Evolution of sodium technology R&D actions supporting French liquid-metal fast breeder reactors

G. RODRIGUEZ, F. BAQUE, J.C. ASTEGIANO
CEA Cadarache -CEA/DEN/CAD
Bldg 201, 13108 St Paul lez Durance - FRANCE
gilles.rodriguez@cea.fr, francois.baque@cea.fr, jean-claude.astegiano@cea.fr

Abstract
This paper describes the evolution of sodium technology R&D in parallel to sodium-cooled fast breeder reactor developments in France as well as providing information concerning operating plants and existing projects. This paper also discusses how supporting research has adapted to the decline in FBR activities since the decommissioning of SUPERPHENIX, while capitalising on knowledge acquired over more than four decades to be passed down to future generations.

1. INTRODUCTION [1]

The very first tests conducted by the CEA using liquid metals date back to 1953. Half a century later, the CEA has significantly progressed in the field of sodium-cooled fast breeder reactor (FBR) technology. Such progress is reflected in the design, construction and operation of three fast breeder reactors: the experimental reactor, RAPSODIE; the demonstration reactor, PHENIX; the commercial-size prototype reactor, SUPERPHENIX; and the European project integrating feedback from operating fast breeder reactor plants in Europe – EFR, European Fast Reactor.

An R&D engineering infrastructure also developed to support the French sodium-cooled fast breeder reactor sector. The CEA has been committed to the fast breeder reactor programme for over fifty years now, providing the human and technical resources needed to follow the fast breeder reactor R&D programme policy. Such resources were adapted according to the specific needs in the fields of reactor studies and design, from sodium technology and thermal hydraulics, to Regulator safety requirements, reactor incident analysis feedback, improvements in fuel performance, computer code and simulation developments and developments in specific dismantling processes.

At the end of 1990s, the programme suffered a setback with the decision to decommission SUPERPHENIX in February 1998, which consequently led to the withdrawal of the EFR programme. However, irradiation activities supporting minor actinide incineration and long-lived waste transmutation research were transferred from SUPERPHENIX to PHENIX – known as the CAPRA-CADRA programme. This programme, composed of six operating cycles will be conducted in the PHENIX reactor after safety re-evaluation studies have been performed on the facility. The first of the six cycles began in 2003.

This paper will discuss the evolution of the main French FBR R&D trends and facilities. How the CEA adapted to the growing demand in fast breeder reactor technologies over the first few decades before the abrupt decline due to the decommissioning of SUPERPHENIX will also be covered. How the CEA preserves and capitalises on the vast quantities of information collected over five decades from R&D activities, not to mention its role in the preservation of sodium technologies for current and future teams will also be discussed.

2. SODIUM-COOLED FAST BREEDER REACTOR DEVELOPMENT PROGRAMME IN FRANCE [1], [2], [3], [4], [5]

A brief account of the French fast breeder reactor programme is necessary to be able to fully appreciate the CEA's dedication to supporting R&D activities.

Date	Reactors and project: RAPSODIE – PHENIX – SUPERPHENIX - EFR
1953	- First experimental studies concerning sodium technologies - Fuel and core physics studies
1957	- RAPSODIE project is launched
1962 - 1966	- RAPSODIE is built at Cadarache
1963	- Beginning of fuel manufacturing activities for RAPSODIE in the Cadarache Plutonium workshop (ATPu)
1965	- PHENIX project is launched
1967	- 28/01: Criticality is reached in RAPSODIE - 17/03: Nominal power of 20 MW is reached - Detailed preliminary project of PHENIX is finalised
1968 - 1973	- PHENIX is built at Marcoule

1969	- The RAPSODIE fuel reprocessing plant at the Hague is commissioned
1970	- RAPSODIE begins operating at 40 MW (FORTISSIMO programme)
1971	- Studies for a 1200 MW fast breeder reactor are launched in France (CEA and EDF)
1973	- 31/08: Criticality is reached in PHENIX - 13/12: PHENIX is connected to the electric grid
1974	- March: Nominal power reached in PHENIX (250 MW) - 14/07: PHENIX becomes commercially operable - 08/07: The Group NERSA (51% EDF, 33% ENEL and 16% SBK) in charge of the SUPERPHENIX project is created
1977	- SUPERPHENIX construction work begins (Nuclear plant is ordered) - Beginning of the SPX2 project (1500 MW)
1980	- RAPSODIE is reduced to 22 MW following a leaktightness defect assumed to be in the safety vessel in 1978
1982	- 13/10: Final shutdown of RAPSODIE
1984	- End of assembly unloading activities in RAPSODIE - Filling of sodium circuits in the SUPERPHENIX reactor
1985	- 07/09: Criticality obtained in SUPERPHENIX
1986	- 14/01 : SUPERPHENIX is connected to the electric grid
1987	- Beginning of primary circuit dismantling activities in RAPSODIE - SPX2 is abandoned for the EFR (European Fast Reactor) project - March: Sodium leakage detected in the fuel storage tank in SUPERPHENIX
1988	- March: Beginning of the EFR "conceptual design" phase
1990	- from 1974 to 1990, PHENIX generated 20 billion kW - from 1989 to 1990, PHENIX experienced 4 emergency shutdowns due to negative reactivity - July: SUPERPHENIX primary sodium loop is polluted - April: Beginning of EFR "concept validation" phase
1991	- April: End of SUPERPHENIX primary sodium loop purification
1993	- End of RAPSODIE primary sodium loop dismantling - Beginning of the EFR "design consolidation" phase
1994	- March: End of RAPSODIE sodium treatment (37 tonnes) - An argon leakage is detected in a intermediate heat exchanger in SUPERPHENIX - Beginning of PHENIX safety re-evaluation studies for a lifespan extension of ten years
1995	- September: SUPERPHENIX is restarted
1996	- December: Programmed shut-down of SUPERPHENIX (320 effective full power days) for the 10-year inspection of the steam generators, after a year of normal operation (availability rate ≥ 80 %)
1997	- PHENIX is declared a "Nuclear Historic Landmark" by the American Nuclear Society
1998	- 02/02: Decision to decommission SUPERPHENIX - End of EFR project - Permission to conduct 50^{th} cycle in PHENIX
1999	- September: SUPERPHENIX's primary coolant pumps are shut down - December: Beginning of unloading activities in SUPERPHENIX
2002	- The sodium-cooled FBR concept is retained by Generation IV (SFR: Sodium Fast Reactor). France participates in the project
2003	- From 1999 to 2003: Safety re-evaluation studies continue in PHENIX - June: Beginning of 51^{st} cycle in PHENIX. Six operating cycles are programmed before the reactor is decommissioned. - 19/03: End of SUPERPHENIX unloading activities (fissile and fertile assemblies)

Table 1: Key events of the FBR programme in France

During a total of 11 years in operation, SUPERPHENIX operated normally at different power levels – including its start-up and test period – for 4 ½ years, was shutdown for 4 ½ years due to political and administrative decisions and was unavailable for 2 years due to maintenance work required following the above-mentioned technical incidents (cf. Figure. 1).

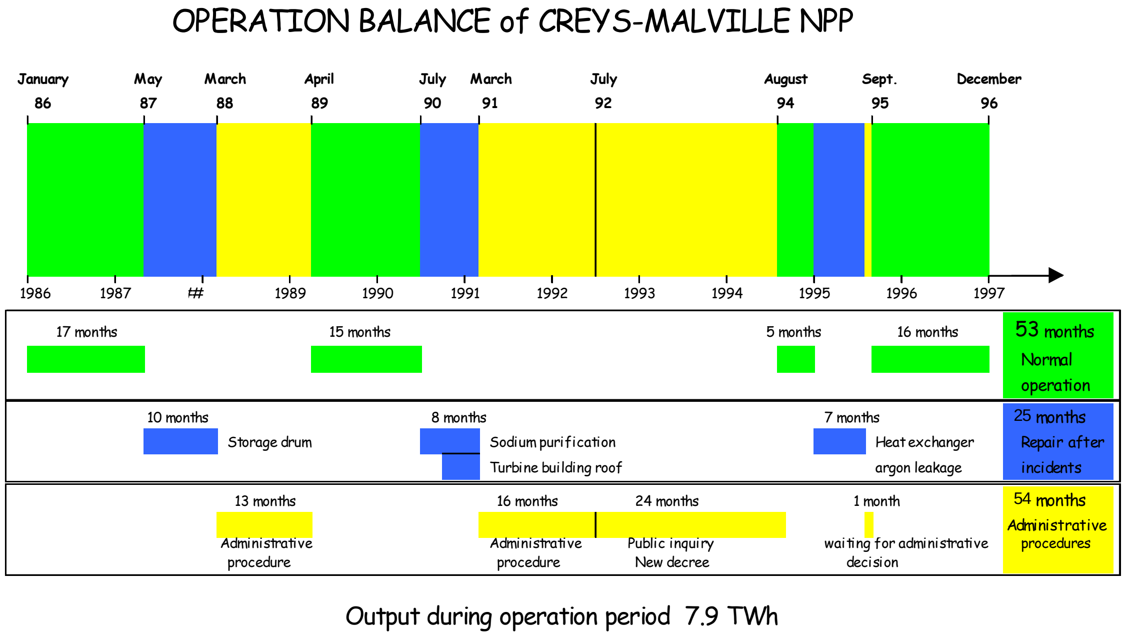

Figure 1: SUPERPHENIX operation

The diagram on the figure 2 provides a visual account of the chronological overlapping of the different phases in reactor and project life-spans

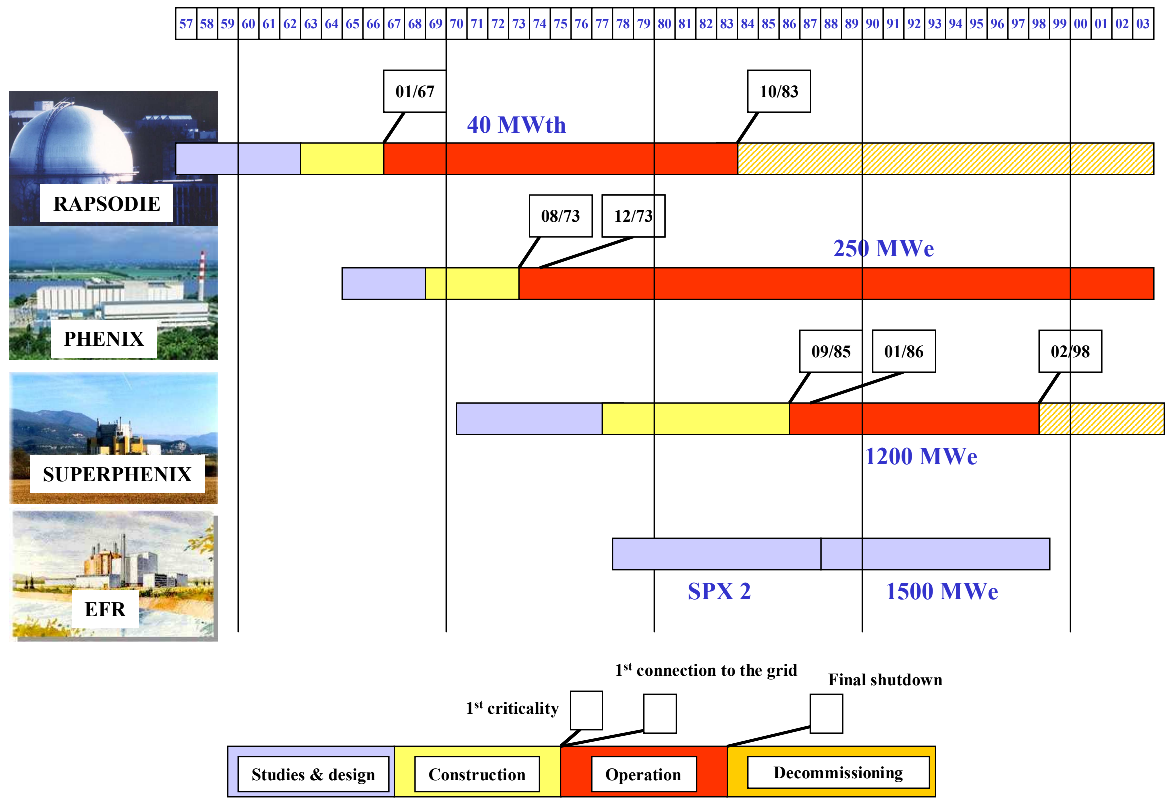

Figure 2: Chronology of the three French Fast breeder reactors and the EFR project

This chronology of French fast breeder reactor developments does not intend to be exhaustive but rather highlight the continuous efforts stretched over more than forty years. It is interesting to note that FBR technology became a European partnership with the beginning of the SUPERPHENIX project.

3. SUPPORTING FAST BREEDER REACTOR R&D ACTIVITIES

3.1. Location

The first R&D studies and tests on liquid metals were conducted in 1953 at the CEA Fontenay aux Roses centre in the Parisian region. In 1958, preliminary comprehensive studies were conducted at the CEA Saclay centre. When the decision to build RAPSODIE on site at Cadarache was made, all supporting sodium technology R&D activities were regrouped in the same location. The CEA Fast Breeder Reactor Department has been established at Cadarache since 1980. Activities at the Saclay Centre focused on material studies, whereas activities at the Grenoble Centre focused on sodium boiling, thermal hydraulics and sodium-water reactions.

Date	Location of CEA sodium technology R&D studies
1953	FONTENAY AUX ROSES
1958	SACLAY FONTENAY AUX ROSES
1960	SACLAY FONTENAY AUX ROSES CADARACHE
1964	SACLAY FONTENAY AUX ROSES CADARACHE GRAND QUEVILLY
1967	SACLAY CADARACHE GRAND QUEVILLY
1970-1985	SACLAY CADARACHE GRENOBLE
Since 1985	SACLAY CADARACHE

Table 2 : Location of CEA FBR R&D studies

Part of the FBR sodium technology R&D activities were led in close collaboration with EDF, which influenced the location chosen for conducting studies. Steam generator development studies for PHENIX and SUPERPHENIX were considered essential by the EDF's R&D Division. The EDF Research Centres in *Chatou* and *des Renardières* (*Moray sur Loing*) actively participated in sodium technology developments with the completion of a high-power thermal test facility (45MW) in 1966[6], [7].

3.2. Research and related resources

It would be rather time-consuming to compile a detailed review of all the fields covered by fast breeder reactor R&D activities, even though the core research topics existing since the beginning of fast breeder reactor construction are few in number. These topics can be grouped into five main themes [8]:

- Core physics and studies.
- Fuel and material studies.
- Reactor safety studies.
- Component design and experimentation studies.
- Studies dealing with sodium coolants and sodium coolant circuits.

The importance attributed to each theme fluctuated with each new breakthrough in the technology over the years. Taking into consideration the regular life cycles of the three reactors over a relatively short time-span, it seems reasonable to assert that efforts were sustained in each field right into the middle of the 1990s. Figure 1 illustrates how fast breeder reactor studies and design were uninterrupted from 1957 to 1998 – the design phases for RAPSODIE, PHENIX, SUPERPHENIX, SPX2 and then EFR all overlap. Construction phases of the three reactors also overlap between 1962 and 1985, as do the operation phases due to PHENIX's long life-span. However, this paper focuses more specifically on sodium-based themes.

a. Reactor studies and design phases (1960 – mid 1980)

With the creation of the fast breeder reactor programme, the main R&D supporting facilities were built at Cadarache at the beginning of the 1960s. The following facilities built on this site are worth mentioning [2] see fig 3 :

- In 1960, construction of the plutonium workshop (ATPu) at Cadarache originally designed to improve future fuels for RAPSODIE was launched and later commissioned in September 1961.
- In July 1961, LECA[1] construction work began. Irradiated fuel from the RAPSODIE reactor was analysed in this building.
- In 1961, the first sodium hall, HR1, was commissioned, followed by a second test hall, HR4, in 1962. These halls are used for full-scale testing of all RAPSODIE components. These halls also contain numerous test benches called sodium loops, specifically designed to improve sodium technologies. A third hall, HR2, was

[1] Laboratoire d'Examen des Combustibles Actifs ≈ Radioactive Fuel Examination Laboratory

specifically built to operate models in water or air in order to study FBR hydraulics and thermal hydraulics [9], a particularly complex element in the FBR integrated concept – RAPSODIE excluded.
- In 1976, the HR1 was extended – called *HR1 bis* – mainly intended for conducting full-scale experiments on future SUPERPHENIX components.
- In 1966, the small reactor, MASURCA, was commissioned to improve neutronic calculation methods used in fast breeder reactor core projects. This facility still operates in 2003.
- In summer 1965, the reactor, HARMONIE, was commissioned. This reactor was built to study materials and radiation – against fast neutrons in particular - protection containments. The final shutdown of HARMONIE was announced in 1996 and is currently in the dismantling phase.
- The CABRI reactor was commissioned in 1963. CABRI was built for safety studies concerning fast breeder reactor core power escalations [12]. CABRI stopped operating for fast breeder reactors in 2001.
- In 1971, the SCARABEE reactor was associated with the CABRI safety programme to study partial/ total fusion of fast breeder reactor assemblies, including fission product and fuel material releases [13]. Tests were conducted in SCARABÉE until 1991.
- In 1981, the ESMERALDA facility was commissioned to study sodium fires and extinction. Between 1981 and 1988, pool-type fires and sodium/concrete interactions were examined, with spray-type fires and mixed fires being tested and analysed between 1990 and 1993. Since 1993, ESMERALDA has been used for studying fires other than sodium fires (hydrocarbon fires, electrical fires and forest fires).

From a sodium technology viewpoint, the first few years were devoted to qualifying the main circuits and components to be implemented in future fast breeder reactors. As the fast breeder reactor programme advanced, feedback from plants in operation influenced the main themes in R&D. Progress made in sodium technologies led to a design and development phase (1960s, 1970 and mid 1980s), then an supporting operational phase in the mid 1970s (PHENIX is commissioned) before the shutdown phase with the decommissioning of SUPERPHENIX in 1998. The series of test benches at Cadarache resulting from fast breeder reactor research in 1983 were: 78 facilities, 38 of which used sodium, 21 used water, 16 used neither water nor sodium, and 3 used a sodium-water combination [14]. Of the 78 facilities, one third were more than 10 years old, one third between 5 and 10 old and the last third less than 5 years old. This calculation does not include laboratory assembly, but does take MASURCA and HARMONIE into account. In 1983, 85 sodium pots were in service: 27 were more than 1 metre in height and 8 were at least 1 metre in diameter.

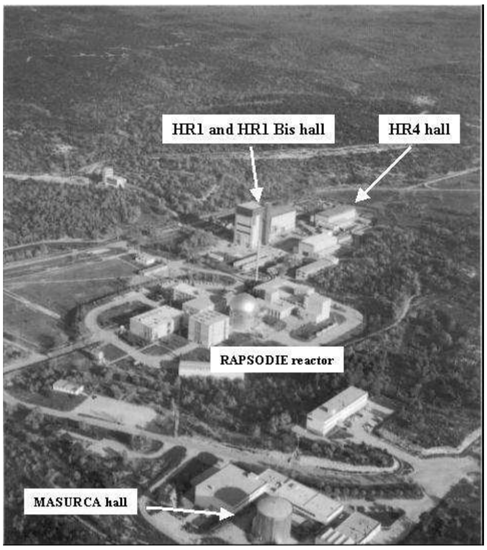

Figure 1: Arial photograph of the fast breeder reactor zone at Cadarache

b. R&D activities supporting fast breeder reactor operation (1980 – 1998)
From the 1980s, sodium technology R&D activities clearly focused on fast breeder reactor operation. Supporting studies were chiefly prompted by:
- integration of feedback from operating reactors with the necessary resources available to improve reactor performances,
- responsive teams specialised in dealing with different incidents occurring in PHENIX and SUPERPHENIX,
- availability of solutions to Regulator safety problems.

The following examples concerning sodium technologies are worth mentioning: sodium purification studies [15], corrosion and contamination product transfers [16], component maintenance (cleaning and decontamination) [17].

As far as response-time to incidents is concerned, it is worth mentioning the two main incidents that occurred in SUPERPHENIX which prompted various developments:

- a fuel storage tank leakage in March 1987 prompted various evaluation studies relating to the mechanisms that provoked the event, as well as studies concerning the possible repair & dismantling of the faulty component [18] before considering the design and development of an in-argon fuel transfer device.
- pollution in the sodium primary loop in July 1990 led to studies concerning 1) sodium quality control rules, 2) procedures to apply to polluted sodium primary circuits and 3) evaluation of the corrosion caused by this exceptional pollution.

Among solutions found to Regulator safety questions concerning sodium control, it is worth mentioning the substantial programmes focusing on sodium fires, detecting sodium leaks under thermal insulation, sodium-water interactions in the steam generators and early detection of such interactions [19] as well as the ISIR[1] programme [20].

In parallel to FBR supporting activities, the CEA also began developing R&D dismantling studies for RAPSODIE which was decommissioned in 1982. These studies no longer specifically focused on sodium technologies, but were oriented towards defining sodium treatment processes considered up until then as radioactive waste. These studies led to the development of a process converting large volumes of sodium into sodium hydroxide in a continuous manner [21]. This process was used on an industrial level for the first time to treat 37 tonnes of primary circuit sodium from RAPSODIE [22]. In 1994 only the emptied reactor primary vessel protected by an argon double containment [23] remained to be dismantled in RAPSODIE.

Various facilities specifically designed for full-scale tests proved to be over-sized and therefore unsuitable for the needs of new programmes. Smaller sodium facilities (limited to 1 tonne of sodium) were built and proved to be easier to operate and more adaptable to a wide range of problems. These small technological test loops outshone the bigger test facilities built in the 60s and 70s requiring an infrastructure and resources that were disproportionate to the end result. From 1993 for example, operating sodium facilities in Cadarache no longer required shift teams. The last operation to date requiring shift teams (in 1994-1995) involved testing a straight tube steam generator using the technological testing facility in the *HRI bis* hall for the EFR project.

c. Consequences of decommissioning SUPERPHENIX (since 1998)

Shortly after the decision to shutdown SUPERPHENIX was made, many R&D programmes supporting SUPERPHENIX's operation or the EFR project were abandoned. Sodium technology R&D studies were therefore re-redirected:

- for safety re-evaluation and restart operations in PHENIX,
- for dismantling operations in SUPERPHENIX.

Supporting activities for PHENIX were numerous and varied including the inspection of the conical shell, core cover plug and hangers [24] [25]; earthquake resistance; sodium fire protection improvements; repairing faulty components (steam generator modules [26], secondary circuits, primary coolant pumps, intermediate heat exchangers).

It is important to remember that dismantling activities carried out on RAPSODIE helped understand FBR dismantling problems and were implemented in SUPERPHENIX. However, the differences in size and concept between RAPSODIE and SUPERPHENIX engendered new problems which require attention [27]. EDF hopes to take advantage of CEA's expertise in order to improve processes specific to SUPERPHENIX dismantling operations [28]. These new requirements led to the commissioning of smaller test facilities requiring smaller quantities of sodium (approximately 10 litres). These "mini-facilities" were built for specific reasons and were immediately dismantled after having obtained satisfactory results.

In 1995, the CEA also began cleaning all dated and inadaptable sodium facility halls no longer in use. From 1995 to 2003, over twenty sodium facilities at Cadarache were dismantled (cf. fig. 4). Most of these facilities were located in the first hall – HR1 – built in 1960 (cf. fig. 5). The CEA aims to completely empty this hall over the next few years and relocate all the necessary sodium loops to the same building (HR4) with other test benches used in R&D studies focusing on different coolants such as lead/ bismuth, helium and lithium. Future R&D activities have been centred on this technological platform designed to study nuclear reactor coolants.

---

[1] Inspection en Service, Intervention et Réparation ≈ In-service Inspection and Repair programme

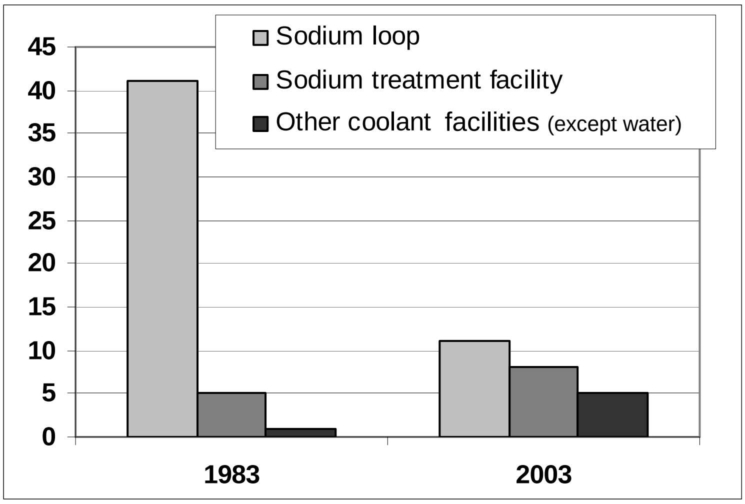

Figure 2: Sodium coolants and alternative coolant solutions used at Cadarache


Figure 3: Inside the HR4 Hall

4. PRESERVING ACQUIRED INSTITUTIONAL KNOWLEDGE

Integrating and preserving knowledge acquired over the past fifty years of fast breeder reactor studies was a constant source of problems for the CEA. Research into sodium technologies has prompted four projects since 1978: the REX project now the ACCORE database, the SYFRA database, the RCC-MR computer code and the MADONA database. This paper only discusses the projects and databases covering a wide range of fast breeder reactor studies. Other databases dealing with specific domains do exist but it would be unreasonable to try and discuss them all in this paper.

4.1. ACCORE data base [29][30]

The ACCORE[1] database was developed in 1990 to manage SUPERPHENIX feedback. The database was originally composed of interviews with experts, before becoming a tool used to access CEA and NERSA fast breeder reactor technical documents: reactor operation (RAPSODIE, PHENIX and SUPERPHENIX) and R&D. This database was completely revised and updated in 1999 and is currently available through the CEA Intranet (available only in French). Each document is catalogued by a reference sheet containing information from the first page: title, abstract, possible key words and other necessary references (author(s), publisher, reference number, publication date…). The full PDF document is accessed using this reference sheet. Links to documents corresponding to key words are included. Data is accessed using a free indexing method. The database currently contains 20,200 reference sheets dealing with fast breeder reactor technology and 2,120 "experience" sheets from 51 interview technical notes and 1,370 resulting from reviewed documents.

[1] Access aux Connaissances Réacteurs ≈ access to reactor knowledge

4.2. SYFRA licensing system

The company SYFRA[1] was created in 1978 by the CEA (60%) and Novatome (40%). The company was founded to manage and transform all knowledge generated by the two companies into industrial licences. Franco-German agreements – the SERENA agreements – signed in 1976-1978 stipulates the decision made by the two European partners to pool their knowledge in the field of fast breeder plants. The main goal behind the SYFRA database – for the French counterparts – was to collect and organise all fast breeder reactor knowledge for all SERENA partners to use [31]. The SERENA agreements produced a fast breeder reactor circuits "book" containing about 1000 documents and 50 computer codes. This collection regroups documents written by experts in specific fields, recommendations and the description of specialised computer codes. The SYFRA database now represents an essential documentary reference in the preservation of acquired knowledge. Access to this database is limited.

4.3. RCC-MR computer code

The RCC-MR[2] computer code was created to define regulations governing FBR design and construction components [32]. The first version of the computer code was finalised in 1985, the second in 1993 and the third in 2002, improved by feedback from activities concerning the PHENIX life-span extension project. The RCC-MR code contains more than 4,000 pages and is divided into 5 sections: description of fast breeder reactor components, materials, examination methods, welding processes and manufacturing [33]. This computer code has been commercialised and can be found in French and English versions.

4.4. MADONA[3] sodium control database [34]

In 2000, the CEA, EDF and FRAMATOME-ANP decided it was important to preserve sodium-cooled fast breeder reactor knowledge collected since the 1960s in a permanent, comprehensive and accessible manner. This database was conceived to enable future fast breeder reactor designers (in several decades time) to access data concerning the design, operation (feedback) and decommissioning of fast breeder reactor technologies to avoid "starting from scratch" in a field where so much ground was covered.

R&D efforts were being dramatically cut back and expertise (specialists) dispersed and declining due to numerous retirements at the time the database was created.

This documentary fund was organised into two complementary structures (see figure 6):

- Firstly, a collection of knowledge acquired during R&D providing a general view of the options available during fast breeder reactor developments: 21 items, 8 of which concern the reactor core and 13 for the nuclear plant,
- Next, information concerning the SUPERPHENIX fast breeder reactor design – a validated industrial size reactor (1200 MW) composed of 9 main systems that can be broken down into 41 elementary sub-systems (system acronyms mentioned in the following figure).

The documentary fund is preceded by an introductory global vision of the sodium-cooled fast breeder reactor design. Each of the 63 different items (1 global vision + 21 R&D themes + 41 SUPERPHENIX elementary systems) is described in a reference sheet. This concise document (10 to 20 pages) includes:

- a brief presentation of the item or system: objectives, required functions, a historical view of studies and processes, reasons behind choices, validation and expertise details,
- a list of sub-items and related subjects,
- the state of art of each sub-theme (commentaries and feedback),
- possible improvements under consideration (R&D perspectives, potential innovation and improvements),
- bibliographical list of documents in the form of a summary (50 to 100 documents). Summaries were used for a clearer presentation of examined physical phenomena without burdening the database with secondary details.

[1] Société de Systèmes Française pour les Réacteurs Avancés ≈ French Advanced Reactor Systems

[2] Règles de Conception et de Construction des Matériels des îlots nucléaires des réacteurs à neutrons Rapides ≈ FBR Design and Construction Material Regulations

[3] Maîtrise des Données sur le sodium (Na)

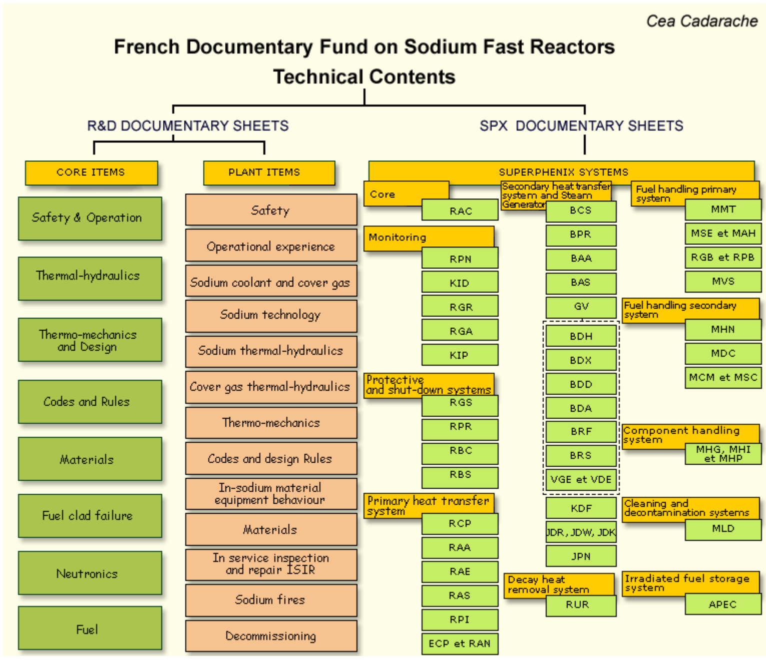

Figure 6: Database architecture

Documents were chosen by specialists and deal with design studies, experiment results, computer models and software programmes, licensing documents, lessons from the Sodium School, minutes from International conferences, expertise, interviews, plans, books and journals… Documentation relating to French reactors – RAPSODIE, PHENIX and SUPERPHENIX –foreign reactors – PFR, BN350, BN600, MONJU – and other projects such as SUPERPHENIX2, RNR1500 and EFR, are well documented thanks to fruitful exchanges and collaborations in the fast breeder reactor field over the decades. The SUPERPHENIX safety report was also included in the French Documentary Fund – 18 files equivalent to a stack of paper two metres high.
The SYFRA Documentary Fund is often mentioned but the documents themselves are not directly available due to industrial property issues; the documentary fund therefore represents a controlled access database (cf. § 4.2) Information contained in the software programmes is preserved through the related documentation.

Documents are archived in two manners:

- on paper (one copy only) as this format is still considered the reference with regard to simplicity and durability. These paper documents are safely conserved by the CEA Archives at Fontenay-aux-Roses (designated by the government as protector of the National Archives),
- computerised format enabling a quick search through the documentary fund from the home page using hypertext links (html format) leading to the document images (PDF images) that are classified according to the selected branch. The fund can therefore be accessed from the different establishments (CEA, EDF, FRAMATOME-ANP). An Intranet server has also been set up. All documents can be found within the fund by means of a key word recognition system based on document titles, authors and references.

Information contained in the documentary fund is confidential and belongs to the CEA, EDF and FRAMATOME-ANP, consistent with the fast breeder reactor technical knowledge protocol dating from 09/02/1990. Reproduction and use of information is therefore strictly limited. 5,240 documents were selected by specialists for the first version in 2002, equivalent to a 50 metre-high pile, 500,000 pages or 20 CD-ROMS (fig 7).

Each document – reference sheet or selected document – has an identification number in the documentary fund. All information recorded during SUPERPHENIX operations is also archived and recorded on magnetic tape (sensor signals recorded in the form of physical parameters).

Figure 7: Image of a CD-ROM from the database

5. TRANSMISSION OF KNOWLEDGE – FRENCH SODUM SCHOOL

The SUPERPHENIX project revealed the growing need to train operators in sodium technology and fast breeder reactor operation. The CEA created a Sodium School at Cadarache in 1975 to teach operators how to run sodium-cooled fast breeder reactors and train safety intervention personnel in dealing with metal liquid fires (fig 8). The course is composed of theoretical and practical teaching units dealing with sodium technologies (2 weeks), sodium practical training (1 week) and sodium safety (three days). The Sodium School is open to all those working in the field of fast breeder reactors. Special sessions were organised for future SUPERPHENIX operators and are still available for PHENIX operators. Training is carried out by CEA staff specialised in each of the specific units. EDF occasionally provides instructors.


Figure 8: Participants of the Sodium course ready for Practical Work

The Sodium School has been thriving for 28 years now. Since its creation, the School has trained about 125 students per year (fig 9). The school's reputation is well-known abroad as specific training units have been organised in English for the Japanese MONJU operators, as well as for non-nuclear organisations using sodium for its chemical properties, such as the UOP company in the United States (fig10). The Sodium School also illustrated its dexterity by being able to adapt to the changing fast breeder reactor industry. In 1997 for example, the School created a new unit called "Managing contaminated sodium/ Dismantling", which specifically deals with fast breeder reactor dismantling phases. It is also important to mention that the Cadarache Sodium School and its Japanese equivalent in Tsuruga near the MONJU reactor have been closely collaborating since 2000. Since 2002, two CEA instructors teach once at year at the Japanese Sodium School.

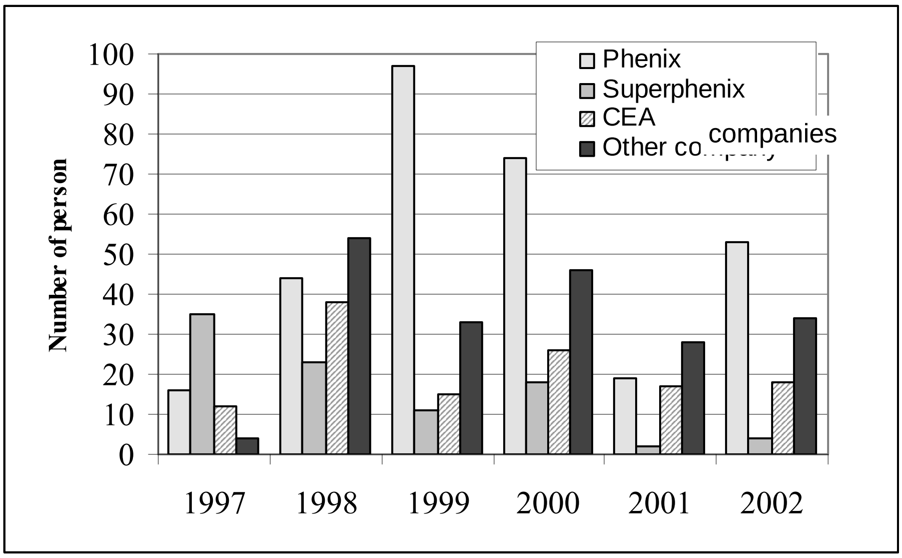

Figure 9: Training courses provided per company from mid 1997 to mid 2003

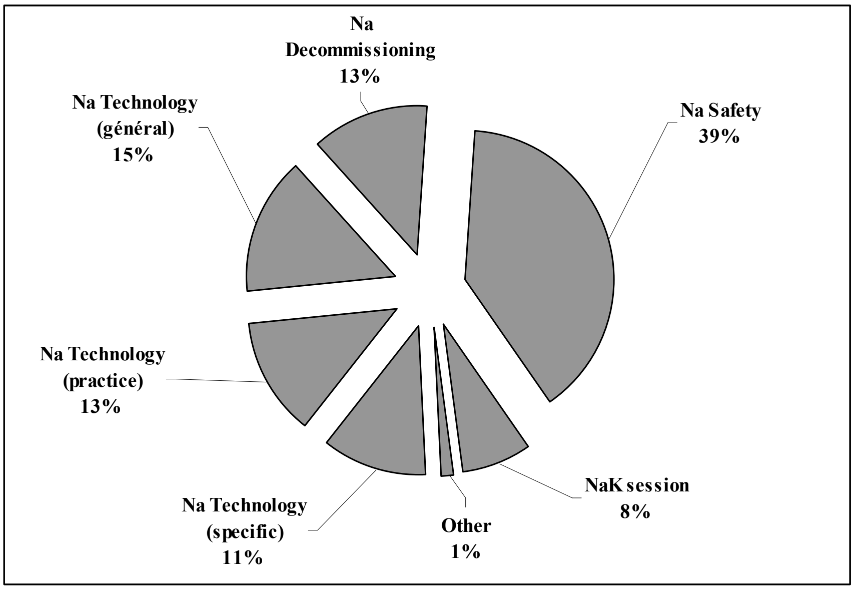

Figure 10: Proportion of different courses from mid 1997 to mid 2003

6. CONCLUSION

The sodium-cooled fast breeder reactor technology was developed in a very sustained and coherent manner in France. Supporting R&D studies had to continuously adapt to the needs and developments of fast breeder reactor plants. The future of fast breeder reactor technology must now be ensured by the integration and preservation of acquired knowledge. This article illustrates how certain approaches have helped preserve such knowledge bases on an international level. From the same perspective, the CEA is currently participating in an IAEA project also focusing on preserving expertise and knowledge [35].

The active participation of the CEA in the Generation IV programme and more specifically the Sodium Fast Breeder Reactor programme will enhance sodium technology knowledge acquired by R&D teams over the last four decades. Progress made in the sodium-cooled fast breeder reactor technology can be considered a scientific success [36] by other innovative and/ or fast breeder reactor technologies.

REFERENCES

[1] : J. LECLERE, B. GIRAUD, G. HUBERT, J.C. LEFEVRE, "Thirty years of fast reactors development in France", ENC'98, Nice, France, Oct. 25-28, 1998, Trans. Vol. IV, pp 31-39.

[2] : G. VENDRYES, "SUPERPHENIX pourquoi ?", Edition Nucléon , Paris, 1997.

[3] : D. BRETON, J. P. CRETTE, R. JANIN, "Les centrales à neutrons rapides. Quel avenir ?", Centre de géo-politique de l'énergie et des matières premières, Université Paris-Dauphine, 1994.

[4] : EFR 98, "Outcome of design studies", brochure EFR associates, 10 rue Juliette RECAMIER – Lyon. France

[5] : P. LE COZ, "Centrale PHENIX : La réévaluation de sûreté de la centrale PHENIX 1994-2003", Brochure de la centrale PHENIX, CEA/VRH/PX, B.P 17171 30207 Bagnols/Cèze Cedex, France.

[6] : M. G. ROBIN et al, "Développement en France des générateurs de vapeur chauffés par sodium liquide", Proceedings of "Sodium cooled fast reactor engineering", Monaco, March. 23-27, 1970.

[7] : J.P. MILLAT, J. BEAUFRERE, P. LECOCQ, M. CHAUVIN, "Circuits d'essais à grande puissance de générateurs de vapeur chauffés au sodium (CGVS), Proceedings of "Sodium cooled fast reactor engineering", Monaco, March. 23-27, 1970.

[8] : H. H. HENNIES, "The French – German – Belgian – Dutch – Italian Breeder research and development programmes", Conference the Breeder reactors and Europe, Organized by l'Association Suisse pour l'Energie Atomique, Luzern, Switzerland, Oct. 14-17, 1979.

[9] : J.P. DUPORT et al, "Incidence des problèmes hydrauliques sur la conception des réacteurs rapides refroidis au sodium", Proceedings of "Sodium cooled fast reactor engineering", Monaco, March. 23-27, 1970, pp 87-104.

[10] : JC ASTEGIANO et al, "EFR Primary Systems Thermalhydraulics Status on R&D and design studies", Proceedings of FR'91, Kyoto Japon, 28 Octobre-1 Novembre 1991.

[11] : G. AZARIAN, JC ASTEGIANO, D. TENCHINE, C. LACROIX, M. VIDARD, "Sodium Thermalhydraulics in the pool LMFBR primary vessel" Nuclear Engineering and Design 124 (1990) 417-430

[12] : G. KUSSMAUL et al, "The CABRI project – overall status and achievements", Science and technology of Fast Reactor Safety, Proceedings of an international conference by the British Nuclear Society, Guernsey, Great Britain, May. 12-16, 1986, pp 103-108.

[13] : A. MEYER-HEINE et al., "The SCARABEE program and the PHYSURA-GRAPPE code – a phenomenological approach for subassembly accidents", Science and technology of Fast Reactor Safety, Proceedings of an international conference by the British Nuclear Society, Guernsey, Great Britain, May. 12-16, 1986, pp 251-256.

[14] : CEA, brochure du Département des Réacteurs à Neutrons Rapides – 1984.

[15] : C. LATGE et al, "Operating experience feedback with start-up purification systems of the SUPERPHENIX and SNR 300 plants, Liquid Metal Technology, LIMET 88, Avignon, France, 17-21 Oct, 1988.

[16] : F. MASSE, G. ROUVIERE, "Activation, corrosion and contamination in fast breeders reactors : validation of models with experimental data, Liquid Metal Systems 2, H. BORGSTEDT, PLENUM Press, New York, 1995, pp 35-46.

[17] : F. MASSE, G. RODRIGUEZ, "Cleaning and decontamination : experimental feedback from PHENIX", IAEA IWGFR Specialists' Meeting on Sodium Removal and Disposal from LMFRs in Normal Operations and in the Framework of Decommissioning, Aix en Provence, France, 3-7 Nov, 1997.

[18] : KERVEGANT. M., POMIE. P., VERDIER. P., FOURNIE. J.L., DAVIOT. J.,"Nettoyage de la cuve et de l'intercuve du barillet de SUPERPHENIX", Liquid Metal Technology, LIMET 88, Avignon, France, 17-21 Oct, 1988.

[19] : J.P. MAUPRE, F. BAQUE et al., "Review of the experimental facilities and techniques used in the sodium water reaction joint European study, Liquid Metal Technology, LIMET 88, Avignon, France, 17-21 Oct, 1988.

[20] : F. BAQUE et al, "ISIR – Inspection en Service et Reparabilité des RNR", Rapport scientifique de la DRN, Edition 1996, Edition CEA.

[21] : N. de SEROUX, C. LATGE, J. ROGER, "Contaminated sodium disposal, NOAH process", SAFEWASTE 93, Avignon, France, 13-18 June, 1993.

[22] : J. ROGER,C. LATGE,G. RODRIGUEZ, "Transformation of sodium from the RAPSODIE Fast Breeder Reactor into sodium hydroxide", International Conference on Decommissioning of Nuclear Installations, Luxembourg, 26-30 Sept, 1994.

[23] : COSTES J.R., ANTOINE P., GAUCHON J.P., "Decontamination before dismantling a fast breeder reactor cooling system", IAEA IWGFR Specialists' Meeting on Sodium Removal and Disposal from LMFRs in Normal Operations and in the Framework of Decommissioning, Aix en Provence, France, 3-7 Nov, 1997.

[24] : L. MARTIN, D. PEPE, R. DUPRAZ, "Lifetime extension of the PHENIX nuclear power plant", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 214 – 258.

[25] : M. GIRAUD et al., "Advance and innovative approaches to inspect the PHENIX fast breeder reactor", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 258-313.

[26] : O. GASLADI, V. GRABON, C. CAVAGNA, "Sodium cleaning in Phenix steam generator modules", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 314 – 337.

[27] : G. RODRIGUEZ, R. FRITH, M. BERTE, "General review of the decommissioning of liquid metal fast reactors in France", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 409 – 461.

[28] : G. RODRIGUEZ, "Recent sodium technology development for the decommissioning of the RAPSODIE and SUPERPHENIX reactors", this scientific review.

[29] : C. EICHENBAUM-VOLIN, S. TAMISIER, "Knowledge engineering on nuclear reactors with the ACCORE system", Document Numérique (éditions Hermès), Vol 1 n°2, pp 189-204., 1997.

[30] : J. LECLERE, S. TAMISIER, "Gestion des connaissances RNR à la DRN : le système ACCORE", Congrès SFEN. Le Parc nucléaire : sa gestion dans la durée, 10-11 Dec1996, Hôtel Adagio, VAUGIRARD.

[31] : K. G. GIESEN, "L'Europe des surrégénérateurs", Publications de l'institut universitaire d'études européennes, Presse Universitaires de France, Paris , 1989.

[32] : R. ROCHE, "French administrative practice and design codes for nuclear vessels", Nuclear Engineering and Design, Volume 129, Issue 3, pp 231-238

[33] : B. RIOU et al., "Present status of the RCC-MR code", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 599 – 618.

[34] : F. BAQUE, "R&D LMFRs knowledge preservation French project", IAEA Technical meeting on Operational and decommissioning experience with fast reactors, Cadarache, France, 11-15 March 2002. pp 694 – 709.

[35] : IAEA, "Consultancy on knowledge preservation in the area of fast reactor technology", IAEA TWG6FR/107, 2-4 April 2002, Argonne National Laboratory-West, Idaho Falls, USA.

[36] : B. BARRE, "Fast breeders : back to the future", ENC'98, Nice, France, Oct. 25-28, 1998, Trans. Vol. IV, pp 70-74.