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Fast Breeder Reactors in France

Mycle Schneider

International Consultant on Energy and Nuclear Policy, Paris, France

France is the only country in the world ever to operate a commercial scale (1,200 MWe) sodium cooled, plutonium fuelled fast breeder reactor, the Superphénix at Creys-Malville. However, the French fast breeder reactor program turned out to be too costly and could never compete with light water reactor technology. Numerous technical problems, low uranium prices and massive opposition exacerbated the poor economic and operational performance of the fast breeder reactor. Superphénix only operated about half of the time that it was officially connected to the grid and was shut down in 1998 with a lifetime load factor of less than 7%.

The Superphénix predecessor, Phénix at Marcoule, which began operating in 1973 and will be shut down later in 2009, has experienced numerous sodium leaks and fires and a series of potentially serious reactivity incidents. The lifetime load factor of approximately 45% is one of the lowest in the world.

France's program to produce and separate plutonium started right after the Second World War. While the initial purpose was to obtain plutonium for the nuclear weapons program, very early on, the fast breeder reactor became a second strategic goal. European cooperation was another goal and the EUROCHEMIC consortium was created in 1957 with the participation of 10 countries of which France and Germany held the largest shares with 17% each.[1]

The first reprocessing plant, the "plutonium factory" (usine de plutonium) UP1 was started up in Marcoule in 1958 and the first proposal for the experimental fast reactor Rapsodie was drawn up that year. Preliminary studies for a 1000-MWe reactor were carried out as early as 1964.

Materials were tested for their behavior under neutron irradiation in *Harmonie* starting in 1965 and breeder core configuration issues in the critical facility, *Masurca,* starting in 1966. These research facilities were located at the Cadarache site in Southern France. Much later, in 1982, the *Esmeralda* facility, also at Cadarache, was designed to study sodium fires. While most of the

Received April 2, 2009; accepted April 9, 2009.
Address correspondence to Mycle Schneider, 45, allée des deux cèdres, 91210 Draveil, France. E-mail: mycle@orange.fr

research costs were financed by the French Atomic Energy Commission (CEA), up to 35% of some research projects were funded by EURATOM.

In 1966, the second commercial reprocessing plant UP2, financed entirely by the CEA (with the civil and military budgets paying equal shares) started operation at La Hague by separating plutonium from gas-graphite reactor fuel. In Belgium the EUROCHEMIC plant started up in 1967. It operated only until 1974 and reprocessed 181.3 t of spent fuel of various types and origins. Two years later the CEA started up an LWR head-end at La Hague (UP2-400) and launched the 100% daughter company COGEMA under private law. Foreign (German) LWR fuel was sent to La Hague as early as 1973. There had been absolutely no experience with reprocessing LWR fuel with much higher burn-ups than gas graphite reactor fuel and it took COGEMA 11 years, until 1987, to operate at a nominal capacity of 400 tons per year.

RAPSODIE, CADARACHE

Construction of France's first experimental sodium-cooled reactor, *Rapsodie,* started in 1962 and it went critical on 28 January 1967 with a nominal capacity of 20 MWth. At the end of 1967, its power was increased to 24 MWth, and in 1970, after core redesign, to 40 MWth. Its operating power was reduced to 22 MWth in June 1980 to minimize the thermal stresses thought to be the source of cracks in the reactor vessel. The reactor operated until April 1983, when it was shut down permanently.

Rapsodie was a loop-type reactor, i.e., with the heat exchanger between the primary and sodium loops outside the reactor vessel. It was as close as possible to the basic design imagined for commercial applications (molten sodium coolant, reactor material, power density, etc). The fuel was 30% PuO_2 and 70% UO_2. The core contained 31.5 kg of plutonium-239 and 79.5 kg of uranium-235. The mean duration of reactor runs was 80 days and the fuel reached burn-ups of up to 102,000 MWd/t.[2]

PHÉNIX, MARCOULE

In February 1968, when *Rapsodie* had been operating for one year, excavation work began at Marcoule for the construction of the 250 MWe (563 MWth) *Phénix* reactor. In 1969, the CEA and Electricité de France (EDF, France's government-owned utility) signed a protocol for the joint construction and operation of the *Phénix* plant. Ownership and costs were shared 80% by the CEA and 20% by EDF. The standard *Phénix* core contains 931 kg plutonium containing 77% Pu-239. The reactor went critical on 31 August and was connected to the grid on 13 December 1973,[3] a year ahead of the PFR in the United Kingdom. Until 2005, the mean length of reactor runs was 90 days and the fuel reached burn-ups of up to 150,000 MWd/t.[4]

On 17 October 1973, between the dates of criticality and grid connection of *Phénix*, OPEC member countries triggered what became known as the first oil shock by their decisions to halt oil deliveries to a number of countries that supported Israel and to significantly increase prices of crude oil. In 1974, the French Government committed to its first large series of power reactors, 16 units. The IAEA forecast up to 4,450 GW of nuclear power installed by year 2000. Between 1973 and 1976 uranium prices went up from \$6 to \$40 per pound of U308 on the spot market. Plutonium was seen as a solution to long-term nuclear fuel supply concerns.

Until the end of the 1980s, *Phénix* had a remarkable operational record. Then, after a number of unexplained reactivity transients, the load factor plunged virtually to zero. The incidents had serious potential safety implications (see below). The reactor remained shut down most of the period between 1991 and 1994 until an extensive research program had been carried out. It was restarted for very short periods, however—probably to avoid the legal requirement of an entire new licensing procedure after a two-year shutdown. In addition, a costly refurbishment program was undertaken between 1994 and 2002 (see Figure 1 for operational history). In June 2003, the national Safety Authority ASN (Autorité de sûreté nucléaire) authorized the restart of *Phénix* for six refueling periods at less than two thirds of its original power. This would allow operation until the end of 2008 and likely into 2009. Nominal power was decreased from 233 MWe net to 130 MWe net.

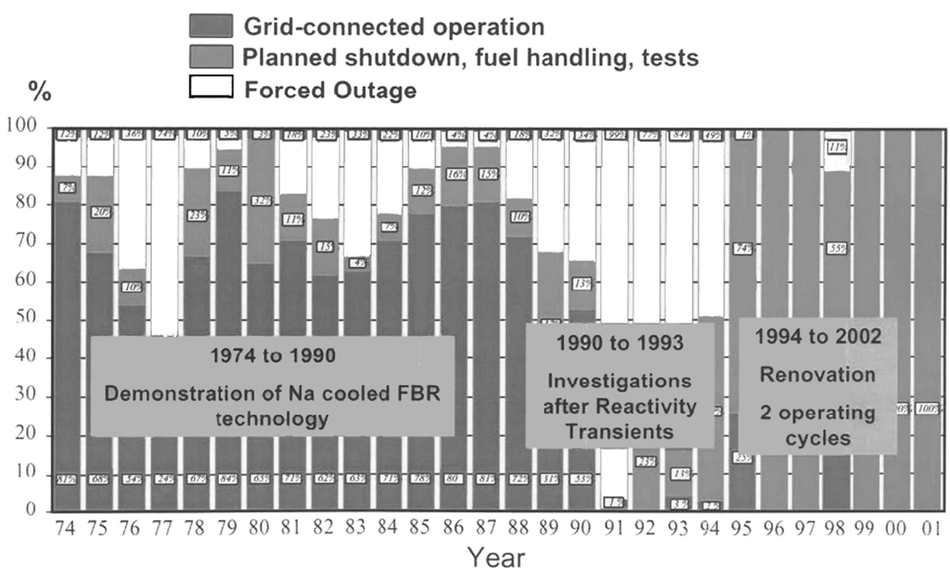

Figure 1: Operational History of France's *Phénix* breeder reactor, 1974–2002 (Na is the chemical symbol for sodium.). Source: IAEA, Fast Reactor Database 2006 Update.

As of the end of 2007 the reactor had a cumulative load factor of 44.66 percent.[5]

SUPERPHÉNIX, CREYS-MALVILLE

In 1971 and 1972, even prior to the first oil shock, utilities from France, Germany and Italy signed a number of agreements, for joint construction of two commercial breeder reactors, one in France and one in Germany. In December 1972 the French Parliament passed a law that granted permission to create companies "that carry out an activity of European interest in the electricity sector."[6] The legislation was tailor-made for the creation of NERSA,[7] which was established in 1974, shortly after the start-up of *Phénix*, with the purpose of building the first commercial-size plutonium-fuelled fast breeder reactor in the world.[8] The *Superphénix* Parliamentary Enquiry Committee later noted that the "public enquiry" into the project was "excessively short." It lasted only a month from 9 October to 8 November 1974.[9]

The project immediately attracted significant opposition. In November 1974, 80 physicists of the Lyon Physics Institute highlighted specific risks of breeder technology and, in February 1975, about 400 scientists initiated an appeal that laid out their concerns about France's nuclear program in general and the fast breeder in particular. The same year the German utility RWE transferred its NERSA shares to the European consortium SBK[10] that planned to build the *SNR-300* breeder reactor in Kalkar in Germany. And André Giraud, then head of CEA, urged the rapid and massive introduction of breeders, since delays in their introduction would have "catastrophic consequences on the uranium savings that are expected."[11] The public enquiry commission into the Superphénix project estimated that fast breeders would supply a quarter of France's nuclear electricity by the year 2000.

In the middle of April 1976, the Restricted Energy Council chaired by President Valery Giscard d'Estaing took the political decision to build *Superphénix*. Site preparation work started immediately at Creys-Malville (45 km East of Lyon, 60 km from Grenoble and 70 km from Geneva). The Parliamentary Enquiry Committee noted 22 years later:

> Once the decision to build was taken, the electricity utilities would not rest until they succeed. Convinced of the well founded decision, they did not allow local consultation to slow them down; the latter can be qualified as minimal.[12]

The "official" public decision to build was only announced a year later. The Parliamentary Enquiry Committee wonders:

> Finally, what to think of a governmental decision to authorize the creation of the plant dated 12 May 1977, thus taking place after the beginning of the preliminary infrastructure and site preparation work and after the beginning of the construction of the reactor?[13]

In the summer 1976 about 20,000 people occupied the site to protest the construction of *Superphénix*. About 50 municipalities in the region had come out in opposition to the project between 1974 and 1976 and, in November 1976, around 1,300 scientists from the Geneva region issued an open letter to the governments of France, Italy, Germany and Switzerland voicing their concerns over the project.

CEA Chairman and soon to be named Minister of Industry André Giraud was more optimistic than ever and, at the December 1976 meeting of the American Nuclear Society in Washington D.C., forecasted 540 commercial breeders in the world for the year 2000, of which 20 would be in France. By 2025, he projected the number of *Superphénix*-size FBR units worldwide would reach exactly 2,766.[14] In fact, not a single *Superphénix*-size FBR was in operation in the world in 2000.

On 31 July 1977, a large international demonstration close to the construction site in Creys-Malville, with some 50,000 participants, turned extremely violent. The riot police used grenades that led to the death of Vital Michalon, a local teacher. Another demonstrator lost a foot and a third had a hand amputated. The events marked a profound trauma for the French anti-nuclear movement. The State did not alter its plans. Three days after the events, René Monory, then Minister, of Industry, declared: "The government will continue the construction at Creys-Malville and *Superphénix*, because it is a matter of life and comfort of the French people."[15] The construction proceeded.

The combination of the EURODIF uranium enrichment consortium that started up its plant at Tricastin in 1979 and the push for a European plutonium industry were attempts to acquire independence from what some decision makers and industry leaders perceived as U.S. nuclear "supremacy." France's President Giscard d'Estaing declared that "if uranium from French soil is used in fast-breeder reactors, we in France will have potential energy reserves comparable to those of Saudi Arabia."[16] US President Jimmy Carter's non-proliferation policy, highly critical of plutonium separation and use, was considered "totally absurd" by the CEA.[17]

In 1982, Jean-Louis Fensch, a CEA engineer, produced a 250-page report on fast breeders for the Superior Council on Nuclear Safety, a consultative body. Fensch concluded that "fast breeder reactors are the most complicated, the most polluting, the most inefficient and the most ambiguous means that man has invented to date to reduce the consumption of nuclear fuel."[18]

By the time *Superphénix* went critical in 1985, international enthusiasm for nuclear power had already peaked and the number of construction starts in the world had gone down from a peak of 40 units in 1975 to 13 in 1985 and 1 in 1986.[19] The Chernobyl catastrophe in 1986 only accelerated the decline in nuclear projects. *Superphénix,* whose objective was to save uranium, was outdated by the time it started up. Uranium prices had dropped from $40 to $15 per pound on the spot market, little more than the 1974 price. In comparison with the demand, uranium resources were abundant.

France's nuclear decision makers did not alter their plans, however. The result was that the country built up both a very large electric-power generating overcapacity (at least a dozen excess nuclear units by the middle of the 1980s) and a full-scale plutonium economy that had long lost its *raison d'être*. Between 1987 and 1997 the reprocessing of spent fuel at La Hague quadrupled to reach a rate of almost 1,700 tons per year, of which about half was for foreign clients. With an approximate 1 percent content of plutonium, the La Hague facilities separated about 17 tons of plutonium in 1997. This is roughly the magnitude of the total cumulated quantity of plutonium that had been irradiated in French breeder reactors as of the end of 1996 when *Superphénix* was shut down permanently.[20]

The core of *Superphénix* contained 5,780 kg of plutonium (4,054 kg of Pu-239). Operated at a nominal capacity with annual one-third core refueling *Superphénix* would have absorbed over 1,900 kg of plutonium per year. But during its 11-year long "operational" period, the reactor did not even use the equivalent of one reactor core (see Figure 2).

Superphénix had a rated power of 1200 MWe net (1240 MWe gross). On 7 September 1985 it went critical and was connected to the grid on 14 January 1986. It was plagued by a number of technical and administrative problems, however, and was shut down more than half of the time until 24 December 1996 when it produced its last kWh. Superphénix generated 8.2 TWh (gross)

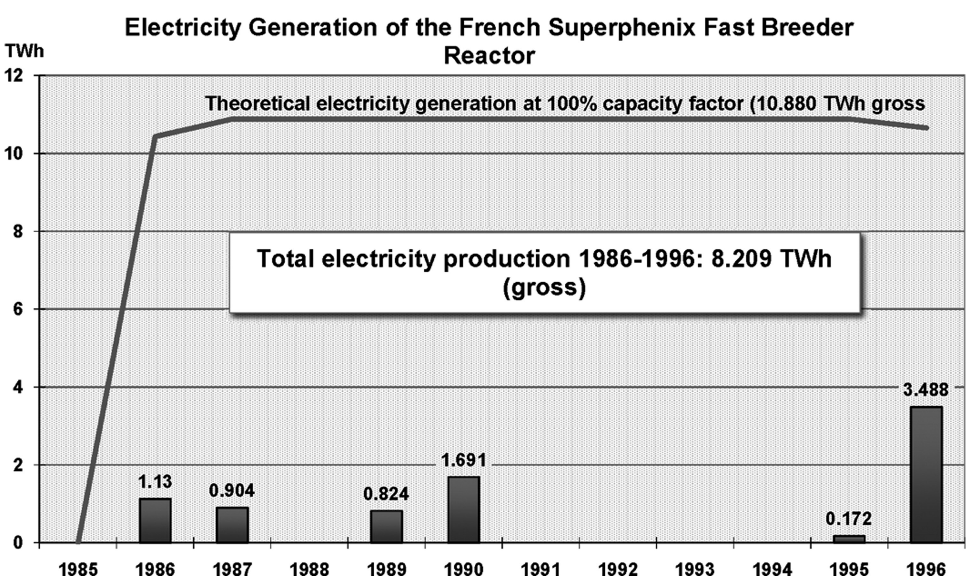

Figure 2: *Superphénix* annual electricity generation. Sources: CEA, WISE-Paris.

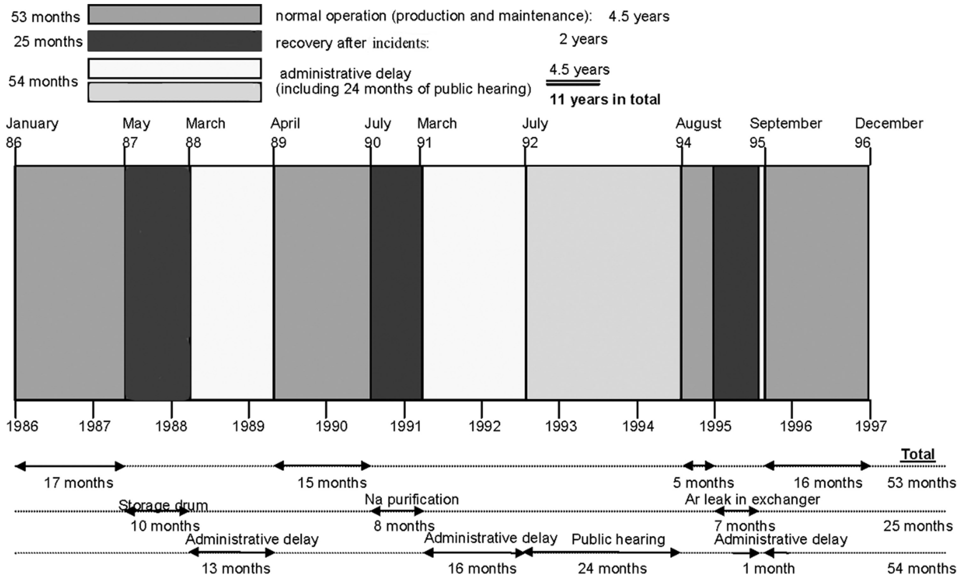

Figure 3: *Superphénix* operational and administrative history, Source: IAEA, Fast Reactor Database 2006 Update.

in total, almost half of which was generated during its last year of operation. Its lifetime load factor was less than 7% (see Figure 3).

As Figures 2 and 3 illustrate, *Superphénix* experienced a series of significant incidents and administrative hurdles. The reactor was never operational more than 17 months in a row. Operation halted in May 1987 with the discovery of a major sodium leak in the fuel transfer tank or storage drum. The tank could not be repaired and it took 10 months to develop a new approach to load and discharge fuel from the reactor core.

The incident also revealed major deficiencies in the French FBR organization. Before the leak, at the end of 1985, FRAMATOME's engineering subsidiary NOVATOME laid off more than half of its staff, 430 of 750 employees. NOVATOME was losing a lot of money because it could not invoice NERSA for work on *Superphénix* until it had gone into commercial operation.[21] In the course of the relocation of its thinned-out engineering teams from Paris to Lyon, many experts took up attractive offers to leave NOVATOME. As a result, when the storage tank leak occurred, NERSA realized that the specialist that had managed the electronic database for the tank had left and it took some time before the database could be accessed. The re-qualification and authorization of the new fuel transfer and storage scheme absorbed another 13 months before the reactor could restart in April 1989. Low-power operation lasted until July 1990 when a defective compressor led to major air leakage into the system and oxidation of the sodium. Sodium purification took another

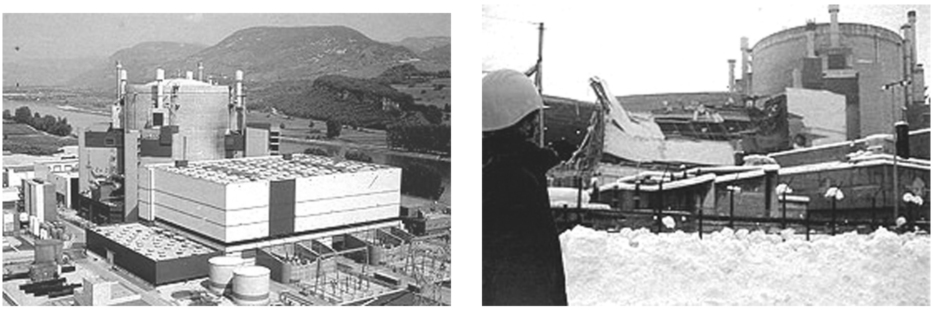

Photo: Dissident-Media

Figure 4: *Superphénix.* a) Turbine Hall in foreground. b) Collapsed Turbine Hall roof.

eight months. In December 1990, the roof of the turbine hall collapsed after a heavy snowfall (see Figure 4).

On 3 June 1991, NERSA requested to restart the reactor by July 1991. On 27 May 1991, however, the French Conseil d'Etat invalidated the 1989 restart license that had been legally challenged by Swiss and French opponents. The restart, unlike the original licensing procedure, became subject to a lengthy process of parliamentary hearings and debates on national and regional level. In June 1992, the government decided to commission expert reports and to request a new public enquiry that was carried out between 30 March and 14 June 1993. The public enquiry commission issued its report on 29 September 1993 and the safety authorities reported to the government in January 1994. A new operating license was finally issued on 11 July 1994. The unit had been back on line for only seven months, however, when an argon leak in a heat exchanger forced a new outage. When the reactor restarted in September 1995, it was for the last time.

On Christmas 1996 Superphénix was shut down for maintenance, core reconfiguration and the launch of a research program into transmutation. On 28 February 1997, however, the Conseil d'Etat nullified the July 1994 operating permit and, on 19 June 1997, incoming Prime Minister Jospin told the National Assembly that "*Superphénix* will be abandoned." The political decision became official on 2 February 2008 when the communiqué of an interministerial committee meeting stated that "the government has decided that *Superphénix* will not restart, not even for a limited period of time."

A Green Party representative had entered a European national government with a senior ministerial position for the first time. Dominique Voynet became Environment Minister, and thereby shared oversight over civil nuclear safety in France with the Industry Minister. Point number one on the Green Party electoral platform had been the closing of *Superphénix*. The issue had always been highly symbolic for France's nuclear power opponents. It would have been difficult to imagine anything less than the end of the *Superphénix* project after the Green Party joined the government.

It is also perfectly clear, however, that at least part of EDF's top management had long considered *Superphénix* and reprocessing a costly error.[22]

French diplomats were quick to downplay the strategic significance of the end of *Superphénix*. The French Embassy in the US stated in its "Nuclear Notes from France"[23]:

> In the wake of recent decisions, made by the French Government, including the closure of the *Superphénix* fast-breeder reactor, some may wonder if France is changing its nuclear policy. Basically, the answer is no. Both Prime Minister Lionel Jospin and Economic Minister Dominique Strauss-Kahn have made it clear France is satisfied with its nuclear "wise" commitment, stressing the large return on investment it provides in terms of economic competitiveness, self-sufficiency and environmental protection. France will stick to its policy of reprocessing and plutonium recycling, a good way to optimize waste management while producing more electricity. Is it surprising? Just remember what everybody in France has in mind: no oil, no gas, and no coal means no choice! It sometimes helps!

A decree dated 30 December 1998 formalized the decision to proceed with the final closure of *Superphénix* and the first decommissioning steps. As of 2008, the fuel has been discharged and transferred to the storage facility APEC on site. The turbine hall has been emptied. A permit for full decommissioning was issued on 20 March 2006.

MILITARY PLUTONIUM FROM *PHÉNIX*

The CEA's military department had a keen interest in fast breeders because of the fact that, as a by-product, they generate super-grade plutonium in the breeder blankets.[24] Even if the utilities involved in the *Superphénix* project always categorically rejected the idea of a military link, it is clear that *Phénix* was used for the generation of plutonium for France's nuclear-weapon program. The potential militarization of Superphénix raised considerable concern, especially in Germany, and was discussed in the context of the possibility that France might develop and deploy neutron bombs in Europe.[25]

In the case of *Phénix*, the fuel design allowed not only for the use of the radial blanket but also part of the axial blanket to produce plutonium for weapons. Usually the axial blanket is integrated with the core fuel in the same fuel pins but it seems that in the case of *Phénix* the upper axial blanket was separate. *Phénix* blanket material was reprocessed at the military UP1 plant in Marcoule, while core material, diluted with gas-graphite reactor fuel, was reprocessed at La Hague and at a dedicated pilot plant at Marcoule (APM with the head end SAP-TOP, later SAP-TOR).

In an unusually blunt statement, General Jean Thiry, former director of the French nuclear test sites in the Sahara and in the Pacific, who prior to these positions had been responsible for eight years for plutonium "counting" at the CEA, told the daily *Le Monde* in 1978: "France is able to make nuclear weapons of all kinds and all yields. It will be able to fabricate them in large numbers as soon as the fast breeder reactors provide it with abundant quantities of the necessary plutonium."[26] In 1987 General Thiry confirmed his statement and declared: "One can always get plutonium, especially if one develops .... This is apparently an idea that one should not say [openly] because it is not moral,[27] but I defend Creys-Malville [*Superphénix*] and the fast breeder reactor type, because there you have plutonium of extraordinary military quality."[28]

Dominique Finon states that *Phénix* was used for military purposes starting in 1978 but that the idea to use *Superphénix* for defense needs was abandoned in 1986.[29]

COSTS (R&D, CONSTRUCTION, OPERATION, DECOMMISSIONING)

France's fast-breeder reactor program was costly to the French taxpayer. A comprehensive historical economic assessment is not available. An extensive analysis to the middle of the 1980s was carried out[30] and the national Court of Auditors provided a cost estimate in 1996. In addition a number of assessments have looked at specific aspects (R&D, decommissioning...). Figure 5 provides an overview of *Phénix* operating costs between 1972 and 2003.

Between 1973 and 1996 the CEA alone spent an undiscounted FRF15.8 billion ($\$_{2008}$ 3.8 billion) on breeder R&D, 50% more than on light water reactors (including the EPR development).[31]

According to an agreement signed in 1969, the CEA provided 80% and EDF 20% of the construction and operational costs of *Phénix*. Construction costs totaled FRF_{1974}800 million ($\$_{2008}$880 million). About € 600 million ($\$_{2008}$950 million) was spent on *Phénix* upgrades between 1997 and 2003 (see Figure 5).

The French state spent some FRF_{1985}44 billion ($\$_{2008}$17.4 billion) on the fast breeder program between 1960 and 1986. The *Superphénix* construction costs increased by 80% to reach FRF_{1985} 26 billion ($\$_{2008}$9.5 billion) by the time the reactor went on line in 1986.[32] At that time, the investment cost ratio per installed kW between breeder and PWR was evaluated by the CEA at 2.58.[33]

The Court of Auditors, in its 1996 annual report, provided an evaluation of the cost of *Superphénix,* assuming that it would operate until the end of 2001. It estimated that the unit had cost FRF 34.4 billion by the end of 1994 and that financial, spent fuel management, decommissioning and waste management costs would reach an additional FRF 27.4 billion. Operating costs were given at FRF 1.7 billion per year. Considering the fact that the unit shut down at the end of 1996, adding two years of operating costs but also of power generation (about 3.65 TWh), the total estimated cost would be somewhere around FRF 64 billion, minus about a FRF one billion electricity generation credit.[34]

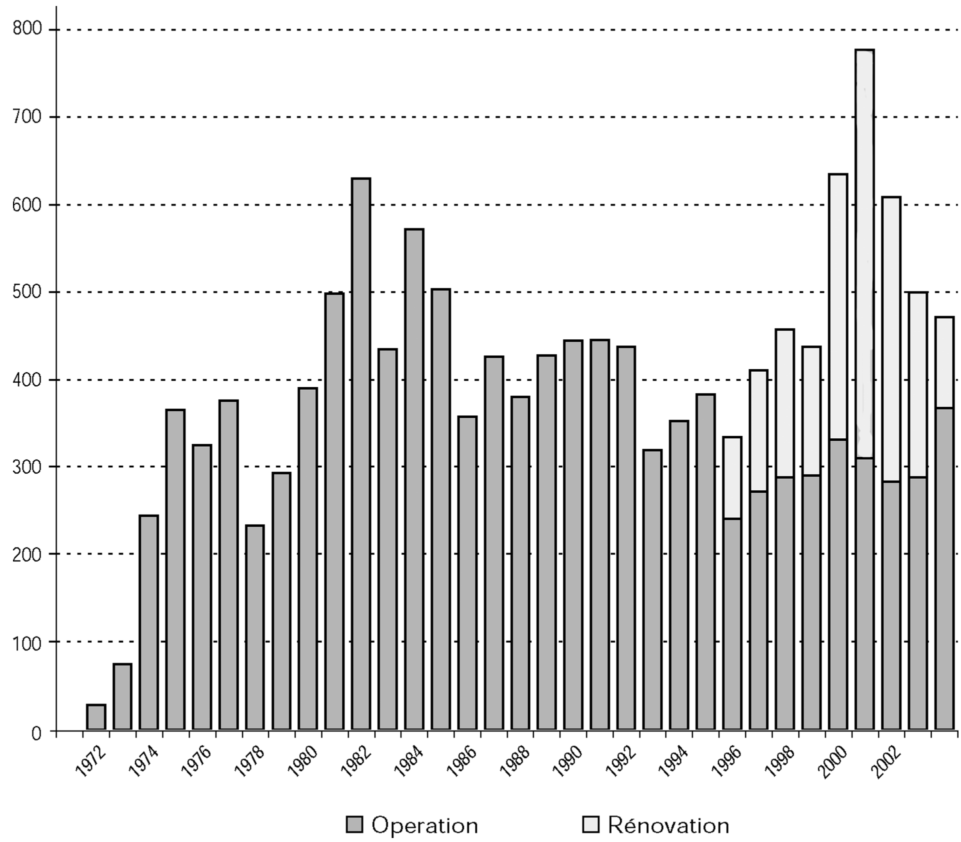

Figure 5: *Phénix* operating costs, 1972–2003 (FRF_{2000}million), *Source: Sauvage 2004.*

Jacques Chauvin, president of the directorate of NERSA stated that "in total, cumulating investment and operating costs and taking into account all future costs, *Superphénix* will have cost FRF 65 billion of which EDF will have paid 38 billion."[35]

The NERSA and Auditor Court figures are closer than the level of uncertainty attached. In particular, the decommissioning costs contain a substantial potential margin of error. They have been raised several times. As of 2003, the Court of Auditors estimated *Superphénix* decommissioning and waste management alone would cost 2.081 billion.

The Parliamentary Enquiry Committee concluded:

> In the end nobody seems to contest the judgment of the Court [of Auditors] that "the record of the fast breeder experience appears unfavorable today in any case on the financial level." Christian Pierret [Secretary of State for Industry] goes as far as qualifying it as 'unacceptable.[36]

SAFETY PROBLEMS IN THE FRENCH FBR PROGRAM

All three reactors, *Rapsodie*, *Phénix* and *Superphénix*, encountered significant safety problems during start-up, operation and dismantling periods, including sodium leaks, reactivity incidents, explosions and material failures.

Rapsodie—Sodium Leaks and a Lethal Explosion

After a rather smooth operational period from *Rapsodie's* start-up at the beginning of 1967, at the end of 1978 a small primary sodium leak was detected, which led to the decision to reduce the operational capacity from 40 MWth to about 22 MWth. In January 1982, another small sodium leak was detected in the nitrogen system (surrounding the primary vessel). Localization of the leak was believed to be too costly and too uncertain. The reactor was therefore shut down on 13 October 1982.

The secondary sodium was drained in April 1983 and is still stored on the Cadarache site. The primary sodium was drained by April 1984. It took two years to retrieve the 468 highly irradiated reflector assemblies from around the core (222 made of nickel, 246 made of steel) from the vessel, wash them to eliminate traces of sodium, and install them in a storage container. The 37 tons of primary sodium were treated in a specially designed facility (DESORA) that turned it into 180 cubic meters of concentrated sodium hydroxide.

On 31 March 1994,[37] an explosion occurred during the cleaning of the residual primary sodium contained in a tank located in a hall outside the containment building. An experienced, highly specialized 59-year-old CEA engineer was killed instantly and four people were injured. About 100 kg of residual sodium had remained at the bottom of a tank at the end of the treatment campaign. An analysis of the accident concluded later:

> The process selected to perform this clean up operation consisted in progressively introducing in the tank a heavy alcohol called ethylcarbitol, while monitoring the reaction through temperature, pressure, hydrogen and oxygen measurements. The major cause of the accident was due to the formation of an heterogeneous physical-chemical environment, complex and multiphasic made of three basic components: alcohol, alcoholate and sodium. This environment turned out to be particularly favourable to the development of thermal decomposition reaction and/or catalytic exothermal reactions. Large quantities of gases (including hydrogen and light hydrocarbon compounds) were thus produced. Shortly after the last alcohol injection on 31 March, the phenomenon ran out of control, leading to a sudden rupture of the overpressurised tank, then to the explosion of the gases mixture blown out in the hall.[38]

Since this accident, the use of ethylcarbitol or other heavy alcohol has been forbidden in the treatment of sodium. But the circumstances of the accident are subject to an ongoing legal dispute. In 2001 an expert court-commissioned analysis accused the CEA, the IPSN (Institute for Nuclear Protection and Safety, predecessor of IRSN) and the safety authorities of "faults by imprudence, negligence and violation of safety obligations."[39] As of March 2009, there still is no published element of information indicating that there has been a final judgment.

Phénix—Sodium Leaks and Reactivity Spikes

As of 1988, *Phénix* had a cumulative average load factor of 60.5 percent. Operation was not without problems, however. The first fuel pin leak occurred in June 1975, secondary sodium leaks occurred in September 1974, March and July 1975 (about 20 liters each for the first two and 1 liter for the last). "Leakage generally led to the slow spontaneous combustion of this sodium in the insulation, without triggering fires external to the insulation."[40] Repair operations proved ineffective and valves in the three secondary systems were eventually replaced by diaphragms.

On 11 July 1976, a sodium leak occurred at the intermediate heat exchanger (between the primary and secondary sodium loops) that led to what was later labeled as the "first real sodium fire in the *Phénix* plant." The fire was extinguished manually. On 5 October 1976, another sodium fire broke out at an intermediate heat exchanger and was again manually brought under control. Figure 6 provides an illustration of the impact of a sodium fire at an unidentified date. A further sodium leak was identified in August 1977. Further secondary sodium leaks were identified in the 1980s, including incidents in March and November 1984, and in September 1988.

In July 1978, two control rods showed a level of swelling that prevented normal extraction from their guide tubes. However, since the blocking was positioned above the insertion level during normal operation, the phenomenon was considered not to constitute an immediate safety issue.

In the first years no events directly impacted on the steam generators. Steam generator failures, which can lead to violent sodium-water reactions are the most feared incidents in fast-neutron reactors. But various incidents took place in the steam generator environment, including four water leaks in the economizer-evaporator inlet of the steam generators between November 1975 and September 1976.

The first cladding failure was detected in May 1979. It led to the "greatest release of fission gas (Xenon-135) ever seen in the *Phénix* plant."

Between April 1982 and March 1983, sodium-water reactions in the reheater stages affected all three steam generators in at least four incidents. In the first event, in April 1982, about 30 liters of water leaked into the sodium and created a combustion flame that burned a hole in two tubes and damaged the reheater module's shell. The other three events apparently involved quantities of water limited to a few liters. These four sodium-water incidents

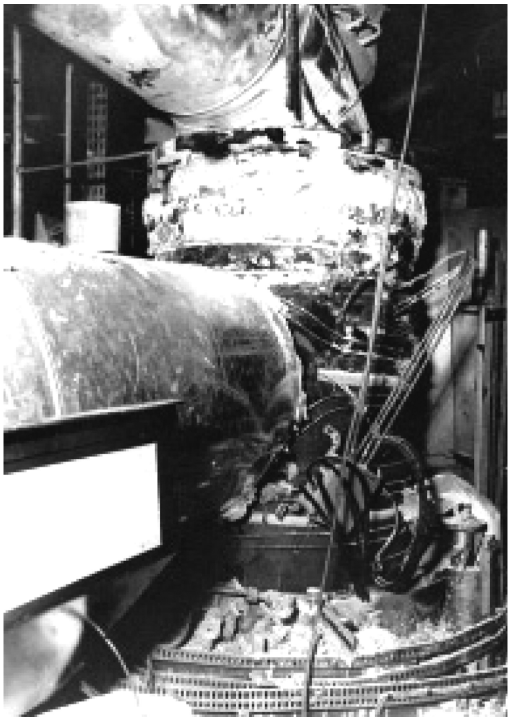

Photo: Sauvage 2004

Figure 6: *Phénix* heat exchanger with insulation removed after sodium fire.

resulted in a total of six months of outage and nine months of operation limited to two-thirds capacity.

The most costly and potentially most significant incidents were rapid reactivity transients in the core on three occasions in 1989 (6 and 24 August, 14 September) and on 9 September 1990. In spite of a research program costing hundreds of millions of francs, 200 person-years of work, and the elaboration of some 500 documents, the cause of the phenomenon was never conclusively identified.

The events were particularly worrying since following reactivity and power drops of 28% to 45% within 50 milliseconds, power actually increased above the original state of the reactor. The fear was that such an event could trigger a power excursion. The cause could possibly have been an argon gas bubble going through the core, but this hypothesis was never confirmed. Subsequent investigations revealed that similar events had taken place in April 1976 and June 1978 and that the explanation at the time (control rod slippage) was wrong.

Superphénix—Sodium Leaks and Missile Attacks

Safety concerns relative to the operation of the *Superphénix* reactor were a key objection of the critics of the project from its very early stages. The over

5,000 tons of highly reactive sodium combined with several tons of highly toxic plutonium raised numerous safety issues. After the Chernobyl accident, which occurred only three months after connection of *Superphénix* to the grid, the question of the positive void coefficient[41] inherent in the design, theoretically favoring power-excursion accidents, only increased the concerns of a number of scientist-critics. Safety concerns played a significant role in generating the opposition, including its most extreme forms.

The first exceptional event took place at Creys-Malville before construction of the reactor was completed. A group of anti-nuclear activists succeeded in obtaining an RPG-7 (Rocket Propelled Grenade) launcher ("tube") and eight warheads ("bonbons") from the German terrorist organization RAF (Rote Armee Fraktion) via the Belgian counterpart CCC (Cellules Communistes Combattantes). On 18 January 1982, five missiles were fired against the *Superphénix* construction site (three other pieces of ammunition had been discarded prior to the attack). There was little material damage but significant political and media attention. The authors of the attack were never caught until the self-accusation of the key person, Chaïm Nissim, 22 years later.[42]

The internal incident database of the French Nuclear Safety Authorities only refers to a single event during the operational period of *Superphénix*: a sodium leak from the main fuel storage tank. The tank was a key element of the plant since it was supposed to serve as transfer and storage tank for new and spent fuel assemblies. The leak was detected on 3 April 1987 and led to a 10-month shutdown. Worse, it became evident that it would be impossible to repair the tank—the leak was determined to be the result of a design error (wrong material). An entirely new fuel loading and unloading scheme had to be developed. It is interesting to note that the original design of the transfer tank did not have double walls. The consequences of the leak would most likely have been much more dramatic if that design had been used.

The National Assembly's Enquiry Committee on *Superphénix* and the Fast Breeder Reactor Line[43] also discussed the three previously mentioned significant events: the sodium pollution of July 1990, the turbine hall roof collapse of December 1990, and the argon gas leak in December 1994.

At present the *Superphénix* reactor is undergoing various decommissioning operations. The dismantling of its reactor block is planned to begin in 2014 and continue for a period of eight years. The entire installation is to be dismantled by 2025.

"After four decades of R&D, design and operation of LMFRs, and facing no project, CEA, EDF and FRAMATOME-ANP [now AREVA NP] decided in 2000 year to preserve the LMFR knowledge-base."[44]

NOTES AND REFERENCES

1. Germany, France, Belgium, Italy, Sweden, Austria, Denmark, Norway, Netherlands, Switzerland, Portugal, Turkey. Spain joined the consortium in 1959. Most of these countries had nuclear weapons programs or ambitions at some point, including Germany, Italy, Sweden and Switzerland.

2. IAEA, *Fast Reactor Database—2006 Update*, IAEA-TECDOC-1531, December 2006, see http://www-frdb.iaea.org/index.html.

3. Two months after the last U.S. reactor order that was not subsequently cancelled.

4. IAEA, *Fast Reactor Database—2006 Update*, IAEA-TECDOC-1531, December 2006, see http://www-frdb.iaea.org/index.html.

5. According to the IAEA PRIS, not including the years 1997–2004; see http://www.iaea.org/cgi-bin/db.page.pl/pris.ophis.htm?country=FR&site=PHENIX&units=&refno=10&opyear=2007&link=HOT.

6. Journal Officiel, 23 December 1972.

7. Centrale Nucléaire Européenne à Neutrons Rapides S.A.

8. A decree dated 13 May 1974 authorized EDF to take part in the consortium. The original shareholders other than EDF (51%) were ENEL, Italy (33%) and RWE, Germany (16%).

9. Robert Galley, Christian Bataille, Rapport fait au nom de la Commission d'Enquête sur Superphénix et la filière des réacteurs à neutrons rapides, enregistré à l'Assemblée Nationale, 25 June 1998.

10. Schnellbrüterkernkraftwerksgesellschaft: 68,85% RWE, 14.75% SEP (consortium of Dutch utilities), 14.75% Electronucléaire (consortium of Belgian utilities), 1.65% CEGB (UK).

11. Jean-Louis Fensch [CEA engineer], Finalités du retraitement, unpublished annex to the First "Castaing Report," commissioned by the Conseil Supérieur de la Sûreté Nucléaire, October 1982.

12. Robert Galley, Christian Bataille, Rapport fait au nom de la Commission d'Enquête sur Superphénix et la filière des réacteurs à neutrons rapides, enregistré à l'Assemblée Nationale, 25 June 1998.

13. *Ibid*.

14. Jean-Louis Fensch [CEA engineer], Finalités du retraitement, unpublished annex to the First "Castaing Report," commissioned by the Conseil Supérieur de la Sûreté Nucléaire, October 1982.

15. *Ibid.*

16. *Time* magazine, 18 February 1980.

17. *Le Point* magazine, 19 September 1977, quoted in [Fensch, 1982].

18. Jean-Louis Fensch [CEA engineer], Finalités du retraitement, unpublished annex to the First "Castaing Report," commissioned by the Conseil Supérieur de la Sûreté Nucléaire, October 1982.

19. IAEA, *Nuclear Power Reactors in the World*, April 1987 edition.

20. Mycle Schneider (Dir.), Xavier Coeytaux, Recyclage des matières nucléaires—Mythes et réalités, WISE-Paris, commissioned by Greenpeace France, May 2000.

21. The status of commercial or industrial operation would be considered achieved if the reactor operated at >60% rated capacity at least for a month of which at least one week was without interruption.

22. The author was an advisor to the French Environment Minister's office from 1998 to 2002. In 1998, one of the top five directors of EDF approached the author with the request to communicate to Dominique Voynet the message that, while EDF obviously could not make any public statements, she should know that she had a lot of support inside EDF. While Voynet became the perfect scapegoat for the plutonium lobby, she was the secret ally of those within the nuclear establishment who wanted to terminate FBR and plutonium activities.

23. Embassy of France in the US, *Nuclear Notes from France n°52*, Jan, Feb, March 1998.

24. The radial breeder elements and axial blanket contain uranium-238 that "breeds" plutonium-239 in very pure form. "Super-grade" plutonium with a share of ≥97% of fissile plutonium (plutonium-239 and plutonium-241) is particularly well suited for nuclear weapons.

25. If France had decided to produce neutron bombs in large numbers, there is little doubt that it could not have generated enough weapons grade plutonium without militarizing additional reactors besides the two *Célestin* heavy water reactors and *Phénix*.

26. *Le Monde*, 19 January 1978.

27. Today one would say "politically correct."

28. Interview with the author, 18 June 1987, unpublished.

29. Dominique Finon, *L'échec des surgénérateurs, autopsie d'un grand programme*, PUG 1989, p. 176.

30. Dominique Finon, L'échec des surgénérateurs, autopsie d'un grand programme, PUG 1989.

31. for details see Mycle Schneider (dir), *Research and Development Expenditure on Nuclear Issues in France 1960–1997*," commissioned by Energy Services, Lohmar, Germany, February 1998.

32. This sum includes financial costs of FRF7.5 billion and engineering as well as pre-operational costs of some FRF2 billion covered by EDF beyond the direct investment costs indicated by the CEA as FRF16.5 billion. (see Dominique Finon, L'échec des surgénérateurs, autopsie d'un grand programme, PUG 1989, footnote 84, p. 305).

33. CEA, Coûts de la centrale SuperPhénix, Note BRPC 86.317, January 1986, quoted in Dominique Finon, L'échec des surgénérateurs, autopsie d'un grand programme, PUG 1989.

34. The Court of Auditors assumed an average price of FRF0.25/kWh, which would mean a credit of less than FRF1 billion for the generation of the 3.65 TWh.

35. Robert Galley, Christian Bataille, Rapport fait au nom de la Commission d'Enquête sur Superphénix et la filière des réacteurs à neutrons rapides, enregistré à l'Assemblée Nationale, 25 June 1998.

36. *Ibid.*

37. Also the date of the final shutdown of the PFR in Dounreay.

38. G. Rodriguez et al., *General Review of the Decommissioning of Liquid Metal Fast Reactors (LMFRs) in France*, in *Operational and decommissioning experiences with fast reactors*, TECDOC 1405, IAEA, August 2004.

39. *Libération*, 15 March 2007.

40. Unless specified otherwise, quotes in this section are from Jean-François Sauvage, *Phénix, 30 Years of History—The Heart of a Reactor*, CEA-EDF, May 2004. The book is available free of charge at http://www.iaea.org/inisnkm/nkm/aws/fnss/phenix/book/index.html

41. A positive void coefficient is when a bubble in the core increases its reactivity.

42. Chaïm Nissim played a key role in the acquisition and firing of the rockets at the *Superphénix* construction site. He has detailed the process of acquisition and attack in a book: *L'amour et le monster—Roquettes contre Creys-Malville*, Ed. Favre, Geneva, February 2004.

43. R. Galley, C. Bataille, Rapport fait au nom de la Commission d'Enqu****ete sur Superphénix et la filière des réacteurs à neutrons rapides, enregistré à l'Assemblée Nationale on 25 June 1998.

44. F. Baque, R&D LMFRs Knowledge Preservation French Project, CEA, Saint-Paul-Lez Durance Cedex, France in operational and decommissioning experiences with fast reactors, TECDOC 1405, IAEA, August 2004.