RESULT

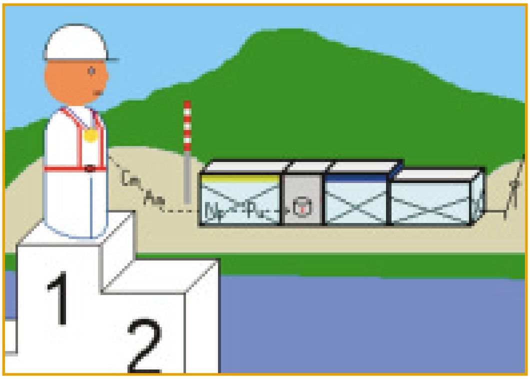
Landmarks

5 May 1969	First concrete poured at the Phénix site
31 August 1973	First divergence of the Phénix reactor
13 December 1973	First connection to electrical grid
12 March 1974	Reactor reaches rated capacity
14 July 1974	Phénix plant commissioned
11 December 1974	Tests with reactor at maximum power (597 MWt)
11 July 1976, 3 October 1976 and 31 August 1977	Secondary sodium leaks from intermediate heat exchangers
29 April 1982, 16 December 1982, 15 February 1983 and 20 March 1983	Sodium-water reactions in steam generators
10 August 1982	Net cumulative electrical output: 10 billion kWh
25 August - 13 November 1983	Uninterrupted operation at rated capacity (81 days)
30 October 1988 - 8 January 1989 16 January - 28 March 1989	Successive cycles running uninterrupted (72 EFPD in 72 days each)
6 August 1989, 24 August 1989, 14 September 1989 and 9 September 1990	Negative reactivity trips
11 May - 18 August 1990	Reactor running uninterrupted at 500 MWt (99 days)
22 July 1990	Net cumulative electrical output: 20 billion kWh
7 April 1995	Boitix 9 experimental sub-assembly reaches 144 174 MWd/t
27 October - 23 December 1999	Inspection check on conical shell
15 March - 6 April 2001	Visual inspection of core cover plug and upper internal structures of the reactor
1 September 2003	100,000th hour supplying EDF electricity grid

The Phénix plant has been in operation for thirty years now - and they have been eventful years. The power plant that opened in 1974 was very different in its organisation and technical equipment from the plant of 2004, fully renovated for its final years of power operation. Yet there has been continuity, great enthusiasm and huge successes.

The design of the plant, highly advanced for its time, and the exemplary manner of its construction provided accumulated feedback still unequalled for a fast neutron reactor. It provided an abundant harvest of information on the overall system that makes up a power-generating sodium-cooled fast neutron reactor; on the design of all its components and their behaviour under representative flux and temperature conditions; on the behaviour of the materials of the core and structures; on the qualification of the fuel at increasingly high burn-up; on demonstration of the transmutation of minor actinides and long-lived fission products; etc.

These thirty years of operation have not been trouble-free, but each incident has provided information that has been deciphered and processed. Leaks from the intermediate heat exchangers, sodium-water reactions in the steam generators, sodium leakage, cracking of type 321 steel pipes, automatic trips due to negative reactivity transients, etc. - all these difficulties were successfully overcome in order to continue operation.



Phénix is a **prototype** facility, built to demonstrate the viability of the French sodium-cooled fast neutron reactor project, which has since been put on hold with the government decision to permanently shut down the Superphénix plant at Creys-Malville in 1998, before its due date. Phénix is thus the only plant of its kind in France, and there are few elsewhere in the world. Most of the results and the specific operations carried out there have been, in a way, world firsts. Today it is one of the most fruitful experiments contributing to the technical credibility of fast neutron reactors, whether the coolant used is sodium or any of the other gases or liquids considered for the international research programme on Generation IV reactors.

With a maximum authorised output of 600 MWth (the rated capacity was 563 MWth), Phénix has so far accumulated an energy generation of more than 2 million MWd (equivalent to about 3,900 days in operation at rated capacity) and a net electrical power generation of 21 billion kWh.

The materials and equipment at the plant have given satisfaction. With the modular design of the steam generators and confirmation that the plant could be run with only two of the three secondary circuits functioning, it was possible to keep the plant in operation even during work on one of the steam generators or secondary cooling systems. This characteristic also made it possible to reduce the reactor's operating power but still irradiate experimental objects under a high neutron flux.

Following automatic trips due to negative reactivity transients, the reactor's **safety** was re-examined in detail and its design was not called into question. The only danger is a reactor shutdown, and the possible causes of these automatic trips cannot lead to a damaging nuclear accident. But it is frustrating not to have identified exactly what caused these phenomena. The safety upgrading concerned a wide range of fields including seismic resistance, pipe cracking, the heat removal systems, leaks and major sodium fires. The work confirmed that the original design was correct, allowing that some improvements were necessary to meet increased safety requirements.

The in-depth renovation work and the checks carried out to enable the reactor's life to be extended in compliance with new safety requirements that were in some cases far removed from the original design, constituted a large-scale operation carried out inside a functioning nuclear power plant. The checks recently conducted on the most critical and heavily-used parts of the reactor block (core cover plug, conical shell) have shown that these structures hold up well over time, despite being subjected to severe stresses. It has been shown to be perfectly possible, although technically difficult, to inspect the internal structures of a sodium-cooled reactor.

Lastly, the use of joint CEA and EDF teams was a definite advantage, not only for the team members, who were introduced to a different corporate culture, but also for the project as a whole, which had the benefit of the two organisations' complementary knowledge, skills and assets. The same applies to the presence of GAAA during the construction phase, and to Novatome alongside the operator for conducting safety studies and renovation work.

The accumulated experience of the fast neutron reactor as such is positive, as regards fuel density, manufacture of the MOX pellets, the particular core studies, the resistance of the cladding at high burn-up rates, etc. The fuel reaches a specific burn-up of 90,000 MWd/t at the centre of the core and 115,000 MWd/t at the periphery. Experimental pins and sub-assemblies have reached specific burn-up values of about 150,000 MWd/t, three times more than the design values.

Thanks to reprocessing the irradiated pins, the fuel cycle was closed several times, i.e. the plutonium recovered in the reprocessing plant was reintroduced into new sub-assemblies. A significant breeding rate was demonstrated at industrial scale: the plutonium produced amounted to 16% more than the initial quantity.

The flexibility of the reactor was put to extensive use to gradually introduce increasingly numerous and varied irradiation experiments. Thanks to its fast neutron flux, the small impact of the presence of targets in maintaining the chain reaction and the ease of loading and unloading individual sub-assemblies, the Phénix plant has become a valuable experimental tool, particularly for destroying or transforming undesirable radioactive elements. This is a major advantage of fast neutron reactors, as is confirmed by the direction now being taken in the Generation IV forum.

Because **sodium** reacts with both air and water, to use it as a coolant it was necessary to interpose adequate protective arrangements to prevent such reactions or limit their consequences. The integrated reactor design has proven its worth. Combined with the presence of secondary sodium circuits, it gives the system considerable inertia, which is particularly appreciable during transients. It is mainly this design we have to thank for the low level of the total cumulative dose received by all those who have worked on the Phénix plant over these thirty years: less than 2 man-Sv to date, which is about the amount received by staff at two EDF's pressurised water reactors in a single year.

There have been few sodium leaks: one or two per year in power operation. All in all they have been small leaks of non-radioactive sodium, which have caused no damage to the facility and required only the repair or replacement of the defective part. The few, small sodium fires that have occurred have been quickly brought under control.

More disturbing was the gradual discovery of the behaviour of type 321 steel in the presence of sodium, a problem solved by replacing virtually all 321 steel in the plant. This type of steel, though commonly used in high-temperature industries, proved vulnerable to delayed re-heat cracking under the conditions in which it was used in the Phénix plant. Above all, it was shown to be highly sensitive to the way the welding was done.

A definite drawback is the opacity of sodium, though technical advances are tackling this problem with increasing success. Liquid sodium is above all an excellent heat conductor, therefore a very effective coolant for extracting the high density of energy produced in the core of a fast neutron reactor. Thanks to its high boiling point, it can circulate in non-pressurized circuits. It also has good neutron characteristics and does not become very active during its passage in the core.

Lastly, this type of power plant has a particularly high thermal efficiency. Although technological progress now enables us to build thermal power plants (using gas at very high temperature) with efficiency of over 50%, the average efficiency of the Phénix plant (40%, despite running at reduced load for a quarter of the time), and its optimum value of 45%, are remarkable for a power plant of its generation.

To sum up, the Phénix plant has fulfilled its original contract to demonstrate the viability of a sodium-cooled fast neutron reactor. The results have even exceeded this objective as regards the fuel, the breeding aspect, the experimental irradiations, the sodium technology and upgradeability while in operation.

All these results are due to the efforts of the hundreds of engineers and technicians who have invested so much heart and energy as they followed one another in designing, building, operating, checking, repairing and upgrading the plant.

May this accumulated experience benefit future generations.

Marcoule, May 2004