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ARTICLE

Teaching Sodium Fast Reactor Technology and Operation for the Present and Future Generations of SFR Users

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This paper provides a description of the education and training activities related to sodium fast reactors, carried out respectively in the French Sodium and Liquid Metal School (ESML) created in 1975 and located in France (at the CEA Cadarache Research Centre), in the Fast Reactor Operation and Safety School (FROSS) created in 2005 at the Phenix plant, and in the Institut National des Sciences et Techniques Nucléaires (INSTN). It presents their recent developments and the current collaborations throughout the world with some other nuclear organizations and industrial companies. Owing to these three entities, CEA provides education and training sessions for students, researchers, and operators involved in the operation or development of sodium fast reactors and related experimental facilities.

The sum of courses provided by CEA through its sodium school, FROSS, and INSTN organizations is a unique valuable amount of knowledge on sodium fast reactor design, technology, safety and operation experience, decommissioning aspects and practical exercises. It is provided for the national demand and, since the last ten years, it is extensively opened to foreign countries. Over more than 35 years, the ESML, FROSS, and INSTN have demonstrated their flexibility in adapting their courses to the changing demand in the sodium fast reactor field, operation of PHENIX and SUPERPHENIX plants, and decommissioning and dismantling operations. The results of this ambitious and constant strategy are first sharing of knowledge obtained from experimental studies carried out in research laboratories and operational feedback from reactors, secondly standardized information on safety, and finally the creation of a "sodium community" that debates, shares the knowledge, and suggests new tracks for a better definition of design and operating rules.

KEYWORDS: sodium fast reactors, technology, safety, education and training

I. Introduction

Since the beginning of nuclear development, France has significantly contributed to the development of sodium fast reactors and liquid metal technology. Research programs have always accompanied the design, manufacturing, operation, and also decommissioning phases of several sodium fast reactors (RAPSODIE, PHENIX, and SUPERPHENIX reactors). Moreover, they have also strongly contributed to French projects, such as the European fast reactor (EFR) project, and more recently, the ASTRID prototype.[2,3] Due to the specificities of a sodium coolant, *i.e.*, liquid metal, chemical reactivity, low density, and viscosity, a very dedicated technology has been developed in the various countries involved in the sodium fast reactors since the beginning and then optimized, on the basis of the experimental and operational feedback shared in the conferences, bilateral collaborative agreements, and education and training activities.

The French Atomic Energy Commission (CEA) is in charge in France in the development of specific courses and proposing dedicated education and training sessions related to the sodium fast reactors and more precisely the so-called sodium technology, including physical and chemical properties, safety, technology for transport, and heat exchanges. This study is aimed at providing descriptions of the French Sodium School (ESML) located in France since 1975 (at the CEA Cadarache Research Centre), the Fast Reactor Operation and Safety School (FROSS) created in 2005 at the PHENIX plant (CEA and EDF: French electrical utilities), and the INSTN-Cadarache. This paper presents their recent developments and the current collaborations throughout the world with some other nuclear organizations and industrial companies, related to the education and training for sodium fast reactors.

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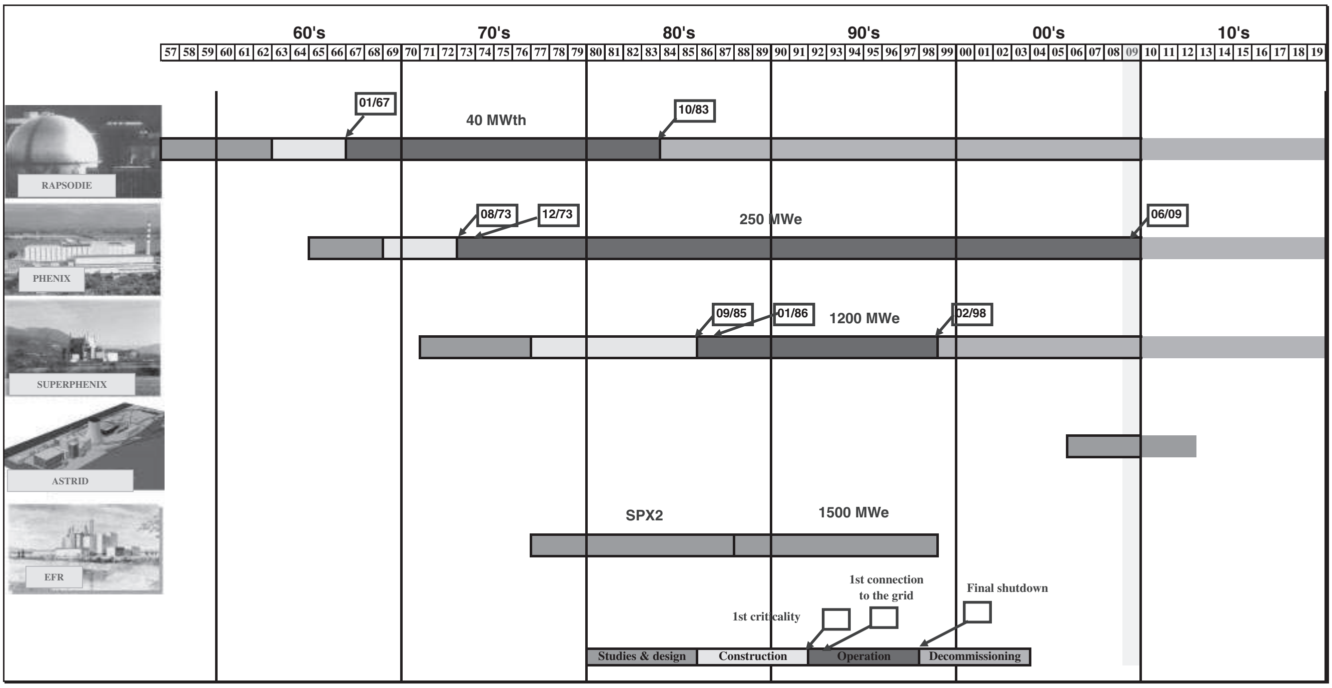


Fig. 1 SFR development and operation in France

II. Brief History of Sodium Fast Reactor Development in France

The very first tests conducted by the CEA using liquid metals date back to 1953. More than half a century later, the CEA has significantly progressed in the field of sodium-cooled fast reactor (SFR) technology. Such progress is reflected in the design, construction and operation of three fast breeder reactors: the experimental reactor (see **Fig. 1**): RAPSODIE; the prototype 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. Since 2007, an important program has been launched by the three partners CEA, AREVA, and EDF in order to develop an innovative SFR concept. The purpose is to reach the construction of a prototype, an advanced sodium technological reactor for industrial demonstration (ASTRID), by 2020.[4)] The whole SFR French program and development can be synthesized in one picture (see Fig. 1). In addition, **Table 1** provides the most relevant news from the past ten years.

III. Cadarache Sodium School

1. CEA Sodium School (ESML): More Than Three Decades of History

The sodium school is located at the Cadarache Research Centre (CEA), which was created in 1959 for nuclear fission activities: it involves three main R&D departments (Nuclear Reactor, Nuclear Fuel, and Nuclear Technology).[1)]

The initial objectives of the sodium school were to

- synthesize knowledge and share it between the CEA experimental facility operators, consequently supporting R&D activities,
- teach operators to work on the sodium fast reactors RAPSODIE and PHENIX,
- form design engineers involved in the SUPERPHENIX Project, and
- train fire brigades.

Its role has always been to adapt its offer and its content to the changing demand for reactor operation, experimentation, design, operation or dismantling.

The sodium school history can be resumed in key dates:

- 1975: creation of the sodium school at Cadarache (training of PHENIX plant teams)
- 1980: accreditation by Electricité de France (EdF), a French national electricity supplier: training of SUPERPHENIX plant teams
- 1984: school opened to foreign companies or utilities (training for SNR300 team — Germany)
- 1995: partnership with French Nuclear Teaching Institute (INSTN)[a]
- 1997: development of modular trainings (10 modules)
- 1998: With the abrupt decision to stop the SUPERPHENIX reactor, the sodium school has defined a new set of modules more orientated towards decommissioning (theory and practice).
- 2000: cooperation with Japan Atomic Energy Agency (JAEA, Japan) to provide 37 lectures at Monju reactor (program scheduled on 1 week per year over 5 years) (see **Table 2**)
- 2005: collaboration with FROSS: training of China Atomic Energy Agency (CAEA, China)
- 2005: collaboration with FROSS: training of Indira Gandhi Centre for Atomic Research (IGCAR, India)

[a] **http://www-instn.cea.fr**

Table 1 Key dates on the French SFR program

	Reactors and project: RAPSODIE — PHENIX — SUPERPHENIX — EFR — ASTRID
1998	- 02/02: governmental decision to decommission SUPERPHENIX/end of EFR project - Authorization to conduct 50th cycle in PHENIX
1999	- September: SUPERPHENIX's primary pumps are definitively shut down - December: beginning of unloading activities in SUPERPHENIX
2002	- The sodium-fast reactor concept (SFR) is retained by Generation IV forum. France participates in the project.
2003	- From 1999 to 2003: inspections and improvements in PHENIX - June: beginning of 51st cycle in PHENIX - 19/03: end of SUPERPHENIX unloading activities (fissile and fertile assemblies)
2004	- August: end of 51st cycle in PHENIX. Other operating cycles are programmed before the definitive shut down of the plant. - Elaboration of the French contributions to the GEN IV SFR R&D program
2005	- August: end of 52nd cycle in PHENIX - October: start of 53rd cycle in PHENIX - Intensification of the R&D on sodium fast reactors and governmental approval of a double track strategy (sodium and gas fast reactors) for industrial deployment in 2040
2006	- January: declaration of President Chirac "*I have decided to launch, starting today, the design work by CEA of a prototype of the 4th-generation reactor, which will be commissioned in 2020.*" - June: end of 53rd cycle in PHENIX — Almost 25 billions kWh produced since 1974 - October: beginning of the 54th cycle; still three cycles to run - From 2002 to 2006: decommissioning of the 52 SUPERPHENIX small primary components
2008	- Carbonation of the four SUPERPHENIX secondary sodium circuits - October: The next French prototype is officially named ASTRID (advanced sodium technological reactor for industrial demonstration).
2009	- June: final shutdown of PHENIX reactor — start of end of life tests - September: official ceremony for the PHENIX reactor end - July: The TNa facility designed to treat the SPX sodium is in operation. - June: After the synthesis of the R&D performed over three years, the design of the ASTRID reactor is started, particularly with the definition of its operating power.

engineers and future operators of the plant under construction PFBR, focusing on the safety.

2. Sodium School Technology Training Objectives

Teaching and training activities on sodium technology are devoted not only to the researchers, the designers, the operators, and the decommissioning staffs but also to firemen: they include technical knowledge on

Table 2 List of lectures provided to JAEA from 2002 to 2006

Title of CEA lecture	Lecture date
Pollutions sources	2002
Quality monitoring	2002
Sodium purification	2002
Operation of cold traps	2002
Hydrogen risks	2002
Cleaning of components after draining	2002
Interventions on circuits for repair	2002
In service inspection and repair: strategy, recent developments	2002
Corrosion with sodium	2003
Contamination in sodium fast reactors	2003
Decontamination in sodium fast reactors	2003
Cold trap processing	2003
Theory of sodium fires	2003
Fires consequences, protections of installations	2003
Safety on sodium facilities	2003
Safety exercise with trainee participation (movie)	2003
Chemical properties of sodium	2004
Physical properties of sodium	2004
Movies on chemical and physical properties of sodium and alkali metals	2004
Technology of circuits	2004
General instrumentation for sodium circuits	2004
Sodium circuit operation	2004
Risks induced on structural materials by cleaning operations	2004
Sodium waste treatment	2004
Interaction between sodium and hydrocarbons	2005
Hydrogen diffusion through walls	2005
Cleaning of subassemblies	2005
Training on cleaning processes (movie)	2005
Ultrasonic monitoring in sodium	2005
Sodium/water reaction in steam generators, hydrogen detection	2005
Sodium leak detection	2005
Experimental feedback of RAPSODIE decommissioning	2006
Experimental feedback of PHENIX in operation	2006
Experimental feedback of SUPERPHENIX in operation	2006
Strategy of sodium fast reactor decommissioning	2006
Chemical and physical properties of NaK	2006
Handling of NaK and safety	2006

- sodium physical and chemical properties, which influence strongly the technology and processes used in research facilities and reactors,
- processes necessary for an efficient and safe operation: filling and draining operations, sodium purification, cleaning prior to repair, inspection, decontamination, and sodium treatment,
- instrumentation for operation and safety,
- design rules for research facilities,
- sodium fires and sodium-water reaction, and
- system descriptions (such as sodium power plant design and operating conditions).

The trainees usually belong to French companies, such as CEA, EDF, and AREVA, and the Safety Research Institute (IRSN), and any companies involved in sodium activities (belonging or not to the nuclear industry). At the early stage of its creation, the sodium school is intended to be opened to foreign countries. As an example, it is highlighted in some specific training sessions for German operators (1983) or Japanese operators for the first start-up of the Monju reactor (90's) or in support to the PFR and DFR decommissioning projects (UK). Some specific sessions were also provided to the chemical industry, *i.e.*, UOP (USA). Moreover, over 5 years, the sodium school in association with the PHENIX plant has extensively increased its opening to foreign institutes, such as CIAE in China, IGCAR in India, and ROSATOM in Russia.

3. Sodium School Means

Sodium teaching is based on the studies of about 35 experts in various fields coming from CEA (25), EDF (5), and AREVA (5). All the CEA people delivering courses at the sodium school are engineers and technicians involved in sodium activities in CEA departments or at the PHENIX plant. Teaching at the sodium school is voluntarily defined as a partial time job to keep a strong connection between recent R&D developments and teaching: this strategy allows first to deliver knowledge based on experimental feedback and secondly to initiate a fruitful contact between specialists and operators or designers. The administrative organization and pedagogical support of the sodium school is provided by French National Institute of Nuclear Science and Techniques (INSTN), which can deliver recognized diplomas. Therefore, the organization implies both INSTN and CEA Nuclear Energy Directorate, as indicated in **Fig. 2**.

All teaching activities are undertaken within the auspices of the ISO 9001:2000 Quality Management system.

Teaching premises are made of a modern teaching room (with video system, computer, and internet connection) for the lectures, several experimental devices (cleaning pit, sodium fountain, sodium dynamic loop called Superfennec, sodium fire cell, and decommissioning hall) for exercise practising, and a collection of technologically specific SFR components plus mock-ups, posters, and samples.

There are ten different sessions (from 1 to 5 day long) focusing on four main purposes:

- physicochemistry of sodium coolant (physical and chemical properties, purification, corrosion, contamination, cleaning, and analysis),

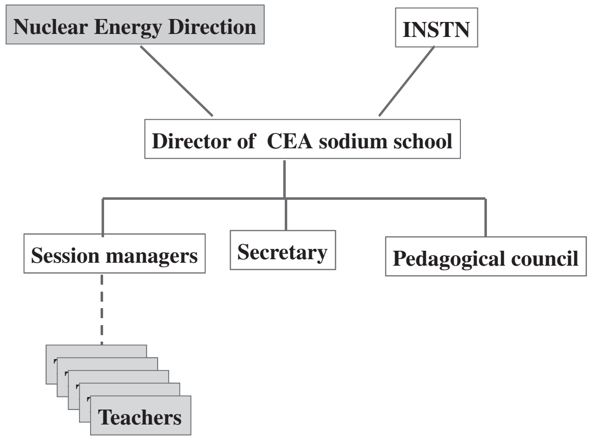


Fig. 2 Cadarache sodium school chart organization

- sodium technology (commissioning and operation, description and operation of components, instrumentation, visualization, inspection and repair, and exercises: operating and intervention on the sodium loop dedicated to education and training),
- sodium safety (specific risks: sodium-water reaction, sodium fires, safety rules, prevention, intervention, and exercise on a real sodium fire) (**Fig. 4**), and
- sodium decommissioning (specific risks, dismantling techniques, sodium treatment, sodium waste storage, and decommissioning of sodium and NaK facilities).

The complete library of courses is composed of about 80 documents, 40 of them being available in English. It is completed by a number of movies and pictures, and by the visit of existing R&D sodium platforms at the Cadarache Center. In **Fig. 3**, one can see the evolution of needs of training since 1997.

4. Pedagogical Approach

Teaching and transmitting the sodium technology knowledge are assumed both through theoretical lectures and practical exercises. The number of trainees for each session is limited: not more than 20 for lectures and not more than 12 for practical exercises (**Fig. 5**). This allows easy and fruitful exchanges and discussions between trainees and teachers: free time is also used for specific cases that the trainees would like to study. The final test of each session checks the proper improvement of each trainee knowledge and understanding of sodium technology.

The teaching activity of the sodium technology specialists is a small part of their job: for most of them, it does not exceed some dozens of hours per year. Of course, the trainees can remain in touch with any of them after the session.

Pedagogical quality is based on the interest of each teacher in the art of teaching and is also improved by specific "teacher training": INSTN proposes such yearly sessions that really transform good scientist into good educators (!).

The pedagogical council is in charge of general education: direction and coherence of the teaching programs, and quality of education (integration of feedback experience). It is composed of nine members (1 INSTN and 8 CEA from the nuclear energy directorate) who meet at least once a year.

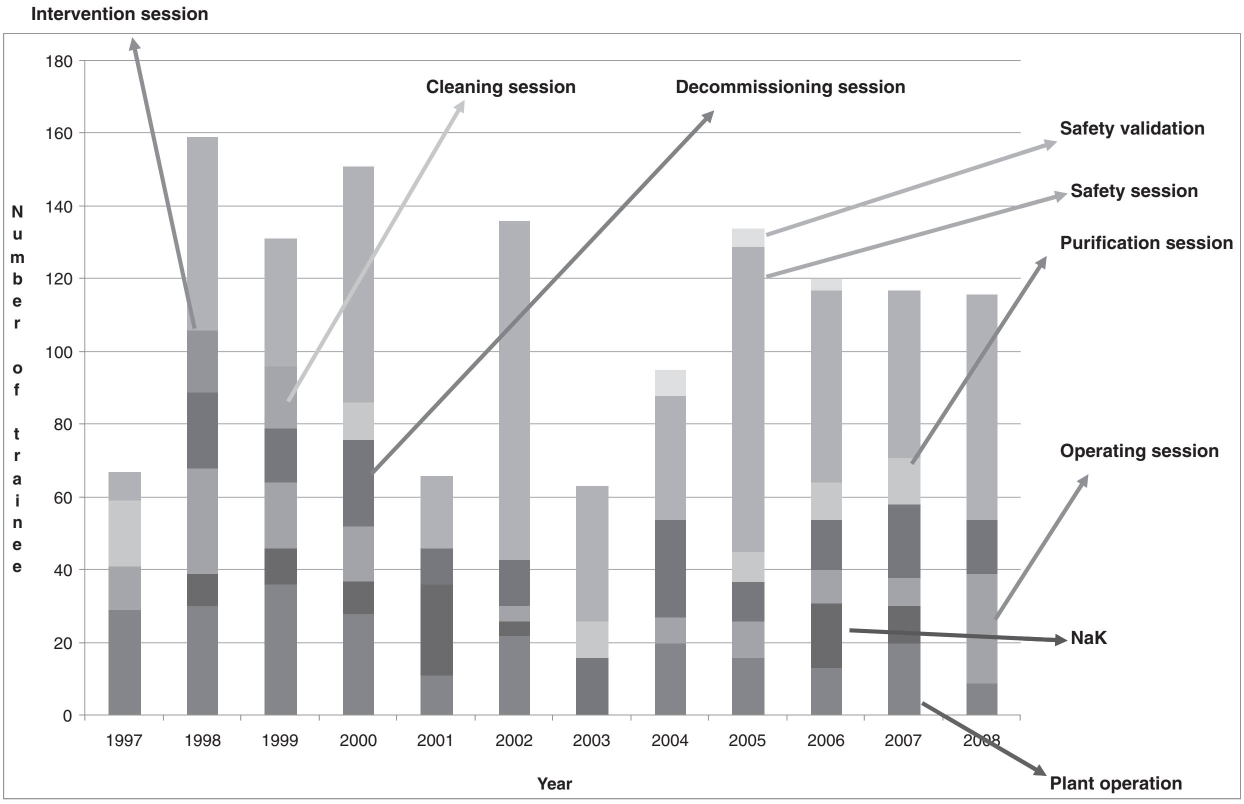


Fig. 3 Numbers of trainees per year and per module

Fig. 4 Trainees operating on a real sodium fire exercise and on the filling of a sodium loop

Since 1975, more than 4,500 trainees have received a training at the sodium school: the present activity corresponds to about ten sessions per year (an average of 130 trainees per year). Due to the evolution of research activities related to the development of the future reactor, ASTRID, there is an increase in the need for training operators of sodium facilities. Moreover, there is a large need to support the increase or activities related to the decommissioning and dismantling of SUPERPHENIX and PHENIX (**Fig. 6**).

IV. Fast Reactor Operation and Safety School

1. PHENIX Nuclear Power Plant: Over Three Decades of History

PHENIX is a prototype sodium fast breeder reactor (FBR), which has been operated for over 35 years: first divergence took place in 1973, and PHENIX delivered, on the French grid, its first kilowatt hours in December 1973. The initial objectives for this prototype were to demonstrate that an FBR is a safe reactor, that it produces electricity efficiently, that it is capable of serving as a breeder reactor, and that it can serve as a tool for increased understanding and further development of this reactor type.

Recent years were marked by significant renovation work following several safety re-evaluations, and operating six cycles with the objectives of carrying out a program of experimental irradiations over a period of six cycles, in the field of transmutation and nuclear waste management, and to provide support for studies on future nuclear reactors (both for fuel and structure materials).

Since its inception, PHENIX has been a joint program between the French Atomic Energy Commission (CEA) (80%) and Electricity of France (EDF) (20%). Both partners contributed proportionally to the plant's operating budget.

Fig. 5 Trainees preparing procedures before operating the circuit

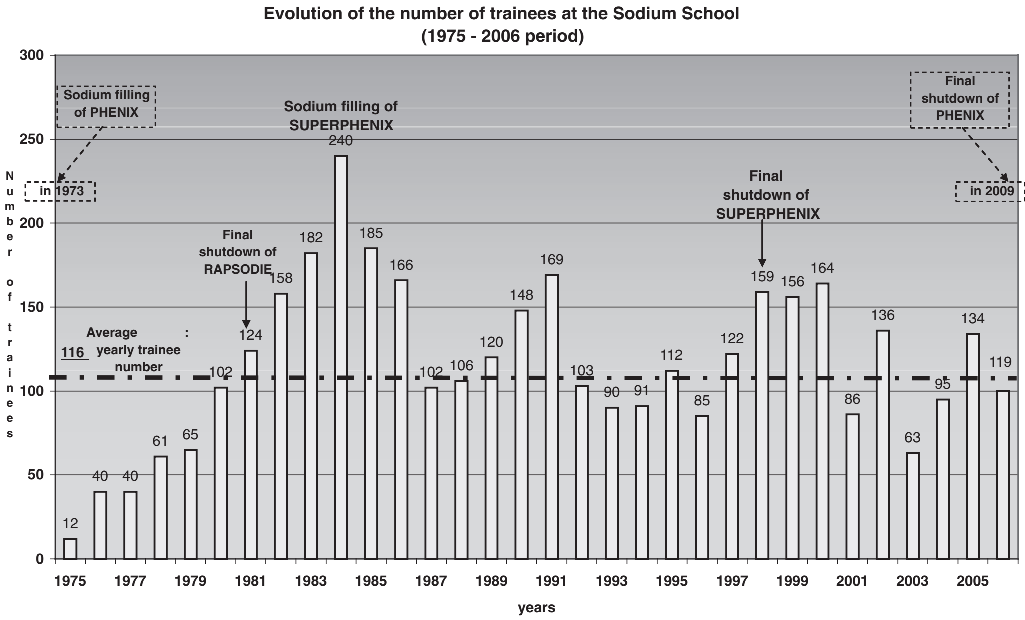
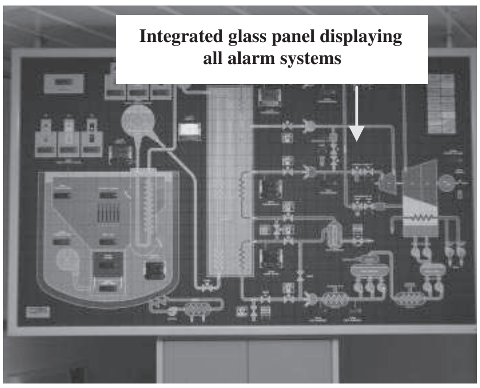


Fig. 6 Cadarache sodium school trainee database from over 30 years



Examples of simulator training courses

- Subcritical approach and criticality
- Reactivity step
- Rod calibration
- Reactor protection
- Feedback effects
- Plant start–up (steam generator in operation)
- Load reduction and normal shutdown
- Scram procedures
- Action to follow in the event of primary coolant pump failure
- Neutronic incidents
- Primary cooling system incidents
- Secondary cooling system incidents

Fig. 7 Mimic board, setup on a stand, graphically representing the main components of PHENIX plant

The personnel (approximately 280 persons) was composed of mixed teams with agents from both companies. CEA manages the joint undertaking and is the nuclear operator.

(1) FROSS Training Objectives

To answer to the training needs of other international partners involved in the development of sodium-cooled fast reactors (SFR), the training objectives of PHENIX-based FROSS are to share Phenix over 35 year experience of FBR operation and provide, in English, a formation on

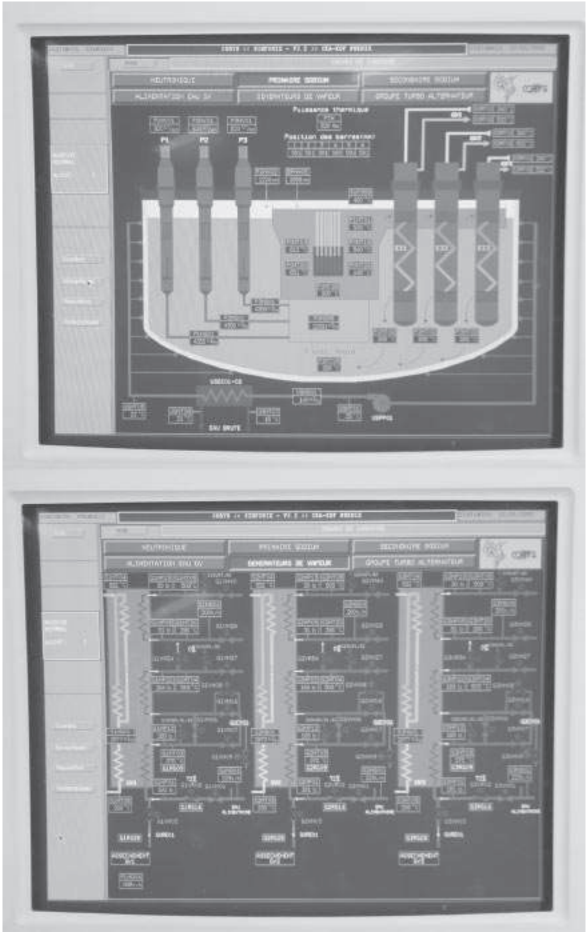


Fig. 8 Examples of computerized boards on operator console

- safety and organizational aspects of SFR operation,
- sodium technology,
- circuit and plant operation, with emphasis on safety and commissioning aspects, and
- normal, incidental, and accidental instructions.

For all the aspects linked with sodium safety and technology, FROSS is associated with the French sodium school, created in 1975 at Cadarache CEA centre, where part of the training takes place. Depending on the initial knowledge and experience in managing installations with sodium coolants, training sessions of 2 and 3 weeks are presently organized. The latter includes 6 days (instead of 2) at Cadarache.

(2) FROSS Means

To fulfill its training objectives, FROSS based the contents of the sessions on

- PHENIX own training program for its operators,
- operating instructions validated (and improved) by more than 35 years of operation, and
- intensive use of the SIMFONIX simulator with over 16 years of teaching experience.

SIMFONIX is a system that simulates the basic principles of the PHENIX power plant (**Fig. 8**). Even if it is not a full-scale simulator, it allows a good display of main parameters and interactions between physical phenomena. Thus, it is used to train the PHENIX personnel how to operate the reactor under normal and incidental conditions (**Fig. 7**).

(3) Pedagogical Approach

It consists of a combination of various educational means:

- lectures, associated with discussions, by PHENIX specialists,
- meetings with plant section managers and staff,
- demonstrations,
- simulator exercises,
- periods with PHENIX operating teams, and
- visits of the plant and some premises.

As for the sodium school, the teaching activity of PHENIX specialists is a small part of their ordinary job, and here also, the trainees can remain in touch with any of them after the session. The ideal number of trainees is 6 (with a maximum of 8) due to practising on the simulator.

Typically, a session includes the following modules:

- ***Welcome***
  - *General presentation of PHENIX, plant tour*
- ***Module 1 Plant organization***
  - *Presentation of the plant sections: operation, maintenance, handling, physics, safety and quality, and engineering: presentations of activities of each section followed by a discussion with the head of the section*
  - *Additional lectures, such as organization of maintenance, overall surveillance, oganization of safety, on-site emergency plan organization*
- ***Module 2 Plant Operation***
  - *Presentation of operating instructions*
  - *Exercises on PHENIX simulator: "Simfonix"*
  - *2 half days with the operating shift teams*
- ***Module 3 Sodium safety technology***
  - *This training is provided at the Cadarache sodium school. It is composed of lectures of general safety aspects of sodium-cooled FRs: presentation of the sodium school, sodium fire, technology, theory of Na fire, fires consequences, protections, safety technology, Na/water reaction in steam generators, H_2 detection, sodium leak detection, safety on sodium facilities, and possibility of visiting some Cadarache Center facilities.*
- ***Module 4 PHENIX accidental instructions***
  - *The module consists of lectures on some of the PHENIX accidental instructions related to module 3: loss of decay heat removal circuit accident, loss of emergency cooling circuit accident, sodium fire in controlled areas, sodium fire in steam generator building, sodium/water reaction in steam generators.*
- ***End of the training***
  - *Assessment of the training and visit of some Marcoule facilities*

(4) Present and Future Activities

Created in 2005, FROSS has, so far, welcome

- 6 sessions for Indian engineers, operators of FTBR, and future operators of PFBR (26 engineers). These sessions were dedicated exclusively to safety.
- 3 sessions for Chinese engineers and future operators of CEFR (24 engineers)
- 3 sessions for Russian engineers from the BN600 reactor (14 engineers) in the scope of the European Commission TACIS program.

More sessions are planned for 2010.

V. Contribution of INSTN-Cadarache for the Sodium Fast Reactors

For the past three years, there has been a new growing interest in the international nuclear community for sodium fast reactor design. In France, a new objective has been defined by the French president to build a GENERATION IV prototype reactor by 2020, called ASTRID. This decision has motivated an important and rapid increase in R&D work, more orientated at the moment to design and concept evaluation. To adjust to this new demand, two new sessions were prepared since 2007, and launched in 2008, within the frame of INSTN, in partnership with the sodium school:

- SFR: history, main options, design and operational feedback, and
- SFR: functional analysis and design.

The duration of each session is one week. The sessions are dedicated to the orientations of the Generation IV forum, the main design options, design through 12 main functions (*i.e.*, core design, reactor design, fuel handling, energy conversion, sodium quality control, monitoring and safety, confinement, inspectability, repair, *etc.*), feedback experience, and a visit to the PHENIX reactor.

On November 23–27, 2009 in Cadarache, the first new European session dedicated to sodium, including physicochemistry, thermal hydraulics, technology, instrumentation, and safety, was organized within the frame of INSTN and the European Commission DG12 (ESFR 7th Framework Project) in partnership with the sodium school and PHENIX.

On November 15–19, 2010 in Cadarache, the second European session dedicated to sodium fast reactors, "ESFR design methodologies, modelling tools and safety," has been organized: 44 trainees from 19 organizations attended this Session (**Fig. 9**). This session provided courses, delivered by 25 lecturers, focused on SFR description, structuring functionalities, design methodologies and modelling tools.

Fig. 9 INSTN training center in Cadarache (France)

VI. Conclusions

The CEA sodium school provides specific and detailed courses on sodium and other liquid metal technologies since the very beginning of the national demand, and over the last five years, it has extensively opened its qualification to foreigners. Over nearly 35 years, this organization has demonstrated its flexibility in adapting its courses and practical exercises to the changing demand in the sodium fast reactor field. Since 1975, about 5,000 trainees have joined the sodium school at Cadarache, the FROSS school at Phénix, or dedicated sessions at INSTN-Cadarache.

This education and training strategy is a key element of the future development of sodium fast reactors, more particularly the ASTRID project. The three entities aimed to deliver training sessions, *i.e.*, the sodium school in Cadarache, FROSS, and INSTN-Cadarache, are also ready to collaborate with other foreign education and training entities, as it is already the case with the Japanese sodium school.

Acknowledgements

Authors would like to thank all the people involved in the three education and training entities (administration, teachers, and operators). Thanks to them, these schools are alive and attractive.

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