18 percent in natural uranium needs." Economic assessments were carried out internally by the French nuclear industry in 1985 but, even though they showed no advantage for the reprocessing option and the reuse of the resulting separated plutonium in MOX fuel, it was decided to develop the "reprocess-recycle" scheme to commercial scale.[12]

It took fifteen years after the launch of France's massive plutonium economy for the first public, comprehensive assessment of the economics of the French nuclear industry, including its fuel chain. The 2000 *"Charpin-Dessus-Pellat" (CDP) Report* was commissioned by France's Prime Minister, and was based on actual data provided by the industry. This report found that, when the decision was taken "to launch in 1985 the reprocessing path and recycling in PWRs, its competitiveness, compared with a long term storage solution, required the cost of uranium to be high" – which did not materialize.[13]

The report estimated the material flows and economic costs of the current French nuclear facilities over their lifetimes on the basis of a year-to-year analysis. The assessment period ran from the start-up of EDF's first pressurized water reactor (PWR) in 1977 until 1999, and projected future costs up to 2049, the end of the operational life of the last reactor in the fleet, assuming an average 45-year operating lifetime.

Different scenarios for spent fuel management were considered:

- The "dual-management" strategy pursued since 1985 in which about 70 percent of France's spent LEU fuel is reprocessed and MOX fuel is used in around 20 PWRs;[14]
- Extension to the reprocessing of all LEU fuel and the use of MOX fuel in the 28 PWRs technically designed to use it; or
- The complete phase-out of reprocessing in 2010.[15]

The first two scenarios assumed reprocessing at La Hague until 2030[16] but no successor reprocessing plant, i.e. storage of spent uranium oxide fuel discharged after 2030.[17] The main results of the comparison are presented in Table 1.

Table 1. Material balances and costs of nuclear power in France industry for four scenarios(1)

Scenario / Reprocessing	End in 2010	Partial	Full	None(2)
Material balances				
Natural uranium (thousand tons)	460	447	437	475
Reprocessed LEU fuel (thousand tons)	15	26.2	36.1	0.0
Plutonium reused (tons)	146	275	387	0
Irradiated LEU fuel(3) (thousand tons)	41	28.6	17.6	58.3
Irradiated MOX fuel(3)(thousand tons)	2	3.5	4.8	0.0
Plutonium Content(4) (tons)	602	555	514	667
Intermediate Level Waste (m^3)	31,786	34,825	38,091	20,000
From operation	*20,000*	*20,000*	*20,000*	*20,000*
From reprocessing	*11,786*	*14,825*	*18,091*	*0*
High Level Waste (m^3)	1,601	3,325	4,808	0
Power Generation Cost(5) ($/MWh)	**29.3**	**29.5**	**29.6**	**28.0**
Total Cost ($ billion)(6)	**592**	**597**	**600**	**566**
• Investment(7)	140	140	140	134
• Operation	266	266	266	266
• Fuel	185	190	193	166
Detail of fuel chain costs	**185.1**	**189.6**	**193.1**	**165.6**
Fuel chain / front-end	***123.4***	***120.7***	***118.5***	***125.3***
Front-end 1977-1998	*55.6*	*55.6*	*55.6*	*55.6*
Front-end 1999-2049	*67.9*	*65.2*	*62.9*	*69.7*
Fuel chain / back-end(8)	***61.7***	***68.9***	***74.6***	***40.4***
Back-end 1977-1998	*19.1*	*19.1*	*19.1*	*0.0*
Back-end 1999-2049	*20.9*	*28.5*	*34.8*	*17.6*
Final disposal ILW + HLW	*2.5*	*4.3*	*5.9*	*0.0*
Final disposal spent fuel	*19.3*	*16.8*	*14.8*	*22.8*

Source: based on CDP (2000), Girard (2000)

Notes:

(1) All scenarios are based on the assumption of a total nuclear capacity of 62.4 GWe and an average 45-year lifetime for nuclear reactors. Total cumulated electricity generation would be 20,238 TWh.

(2) Retrospective scenario corresponding to the same operation of the current nuclear power plants without any reprocessing, even in the past (1977-2000).

(3) Quantities of irradiated uranium oxide fuel and MOX left in storage in 2050.

(4) Plutonium content (including Americium-241) in spent uranium oxide and MOX fuels that are not reprocessed at the end of the period (by the time the last reactor closes).

(5) Conversion to $ from constant 1999 French Francs (FRF)., Undiscounted estimated costs levelized over the operational life of the power plants.

(6) Conversion of 1999 FRF, with the rate 1 FRF = 0.20499 $.

(7) The difference in investment costs between the scenarios with and without reprocessing is due to the FRF30 billion of R&D costs ($6 billion) for the back-end of the fuel chain in the reprocessing scenarios.

(8) The "back-end" lines include reprocessing and interim storage of final waste. The "final disposal" lines include geological disposal of unreprocessed spent uranium oxide and MOX fuels and ILW and HLW from reprocessing (but not ILW from reactor operation).

Even with "optimistic" assumptions about the smooth operation of the fuel-cycle facilities, the report concluded that the direct disposal option had a clear economic advantage.[18] Despite the fact that the capital investments in the reprocessing and MOX-fuel fabrication plants were sunk costs, phase-out of reprocessing in 2010, compared to its extension to "all-reprocessing," would save FRF39 billion ($8 billion). Per year, the savings would be FRF800 million ($160 million) or 12 percent of the 2001 operating costs of France's fleet of LWRs.

The report also calculated the savings had France not built the reprocessing and MOX-fuel fabrication facilities and instead operated its nuclear fleet with a once-through fuel strategy for its entire lifetime. Compared to the “all-reprocessing” scenario, the total savings would have been FRF164 billion ($33.5 billion) or a 5.5 percent decrease in the cost of nuclear electricity.

In April 2000, Bernard Estève, then Director of EDF’s Nuclear Fuel Division, declared that there was no market for plutonium and that, even if there was, the plutonium value would be negative.[19] (Apparently the Dutch utilities have paid the French industry to keep the plutonium and uranium recovered from the reprocessing of their fuel.) This reflects the fact that, even if plutonium was obtained at no cost (instead of the actual cost of reprocessing), using it in MOX fuel still represents a loss compared to using uranium fuel. The reason is the substantial difference in fuel fabrication costs.[20]

In 2003, the French Government’s General Directorate of Energy and Primary Materials (DGEMP) acknowledged that “for the time being, the low prices in the front-end of the fuel cycle (natural uranium and enrichment services) do not justify the reprocessing of spent fuel on purely economic grounds.”[21]

DGEMP introduced new cost assumptions, however, that reduced the cost difference between reprocessing and direct disposal from $1.6 to $0.13 per megawatt hour. It explained that the cost numbers used in the CDP report are “representative of the current economics of the fuel cycle, but in some cases quite different from those envisaged by the industry for the period 2015-2075.”[22] The projected lower costs were established in confidential discussions with AREVA, the company that built and operates France’s reprocessing plant.[23]

Specifically, the DGEMP report assumed a cost for reprocessing of 450 €/kg (605 $/kg) on average for the period 2025-2085. This value is less than half the cost calculated in the CDP report, which is in the range of 1,200 to 1,600 $/kg.[24,25] The difference of about $1000/kgHM for a burnup of 60 MWd/kgHM would correspond to a difference of $2.1/MWh, which is, indeed, enough to explain the reduction in the difference with direct disposal. Future costs would include the investment cost of a new reprocessing plant. AREVA chose to assume a reduction by half or so in both the investment costs (including decommissioning) and the operation costs of this new plant compared to the existing ones. As DGEMP explained, “the cost of reprocessing used in the study is the cost objective needed to guarantee the competitiveness of reprocessing compared to the direct disposal option.”[26]

The optimism of these projected costs is not shared by all players in the French nuclear industry. In a March 2007 note presented to a working group updating the DGEMP report, Electricité de France, the main customer of the La Hague plants says that it “expects the new [reprocessing] facilities to allow for some gains in productivity, in investment as well as operating costs, thanks to the cumulated experience, technological progress, and possibly scale effects” but that “one must remain cautious about the final impact on reprocessing costs, which will also strongly depend over a time scale of a few decades on the environmental performances sought and potential changes of the costs of goods and services.” The note concluded that, therefore, “EDF regards the values used in the [DGEMP’s 2003] report as a low estimate.”

ANDRA's projected geological disposal costs for France's radioactive wastes, as summarized by the Cour des Comptes (CdC), the French Government Accounting Office, rose from €14.7 billion ($19.8 billion) in 1996 to a range of €15.9 billion to €58.0 billion ($21.4 billion to $78.0 billion) in 2003.[27] In the 2003 estimate, ANDRA found ending reprocessing in 2010 to cost more than twice as much as continued reprocessing $46.7 billion to $78.0 billion versus $21.4 billion to $32.7 billion). In the full reprocessing scenario, however, more than half of the separated plutonium and uranium is transferred to a hypothetical next generation of reactors and therefore is not accounted for in any way in the cost assessment.

Reducing cost uncertainties became critical with the requirement in France's 2006 law on radioactive waste management that nuclear plant operators establish funds to cover the long-term costs of waste management. DGEMP set up a working group with the concerned industry players to establish common assumptions.[28] The group proceeded with two studies. The result was a reduction of cost estimates for the total reprocessing scenario to €11.5-12.9 billion ($15.5-17.4 billion). The working group failed to address two key issues raised by the CdC, however: the uncertainties of waste-site design and size. The CdC criticized the working group exercise in its subsequent annual report, noting that the assumptions used are "a choice the authors justify by the strategy announced by EDF," but that "announcing a strategy doesn't make it necessarily happen, as it will depend both on decisions by government…and on its feasibility."[29]

Table 2 shows that, in 2003, the plutonium separation plants at La Hague and Marcoule accounted for over 88 percent of AREVA NC's total provisions for future decommissioning costs. If one adds the plutonium fuel factories MELOX and Cadarache, the percentage increases to over 92%. The funds are expected to fully cover the decommissioning costs.

The decommissioning funds decreased by over €4 billion ($5.7 billion) in 2005 because of a bail-out agreement in which the operating license and decommissioning responsibility for the Marcoule site were transferred from COGEMA's parent company, AREVA NC, to the CEA (i.e. France's Government) in exchange for a lump sum payment by AREVA of €427 million ($574 million) and its commitment to make a future contribution of €158 million ($212 million) to the decommissioning fund. The large third-party share at La Hague in the table represents expected contributions by EDF.

Table 2. Decommissioning Funds by Site (in M€, COGEMA is now part of AREVA)

	Provisions in 2003 (in M€)			**Provisions in 2004 (in M€)**		
Site	**Provision**	**Third Party Share**	**COGEMA Share**	**Provision**	**Third Party Share**	**COGEMA Share**
La Hague	6,479	4,298	2,181	6,415	4,163	2,252
Marcoule	4,325	3,656	669	158		158
Pierrelatte	239	206	33	189	142	47
Melox	404		404	423		423
Cadarache	149		148	220		220
Eurodif	471		470	492		492
Others	162	30	134	115	3	113
Total	**12,229**	**8,190**	**4,039**	**8,012**	**4,308**	**3,705**

Source: COGEMA in CdC (2005)

III. Reprocessing and Nuclear Waste Management

In the early 1970s, the CEA began to link its strategic goal of separating plutonium from LWR fuel to feed a fast breeder reactor program with a second objective, the reduction of the radiotoxicity levels of the final waste to be disposed of in a geological repository. Given that plutonium would be the largest contributor to the overall radiotoxicity of irradiated fuel in the longer term, indefinitely recycling plutonium was presented as a way to eliminate it from the final waste inventory, and therefore to reduce by as much as ten-fold the corresponding long-term radiotoxicity.[30]

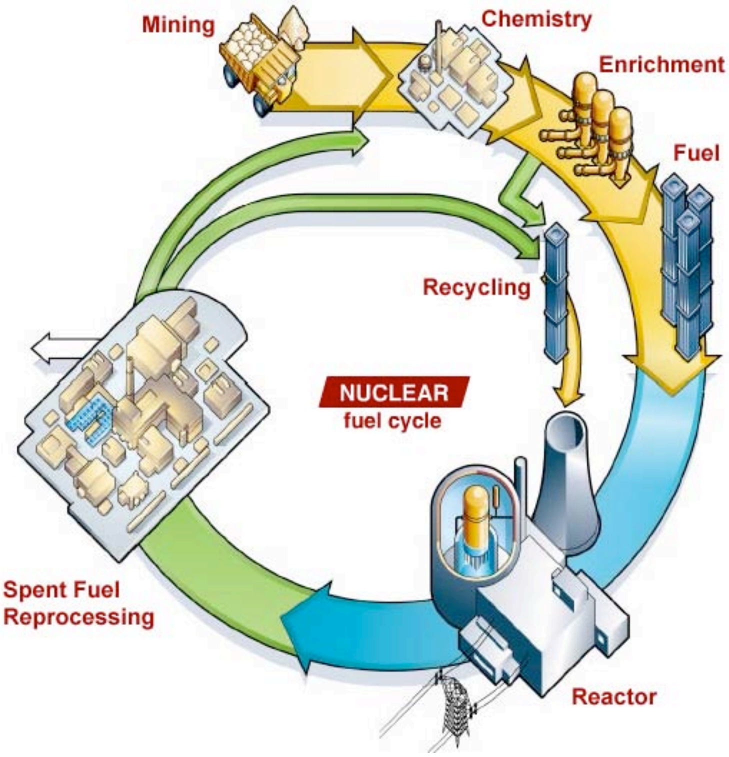

Figure 2. The fuel cycle according to AREVA. The reprocessing of spent nuclear fuel and reuse of the recovered plutonium and uranium are often referred to as "closing the fuel cycle." This simplified diagram does not, however, reflect the complexity of the materials flows resulting from reprocessing (source: www.areva.com).

More recently, after the failure of the effort to commercialize fast breeders, the reprocessing industry elaborated the waste minimization rationale for reprocessing and recycling. Specifically, AREVA claims that "the volume of ultimate waste to be disposed of in any geological repository is drastically reduced by treatment-conditioning."[31] According to AREVA, reprocessing would produce 0.5 m^3 of intermediate (ILW) and high level waste (HLW) residues per ton of heavy metal (tHM, i.e. uranium) in uranium oxide fuel (UOX), compared to more than 2 m^3/tHM to be disposed of in case of direct geological disposal of the irradiated fuel.[32] During one of the public meetings of the French national debate on long-lived radioactive waste management that took place between September 2005 and January 2006, an EDF spokesman explained that reprocessing, compared to the direct storage of spent LWR fuel, is "a process that reduces by a factor 10 the volume of highly active long-lived waste."[33] The Commission Particulière du Débat

Public (CPDP), in charge of the preparation and organization of this public debate, noted that "for AREVA the … impact of reprocessing on the volume of final waste is the remarkable result of research conducted since 1991. AREVA actually stresses that this is the argument to sell reprocessing to the Americans, who study geological disposal but consider the reprocessing option as a way to reduce the volume of disposal."[34]

The nuclear waste law of 1991 set a time frame of 15 years for the decision-making process on France's waste management options.[35] The national public debate came during the preparation of a draft bill, which was discussed in Parliament and passed in June 2006.[36]

The 2006 legislation emphasizes the role of reprocessing in the French nuclear waste management strategy. Article 6-I of the new law stipulated that a National Radioactive Material and Waste Management Plan had to be established by the end of 2006.[37] The first of the guidelines is that "the reduction of the quantity and toxicity of radioactive waste shall be sought especially by processing spent fuel and by processing and conditioning radioactive waste." The licenses of the La Hague plants had already been modified in 2003, to allow them to reprocess in addition to spent fuel various other materials containing uranium or plutonium such as scrap from the production of plutonium-containing fuels.[38]

France defines six classes of radioactive waste on the basis of the concentration and the lifetime of their radioactivity. Table 3 shows these categories and the current management status of each.

Short-lived intermediate and low-level wastes (SL-ILW/LLW) are disposed of in dedicated surface sites. A decision has yet to be taken, however, on the long-term management of the high-level and long-lived intermediate-level wastes (HLW and LL-ILW), most of which arises from spent fuel management. According to Article 3 of the law of 28 June 2006, research on the management of these wastes must be pursued in three "complementary" programs, each with its own deadlines:[39]

1. Partitioning and transmutation of long-lived radionuclides. A strategy is to be selected in 2012 and a prototype reactor is to be in operation by 2020;[40]
2. Interim storage. By 2015, existing sites must be expanded or new ones created to satisfy estimated needs; and
3. Geological disposal. The licensing process for a site is to be started by 2015 and it is to be put into operation in 2025.

Table 3. Categories of radioactive waste in France and their current management status

		LL – Long-lived	*SL - Short-lived*	*VSL – Very short-lived*
	Period Activity	> 30 years	≤ 30 years > 100 days	≤ 100 days
HL - High Level	$> 10^8$ Bq/g	Under study Art. 3 of the law of 28 June 2006 1 laboratory for geological disposal: **Bures**		Management by radioactive decay
IL - Intermediate Level	$\leq 10^8$ Bq/g $> 10^5$ Bq/g	Under study Art. 3 of the law of 28 June 2006	Surface disposal(a) 1 closed facility: **Centre de stockage Manche (CSM)** 1 facility in operation: **Centre de stockage de l'Aube (CSA)**	
LL - Low Level	$\leq 10^5$ Bq/g $> 10^2$ Bq/g	Study of dedicated subsurface disposal		
VLL - Very Low Level	$\leq 10^2$ Bq/g	Dedicated surface disposal 1 site in operation: **Morvilliers** Limited recycling for some categories		

Notes: (a) With the exception of specific waste, e.g. contaminated with tritium, for which dedicated management is still being studied.

Reprocessing definitely makes waste management more complex qualitatively (see Figure 3). In the direct disposal option, there is basically one type of high-level waste to deal with, spent fuel assemblies; and one type of intermediate-level waste, irradiated pressure vessels and their internal core-support structures.[41] There are also large volumes of long-lived low-level or very low-level waste in the form of uranium mill tailings and depleted uranium.

In the reprocessing option, many more waste streams need to be dealt with. First, there are the wastes from reprocessing itself:

- High-level vitrified waste, containing the minor transuranic elements and fission products;
- Intermediate-level structural wastes—such as hulls and nozzles from LWR fuel assemblies; and
- Intermediate level process waste -- sludge from liquid effluent treatment in particular.

Unlike the case of direct disposal, however, the residual uranium in the fuel (95% of the original LEU) and plutonium (1%) are separated for reuse. Their reuse produces new irradiated material and waste streams:

- Spent MOX fuel and scrap MOX from the fuel fabrication process,
- Spent re-enriched reprocessed uranium fuel and the depleted reprocessed uranium from the re-enrichment process.

Finally, each of the industrial processes eventually produces decommissioning waste-- especially intermediate-level waste from the reprocessing plants.

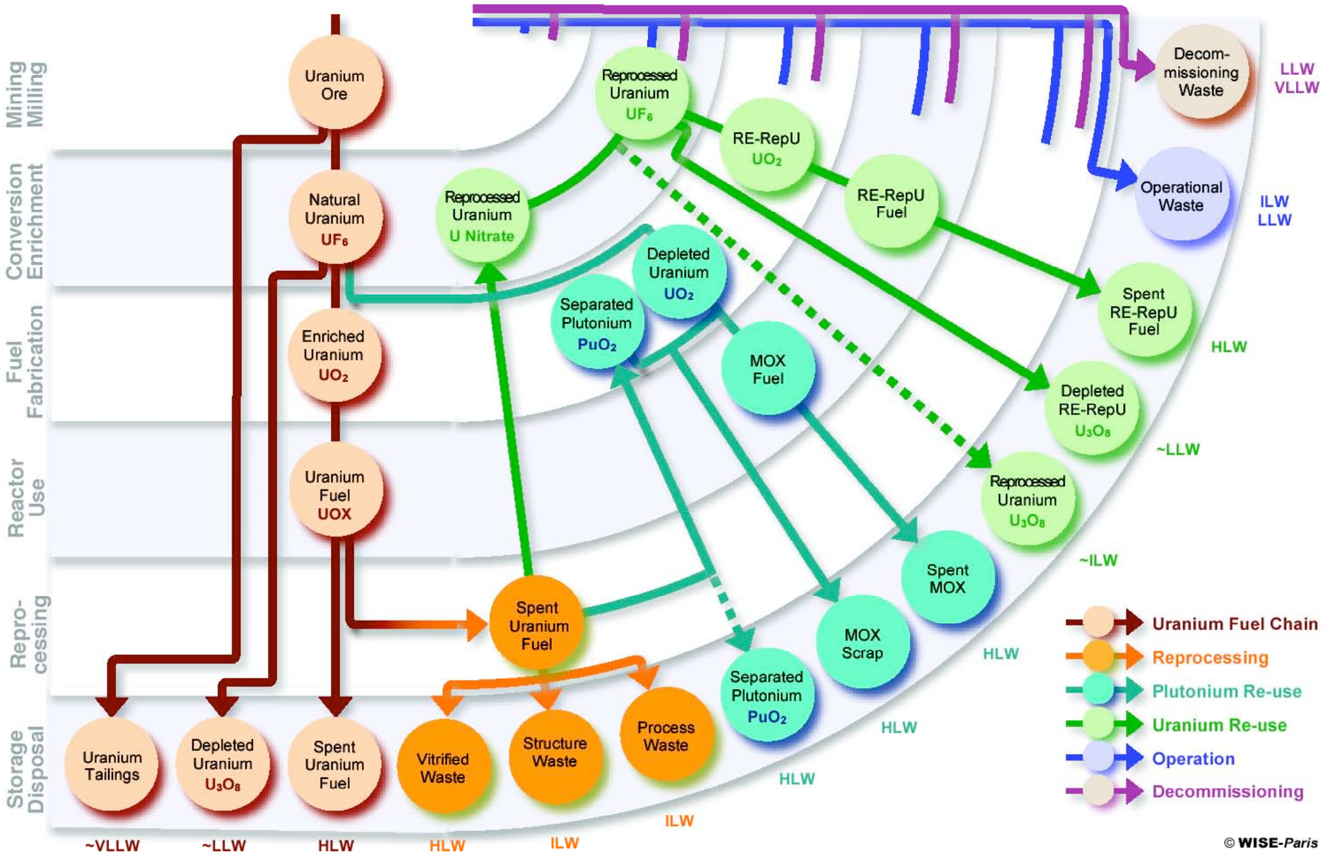

Figure 3. Waste and materials generated in the nuclear fuel chain

IV. Reprocessing at Marcoule

France's first large reprocessing plant, UP1 (Usine de Plutonium, or Plutonium Factory) started operating in 1958 in Marcoule. The plant, which reprocessed up to 960 tons/year of heavy metal in spent fuel, was operated by CEA until 1976, when COGEMA was created as a 100% subsidiary (but in the private sector) and took over the plant. Originally UP1 reprocessed only gas graphite reactor (GGR) fuel from military plutonium-production reactors. Later it also processed fuel from GGR power reactors for EDF and for Spain, and blanket material from the Phénix fast breeder reactor.[42] It also reprocessed fuel from two heavy-water reactors that were used for plutonium and tritium production, Célestin-1 and -2, also based at Marcoule.

UP1 stopped the separation of plutonium for military purposes in 1993.[43] By 30 September 1997 when reprocessing at Marcoule ended altogether, a total of 13,330 tons of GGR fuel had been reprocessed at UP1.[44]

In 2005, administrative oversight at Marcoule was reorganized and the CEA took over responsibility for the site again.[45] COGEMA, which had been absorbed into AREVA NC on 1 March 2006, operates as a contractor for the CEA.

Figure 4. The Marcoule site. The site is a huge R&D and industrial complex, with shut-down facilities (including the reprocessing plant UP1 and several gas-graphite reactors) and operating ones (including the MOX fuel fabrication plant MELOX, and the fast breeder reactor Phénix).

Process Waste Produced at Marcoule

Marcoule currently serves as the storage site for a large variety of nuclear and radioactive wastes and materials. Some materials, such as uranium separated during reprocessing, are not officially classified as waste. In its 2005 *Annual Report*, EDF states, however that: “The Group does not value the uranium obtained from reprocessed burnt fuel, due to uncertainty over its future use.” EDF owns some 3,800 tons and the CEA and AREVA some 4,800 tons of reprocessed uranium that is stored on the site in the form of liquid uranyl nitrate. AREVA recently started to ship this material to Pierrelatte for conversion to U_3O_8 (632 tons were shipped in 2005).[46]

Vitrification of high-level radioactive waste involves solidifying the waste by mixing it with molten glass. The vitrification facility at Marcoule (AVM-PIVER) was the first high-level waste conditioning installation in France. Its capacity is 30 m^3 or 80 tons per year. Since the shutdown of the reprocessing line in 1998, it has also been vitrifying high-level solutions from clean-up operations at UP1.

Wastes from the liquid effluent treatment station are “bituminized” (i.e. mixed into bitumen) and stored in 200-liter stainless steel drums. During the last few years, on average a little over 100 drums have been filled annually.

Until 1998, those wastes were stored in carbon steel drums that have begun to corrode. The carbon steel drums are therefore being placed inside stainless steel over-packs. As of the end of 2005, over 5000 carbon steel drums had been overpacked. According to the French Court of Accounts, however, as many as 61,597 drums require reconditioning. It commented: “The circumstances of this reconditioning are complicated by the ignorance of the operator of the exact content of the drums produced prior to 1995 and therefore the level of radioactivity: it is one of the stunning facts from a time when nuclear safety was not at the center of preoccupations.”[47]

In 1967 and 1969, a total of 46,396 waste barrels were dumped into the sea off the coasts of Spain and Brittany, including 3,479 bituminized waste packages from the liquid waste treatment station (STEL). The total is estimated to have a mass of 14,300 tons with contain a total radioactivity of 353 TBq.[48] However, these figures are highly uncertain because of uncertainties in the accounting and inventorying of radioactive waste on the Marcoule site.

Between 2002 and 2005, on average about 2,500 m^3 of low level wastes were shipped annually from Marcoule to the national radioactive waste management agency, ANDRA. (An overall inventory of waste from reprocessing operations at Marcoule and La Hague is presented in Table 11).

Clean-up and Dismantling[49]

The clean-up of UP1 started immediately after fuel reprocessing ended in 1997. The processes of clean-up, decommissioning and waste conditioning are expected to continue until 2040. The cost estimates have gone up steadily.

In 1999, the CEA estimated that decommissioning and waste management operations at the Marcoule site would cost over €6 billion (approximately the same in $2003). The cost breakdown is given in Table 4.[50]

Table 4. Cost estimate by type of operation at Marcoule (in €million)

Expense by program	M€($)2003	Share
Dismantling	2,113	34.2%
Waste conditioning	2,237	36.2%
Final closure	689	11.1%
Cross-cutting	1,147	18.5%
Total	**6,186**	**100.0%**

Source: CdC (2005)

The "cross-cutting" category refers to administration and logistics costs that are common to all programs. Of the estimated waste-conditioning costs about half (€1.1 billion) of €2.2 billion, stem from ANDRA's storage cost estimates.

V. Reprocessing at La Hague

The plutonium separation plant UP2 on La Hague (Figure 5) was originally designed to reprocess gas graphite reactor (GGR) fuel at a rate of 800 tons per year. Half the investment was covered by the military and the other half by the civilian budget of the CEA. Between 1966 and 1987, a total of 4900 tons of GGR fuel were reprocessed at La Hague.[51]

In 1976, the capabilities of UP2 were extended by installation of a head end that could process LWR fuel; it was dubbed UP2-400 or UP2-HAO (Haute Activité Oxyde).[52] The beginning of LWR spent fuel reprocessing at La Hague was difficult. The "nominal capacity" of UP2-HAO was lowered from 800 to 400 to 250 tons per year and then raised back to 400. Finally, after 11 years, the plant reached its "design throughput" of 400 tons per year.

Figure 5. The reprocessing complex at La Hague. The site comprises the old UP2-400 plant and the operating plants UP2-800 and UP3 and their annex facilities (spent fuel storage, waste treatment).

Reprocessing Contracts and Operational History

In 1989 a second plant, called UP3 with a nominal capacity of 800 tons was started up at La Hague. It was almost entirely financed by pre-paid foreign contracts. The two main foreign client countries, Germany and Japan, each paid for about 42% of what was called “base load customer contracts” or “service agreements” covering a total of 6685 tons of fuel to be reprocessed in UP3’s first decade of reprocessing.[53]

German utilities added 1,133 tons to their reprocessing contracts with COGEMA under so-called “post service agreement” contracts after abandoning the Wackersdorf reprocessing plant project in Bavaria in 1989 and thereby became by far COGEMA’s largest foreign reprocessing customer with a share of 54% of the total foreign contracts through the end of 2005. That was the end, however. Germany’s nuclear phase-out legislation prohibited the shipment of spent fuel to reprocessing plants after 1 July 2005.

France’s other major customer, Japan, decided to build and operate its own reprocessing plant at Rokkasho-mura and started active testing in 2006. France’s two largest foreign reprocessing customer countries therefore will not extend their contracts for reprocessing at La Hague.

In 1994, a third reprocessing plant was started up at La Hague under the name of UP2-800. The UP2-400 plant, which has common facilities with UP2-800, was officially closed on January 1, 2004. The license for the La Hague plants, as revised in 2003, limits throughputs to 1000 tons per year for UP2 and UP3 individually with an overall site limit of 1700 tons per year.

According to AREVA, about 6000 people work on the 300 hectares (750 acres) site today, of which 3,400 are AREVA NC staff.

Between 1976 and the end of 2006, a total of 22,658 tons of LWR fuel were put through the UP2 and UP3 plants. This included two small batches of LWR MOX fuel, 4.7 tons in 1992 and 4.9 tons in 1998. Five batches of Phénix fast breeder reactor fuel, totaling 10 tons, were processed in the period 1979-1984, diluted with gas-graphite reactor fuel because of the high concentration of fissile material in breeder fuel. Until around 2004, close to half of the LWR spent fuel throughput was foreign-origin.

As shown in Figure 6, over the period 2001-2006, the La Hague plants processed on average less than 1100 tons per year or 62% of licensed throughput. The throughput of the UP2 plant (317 tons in 2006) fell back to the level of the 1980s prior to the UP2-800 extension. As far as is known, this development is not due to technical problems but rather to the lack of contracts. The loss of the main foreign reprocessing customers, Japan and Germany, has not been compensated by either new foreign contracts or significantly increased commitments from Electricité de France (EDF).

There has been only one recent new foreign contract, an agreement between AREVA NC and the Italian company SOGIN announced on 9 May 2007. It covers the transport and reprocessing of 235 tons of spent fuel from Italy’s shutdown Caorso, Trino and Garigliano nuclear power plants (190 tons, 32 tons and 13 tons respectively).[54] Italy shut down its nuclear reactors after the Chernobyl accident in April 1986 and a national referendum in 1987 confirmed the country’s choice to abandon nuclear power. Since Italy cannot use the separated plutonium and uranium, it will have to find a foreign utility willing to take over the materials.[55]

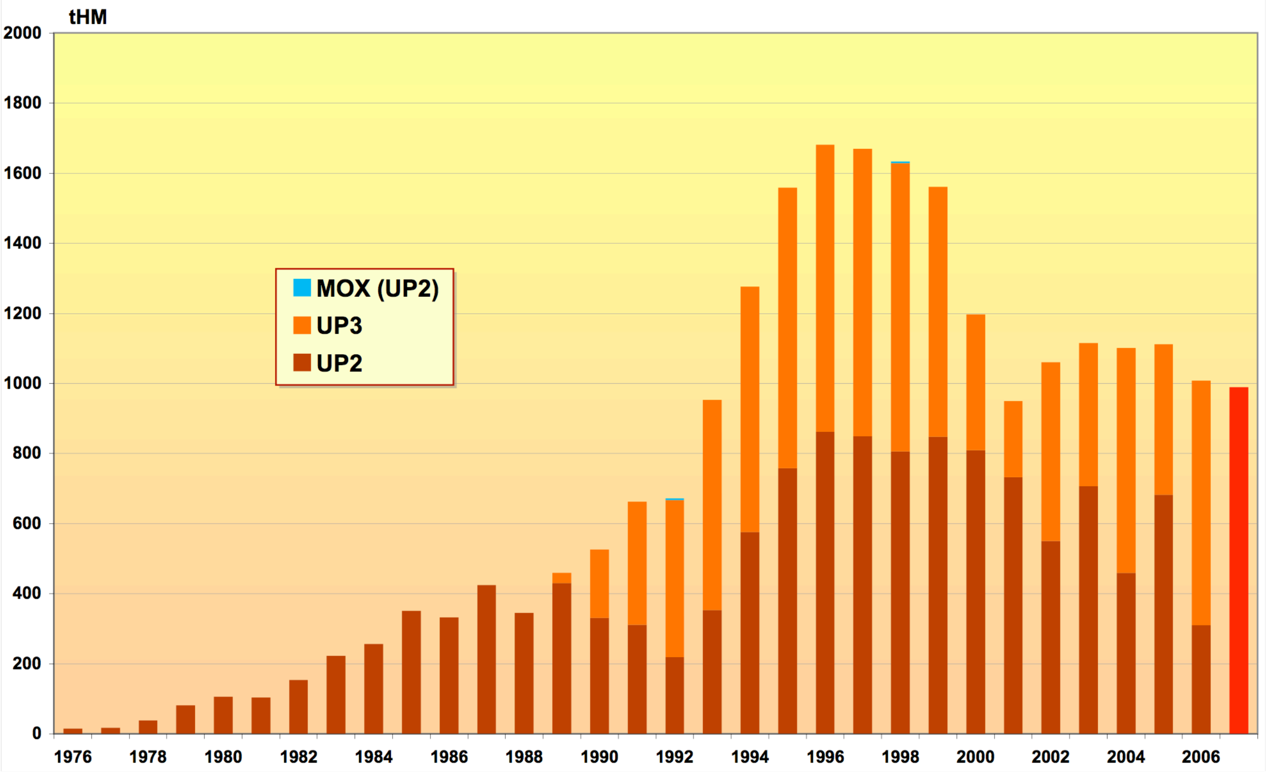

Figure 6: Combined Annual LWR Fuel Reprocessing at La Hague, UP2 and UP3 (as of 31 Dec. 2006, cumulated annuals, tons of heavy metal).
Sources: COGEMA 2002, ASN Annual Reports, Ouest France, 16 February 2008.

As shown in Figure 7, as of the end of 2005, 94% of the foreign LWR spent fuel reprocessing contracts had been fulfilled. Since only 155 tons of German spent fuel of the remaining 376 tons under contract had been delivered prior to Germany's shipment prohibition entering into force on 1 July 2005, the total amount of foreign LWR spent fuel yet to be processed as of the end of 2005 was only 319 tons. Including the Italian contract for 235 tons, to be delivered until the end of 2015, the foreign contracts are the equivalent to only four months of work for the La Hague facilities operating at full capacity. According to plans as of the end of 2005, all of the foreign spent fuel then at the La Hague site will be reprocessed by the end of 2008 (see Table 5 and 6).

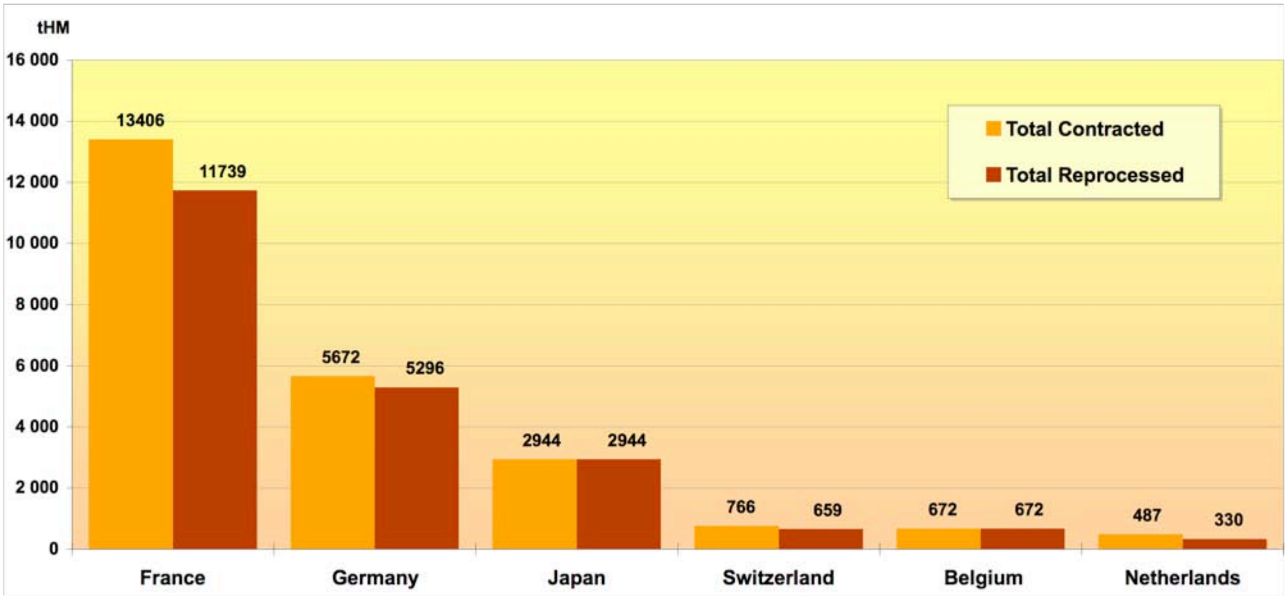

Figure 7. Contracted versus reprocessed LWR fuel at La Hague, as of 31 Dec. 2005 (tons of heavy metal). *Source: COGEMA-La Hague (2004).*[56]

Table 5: Quantities of Spent Fuel in Storage at the La Hague Site[57] by national origin
as of the end of 2005 (tons) and periods during which it was received

Country	*Fuel Type*	LEU	Re-enriched reprocessed uranium	MOX	Research reactor fuel
France	tons	7,410	172	543	1
	years	1985-2005	1991-2005	1996-2005	1997-2005
Germany	tons	106	1	48	
	years	1995-2005	1992	1990-2004	
Belgium	tons				0.4
	years				1998-2004
Switzerland	tons	103		5	
	years	1998-2005		2004-2005	
Netherlands	tons	9			
	years	1994-2005			
Australia	tons				0.2
	years				2000-2005

Source: www.cogemalahague.fr, CSPI (2007)

Table 6: Provisional Schedule for the Processing of Foreign Spent Fuel at La Hague
(as of 31 December 2005)

Country	Fuel Type	2004	2005	2006	2007	2008
Germany	Uranium Oxide	🟦	🟦	🟦	🟦	
	Reprocessed Uranium Oxide			🟪		
	MOX	🟩		🟩	🟩	
Belgium	Research Reactor Fuel		🟨	🟨	🟨	🟨
Switzerland	Uranium Oxide		🟦	🟦	🟦	
Netherlands	Uranium Oxide	🟦	🟦	🟦	🟦	🟦
Australia	Research Reactor Fuel		🟨	🟨	🟨	🟨

Source: COGEMA, private communication CSPI, 24 May 2007

It appears, therefore, that the La Hague facilities will depend almost entirely on the French utility EDF for future business. A minor new contract with the Dutch nuclear operator to reprocess fuel of the 34-year old 480 MW Borssele until the end of its lifetime, the Italian contract and very small quantities of research reactor fuel from Australia and potentially from other countries will not change that situation.

The French government seems in favor of continued reprocessing.[58] However, the current status of the reprocessing agreement between AREVA and EDF is unclear. As of the end of 2005, EDF had a large backlog of 12,005 tons of spent fuel.[59] It has not indicated, however, whether it intends to increase its current contracted reprocessing rate of about 850 tons per year. This means that, out of an average of some 1,150-1,200 tons per year that are discharged from EDF's 58 PWRs, some 300-350 tons per year (of which about 100 tons are spent MOX) continue to be added to its stockpile of stored spent fuel.[60] While limited amounts of German and Swiss MOX fuel have been delivered for reprocessing, EDF does not seem to be planning to reprocess its MOX fuel, at least in the short and medium term.

With the liberalization of the electricity sector in the European Union the pressure to lower costs has increased significantly. EDF's massive subsidy of AREVA's plutonium industry is becoming unbearable. The need to share the cost burden as foreign clients vanish is further weighing on the two state-controlled companies. Cost issues are reported to prevent EDF and AREVA from reaching a follow-up agreement to the long-term reprocessing/MOX fabrication contract signed in 2001 that ended in 2007. In an unusual press statement, AREVA's CGT trade union section alleges that "in the difficult year 2007 EDF has not respected its contractual engagements… The CGT is concerned that EDF's posture, including the request for drastic cost reductions in reprocessing-recycling, would not be without consequences on safety, security and working conditions."[61]

Plutonium Separation and Use

The original reason for the separation of plutonium from power-reactor fuel was to provide initial fuel for the fleet of fast breeder reactors that was supposed to come on line starting in the 1990s. Also, the massive expansion of the capacity of the La Hague reprocessing plants was planned in the late 1970s when uranium prices were soaring. The French President compared the energy potential of plutonium breeder reactors to Saudi Arabia's oil reserves and construction of the world's first commercial fast breeder reactor, the Superphénix, was forced through against massive local, national and international opposition.[62]

In 1976, COGEMA was created with 100% CEA ownership but under private law[63] and signed contracts with European and Japanese utilities to build the UP3 reprocessing plant at La Hague – again despite significant opposition.[64]

Even before Superphénix went critical in 1985, however, it had become clear that the large-scale introduction of fast breeder reactors would not take place, either in France or elsewhere.[65]

France's LWR MOX program was therefore launched in 1987 to absorb the massive quantities of French plutonium that were being separated at the Marcoule and La Hague facilities and that were about to increase significantly with the startup of the new reprocessing units at La Hague. It began with the introduction of a third of a reload of MOX fuel into one EDF 900-MWe reactor.

In response to the expansion of reprocessing at La Hague, up to 20 in the number of 900-MWe reactors were licensed to be 30-percent fueled with MOX (see Figure 8). Nevertheless, the EDF stockpile of separated plutonium grew from less than one ton in 1988, to 50.9 tons in 2005 (see Figure 9). This is in part because EDF has been using less MOX than it was authorized to.

One potential bottleneck for the reuse of plutonium is MOX-fuel fabrication capacity. France's older Cadarache and the Belgian Dessel MOX plants shut down in 2003 and 2006 respectively. Dessel had produced for EDF and foreign clients and Cadarache had worked during the last few years of its operation exclusively for German customers. In April 2007 AREVA was granted authorization to increase the throughput of its MELOX MOX-fuel fabrication facility at Marcoule from 145 tons to 195 tons per year.[66] Whether MOX fuel fabrication capacity will constitute a bottleneck for French plutonium use in LWRs, however, will depend on EDF's future fuel strategy and the attitude of potential Japanese customers that are still holding a large quantity of plutonium at La Hague. The Japanese plutonium is most likely to be returned in the form of MOX fuel.

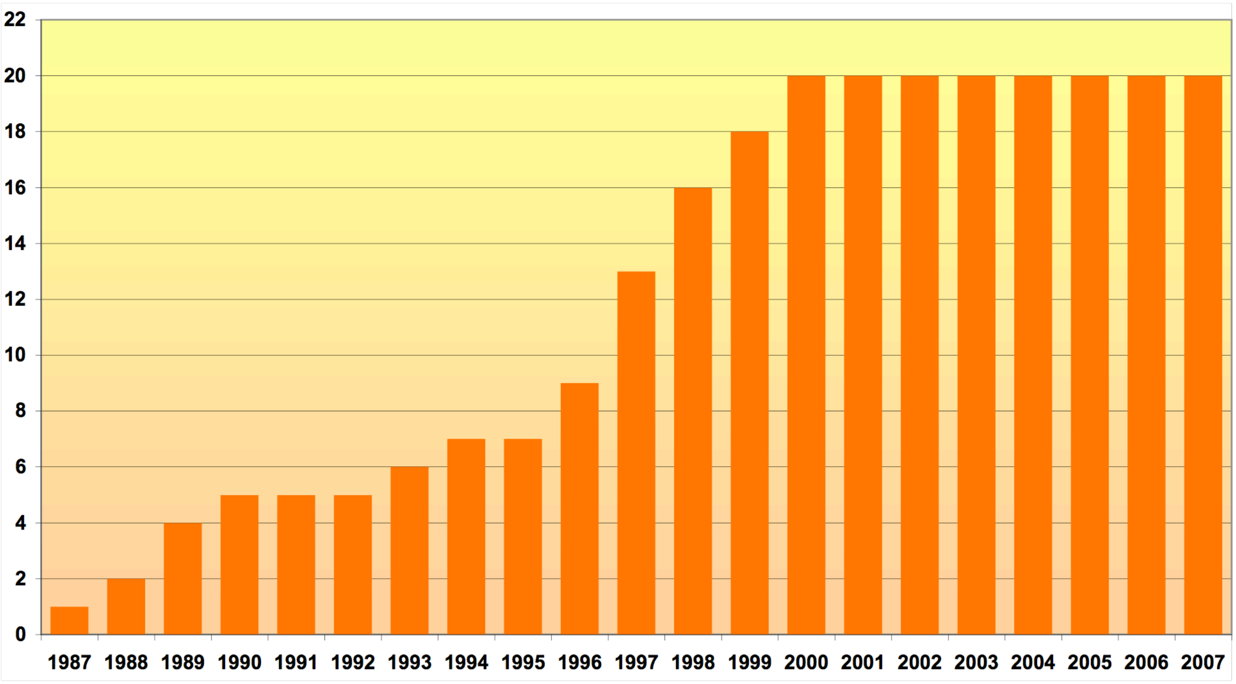

Figure 8. Growth in number of French LWRs using MOX (as of Dec. 2006)
Sources: COGEMA, ASN, WISE-Paris.

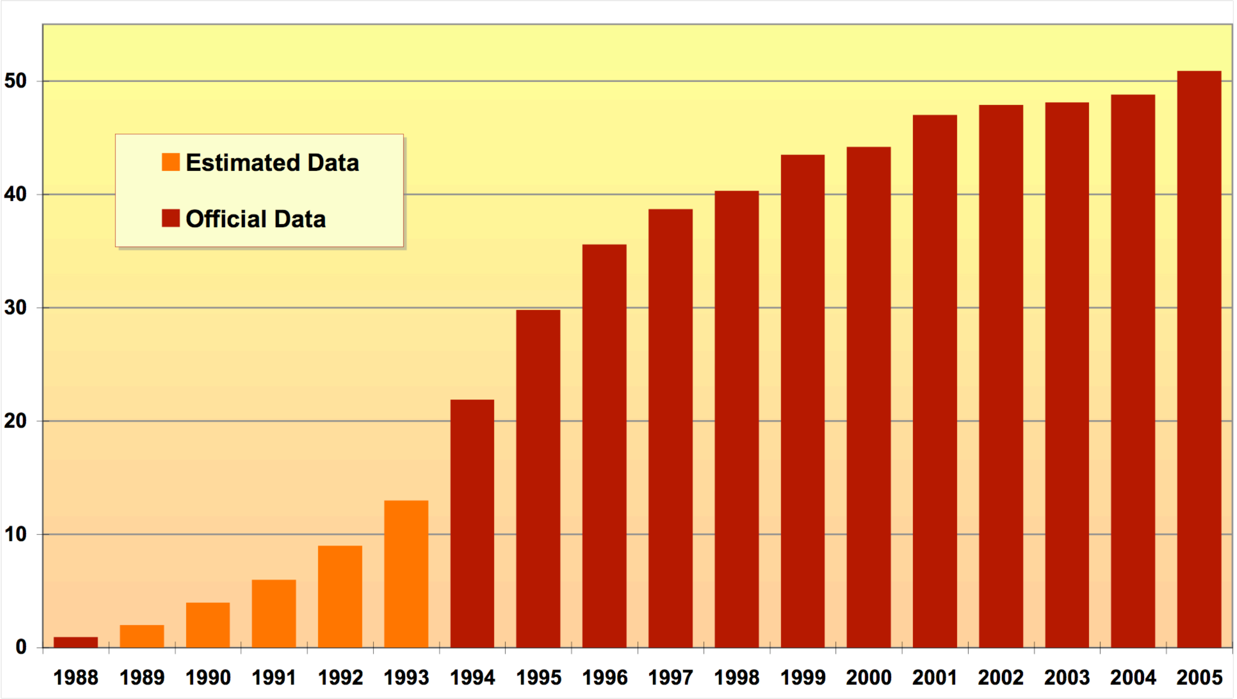

Figure 9. Growth of France's stockpile of separated plutonium (tons, as of 31 December)
Sources : EDF, MINEFI, COGEMA, WISE-Paris, IAEA 2006.

The second bottleneck factor is the safety limitations to the use of MOX fuel in reactors. Twenty-eight of France's 900-MWe reactors are designed with additional control rods to allow them to operate with MOX fuel constituting up to 30% of the core. Only 22 of them are currently licensed to do so. In 2006 EDF asked for permission to extend the MOX use license to four additional 900-MWe units. Two have been allowed and two are pending. Meanwhile, EDF was allowed in 2007 to increase the maximum average plutonium content in the MOX from 7.08% to 8.65%.[67]

With the phasing out of reprocessing of foreign fuel and the reuse of some of the separated plutonium belonging to Germany and other European customer countries, the amount of foreign plutonium stored in France decreased between 2000 and 2005 from 38.5 to 30.3 tons (see Figure 10).

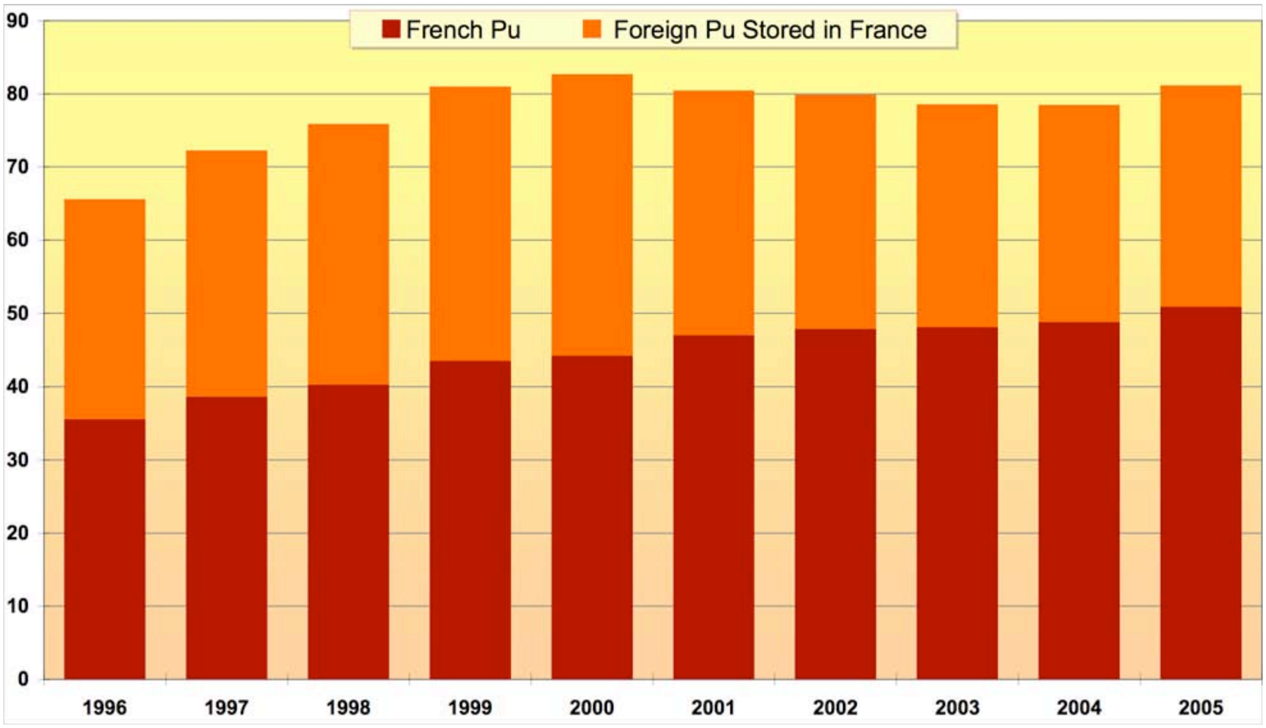

Figure 10. French and foreign plutonium stocks in France (in tons, as of 31 December)
Sources: French Statements to the IAEA 1997-2006

As of the end of 2005, over 60%, or 49.8 tons, of the separated plutonium in France was held as oxide at the La Hague reprocessing plant. According to France's public annual declarations to the IAEA, however, a constantly increasing amount of its plutonium is contained in fresh MOX fuel "or other fabricated products" stored either at reactor sites "or elsewhere" (see Figure 11). The amount of plutonium in fresh MOX fuel or MOX scrap assemblies more than tripled from 5 tons in 1996 to 15.9 tons in 2005. A significant share of that plutonium is present in the relatively unprotected La Hague spent-fuel pools. As of the end of 2001, a total of 98 tons of MOX scrap assemblies with a plutonium content of at least 5% were stored at La Hague.[68] No updates of this information have been made publicly available.[69]

In 2006, AREVA stated that, as of the end of 2004, EDF owned 26 tons of the then 50.7 tons of separated plutonium stored at La Hague versus about 25 tons for foreign clients (Japan 20.5 tons, Germany 3.3 tons and Switzerland about 1 ton).[70]

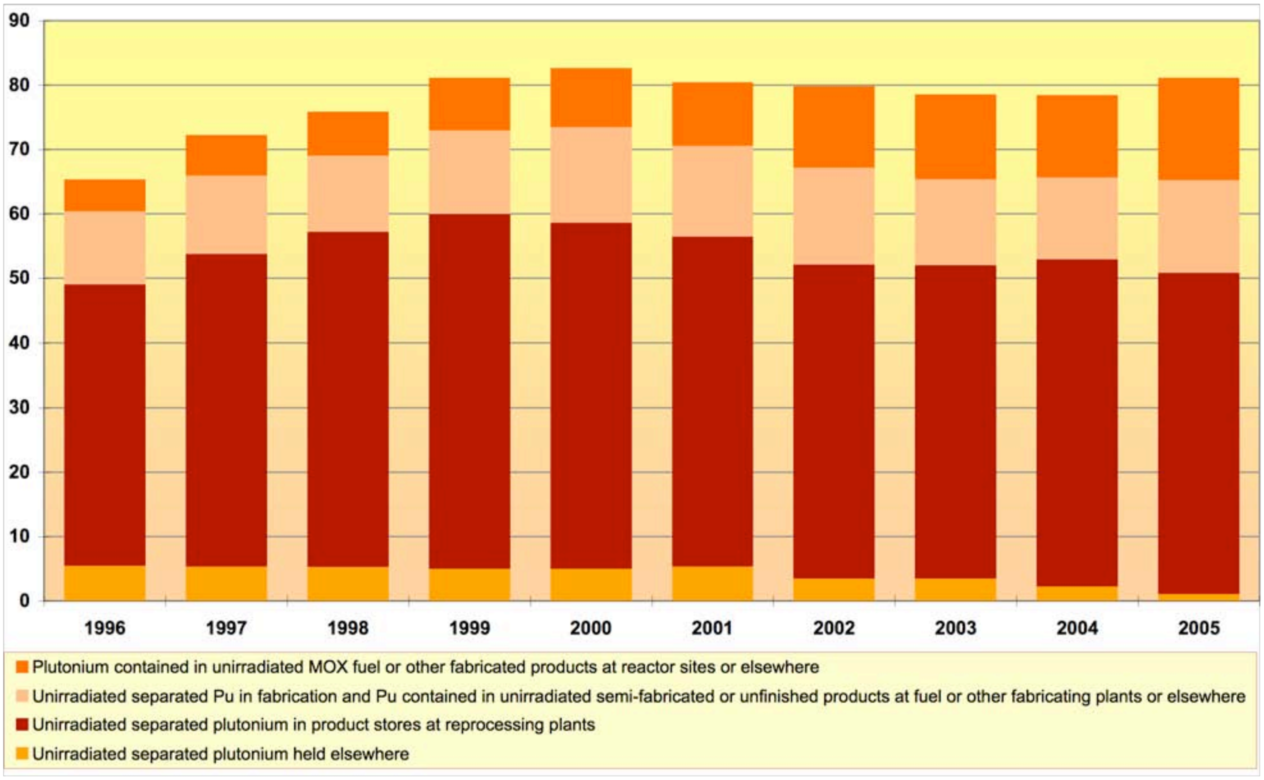

Figure 11. Unirradiated Plutonium in France by Location and Form (in tons, as of December 31).
Sources: French Statements to the IAEA 1997-2006.

The launch of a full-scale plutonium economy has resulted in many plutonium shipments from reprocessing to fuel fabrication plants. Appendix B shows the quantities of material that have been shipped annually from La Hague to the Dessel plant in Belgium, and to the Cadarache ATPu and Marcoule MELOX plants over 1000 km away in the south of France. The quantity of separated plutonium shipped each year has been over 10 tons since 1998. There are about 89 shipments of plutonium oxide and 68 of unirradiated MOX annually in France.[71]

Radioactive Discharges and Health Effects

The limits on radioactive discharges to the atmosphere and ocean from the La Hague reprocessing plant are two to four orders of magnitude larger than those for a 1300 MW reactor at the Flamanville site, just 17 km (10 miles) down the coast. Revised discharge limits were issued in January 2007.[72] While the new license has significantly reduced the limits on discharges for some radioisotopes,[73] La Hague still has permission to discharge very large amounts of radioactivity into the environment.[74] Appendix C provides a comparison of the former and the new discharge limits for La Hague with the limits for one Flamanville reactor.

The history of radioactive discharges of La Hague (see Appendices D and E) shows that, for certain radioisotopes, improved removal technology and waste-stream management led to very significant reductions. This is the case for plutonium and cesium-137 for example. Technetium-99 emissions were also significantly reduced -- first due to the phase-out of metal fuel in the middle of the 1980s and, since 1996, due to the use of specific evaporation and vitrification processes. According to the OSPAR Commission for the Protection of the Marine Environment of the North-east Atlantic, less than 0.06% of the Technetium-99 input to the plant is now released to the environment.[75]

Some other changes in effluent management have shifted releases that formerly went into the atmosphere to the ocean. Iodine-129, in particular, is now filtered out of the gaseous effluent stream and pumped into the sea. With increased spent fuel throughput and burn-up, however, the discharges of krypton-85, tritium, carbon-14 and iodine-129 have increased sharply.

The overall trend is towards the reduction of doses to the local population from isotopes such as 30-year half-life cesium-137 and strontium-90, and an increase in long-term global, collective doses due to increased releases of krypton-85 (11-year half-life), carbon-14 (5,736 years) and iodine-129 (16 million years).[76]

A recent study funded by the European Commission evaluated cumulative collective doses from the Sellafield and La Hague reprocessing plants over various periods.[77] Tables 7 and 8 show estimated cumulative doses to the world population due to releases from La Hague summed over 100,000 years and compares these doses to some other anthropogenic doses. On the basis of the average of routine discharges between 1999 and 2003, the *annual* discharges of La Hague cause a collective dose of 3600 person-Sv. Applying the risk factor recommended by the International Commission on Radiological Protection, this dose would result in about 180 fatal cancers.[78] Assuming the same annual discharges for the planned remaining operational life of the La Hague facilities, the global, long-term collective dose due to La Hague would be 65,000 person-Sieverts, which implies a theoretical fatal cancer toll of 3,250 cases.

Table 7: Collective doses to world population due to annual discharges from La Hague (in person-Sv)

	First pass	Truncation 50 years	Truncation 100,000 years
Gaseous Releases	15	190	2,100
Liquid Discharges	32	22	1,500
Total Collective Dose	**32**	**212**	**3,600**

Source: UK HPA / CEPN (2006).[79]

Notes:

(1) For an assumed world population of 10 billion people

(2) Average annual discharge between 1999 and 2003

(3) The first pass dose is that due to the initial discharge to the environment. The truncated totals also include any contribution from the environmental recirculation of relevant radionuclides.

Table 8: Global Collective Doses From Anthropogenic Radiation Sources

Source of Exposure	Global collective dose (Person-Sv)
Chernobyl Accident	600,000
World Nuclear Power Production to 1989	400,000
World Radioisotope Production and Use to 1989	80,000
La Hague (planned operation 2008-2025)	65,000
World Nuclear Weapons Fabrication to 1989	60,000
Kyshtym Accident USSR 1957	2,500
Windscale Accident UK 1973	2,000
World Underground Nuclear Testing to 1989	200
Three Mile Island Accident US 1979	40

Sources: derived from Bennett (1995)[80]*; UNSCEAR (1993)*[81] *and UK HPA / CEPN (2006).*[82]

VI. Waste Generation

Nuclear waste versus re-usable materials

Under the principles of French and European environmental law, materials should be regarded as waste unless and until they are actually undergoing an industrial recycling process. France's nuclear industry has developed the more permissive view that, if a material could be potentially reused at an undefined time in the future, it can be exempted from being classified as waste. The 2006 law on radioactive waste management (Article 5) codified this permissive approach:

- "A radioactive material shall include any radioactive substance that is intended for further use, after treatment, if need be."
- "Radioactive waste shall include any radioactive substance for which no further use is prescribed or considered."
- "Ultimate radioactive waste shall include any radioactive waste for which no further processing is possible under current technical and economic conditions, notably by extracting their recoverable fraction or by reducing their polluting or hazardous character."

This classification has generally provided the basis for excluding materials containing uranium or plutonium from any official assessment for future waste management.[83] One notable exception to this approach is the "Charpin-Dessus-Pellat Report" to the Prime Minister in 2000 (the CDP report). It concluded that even reprocessing of *all* the French spent LEU fuel – a scenario that is currently excluded – would only lead to a 23% reduction of the amount of plutonium remaining at the end of the lifetimes of the currently operating LWRs, if compared to no reprocessing at all.[84]

Full reuse could not be practically achieved with the current fleet of French nuclear power plants. Table 9 shows ANDRA's projections of France's inventory of spent fuel and of separated plutonium and reprocessed uranium out to 2020, the end of the lifetime of the twenty-eight 900 MWe LWRs that EDF could operate with MOX and reprocessed uranium fuels.[85]

Table 9: Past evolution and projection up to 2020 of "re-usable" materials in storage

Quantities in storage (tons heavy metal)	1987	1997	2000	2010	2020
Spent LEU fuel (~1% plutonium)	3,050	9,020	10,350	11,250	10,850
Spent MOX fuel (4-6% plutonium)	0	195	520	1,300	2,350
Spent re-enriched reprocessed uranium fuel (1% plutonium)	0	0	150	350	700
Reprocessed uranium	~7,500	~12,000	16,000	20,000	25,000
Separated plutonium	2.5	38	48	~48	~48
Availability of reactors (years)	25 to 35	15 to 25	10 to 20	2 to 12	0 to 2

Notes: The availability of reactors is the calculated expected number of remaining operating years, as an average for the 28 reactors of 900 MWe in which EDF theoretically could pursue the use of re-enriched reprocessed uranium fuel or MOX. These reactors were started-up between 1977 and 1987, with a planned lifetime of 30 years, recently extended by the operator to 40 years. However, the extension has yet to be approved by the Nuclear Safety Authority on a case-by-case basis. The low and high values respectively correspond to 30 and 40 years of operation.

Source: WISE-Paris estimates based on CDP (2000), ANDRA (2006).

Estimates of Waste Volume

In 2005, ANDRA discussed the implications for a projected geological disposal facility if reprocessing were phased out and presented the results in the National Debate, and to the Government and the Parliament during the preparation of the 2006 law.[86]

Two main scenarios were compared. One assumed that all the spent fuel unloaded from currently operating reactors would be reprocessed: 41,500 tons of LEU spent fuel, 800 tons of spent fuel produced by re-enriching reprocessed uranium, and 2,700 tons of MOX. The other scenario assumed that reprocessing would end in 2010, requiring the direct disposal of 26,500 tons of LEU spent fuel, 500 tons of spent fuel made from re-enriched reprocessed uranium, and 2000 tons of MOX spent fuel. ANDRA's calculations found that the area of underground repository needed for disposal would almost double if reprocessing were phased out.[87]

The reprocessing scenario assumed, however, that 200-300 tons of separated plutonium and about 30,000 tons of reprocessed uranium would be stored for future reuse in new reactors. Thus, in the case of direct disposal, all the remaining uranium and the plutonium in the spent fuel generated by the current reactors would be disposed of in the repository, while, in case of the reprocessing scenario, less than half of the nuclear materials in the spent fuel would be sent to the repository.[88]

The exclusion of "re-usable" materials from the inventory of waste -- and any waste linked to their management and/or eventual disposal -- is the most significant bias that regularly appears in comparisons by ANDRA, EDF and AREVA of waste volumes from reprocessing and direct disposal.

In addition these official comparisons usually focus on high-level and long-lived intermediate-level wastes, ignoring the fact that reprocessing significantly increases the volumes of low-level and very low-level wastes. Finally, the issue of discharges by the reprocessing plants to the environment of radioactive liquids and gases are never factored into the comparison. They should be included in overall comparisons of waste management strategies.[89]

Extrapolation of current performance. Another area of bias in official French comparisons of the impact on waste volumes of reprocessing is the application of current or even projected practices to both past and future inventories. Sustained efforts using techniques such as compaction and incineration have resulted in dramatic reductions in the volumes of some categories of long-lived wastes.[90] Table 10 shows the volumes of long-lived wastes from the reprocessing of 1 ton of spent LEU fuel during three periods: start-up of the UP3 and UP2-800 plants (ranging from 1989 to 1994), at the end of 1995 after a first series of waste volume-reduction innovations, and from "optimized" practices as of the end of 2004. Applying current or future volume-reduction factors to past wastes is obviously misleading.[91]

Table 10: Waste Arising from Reprocessing of a ton of uranium oxide spent fuel at La Hague,
as of the start-up of the UP3 and UP2-800 plants, the end of 1995, and the end of 2004

Waste		**Drum Volume**[a]	**Number of Packages per tHM**[b]		
			Start-up	**End 1995**	**End 2004**
HLW					
Vitrified waste		0.180	0.73	0.54[c]	0.66[d]
LL-ILW					
Hulls and nozzles	Cemented	1.800	0.37	0.43[e]	—
	Compacted	0.180	—	—	0.63[f]
Process waste	Bituminized sludge	0.238	3.0	1.7[g]	0.08[i]
Technological waste	Cemented, asbestos-cement drum	1.180	1.2	0.29[h]	—
	Cemented, large cement drum	1.180	—		0.26[i]
SL-ILW/LLW					
Technological waste	Cemented, small cement drum	0.660	5.3	4.7[h]	0.43[i]
	Cemented, large cement drum	1.180	—	—	0.21[i]
	Cemented, iron drum	0.225	—	—	1.8[i]
	Incinerated	no data	—	—	0.03[i]

Source: IRSN (2006).[92]

Notes:

a. Primary conditioned waste in m^3.

b. Average number of primary packages produced per ton of spent fuel reprocessed.

c. Mean value corresponding to 5,121 tHM of spent fuel reprocessed in UP2-400, UP2-800 and UP3 between January 1991 and December 1995 (on average 28.9 GWd/tHM, 7.87 years after unloading).

d. Mean value corresponding to 5,414 tHM of spent fuel reprocessed in UP2-800 and UP3 between January 2000 and December 2004 (37.4 GWd/t, 7.49 years after unloading).

e. Based on the number of drums produced by the head-ends (R1 and T1) between their start-up and August 1995.

f. Based on the number of drums produced by the compacting facility *Atelier de compactage des coques* (ACC).

g. Based on reprocessing in UP2-800 and UP3 between January 1991 and December 1995.

h. Based on reprocessing in UP2-400, UP2-800 and UP3 between January 1991 and December 1995.

i. Based on reprocessing in UP2-800 and UP3 between January 2000 and December 2004.

Misleading comparisons. Official accounts of the effects of reprocessing on waste inventories are also biased by misleading comparisons. For example, the comparison is often made between the volume of spent fuel assemblies packaged in casks for direct disposal and the unpackaged volume of waste from reprocessing, despite the fact that packaging increases the volume of reprocessing wastes by a factor of 3 to 7.

Of course, volume may not be the appropriate indicator at all. Other important indicators include: quantity of transuranics, mass, radiotoxicity, chemical toxicity, and thermal output. In fact, thermal output is a decisive determinant of repository volume for high-level waste and spent fuel because of temperature limits for the repository rock. As shown in Figure 12, the heat outputs of vitrified waste and various spent fuels differ greatly, in particular the thermal output of MOX fuel assemblies is much higher to begin with and decreases much more slowly than for any other HLW type considered.

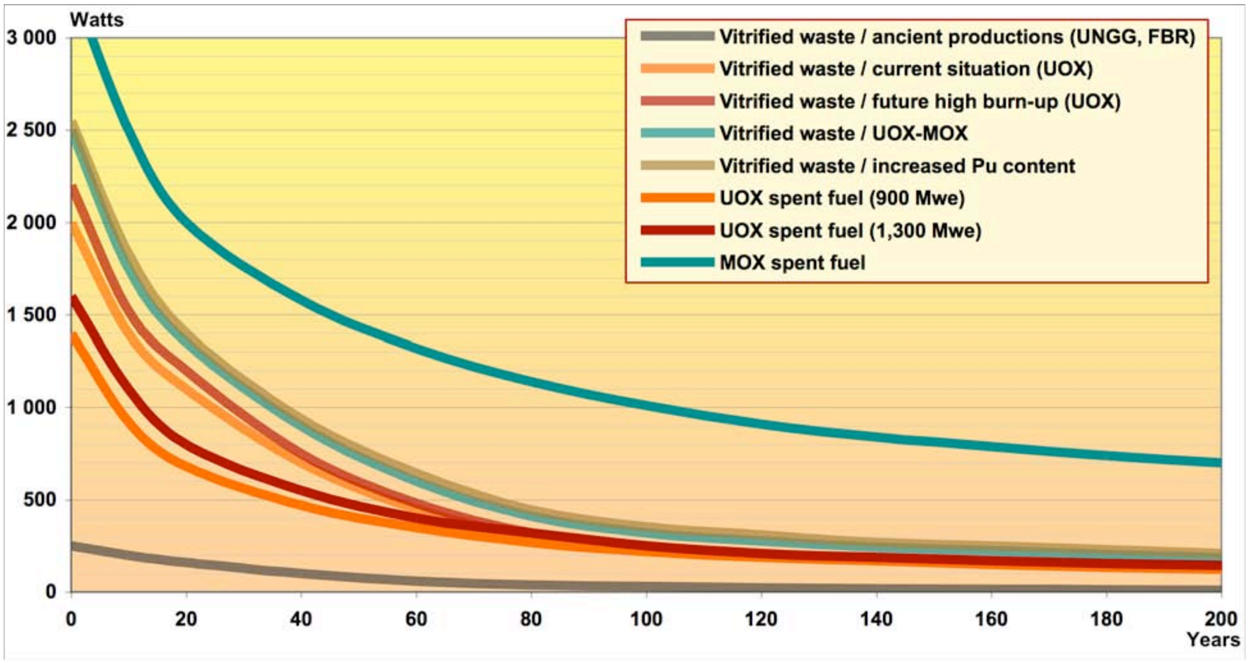

Figure 12. Thermal Output of Spent Fuel Assemblies and **Vitrified Waste** as a function of time after unloading from the reactor or vitrification**.** In the case of spent fuel, thermal output in Watts per fuel assembly; in the case of vitrified waste, thermal Watts per package. *Source: ANDRA (2005).*

Spent MOX fuel needs either a much longer intermediate storage period before geological disposal than spent LEU fuel or a much larger volume in the final repository. The Charpin-Dessus-Pellat report highlighted EDF's conclusion that spent MOX fuel would have to cool on the surface for 150 years, compared to 50 years for spent LEU fuel or vitrified waste.[93] The French Commission for Sustainable Development (Commission Française du Développement Durable) expressed the concern that a plan for prolonged surface storage was "not an equitable one for future generations."[94]

Alternative Estimates of Waste Inventories

In 2006, ANDRA published an inventory of the radioactive waste generated by reprocessing of French and foreign spent fuel in France up to the end of 2004.[95] ANDRA distinguished 38 categories of waste associated with reprocessing.[96] These wastes are at various sites, including the reprocessing plants and France's disposal sites for short-lived intermediate-level and low-level wastes at the Centre de stockage de la Manche (CSM),[97] now closed, and the Centre de Stockage de l'Aube (CSA), which is still in operation.

The waste volumes shown in Table 11 (broken down by origin, category, status and location) are final volumes expected by ANDRA *after* conditioning or re-conditioning is carried out. This is subject to some uncertainty, as some of the techniques still remain to be fully developed. The allocation to categories is also based on the industry's arguable hypothesis that a large part of the yet-to-be-conditioned structural, process and technological waste will qualify as short-lived intermediate-level and low-level waste instead of long-lived intermediate-level waste.

The inventory also does not account for Marcoule waste that was dumped into the sea in 1967 and 1969, the equivalent final volume of which is estimated at 12,000 m^3 or more.[98] It also does not account for very large volumes of very low-level waste that can be expected from the decommissioning of reprocessing plants. Most importantly, it does not include any of the "re-usable materials" currently in stock. These are spent fuels stored at La Hague (LEU, re-enriched reprocessed uranium, and MOX), separated plutonium and reprocessed uranium, and scrap MOX. One irradiated and one unirradiated core of the Superphénix fast-breeder, both still stored on the reactor site, are also not included.

With the above exceptions, there was a total volume of some 344,600 m^3 of conditioned high, intermediate and low-level waste as a result of spent-fuel reprocessing in France as of the end of 2004.

Table 11: Waste Volumes Generated by Spent Fuel Reprocessing in France
by category, status and location (in cubic meters, as of December 31, 2004)

Waste Category and Form		**La Hague**		**Marcoule**		**EDF Sites**	**CSA**[d]	**CSM**[e]
		Cond.[a]	**Uncond.**[b]	**Cond.**[a]	**Uncond.**[b]		**Disposal Sites**	
High-level	Vitrified	1,437[c]	778	554	27	—	—	—
Long-lived intermediate - level	Structure	2,657	2,959	—	2,728	—	—	—
	Process	2,458	9,520	421	10,060	—	—	—
	Technological	4,310	2,795	—	1,502	—	—	—
Long-lived low-level	Structure	—	2,907	—	2,229	6,078	—	—
Short-lived intermediate and low-level	Structure	—	—	—	5,751	—	1,925	160,049
	Process	—	—	—	42,567	—	—	
	Technological	3,918	9,534	1,855	7,629	—	57,937	

Source: WISE-Paris based on ANDRA (2006)

Notes:

a. Waste in primary conditioning corresponding to specifications envisaged for final disposal.

b. Waste unconditioned or under insufficient primary conditioning in view of future disposal.

c. This total includes 96 m^3 of vitrified waste produced at La Hague but stored in foreign client countries to which it has been returned, as of the end of 2004.

d. Centre de Stockage de l'Aube.

e. Centre de Stockage de la Manche.

About 64% of the waste volume has been disposed of, 5% is stored with primary conditioning, and 31% with insufficient or no conditioning (see Figure 13).

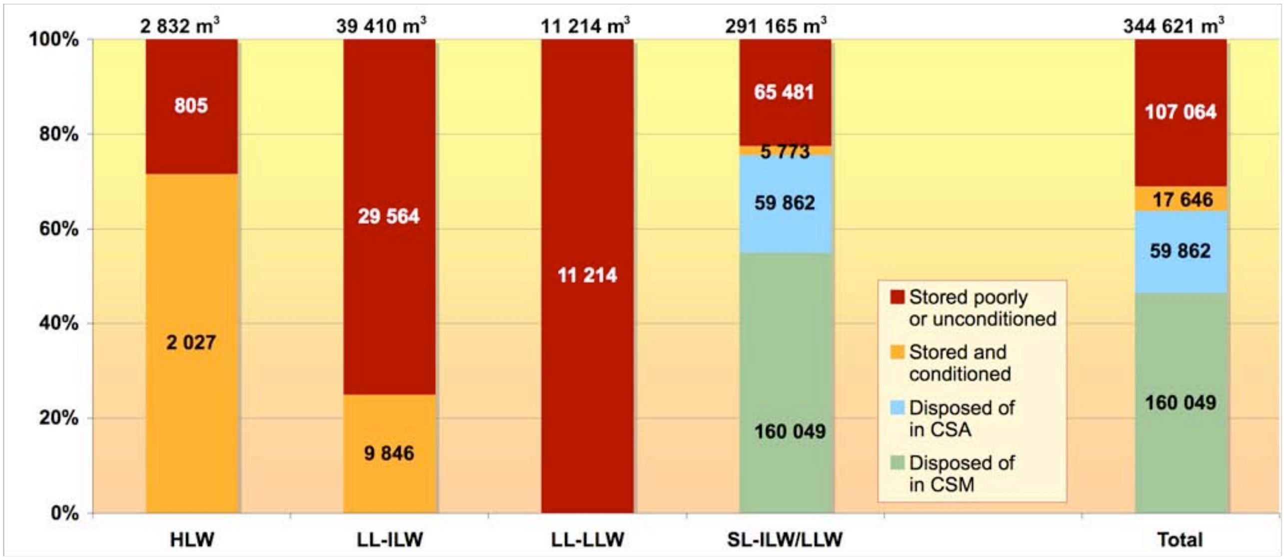

Figure 13. Relative shares of different categories of French reprocessing waste conditioned, unconditioned, stored and disposed of (in m^3, as of December 31, 2004). *Source: WISE-Paris based on ANDRA (2006).*

Short-lived intermediate and low-level waste, representing 85% of the total waste volume, is the only waste form that can be disposed of in existing disposal sites. Twenty five percent of it is still stored at reprocessing plants. About 75% of long-lived intermediate-level waste (a category which accounts for 11.4% of the total reprocessing waste volume) and all long-lived low-level waste (3.3% of the total) are stored with inappropriate conditioning. High-level waste represents only 0.8% of total reprocessing waste volume but it represents a major release hazard while it is in liquid form. Unfortunately, almost 30% of it remains unconditioned.[99]

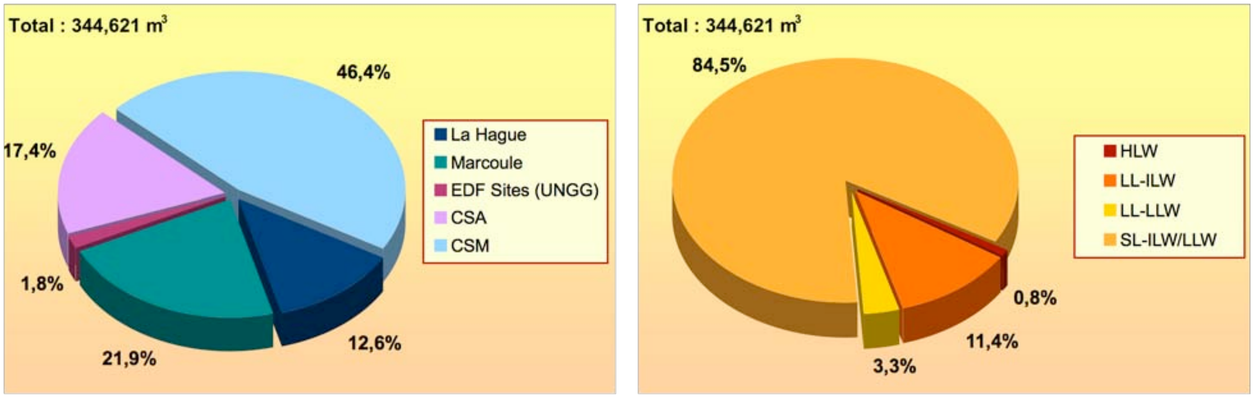

Figure 14. Waste volumes generated by spent fuel reprocessing in France: Fractions by site and category of waste (in m^3, as of December 31, 2004) *Source: WISE-Paris based on ANDRA (2006).*

Figure 14 shows the distribution of the waste volumes by category and by site. About 12.6% of the total inventory is still stored at La Hague and 21.9% at Marcoule. Almost 25% of the waste volume produced by La Hague is still stored there, 66% of it with inadequate conditioning. Almost 50% of the waste volume produced by Marcoule is still on site, with only 4% of it having received appropriate conditioning.

The Impact of Reprocessing on Final Waste and Disposal Volumes

Finally, in this section, we compare the deep underground volume required for direct disposal to that required for the long-lived waste from the reprocessing of LEU fuel. The comparison is based on information and analysis presented by ANDRA in 2005. We also summarize an independent analysis that attempts to correct some of the biases identified above in the official comparisons.[100]

France's reprocessing industry asserts that reprocessing reduces the final volume of waste to be disposed of. Shortcomings underlying this rationale for reprocessing were discussed in the lead-up to France's National Debate on Radioactive Waste Management in 2005-2006. Although France's reprocessing policy was ratified in the subsequent 2006 law on radioactive waste management, the conclusion of the National Debate recognized the need for a more complete analysis of the impact of reprocessing on waste management.

AREVA's claim of waste volume reductions through reprocessing is that a ton of heavy metal in spent LEU fuel would require 2 cubic meters, whereas the intermediate and high-level waste from reprocessing that ton of spent fuel would require only 0.5 m^3 of repository space. According to EDF from the reduction is even more dramatic: from 3 to 0.33 m^3. These claims are misleading, however, because they:

- Ignore the increased complexity of waste management that reprocessing and plutonium recycle create, including the creation of spent MOX fuel and large stocks of separated plutonium and reprocessed uranium that may or may not be used in the future.
- Focus only on categories of radioactive waste requiring deep geological disposal, i.e. high-level and long-lived intermediate level waste. The operation and decommissioning of reprocessing and MOX fuel fabrication plants generate much larger volumes of short-lived intermediate and low and very low-level waste than does interim storage of spent LEU fuel and its subsequent direct disposal.[101]
- Ignore the impact of earlier reprocessing. The industry figures assume the latest achievements of waste compaction techniques. Reprocessing up to the end of 2004 produced an average of about 1 m^3 of high level and long-lived intermediate level waste for every ton of spent fuel reprocessed – two to three times the numbers quoted by AREVA and EDF.[102]
- Ignore the effect of packaging. According to Institute for Radiation Protection and Nuclear Safety (IRSN) projections of waste volumes in a potential geological disposal, one ton of spent LEU fuel would, after packaging, take up a volume of 3 m^3, and the reprocessing of 1 ton of spent LEU fuel would produce about 2.15 m^3 of packaged high and intermediate-level waste.

More fundamentally, the official French approach implies that volumes are the main indicator of the performance of nuclear waste management policies. Comparative risk assessments might well lead to very different conclusions, as reducing volumes does not necessarily decrease the intrinsic danger of the final waste store while it produces risks from the additional conditioning operations.

Our own comparison of the repository requirements for the direct-disposal and reprocessing scenarios compares the requirement for the geological disposal of one ton of spent LEU fuel with those of the high-level and long-lived intermediate wastes from the reprocessing of a composite ton of spent fuel made of a mixture of LEU spent fuel and the spent MOX and the re-enriched uranium fuels derived from it. It also takes into account the changes in waste volumes between the start-up of the plants and the "optimized" techniques of 2004.[103] And it takes into account both the volumes required in underground galleries and the volumes of rock reserved around the galleries to absorb decay heat.[104] We present first the results obtained using official assumptions (in Figure 15) and then show the sensitivity of these results to an alternative set of assumptions (in Figure 16).

In the alternative set of calculations, three major changes are made to the official assumptions:

1. Spent LEU fuel is disposed in casks such as the German BSK-3 cask, where – unlike the French assumption – the fuel assemblies are disassembled and the rods are stored densely packed, resulting in a factor of 5.8 decrease in the volume of the final conditioned waste.[105]
2. Vitrified waste is buried in excavated galleries in clay with the same engineered barriers that ANDRA assumes for spent fuel.[106]
3. The assumption of delayed burial of spent MOX disposal is replaced by an assumption of 60-year surface storage for all high-level waste.

Figure 15 shows the result of using the official assumptions to calculate the volumes of primary and packaged waste and the requirements for underground gallery volume and surface area above for direct disposal with those for reprocessing as practiced at the start up of reprocessing in France, as of the end of 1995 and as of 2004. The results do not support a clear advantage for the reprocessing option claimed by the industry. Appendix F and G provide the back-up tables.

Primary volumes appear larger in all the reprocessing cases – even without taking spent re-enriched reprocessed uranium and MOX fuels into account. For the practices at the start-up of UP2-800 or UP3, the volume of conditioned and packaged waste produced in the reprocessing option would be more than 2.5 times larger in volume than for direct disposal. Only recent compaction techniques provide a reduction in final package volume from reprocessing to 23% less than for direct disposal.

In terms of requirements for underground excavated volume, the reprocessing option, using the 1995 or 2004 practices, provides reductions of necessary excavation volumes, but there is little room for further progress since, with 2004 practices, the volume is dominated by the large volume requirements for spent MOX. For the same reason, the reduction of the surface area above the repository for the reprocessing waste only brings the two options to the same level for the practices of 2004.

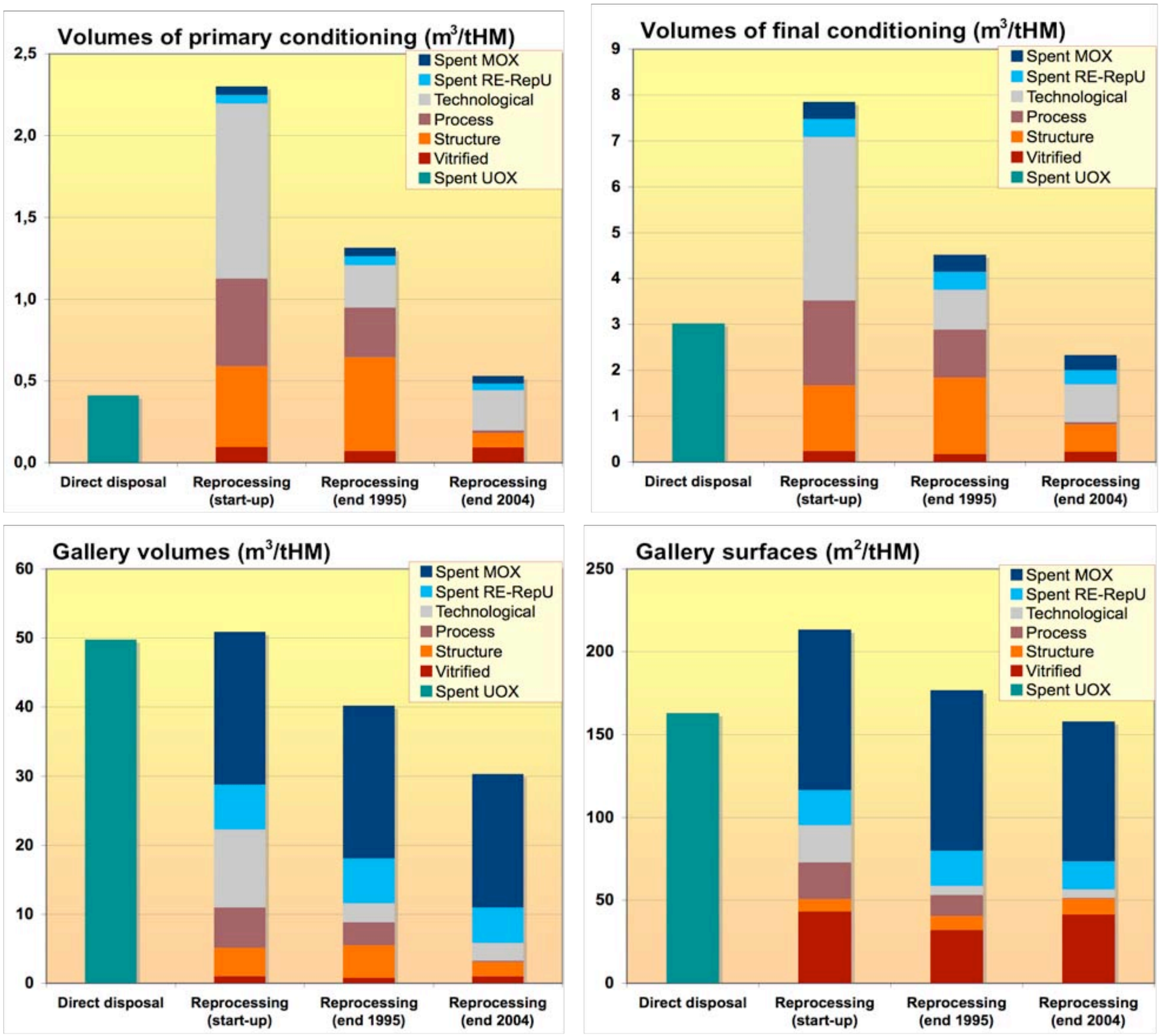

Figure 15. Comparison of waste volumes, gallery volumes and surface areas above the repository for the direct-disposal and reprocessing options (official assumptions, for equivalent energy).

Source: WISE-Paris estimates based on ANDRA (2005); IRSN (2006).[107]

The comparison between the options is very sensitive to the assumptions, however. This is shown in Figure 16, which shows the same comparisons for the alternative assumptions discussed above. It will be seen that the alternative assumptions turn a ratio in the gallery volume of 1.64 in favor of reprocessing into a ratio of 1.65 in favor of direct disposal.

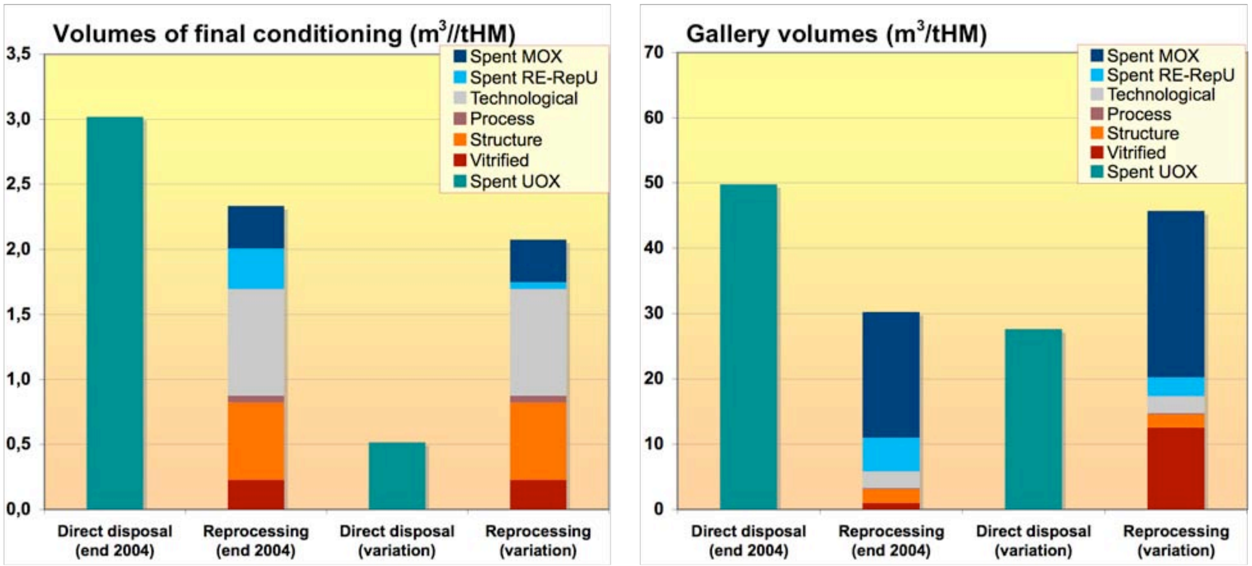

Figure 16. Sensitivity analysis for calculations of waste and gallery volumes for geological disposal in the reprocessing and direct disposal options (for equivalent energy outputs).

Source: WISE-Paris estimates based on ANDRA (2005); GRS (2005),[108] *and IRSN (2006).*[109]

VII. Conclusions

France has reprocessed spent nuclear fuel since 1958. Originally the separation of plutonium was justified by military needs and later by the projected large-scale introduction of plutonium fuelled fast breeder reactors. The separation of plutonium for weapons ended in France in 1993 and the projected dozens fast breeder reactors never materialized. Nevertheless, instead of terminating reprocessing, France's nuclear establishment started up two large new reprocessing lines at La Hague and the use of plutonium in light-water-reactor MOX fuel was introduced. The reprocessing-plutonium use strategy failed, however, as an adequate framework for spent fuel management in France. Large stocks of both spent fuel and of separated plutonium have been the result.

The separation and use of plutonium in MOX fuel and the re-enriching of reprocessed uranium are both uneconomic activities. This remains the case even in France, which has the most favorable political and industrial conditions. Consequently, since 1995 the state electricity utility EDF has assigned in its accounts a zero value to its stocks of separated plutonium, as well as to its stocks of reprocessed uranium.

Only countries that had previously embarked on or participated in fast breeder reactor programs have reprocessed commercial spent fuel. Virtually all other European countries, apart from the United Kingdom, have abandoned reprocessing and the U.K. plans to do so. EDF is unwilling to fill the capacity gap left by the foreign reprocessing clients and continues to reprocess only about three quarters of its discharged fuel. EDF and AREVA NC have not been able to agree on a follow-up contract to their reprocessing agreement that ran out in 2007.

A major argument made for reprocessing is that it would dramatically reduce the volume of radioactive waste. A number of serious biases have been found, however, in official comparisons. Under past and current industrial conditions, there is no clear advantage for the reprocessing option -- either in terms of waste volumes or repository area. Depending upon assumptions, the underground volume required for spent MOX fuel and vitrified waste can be smaller or larger than that required for direct disposal of spent LWR fuel.

La Hague is currently the largest man-made source of radioactivity releases to the environment. The global, collective dose over 100,000 years has been estimated at 3600 man-Sieverts. Continuing discharges at this level for the expected remaining years of La Hague's operation *theoretically* could cause 3000 additional cancer deaths over the long term.[110]

Reprocessing also has significant impacts in terms of safety and security. The reuse of European power-reactor plutonium separated at La Hague results in an average of almost two truck shipments of separated plutonium per week from La Hague to the MELOX MOX fabrication plant at Marcoule, over 1000 km away.

An overall cost-benefit analysis of spent fuel reprocessing in France would find that the economic, environmental, health, safety and security costs clearly outweigh the benefit of minor savings of natural uranium.

Endnotes

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[1] An 18 October 1945 decree by President Charles De Gaulle established France's Commissariat à l'Energie Atomique, CEA, with a mandate to conduct "scientific and technical research with a view to the utilization of atomic energy in the several areas of science, industry and national defense." Translation cited in Lawrence Scheinman, *Atomic Energy Policy in France Under the Fourth Republic*, Princeton University Press, 1965, p. 8.

[2] M. Schneider, X. Coeytaux, *Recyclage des matières nucléaires – Mythes et réalités*, WISE-Paris report commissioned by Greenpeace France, Paris, May 2000. The report noted that these estimates were consistent with others, e.g., Albright, D., "Production and status of military plutonium stocks, end of 1998", ISIS Plutonium Workshop, Washington, March 2000.

[3] The French national utility EDF held a stake of 51%, Italy 33% and the German led SBK 16% (representing also Belgian, Dutch and UK capital). Today EDF has taken over the entire project.

[4] This was mainly for economic reasons, but also because part of the EDF management was convinced that the acceptance of nuclear power would strongly benefit from "cutting off the bad plutonium branch." Personal communication to one of the authors.

[5] Image courtesy of WISE-Paris, 2008.

[6] EDF, Direction Production Transport, *Combustible MOX – Aspects techniques, économiques et stratégiques*, EDF, 24 November 1989. This document is sometimes referred to as "Note Beaufrère" from the name of its main author.

[7] *ibid*

[8] 34x900 MWe, 20x1300 MWe, and 4x1500 MWe.

[9] Nuclear Energy Agency, *The Economics of the Nuclear Fuel Cycle,* OECD, Paris, 1994, www.nea.fr/html/ndd/reports/efc/EFC-complete.pdf. This study found reprocessing 10 percent less costly than the once-through cycle.

[10] These so-called "reference costs" are published in a regularly updated report. The latest revision occurred in 2003, DGEMP (2003). A new revision was to be published before the end of 2007.

[11] J.-L. Fensch, *Finalités du Retraitement*, Report presented to the Conseil Supérieur de la Sûreté Nucléaire, Paris, 1982.

[12] The decision was taken to use the investments in the new reprocessing plants in La Hague (UP2-800 and UP3), and in the commercial MOX fabrication plant in Marcoule (MELOX), and a contract was signed between EDF and COGEMA covering the reprocessing of 8000 tons of spent fuel over the 1990-2000 period.

[13] See CDP (2000) and Girard (2000). The study assumed a uranium price range from 900 to 1,700 FF/kgU (184 to 348 $), i.e. levels that were only reached historically during the peak of 1975 to 1979. In 1985 the price was down to 500 FF/kgU (or 102 $/kgU). Through this section costs and prices are given (if not stipulated otherwise) in the value of currency as of the year considered, FRF until 2000 and € from 2001 (with the fixed rate of 1 € = 6.55957 FRF). The dollar exchange is based on the rate 1 € = 1.3447 $ as of 4 June 2007 (consequently, 1 FRF = 0.20499 $).

[14] The expression "dual management" was introduced by a parliamentary report that criticized the nuclear industry for pretending to pursue full reprocessing of spent fuel while actually implementing it only partially: Ch. Bataille, *Les possibilités d'entreposage à long terme de combustibles nucléaires irradiés*,, Rapport de l'Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques (OPECST), Assemblée Nationale, May 2001. www.assemblee-nationale.fr/legislatures/11/pdf/rap-oecst/r3101-1.pdf.

[15] The authors also considered and calculated a scenario of immediate phase-out of reprocessing in 2001, but eventually decided not to publish it, mainly for political reasons. Some indications are included as an appendix to CDP (2000).

[16] AREVA assumes in its *Annual Report 2005* that the La Hague reprocessing plant will only operate until 2025.

[17] In the methodology developed in [Girard 2000], the material balance and economics of the current nuclear fleet is assessed separately from the potential decisions on the continuation of the nuclear option. Reprocessing is therefore

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only considered up to the point where separated materials could be no longer be re-used in the existing reactors, which roughly coincides with the assumption on the planned operating life of UP2-800. In the "all-reprocessing" scenario, 17,600 tHM of spent uranium oxide fuel are therefore stored at the end of the period (2050). The re-use of materials contained in spent fuel discharged after the UP2-800 shutdown, and the possible construction of a new reprocessing plant, are left for the assessment of a new reactor fleet, which is another part of the "Charpin-Dessus-Pellat" Project not associated with an economic assessment. The global cost estimate for the existing fleet uses the conservative assumption that this spent fuel is eventually disposed of directly, i.e. without reprocessing.

[18] All unit costs used in the report are based on economic data or projected costs provided by the French nuclear industry, which assumes operation at close to nominal capacity of all equipment and facilities and proposes questionably low figures for key future costs. For example, the costs of reprocessing or MOX fabrication are estimated for operation of the plants at full capacity although this condition is not fulfilled in some scenarios. The discussion of the consequences of operational difficulties on the economics would go beyond the scope of the present report. The higher complexity of the reprocessing option suggests that it could be more vulnerable to deviations from projected nominal operation. A sensitivity analysis could be used to examine the cost impacts of such deviations.

[19] Quoted in *Nuclear Fuel*, 1 May 2000.

[20] This does not include the R&D costs, which, according to the report, are higher by FRF30 billion ($6.1 billion) in the reprocessing option. Also, the additional costs in the back-end are not compensated by savings from plutonium recycle in the front-end that, using assumptions on uranium price of 2000. The extended reprocessing scenario, as compared to the total direct disposal, would only save 8% of the needs of natural uranium and enrichment work. Other ways to express the difference are: 17% increase of the total the back-end costs, from FRF808 billion ($166 billion) to FRF942 billion ($193 billion; a cost increase of FRF2 billion ($410 million) per year of service life of the current 63 GWe nuclear fleet; a cost increase of FRF2.7 billion ($550 million) per GWe installed; or an average generation cost of 144.6 FRF/MWh (29.6 $/MWh) with reprocessing instead of 136.5 FRF/MWh (28.0 $/MWh) with direct disposal. Constant FRF 1999 undiscounted levelized costs estimated from total cost over the operational life of the power plants.

Since 1995, EDF has assigned in its accounts a zero value to its stocks of separated plutonium (as well as to the stocks of reprocessed uranium). Nevertheless, 10 years later, AREVA stated that "recycling the plutonium separated annually at La Hague" would be equivalent to "100 large oil tankers (200,000 t)" See Philippe Knoche, *Traitement des combustibles usés et recyclage – Passé, présent et futur,* CPDP, Cité des Sciences, 18 October 2005.

[21] DGEMP (2003).

[22] This period of 2015-2075 corresponds to the projected period of operation of a new EPR reactor starting-up in 2015, the lifetime cost of which is calculated in DGEMP's study.

[23] The preparation of the reference cost reports usually involves working groups that discuss the various assumptions to be used in the calculations based on proposals by the industrial players involved. In 2003, the new competition on the French electricity market was used as justification for restriction of the discussion of unit costs to bilateral talks between the DGEMP and each company or utility.

[24] The reprocessing costs in "Charpin-Dessus-Pellat" are based on the economic experience of the La Hague plants. The estimate for the overnight construction cost (for UP2-800) is FRF37 billion ($7.5 billion), corresponding to a complete construction cost, including interest, of FRF45 billion for EDF ($9.2 billion). This does not include a projected decommissioning cost (UP2-800) of FRF20 billion ($4 billion). This assumption was eventually preferred to the assumption of FRF10 billion ($2 billion) for refurbishment at half-life of the plant and FRF15 billion ($3 billion) for decommissioning. Operating costs were taken as 8000 FRF/kg reprocessed (1,640 $/kg) in UP2-400, 4000 FRF/kg (820 $/kg) in UP2-800 in its first years of operation and 3000 FRF/kg (615 $/kg) starting in 2002. About 80% of the operating expenditures are fixed costs and 20% are proportional to throughput. Total reprocessing cost, including investment and operation, is sensitive to operational lifetime and average throughput. For a nominal 800 tHM/year throughput, the total cost would range from 1,496 $/kg for a 30-year lifetime to 1,373 $/kg for a 40-year lifetime. For the 30-year lifetime case, the global cost estimate would range from 1,681 $/kg for 700 tHM/year to 1,353 $/kg for 900 tHM/year.

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[25] The DGEMP report presents some calculations of the reprocessing cost in the DGEMP methodology using the CDP (2000) assumptions, which result in a range from 870 €/kg to 1,500 €/kg (or 1,170 $/kg to 2,020 $/kg). This range, the DGEMP explains, is consistent with values used in the previous reference cost report published in 1997.

[26] This is not accurate. CDP (2000) did not calculate the cost of a new plant, but considered a strong reduction in operating costs of UP2-800, based on assumptions of technological optimization. Fuel chain costs were discussed in March 2007 by a working group in the preparation of the 2007 update of DGEMP (2003). AREVA presented a note to the group, which introduced only small differences to the assumptions used in the 2003 report. The reprocessing period corresponding to a new European Pressurized Reactor is postponed to 2035-2100, and would therefore concern a new reprocessing plant, although the projected operating life of the existing La Hague plants is extended up to 2040. (This is contradicted by other sources, including AREVA's *Annual Reports*, which assume a shutdown of the La Hague plants in 2025). The note concludes that "the estimate of the cost objective is 500 €/kg in 2007 economic conditions," which AREVA says is "a number equivalent to the 450 €/kg value of the previous report," AREVA. *Le cycle du combustible nucléaire – Eléments fournis par AREVA*, note for the "Exercice Coûts de Référence 2007", 21 March 2007. This, AREVA underlines, *is* "very comparable to the value provided by BCG in a study of processing and recycling of spent fuel in the USA, that is 630 $/kg (in 2005 value) without potential incentives." This references the Boston Consulting Group report, *Economic Assessment of Used Nuclear Fuel Management in the United States,* Executive Summary, July 2006. www.bcg.com/publications/files/2116202EconomicAssessment_Summary24July06SR.pdf.

That report contains the disclaimer that "this report was prepared by The Boston Consulting Group at the request of AREVA. BCG reviewed publicly available information and proprietary data provided by AREVA, but did not undertake any independent verification of the facts contained in those source materials. Changes in these facts or underlying assumptions could change the results reported in this study." The "integrated recycling plant unit cost" of 630 $/kg was calculated by BCG assuming $16 billion of capital cost and $900 million annual operating cost, for a plant of 2,500 tHM/year capacity and operation at about 80% of nameplate capacity. This corresponds to $6.4 million investment per metric ton (heavy metal) (tHM) of capacity, and $0.45 million operating cost per tHM reprocessed, compared to the actual costs, based on La Hague experience, used in "Charpin-Dessus-Pellat," of an investment cost equivalent to $15.6 million/tHM of capacity and an operating cost of $0.82 million/tHM reprocessed, respectively 2.4 and 1.8 times the BCG figures.

[27] To facilitate the comparisons, all the cost of geological disposal presented here are expressed in 2003 €.

[28] DGEMP, *Rapport du Groupe de travail relatif au "Coût d'un stockage souterrain de déchets radioactifs de haute activité et à vie longue*, July 2005, www.industrie.gouv.fr/energie/nucleair/pdf/rapport-gt-cout-stockage.pdf.

[29] CdC (2006).

[30] The calculation is based on the total radiotoxicity of the radionuclides contained in spent fuel assemblies, and its evolution through time. Plutonium would represent 90% or more of the total radiotoxicity for the period from 100 years to 50,000 years after irradiation. This calculation doesn't consider the actual risk of potential exposure to the radiotoxic elements, i.e. the fact that some of them would more likely migrate in the disposal environment than others. It is worth noticing that the CEA was at the same time arguing in favor of geological disposal referring to studies of the some 1.5 billion-year-old natural underground uranium reactor of Oklo in Gabon, in which it claimed that plutonium and uranium remained very much contained.

[31] In a technical paper by COGEMA, available on the US Department of Energy's web library: P. Kaplan, R. Vinoche, J.-G. Devezeaux, F. Bailly, *Spent-Fuel Reprocessing: More Value for Money Spent in a Geological Repository?*, WM' 03 Conference, 23-27 February 2003, Tucson, Arizona. www.osti.gov/bridge/servlets/purl/826233-B5nT4B/native/826233.pdf.

[32] See, for instance, the technical paper by COGEMA, available on the US Department of Energy's web library: J. Thomasson, S. Barithel, et al., *The Universal Canister Strategy in Spent Fuel Reprocessing: UC-C a Real Industrial Improvement*, WM' 03 Conference, 23-27 February 2003, Tucson, Arizona. These figures are discussed in chapter 6. www.osti.gov/bridge/servlets/purl/825858-hp0qUi/native/825858.pdf

[33] See EDF's S. Granger presentation, "Pourquoi traiter les combustibles usés?" 8 October 2005 at Cité des Sciences et de l'Industrie, Paris, www.debatpublic-dechets-radioactifs.org/docs/pdf/verbatims/presentation/mr-granger-edf-0810.pdf. EDF compares the 1.5 m^3 volume per final conditioned uranium oxide fuel assembly in the case of direct

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disposal with the 0.07 m^3 of conditioned vitrified high level waste (HLW) and 0.1 m^3 of conditioned intermediate level waste (ILW) arising from the reprocessing of one uranium oxide fuel assembly.

[34] Commission particulière du débat public sur la gestion des déchets radioactifs, *Compte-rendu du débat public sur les options générales en matière de gestion des déchets radioactifs de haute activité et de moyenne activité à vie longue – Septembre 2005 - Janvier 2006*, 27 January 2006, p. 47. www.debatpublic-dechets-radioactifs.org/docs/pdf/compte-rendu.pdf.

[35] Loi n° 91-1381 du 30 décembre 1991 relative aux recherches sur la gestion des déchets radioactifs, *Journal Officiel*, 1st January 1992. See: www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=INDX9100071L

[36] Loi n° 2006-739 du 28 juin 2006 de programme relative à la gestion durable des matières et déchets radioactifs, *Journal Officiel*, 29 June 2006, www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=ECOX0600036L.

A consolidated English version prepared by ANDRA is provided by the Ministry of Industry at www.industrie.gouv.fr/energie/anglais/pdf/loi-28-06-06-ang.pdf.

[37] *Plan National de Gestion des Matières et des Déchets Radioactifs 2007-2009 – De l'Inventaire national des déchets radioactifs et des matières valorisables à un bilan et une vision prospective des filières de gestion à long terme des déchets radioactifs en France*, 26 January 2007. See www.industrie.gouv.fr/energie/nucleair/pdf/pngmdr.pdf

Under Article 6-II of the same law, this Plan had to be established for the first time no later than 31 December 2006. It was published by the Ministry of Industry and by the Nuclear Safety Authority in April 2007.

[38] Décret n° 2003-31 du 10 janvier 2003 autorisant la Compagnie générale des matières nucléaires à modifier les périmètres des installations nucléaires de base du site de La Hague, *Journal Officiel*, 11 June 2003. www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=INDI0200837D

Décret du 10 janvier 2003 autorisant la Compagnie générale des matières nucléaires à modifier l'installation nucléaire de base UP 3-A située sur le site de La Hague, *Journal Officiel*, 11 June 2003, www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=INDI0200838D

Décret du 10 janvier 2003 autorisant la Compagnie générale des matières nucléaires à modifier l'installation nucléaire de base UP 2-800 située sur le site de La Hague, *Journal Officiel*, 11 June 2003, www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=INDI0200839D

Décret du 10 janvier 2003 autorisant la Compagnie générale des matières nucléaires à modifier l'installation nucléaire de base STE 3 située sur le site de La Hague, *Journal Officiel*, 11 June 2003, www.legifrance.gouv.fr/WAspad/UnTexteDeJorf?numjo=INDI0200840D

[39] Also, under Article 4, a repository site for long-lived, low-level waste (LL-LLW), including the graphite residues from the first generation of French gas cooled graphite moderated reactors, should be put into operation in 2013.

[40] France, as part of the Generation IV Forum, focuses on liquid-sodium-cooled fast breeder reactors (Superphénix was in that category), and gas-cooled fast reactors as an alternative.

[41] These ILW are produced by the operation of reactors in similar quantities, whatever the spent fuel management option. The volume of ILW generated by reprocessing is five to six times larger than from all other sources, including reactor operations. ANDRA (2006) estimates the ILW waste generation from reprocessing of fuel from the French nuclear fleet over its lifetime as from 150,000 to 175,000 waste packages of long-lived ILW, compared to 22,000 from all other sources.

[42] Plus other small quantities, including German fast breeder reactor fuel.

[43] CdC (2005). AREVA NC indicates the period 1991-1993 for the "stop of military plutonium production," AREVA NC, *Rapport Environnemental, Social et Societal 2005 – Etablissement de Marcoule,* 27 September 2006.

[44] CDP (2000).

[45] The lack of public scrutiny and interest is illustrated by the fact that in this year of profound change the total number of journalist requests for information did not exceed 18, according to AREVA NC. Marcoule issued a total of 3 press releases.

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[46] AREVA NC, *Rapport Environnemental, Social Et Societal 2005 – Etablissement De Marcoule*, 27 September 2006.

[47] CdC (2006).

[48] CdC (2005).

[49] This section is largely based on Mycle Schneider, *Comparison among Different Decommissioning Funding Methodologies for Nuclear Installations - Final Country Report: France*, commissioned by the European Commission, Wuppertal Institute for Climate, Environment and Energy,Wuppertal, 2007, www.wupperinst.org/uploads/tx_wiprojekt/EUDecommFunds_FR.pdf.

[50] The indicated degree of precision of the cost estimates is, of course, unrealistic. Expressed in 2003 dollars the numbers would be practically identical to the euro figures.

[51] CDP (2000).

[52] References are made to the plant as UP2-400 or UP2-HAO (Haute Activité Oxyde).

[53] The other foreign countries participating in those baseload contracts were Belgium, Switzerland and the Netherlands. Sweden also contracted for reprocessing of a limited quantity of spent fuel but later sold its contracts to German utilities.

[54] The first spent fuel transport from Italy to AREVA's La Hague plant was planned by the end of 2007, AREVA NC, Press Release, 9 May 2007.

[55] In a similar case, the operator of the only still-operating reactor in the Netherlands, at Borssele, entered into a reprocessing agreement with AREVA and apparently paid the French utility EDF to take the plutonium.

[56] COGEMA, *Exécution des contrats de traitement et recyclage avec les clients étrangers*, 11.2004; www.cogemalahague.fr

[57] There are also substantial amounts of non-irradiated scrap MOX elements that are stored in the La Hague cooling ponds. However, information on the quantity is no longer made available.

[58] There is no explicit statement yet by the new Fillon government on the reprocessing issue. But there is no doubt that President Nicolas Sarkozy is strongly in favor of nuclear energy.

[59] 8,125 t (including 543 t of spent MOX fuel) was at the La Hague site and 3,880 t (of which 262 t is spent MOX fuel) at the reactor sites, CSPI, personal communication, 24 May 2007; ASN, Joint Convention on the safety of spent fuel management and on the safety of radioactive waste management, *France's Answers To Questions And Comments Received From Other Contracting Parties On Its Second Report For The Joint Convention*, prepared for the Second Review Meeting, 15-24 May 2006, 6 April 2006.

[60] Based on EDF's *Annual Report, 2006*, the discharges for the years 2004-06 were 1,151 t, 1,190 t and 1,199 t.

[61] CGT-AREVA, "Négociations AREVA/EDF sur le retraitement recyclage des combustibles usés : le torchon brûle," Press Release, 28 February 2008.

[62] In November 1976 about 1,300 scientists from the Geneva region, signed a letter to the French, German and Italian governments opposing the construction of the Superphénix fast breeder and the launch of a plutonium economy. The extremely violent attitude of French riot police, including the use of offensive grenades, during a demonstration of 50,000 people from all over Europe on 31 July 1977, led to a civil war type situation at the building site in Malville leaving one demonstrator dead and many injured.

[63] The privatization resulted in the dismantlement of a strong trade union section at La Hague, because key union leaders left the site to stay within the public CEA; see Mycle Schneider, "Safety of French Nuclear Plants," *Nature*, *321*, 22 May 1986, p. 376,

[64] The opposition against the French nuclear program culminated in a "national petition" calling for a freeze of the nuclear program and the abandoning of the Superphénix project. As of 1980, the petition had collected over 500,000 signatures, including that of François Mitterrand's Socialist Party. However, the license for the La Hague expansions, UP2-800 and UP3, was issued on 12 May 1981, signed by the outgoing government two days after the election of François Mitterrand to the French Presidency.

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[65] After the 1986 Chernobyl accident, the European fast breeder alliance began to fall apart. Most dramatically, Italy confirmed, by referendum in 1987, its abandonment of nuclear energy. The Italian public utility ENEL held 33% of the capital of NERSA, the builder of Superphénix With 51% held by EDF and 16% by SBK (68.85% RWE, Germany, 14.75% SEP, Netherlands, 17.75% Electronucléaire, Belgium, 1.65% CEGB, UK) NERSA was a truly European company. After the Jospin Government's decision to shutdown the Superphénix reactor in 1998, EDF took over the shares of the foreign utilities.

[66] Decret dated 26 April 2007, published in the *Journal Officiel* on 27 April 2007. MELOX already had the technical capability to operate at this capacity.

[67] The plutonium content of MOX fuel increases with its average design burn-up. EDF has unsuccessfully tried for many years to get permission to raise MOX fuel burn-up to the same level as authorized (and reached) with uranium fuels. A first increase of the authorized plutonium content from 5.25% to 7.08% in 1998, initially planned to allow for the increase in MOX burn-ups, turned out to merely compensate for the lower fissile fraction of the plutonium from higher burn-up uranium oxide fuel. For details, see X. Coeytaux, Y. Marignac, *MOX Fuel and High Burn-Ups: Struggling with Antagonistic Aims*, report commissioned by Greenpeace International, WISE-Paris, 29 July 2004.

[68] Including 11 t of material from the German Hanau MOX plant clean-up.

[69] Since it has not been reported that any of the MOX scrap assemblies were reprocessed, it is to be assumed that the amount has remained at least constant. It is more likely that this inventory has increased. Also, the shut-down of the Cadarache MOX fabrication plant, ATPu, is generating significant quantities of scrap material that is to be transferred to La Hague.

[70] AREVA, Note d'information, transmitted to the Commission Particulière du Débat Public – Déchets Nucléaires, 17 January 2006.

[71] Including 30 shipments of MOX scrap assemblies that go to La Hague. While the evaluation took into account shipments to and from the now closed Cadarache and Dessel MOX plants, the increased authorized throughput of the MELOX plant has made up for both. Therefore the overall order of magnitude of numbers of shipments and quantities of materials involved should have remained approximately the same, Yves Marignac, Mycle Schneider, Xavier Coeytaux, Julie Hazemann, Yacine B. Faïd, *Les Transports de l'industrie du plutonium enFrance – Une activité à haut risque,* commissioned by Greenpeace, February 2003.

[72] "Arrêté du 8 janvier 2007 modifiant l'arrêté du 10 janvier 2003 autorisant la Compagnie générale des matières nucléaires à poursuivre les prélèvements d'eau et les rejets d'effluents liquides et gazeux pour l'exploitation du site nucléaire de La Hague," *Journal Officiel*, 10 January 2007.

[73] By a factor of almost 15 for gaseous tritium and by a factor of 14 for liquid beta-gamma discharges of isotopes other than tritium,

[74] If compared to a Flamanville unit, including over 20,000 times the quantity of noble gases released, over 500 times liquid tritium and beta/gamma emitters other than tritium. Also, while any discharge of alpha emitters is prohibited at reactor sites, it is authorized at La Hague within the limits of 0.01 GBq in gaseous and 140 GBq in liquid effluents. A positive development is that there are now isotope specific limits for some additional radioisotopes that until recently were only limited within the overall beta-gamma maximum.

[75] *First Periodic Evaluation of Progress towards the Objective of the OSPAR Radioactive Substances Strategy*, OSPAR Commission, 2006.

[76] STOA (2001).

[77] K.R. Smith, A.P. Bexon, K. Sihra, J.R. Simmonds (HPA), J. Lochard, T. Schneider, C. Bataille (CEPN), *Guidance on the calculation, presentation and use of collective doses for routine discharges,* UK Health Protection Agency / CEPN, Radiation Protection n°144, commissioned by European Commission, August 2006. The authors of the present report estimate that, while segmentation of collective doses between different periods of times might be justifiable in some comparisons, the use of untruncated collective dose evaluations is necessary to treat equally the protection level of present and future generations.

[78] *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 60, Annals of the International Commission on Radiological Protection 21, Nos 1-3, Oxford, 1991.

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[79] K.R. Smith, *et al., op. cit.*

[80] B. Bennett, "Exposures from Releases of Radionuclides". In *Proceedings of an International Atomic Energy Agency Symposium on The Environmental Impact of Radioactive Releases*, Vienna, May 1995. IAEA-SM-339/185.

[81] UNSCEAR, *Sources, Effects and Risks of Ionising Radiation - Appendix B*, United Nations Scientific Committee on the Effects of Atomic Radiations, Vienna, 1993.

[82] K.R. Smith, *et al., op. cit.*

[83] Independent experts recommended and it was recognized during France's National Public Debate on radioactive waste management that the management of re-usable materials and the waste management options cannot be discussed as separate matters. See B. Dessus, B. Laponche, Y. Marignac, *Gestion des déchets nucléaires à vie longue – Analyse contradictoire*, invited contribution to the National Public Debate on radioactive waste management. www.debatpublic-dechets-radioactifs.org/docs/pdf/dossier-initialisation/analyse-contradictoire.pdf.

[84] Girard (2000).

[85] ANDRA(2006). This report is an update of the first of its kind inventory, published in 2004. See: www.andra.fr/popup.php3?id_article=820#

[86] ANDRA (2005). The dossier contains one main report, plus one synthesis report and three volumes of detailed reports for each type of geological site considered (clay and granite). See: www.andra.fr/popup.php3?id_article=644

[87] ANDRA's concept of geological disposal in clay supposes that all galleries are dug at the same depth of about 500 m. Therefore, there is an associated surface area. According to ANDRA (2005), the area covered would reach 608 hectares if reprocessing is completed, and 1,358 hectares if it is ended in 2010.

[88] In the reprocessing phase-out scenario, 26,000 tons of uranium fuel, 500 tons of reprocessed uranium fuel and 2000 tons of MOX fuel would be disposed of in the geological repository. No plutonium or uranium containing material would remain exempt from disposal. In the reprocessing scenario, 41,500 tons of spent uranium fuel, 800 tons of spent reprocessed uranium fuel and 2,700 tons of spent MOX fuel would be reprocessed, and no spent fuel would remain unreprocessed. The following rough calculation can be made:

- 41,500 tons of uranium fuel reprocessed produces about 39,700 tons of reprocessed uranium and 420 tons of plutonium,
- The production of 800 tons of reprocessed uranium fuel requires about 6,400 tons of reprocessed uranium, and produces in turn, when reprocessed, 760 tons of uranium and less than 10 tons of plutonium,
- The production of 2,700 tons of MOX fuel requires up to 230 tons of plutonium (at 8.65%), and its reprocessing produces in turn 2,400 tons of uranium and 110 to 130 tons of plutonium.

In total, therefore, about 30,000 tons of reprocessed uranium and between 200 and 300 tons of plutonium would remain unused at the end of the scenario but were not accounted for in the dimensioning of the repository. These quantities correspond to more than half of the total throughput of nuclear materials considered in the scenario (45,000 tons of fuel, of which 44,770 tons of uranium and 230 tons of plutonium prior to irradiation, and 42,900 tons of uranium and around 550 tons of plutonium once irradiated).

[89] See F. Homberg, M. Pavageau, M. Schneider, *COGEMA-La Hague: The Waste Production Techniques,* commissioned by Greenpeace International, WISE-Paris (ed.), Paris, France, May 1997. La Hague's radioactive discharges are discussed in chapter 4.

[90] The figures presented in the table are based on IRSN's estimates, in IRSN, *Colis de déchets produits par l'établissement COGEMA de La Hague – Colis de stockage définis dans le "Dossier 2005 – Argile" de l'ANDRA – Détermination des "facteurs volumiques"*, appendix to a letter to the Commission spéciale permanente d'information (CSPI) of La Hague, 21 March 2006. This note responded to a letter of ACRO's representative in the CSPI, Guillemette, A., *Point sur le retraitement et les réductions de volumes des déchets ultimes – Comparaison des solutions retraitement / non retraitement des combustibles irradiés*, ACRO, 14 February 2006.

[91] A large amount of the accumulated waste is still unconditioned or poorly conditioned. Its final volume will depend on the licensing and technical implementation of the planned conditioning techniques. The volumes arising from

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future reprocessing are also uncertain, as increases in fuel burn-up pose new challenges (e.g. increased concentrations of fission products, creation of additional activation products, degraded plutonium composition).

[92] IRSN, note to CSPI, March 2006, *op. cit.*

[93] The concept presented by ANDRA in 2005 was based on slightly different storage periods, 90 years for spent MOX, 60 years for other spent fuels.

[94] Commission Française du Développement Durable, *Avis n° 2001-05 sur le Rapport « Charpin-Dessus-Pellat »*, February 2001. Comments and original text at: www.wise-paris.org/francais/nosbreves/annee_2001/nosbreves010322a.html. The English translation is available at: www.wise-paris.org/english/ournews/year_2001/ournews010322a.html

[95] This is detailed in Yves Marignac, *Volumes de déchets liés à l'activité de retraitement en France : un inventaire par origine et par état de conditionnement*, WISE-Paris, May 2007.

[96] These can be aggregated according to the following criteria:

- The **type** of waste, including vitrified waste (or solutions of fission products awaiting vitrification), structural waste (e.g. cemented hulls and nozzles from LWR fuel, or magnesium or graphite waste from GGR fuel), process waste (bituminized sludges from liquid effluents treatment), and technological waste from operation (of various kind, mostly cemented);
- The radiological **category** of waste, including high level waste (HLW), long-lived intermediate level waste (LL-ILW), long-lived low level waste (LL-LLW) and short-lived intermediate or low level waste (SL-ILW/LLW); and
- The status of the waste in terms of **conditioning**, i.e. whether its conditioning is adequate for final disposal or it is unconditioned or poorly conditioned and needs (re)conditioning.

[97] The CSM, which operated from 1965 to 1994, also contains some waste from reprocessing plants, which should have been managed as LL-ILW, especially due to plutonium contamination. See: ACRO, *Gestion des déchets radioactifs: les leçons du Centre de Stockage de la Manche (C.S.M.) – Centre sans Mémoire, Centre sans Avenir?* Report commissioned by Greenpeace France, April 2006, www.acro.eu.org/CSM_GP06.pdf. An English summary is available: www.acro.eu.org/CSM_GP_GB06.pdf.

[98] In total, 3,479 bituminized waste packages and 42,917 other packages were dumped. The equivalent final volume of conditioned bituminized waste is planned to amount to 0.238 m^3 per re-conditioned package. If this figure, which is likely low, is applied to all of the packages dumped into the sea, the additional volume would amount to 11,170 m^3, of which 800 m^3 would be LL-ILW.

[99] Including uranium-molybdenum solutions produced in the 1960s at La Hague.

[100] This is detailed in Yves Marignac, *Volumes de déchets en stockage géologique: une comparaison des options stockage direct et retraitement*, WISE-Paris, May 2007.

[101] The reprocessing industry, including French and foreign fuel reprocessing, produced an expected conditioned 291,165 m^3 of SL-ILW/LLW as of the end of 2004, or more than half of the whole amount produced by the nuclear power industry, 550,350 m^3 according to ANDRA.

[102] All kinds of spent fuel included (0.82 m^3/tHM in the Marcoule case, 1.06 m^3/tHM for La Hague). This is assuming that the primary conditioning and reconditioning of the 75% of long-lived intermediate level waste and 28% of the high level waste remaining poorly or entirely unconditioned goes according to plan.

[103] The primary conditioning volume of HLW plus LL-ILW waste arising from reprocessing of uranium oxide fuel was reduced by a factor of 5.25 between the start-up of the plants and the 'optimized' techniques of 2004. The volume reduction in terms of final conditioning was 4.45, however. Calculations are made for each of the three periods chosen as representative of this evolution: the start-up of UP3 and UP2-800 plants (respectively 1989 and 1994), the end of 1995 and the end of 2004.

[104] These do not take into account the volume of or surface area above common operational galleries. Estimates of the total volume of excavated rock or the total horizontal area of the repository by type of waste are discussed in the technical note in Yves Marignac, *Volumes de déchets en stockage*, *op. cit.*

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[105] The BSK-3, developed in Germany, is a cylindrical cask with a volume of 0.71 m^3 that can hold up to 3 disassembled fuel assemblies. The French ANDRA concept uses a cylindrical cask of 1.39 m^3 in which up to 4 assemblies can be placed.

[106] The Industry Ministry Working Group Report on Final Disposal notes "The application of an engineered barrier could entail a significant additional excavation volume. ANDRA has retained as reference concept a version without engineered barrier and considers it as technically convincing. However, a variation with engineered barrier cannot be definitely excluded at this stage." DGEMP, *Rapport du groupe de travail relatif au "Coût d'un stockage souterrain de déchets radioactifs de haute activité et à vie longue"*, July 2005.

[107] IRSN, note to CSPI, March 2006, *op. cit.*

[108] Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, *Jahresbericht 2004/2005*, November 2005

[109] IRSN, note to CSPI, March 2006, *op. cit*.

[110] The figure of 3000 cancer deaths is based on the application of the liner non-threshold dose-response hypothesis to a very long-term collective dose. It should be considered for comparison of relative impacts of various spent fuel management options rather than as a death toll prediction in itself.

General References

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ANDRA 2006: ANDRA**,** *Inventaire national des déchets radioactifs et des matières valorisables,* Edition 2006, www.andra.fr/popup.php3?id_article=820.

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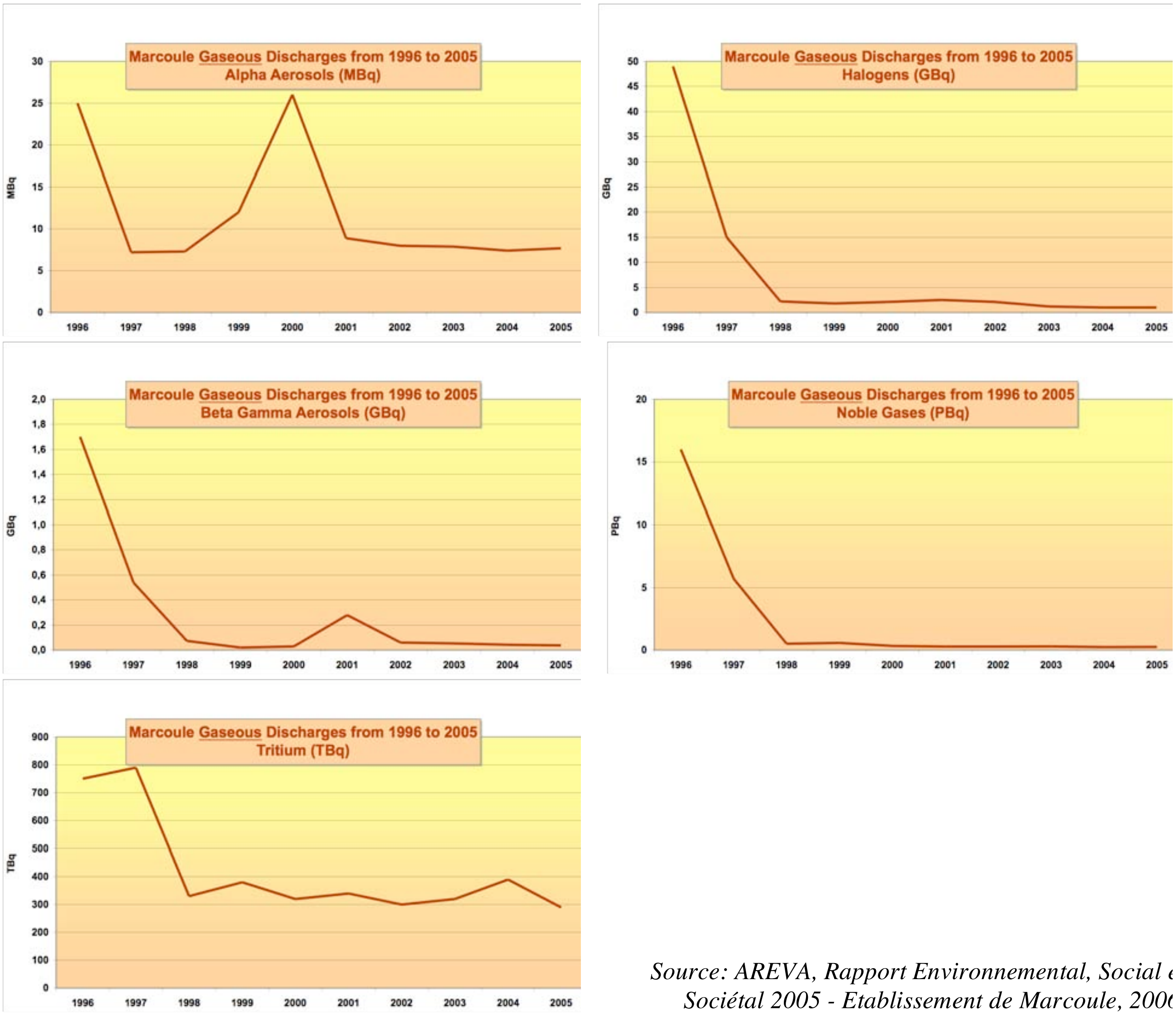
Appendix A. History of radioactive discharges from Marcoule

The history of radioactive discharges from the Marcoule site is not publicly available for its entire operational period. There is information available on a number of radionuclides, however, for the period 1996 to 2005. While it is logical that there was a sharp decrease in emissions after the UP1 reprocessing plant shut down in 1997, it is remarkable that some clean-up activities – it is unclear, which ones – resulted in pre-shutdown release levels of cesium-137 in liquids in 2004 as well as some significant spikes in gaseous discharges of aerosols in 2000/2001. The continued tritium discharges are likely due to continued operation of the two Celestin tritium-production reactors.

Figures A-1. Gaseous radioactive discharges from the Marcoule site 1996 – 2005



Source: AREVA, Rapport Environnemental, Social
Sociétal 2005 - Etablissement de Marcoule, 200

Figures A-2. **Liquid radioactive discharges from the Marcoule site 1996 – 2005**

Source: AREVA, Rapport Environnemental, Social et Sociétal 2005 - Etablissement de Marcoule, 2006.

Appendix B. Annual shipments of plutonium from the reprocessing of LWR spent fuel at La Hague (metric tons per year)

				Subtotal	**Subtotal**	**Total**
	French Pu	**French Pu**	**French Pu**	**French Plutonium**	**Foreign Plutonium**	**Plutonium Shipments**
	P0 Dessel (B)	**ATPu Cadarache (F)**	**MELOX Marcoule (F)**			
1976					0.1	0.1
1977						
1978					0.3	0.3
1979						
1980		0.4		0.4	0.3	0.7
1981		0.3		0.3	0.3	0.6
1982		0.2		0.2	0.5	0.7
1983		0.2		0.2	0.7	0.9
1984		0.1		0.1	1.0	1.1
1985		0.4		0.4	1.6	2.0
1986	0.2	0.4		0.6	0.6	1.2
1987	0.9	0.3		1.2	0.5	1.7
1988	0.9	0.6		1.5	0.8	2.3
1989	1.2			1.2	0.7	1.9
1990	2.0	0.5		2.5	1.2	3.7
1991	1.1			1.1	0.7	1.8
1992	0.8	0.7		1.5	2.4	3.9
1993	1.4	0.9		2.3	0.3	2.6
1994	0.4	0.8	0.4	1.6	1.6	3.2
1995		2.1	2.0	4.1	1.7	5.8
1996		0.2	3.5	3.7	3.2	6.9
1997			5.7	5.7	3.6	9.3
1998			6.3 (1)	6.3 (1)	4.8	11.1
1999		0.1	5.4	5.5	6.1	11.6
2000			6.5	6.5	5.7	12.2
2001		0;2	5.7	5;9	5;4	11.3
2002		0.3	7.1	7.4	5.4	12.8
2003			6.5	6.5	3.6	10.1
Total	**8.9**	**8.7**	**49.1**	**66.7**	**53.1**	**119.8**

Source: COGEMA, Etablissement de La Hague, Exécution des contrats de traitement et recyclage avec les clients étrangers, 21 October 2004

Note: (1) including 1.3 t of gas-graphite reactor plutonium

Appendix C. Radioactive discharge limits for La Hague versus Flamanville reactors

	La Hague		Flamanville	
Type of Effluent	**Former Discharge Limits (in GBq)**	**New (Jan. 2007) Discharge Limits (in GBq)**	**Discharge Limits for 2 x 1300 MWe (in GBq)**	**La Hague vs. 1 x 1300 MWe Flamanville Former/New**
Gaseous Releases				
Tritium	2,200,000	150,000	5000.0	880/60
Other than tritium	480,000,000		46,401.0	20,690/20,260
Noble gases		470,000,000		
Carbon-14		28,000		
Halogens (Iodine, Chlorine…)	110		0.8	275/48 (8)
Iodine		18		
Other ß, γ		1		
Alpha	(1)	0.01	prohibited	
Liquid Discharges				
Tritium	37,000,000	18,500,000	60,000	1,233/617
Other than tritium	1,700,000		425	8000/572 (9)
Cesium-134		500		
Iodine		2,600		
Ruthenium-106		15,000		
Cobalt-60		1,400 (4)		
Carbon-14		42,000 (5)		
Other ß, γ		60,000 (6)		
Strontium-90 + Cesium-137	220,000			
Strontium-90		11,000 (2)		
Cesium-137		8000 (3)		
Alpha		140 (7)	prohibited	

Notes:

(1) There were no specific gaseous alpha discharge limits for La Hague (although the plutonium is included in the aerosols, except for the Pu-241).

(2) The limit is 1200 GBq/year for operational discharges and 9,800 GBq/year for clean-up, dismantling and reconditioning of waste (until 2015).

(3) The limit is 2000 GBq/year for operational discharges and 6000 GBq/year for clean-up, dismantling and reconditioning of waste (until 2015).

(4) The limit is 900 GBq for operational discharges and 500 GBq for clean-up, dismantling and reconditioning of waste (until 2015).

(5) Includes gaseous discharges.

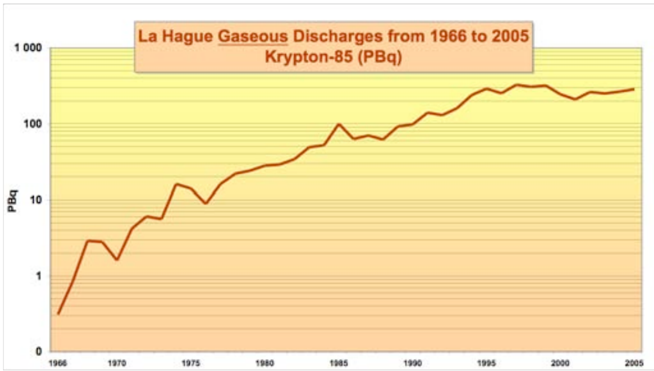
(6) The limit is 30,000 GBq for operational discharges and 30,000 GBq for clean-up, dismantling and reconditioning of waste (until 2015).

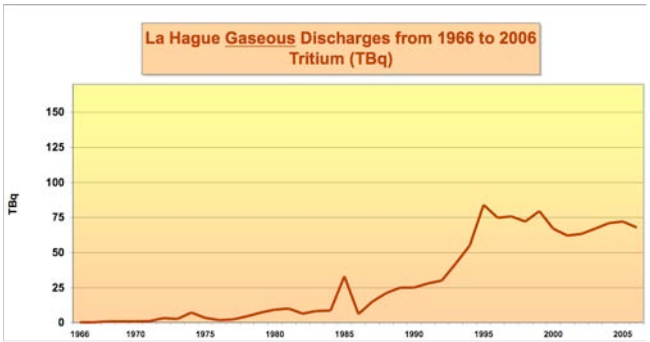
(7) The limit is 70 GBq for operational discharges and 70 GBq for clean-up, dismantling and reconditioning of waste (until 2015).

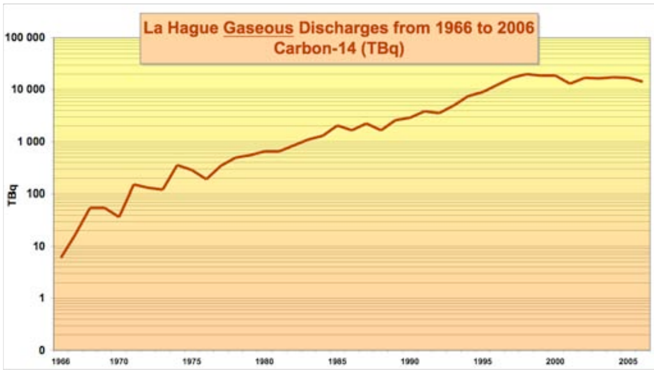
(8) New La Hague limits for iodine + other beta-gamma versus total halogens for 1 Flamanville unit.

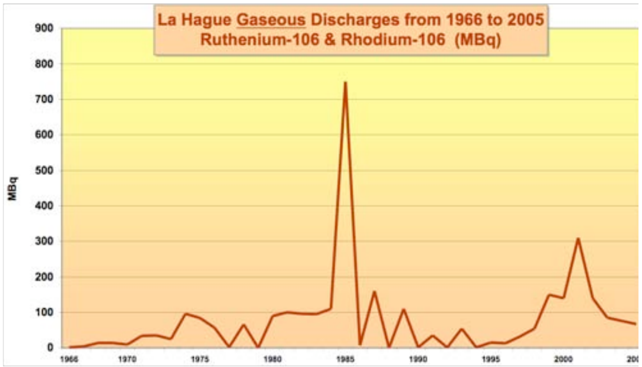
(9) New La Hague limits for Caesium-134, Iodine, Ruthenium-106, Cobalt-60, Carbon-14 and other beta-gamma combined versus 1 Flamanville unit.

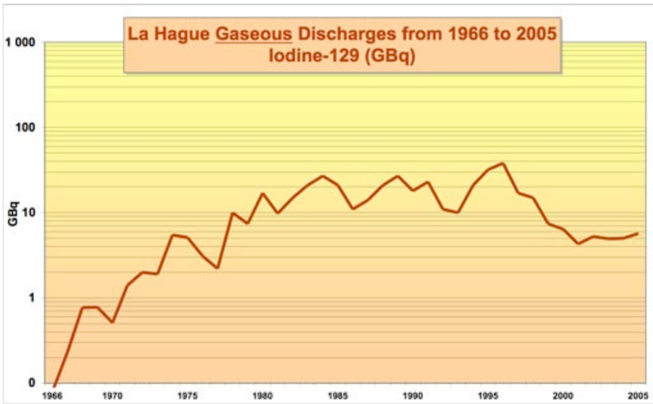
Appendix D. Gaseous radioactive discharges, La Hague site 1966-2005

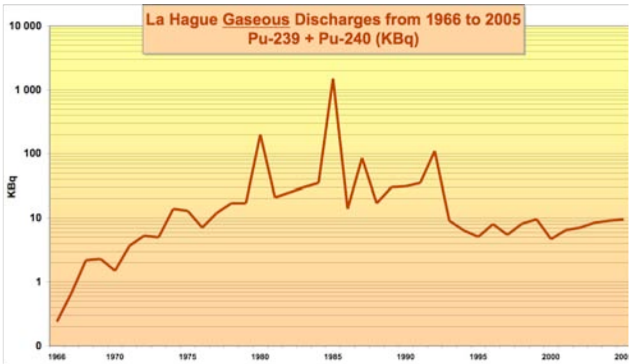






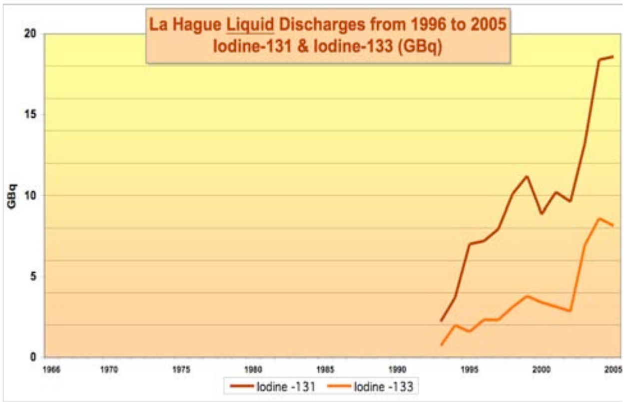


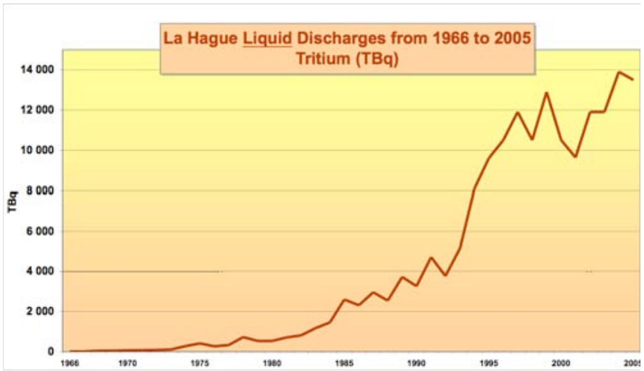


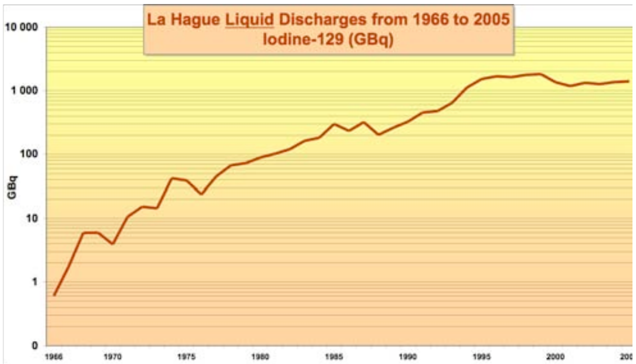


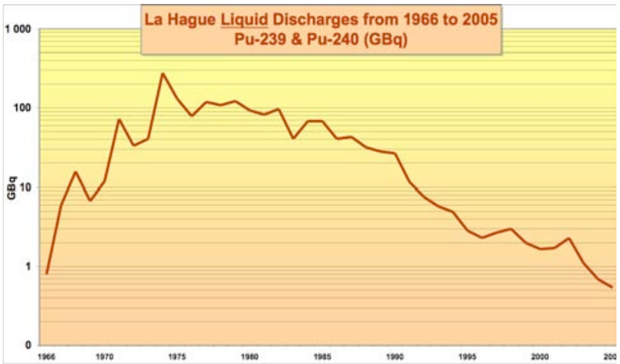
Source: IRSN (DRPH/SER/UETP), personal communication, 28 March 2007.

Appendix E. Liquid radioactive discharges, La Hague site 1966-2005









Source: IRSN (DRPH/SER/UETP), personal communication, 28 March 2007.

Appendix F. Comparison of waste volumes, gallery volumes and surface area underlain by the repository for reprocessing and direct disposal options (for the same total fission energy release[a])

	Primary Conditioned Waste Volume (m^3)			Final Conditioned Waste Volume (m^3)			Gallery Volume (m^3)			Repository Surface Area (m^2)		
	Start -up	*End 1995*	*End 2004*	*Start -up*	*End 1995*	*End 2004*	*Start -up*	*End 1995*	*End 2004*	*Start -up*	*End 1995*	*End 2004*
Direct disposal	**0,413**	**0,413**	**0,413**	**3,02**	**3,02**	**3,02**	**49,8**	**49,8**	**49,8**	**163,0**	**163,0**	**163,0**
Reprocessing	**2,302**	**1,315**	**0,531**	**7,85**	**4,52**	**2,33**	**50,9**	**40,2**	**30,3**	**213,4**	**176,8**	**157,9**
Vitrified	0,098	0,072	0,093	0,24	0,18	0,23	1,0	0,8	1,0	43,4	32,1	41,5
Structure	0,494	0,575	0,089	1,43	1,67	0,59	4,1	4,8	2,1	7,4	8,6	9,4
Process	0,535	0,303	0,015	1,85	1,05	0,05	5,8	3,3	0,2	22,3	12,6	0,6
Technological	1,069	0,258	0,245	3,56	0,86	0,82	11,3	2,7	2,6	22,3	5,4	5,1
Total	***2,196***	***1,208***	***0,443***	***7,09***	***3,75***	***1,69***	***22,3***	***11,6***	***5,8***	***95,3***	***58,7***	***56,6***
Spent re-enriched RepU fuel	0,054	0,054	0,043	0,39	0,39	0,31	6,5	6,5	5,1	21,2	21,2	16,9
Spent MOX fuel	0,053	0,053	0,046	0,38	0,38	0,33	22,1	22,1	19,3	96,8	96,8	84,4

Source: WISE-Paris estimates based on ANDRA (2005), AREVA (2005), GRS (2005), IRSN (2006)

a. The ‘energy equivalence’ is based on the evolution of fuel management in EDF reactors, including:

- Spent uranium oxide fuel reprocessed from start-up to 1995 had an average burn-up of 25 to 30 GWd/t (initial enrichment 3.25%), uranium oxide fuel reprocessed from 1995 to 2004 had an average burn-up of over 35 GWd/t (initial enrichment 3.7%);
- The use of re-enriched reprocessed uranium fuel started in 1994, with a reprocessed uranium re-enrichment level of 3.7%, which was increased to 4.1% in 1999; and.
- The use of MOX fuel started in 1987, with a maximum average plutonium content of 5.25%, which was increased to 7.08% in 1999.

Using those assumptions, calculations for each of the chosen indicators of volume or surface are made for the direct disposal option, and for the reprocessing option as it stood in the early years, in 1995 and in 2004. The equivalence in energy is based on the following:

(1) Direct disposal: 1 tHM of spent uranium oxide fuel.

(2) Reprocessing, start-up and end of 1995: 0.742 tHM of uranium oxide fuel reprocessed, 0.130 tHM of spent re-enriched reprocessed U and 0.127 tHM of spent MOX disposed of;

(3) Reprocessing, End of 2004: 0.786 tHM of uranium oxide fuel reprocessed, 0.103 tHM of spent re-enriched reprocessed U and 0.111 tHM of spent MOX disposed of.

Appendix G. Volumes of waste packages, volumes of galleries and surface area underlain by the repository for different types of primary conditioning packages (PCP)

	Geological Disposal Volume (ANDRA)[a]				Variation[b]	
Content of Package	**Volume of PCP**[c] (m^3)	**Final Waste by PCP** (m^3)	**Gallery Volume**[d] **by PCP** (m^3)	**Repository Surface Area**[e] **by PCP** (m^2)	**Final Waste by PCP** (m^3)	**Gallery Volume**[d] **by PCP** (m^3)
LL-ILW						
Hulls & nozzles, cemented	1.80	5.22	14.9	27	5.22	14.9
Hulls & nozzles, compacted	0.18	1.20	4.21	19	1.20	4.21
Bituminized sludges	0.24	0.83	2.62	10	0.83	2.62
Technological, cemented	1.20	4.00	12.7	25	4.00	12.7
HLW						
Vitrified waste	0.18	0.44	1.93	80	0.18	24.2
Spent uranium oxide fuel	0.19[d]	1.39	22.9	75	0.24	12.9
Spent re-enriched RepU fuel	0.19[d]	1.39	22.9	75	0.24	12.9
Spent MOX fuel	0.19[d]	1.36	80.0	350	1.36	105.6

a. The waste volume and surface estimates are calculated using ANDRA's assumptions on the final conditioning and assuming geological disposal in clay.

b. The variation takes into account the following alternative assumptions:

(1) Clay overpack around vitrified waste with the same thickness assumed around spent uranium oxide fuel;

(2) Spent uranium oxide fuels are disassembled and packed in BSK-3 type container;

(3) Irradiated MOX is disposed of after 60 years of storage like other waste, instead of 90 years (higher residual heat requiring larger spacing between spent-fuel canisters).

c. For spent fuels the primary package is the fuel assembly itself. The volume figures indicated refer to short fuels (from 900 MWe reactors).

d. The gallery volumes accounted for are those receiving the waste. In other word, this does not include the volume of common operational galleries used for transportation, surveillance, cooling, etc.

e. The repository area is the total area covered including the areas between galleries. This does not include the area covered by common operational galleries.

Source: WISE-Paris based on Dossier Stockage Géologique, ANDRA (2005); IRSN, courrier CSPI (2006).

About the Authors

Mycle Schneider is an independent nuclear and energy consultant. He founded the Energy Information Agency WISE-Paris in 1983 and directed it until 2003. Since 1997 he has provided information and consulting services to the Belgian Energy Minister, the French and German Environment Ministries, the International Atomic Energy Agency, Greenpeace, the International Physicians for the Prevention of Nuclear War, the Worldwide Fund for Nature, the European Commission, the European Parliament's Scientific and Technological Option Assessment Panel and its General Directorate for Research, the Oxford Research Group, and the French Institute for Radiation Protection and Nuclear Safety. Since 2004 he has been in charge of the Environment and Energy Strategies lecture series for the International MSc in Project Management for Environmental and Energy Engineering Program at the French Ecole des Mines in Nantes. In 1997, along with Japan's Jinzaburo Takagi, he received Sweden's Right Livelihood Award “for serving to alert the world to the unparalleled dangers of plutonium to human life.”

Yves Marignac is Executive Director of the Energy Information Agency WISE-Paris, which he joined in 1997 after four years shared between academic research in Paris-XI University, applied studies in the French Atomic Energy Commission (CEA) and a position at the nuclear company STMI. He has authored or contributed to many publications and studies on energy, nuclear and global environmental issues. In 1999-2000, he participated in the economic evaluation of the nuclear option commissioned by France’s Prime Minister, which resulted in what became known as the Charpin-Dessus-Pellat report. He also contributed to the 2001 report to the European Parliament's Scientific and Technological Option Assessment Panel on reprocessing plant discharges. In 2005-6, he was Scientific and Technical Advisor to the commission preparing France’s public debate on the new European Pressurized Water Reactor.

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