Review of the Experience with Worldwide Fast Sodium Reactor Operation and Application to Future Reactor Design

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18 sodium-cooled fast reactors (two of which use sodium-potassium coolant) have been operated or are currently in operation throughout the world. These reactors account for a cumulative 385 years of operating experience.

This article summarises the incidents and problems encountered during reactor operation, classifies them on a functional basis, and describes the solutions implemented to such events.

It also briefly describes how this experience has been taken into account in the design of future reactors.

1. INTRODUCTION

This article solely focuses on operating problems occurring in the "sodium" part of the fast reactors. The difficulties experienced in the classic water/steam part of the reactor are not described.

The work is based on the voluminous existing data base. There is significant feedback from experience for the reactors which are now shut down (PFR, KNK II, DFR…).
In particular, NERSA established routine reports on these reactors, which were then applied to Superphenix.
A similar approach was undertaken by AREVA-NP within the scope of the EFR studies.
The AIEA, through the Technical Working Group – Fast Reactor (TWG-FR) has also contributed to capitalising on feedback experience.
Lastly, within the scope of the bilateral relations maintained with other fast reactors in the world, the Phenix power station disposes of regularly updated data.

2. FAST SODIUM REACTOR OPERATIONS REVIEW

Table I presents the assessment of fast sodium reactor operations in the world, from the start to the present time.

As a reminder, the first nuclear reactor to produce electricity was a sodium-potassium cooled fast reactor in 1951, EBRI I in the United States.

The white column shows the reactors which have since been shut down. Dark green shows operating reactors, and light green the three reactors currently under construction in India, China and Russia.

The cumulated operating experience from 18 reactors comes to 385 years, a value that can serve as an order of magnitude. Indeed, this 385-year time period includes by definition the stoppage periods during unavailability due to technical or administrative reasons. Moreover, experience from some of these reactors remains limited due to their small size and the absence of steam generators.
Nevertheless, this cumulated experience remains highly significant and has already widely supplied feedback which has been integrated, from Rapsodie to Phenix, from Phenix to Superphenix, then the EFR project.

The present analysis is based primarily on the French reactors Rapsodie, Phenix and Superphenix, the British reactors DFR and PFR, the German KNK II reactor, the FBTR in India, the Russian reactors BR 10, BOR 60 and BN 600, the Kazakhstan reactor BN 350, and Monju in Japan.

Table 1

FAST REACTORS OPERATIONAL DATA 2007				
Réacteur (pays)	**Reactor power MW Thermal (Electrical)**	**First criticality**	**Final shut-down**	Operational period (years)
EBR-I (USA)	1.4 (0.2)	1951	1963	12
BR-5/BR-10 (Russia)	8 (0)	1958	2002	44
DFR (UK)	60 (15)	1959	1977	18
EBR-II (USA)	62.5 (20)	1961	1991	30
EFFBR (USA)	200 (61)	1963	1972	9
Rapsodie (France)	40 (0)	1967	1983	16
BOR-60 (Russia)	55 (12)	1968		39
SEFOR (USA)	20 (0)	1969	1972	3
BN-350 (Kazakhstan)	750 (130)	1972	1999	27
Phenix (France)	563 (250)	1973		34
PFR (UK)	650 (250)	1974	1994	20
JOYO (Japan)	50-75/100 (0)	1977		30
KNK-II (Germany)	58 (20)	1977	1991	14
FFTF (USA)	400 (0)	1980	1993	13
BN-600 (Russia)	1470 (600)	1980		24
Superphenix (France)	3000 (1240)	1985	1997	12
FBTR (India)	40 (13)	1985		22
MONJU (Japan)	714 (280)	1994		13
CEFR (China)	65 (25)	En construction (2009)		
PFBR (India)	1250 (500)	En construction (2010)		
BN-800 (Russia)	2100 (880)	En construction (2012)		
			Total	385

3. STEAM GENERATOR OPERATIONS (SODIUM/WATER REACTIONS)

All the first-generation steam generators (SG) experienced sodium/water reactions, summarised in the following table. Superphénix and FBTR however are exceptions, and never had sodium/water reactions.

	PHENIX	PFR	BOR 60	BN 350	BN 600
Nombre de réactions sodium/eau	5	21	1	Nombreuses fuites dans les premières années de fonctionnement du réacteur, 3 après 1980	12

Although the sodium/water reactions corresponded to different SG designs, three types of causes can be defined.

* Manufacturing problems
  Several sodium / water reactions occurred at sodium-filling or shortly afterwards, due to constructional faults, in particular on the Russian reactors.
  At the PFR reactor, a crack was found in a sheet metal/plate weld during filling (1976).
* Fatigue cracks
  The combination of a design flaw or inappropriate operating procedures led to thermal shocks and mechanical fatigue. Fatigue cracks can initiate sodium/water reactions. This was the case for the first 4 reactions at Phénix where the spurious arrival of cold water in the reheater during start-up caused fatigue cracking.
* Corrosion
  Corrosion phenomena can lead to a surface-breaking crack and a sodium/water reaction. This was the case for the PFR, where repeated corrosion occurred at the tube/plate junctions.

Phenix – Initrating defect on the steam tube of steam generator – Sodium/water reaction n°5

In all cases, the pressurized steam jet increased rapidly. In reacting with the sodium it created a torch whose inner cone can quickly bore through the nearby steam tubes of the SG shell (wastage effect).

In some cases, these early sodium/water reactions caused significant damage due to the relatively too long response time before detection and the time to drain and blanketing of the SG.

Examples of sodium/water reactions :

- The 1st sodium/water reaction at Phenix: 30 kg/water injected. Improvements made resulted in limiting the injections during the 4 following reactions between 1 and 4 kg.
- The reaction which occurred in February 1987 at PFR, in the main section of the #2 superheater tube, where a tube cracked following bundle vibrations. Holes were bored into the 39 tubes around the initial tube during the 10-second time it took to lower the steam pressure. The corresponding rise in pressure in the secondary sodium circuit caused the burst diaphragm to rupture.
- Significant sodium/water reactions occurred on BN 350 and BN 600 (the biggest event took place in January 1981 with 40 kg of water injected).

The lessons learned from these incidents, for incorporation on future reactors, are as follows :

In terms of protection :

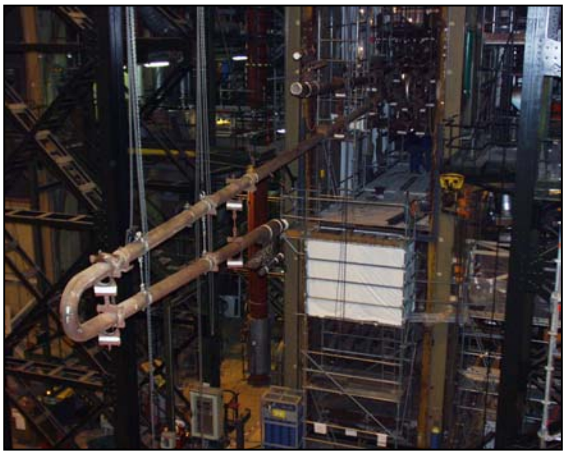
- Indispensable : reliability and rapidity of the hydrogen detection system.
- Automatic shutdown accompanied by rapid depressurisation on the steam side.
- Design of a casing around the self-supporting SG, capable of confining even the most violent sodium/water reaction.
- Existence of security membranes to limit any pressure increase.

In terms of prevention, several requirements must be combined :

- Better thermo-mechanical design.
- The right materials.
- Extreme quality in manufacturing (100% inspection, non-extended welds, etc…).
- Precautions in use (prevention of spurious thermal shocks, circuit well-protected during drainages, etc….).

It should be pointed out that Superphenix, where the SG benefited from this feedback, did not have any sodium-water reactions. However reactor lifetime did not allow for definitive validation of this component.

Likewise, since 1991, BN has had no further sodium/water reactions.



Phenix : disassembling of a SG module for repair

4. OPERATION OF PRIMARY COMPONENTS (PUMPS AND EXCHANGERS)

These components displayed excellent operations.

The following observations are made :

- For the Phenix exchangers, an initial design defect which was corrected on Phenix and on all the following rapid reactors,
- For the pumps, a technological defect on the hydraulic bearing of the Phenix pumps (bearing ringed on the shaft, falling during a hot thermal shock) and a filter problem on a PFR pump during a major oil loss in the primary sodium.

In conclusion, these components operate well and pose no particular problem for future reactors.

Transfer flask for large primary components in position on reactor top

5. HANDLING OPERATIONS

Blind handling of the core elements in sodium, occurred well overall for all the reactors.
The single serious incident was a spurious rotation of the core cover plug during a sub-assembly handling on FBTR in 1987, which led to deformation of a fuel sub-assembly and a guide tube.
Manufacture of special devices created to shear them then remove them led to reactor shutdown during two years.

In conclusion, and under the condition of the use of an effective core cover plug ultra-sound vision system (visus), sodium handling operates satisfactorily.

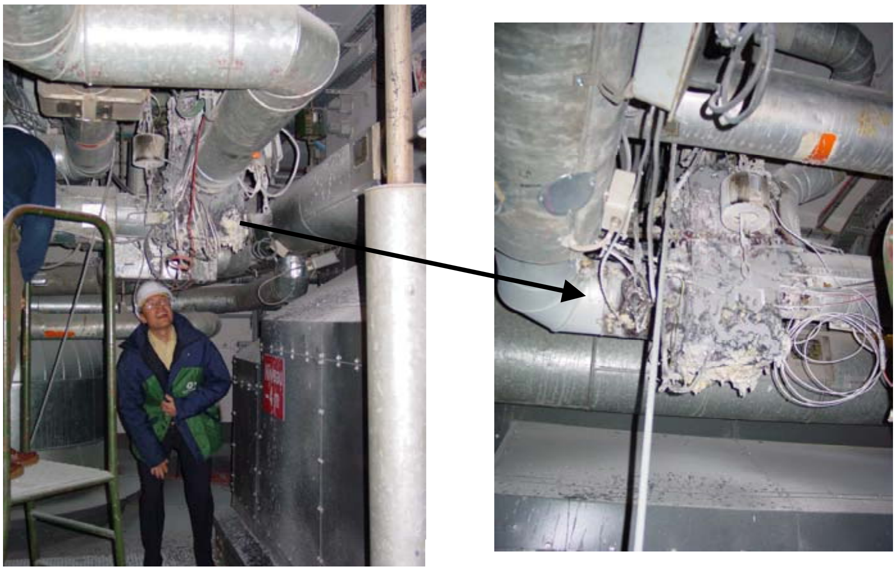
6. SPURIOUS LEAKS OR TRANSFERS OF SODIUM

* Sodium leaks

Several sodium leaks took place on the installations, sometimes leading to sodium fires.

	PHX	KNK II	PFR	BR5/ 10	BN 350	BN 600	MONJU
Sodium leaks nb	29	5	≥ 40	18	15	27	1

The most serious sodium leak, in terms of the consequences, occurred at Monju (approximately 640 kg of Na), which resulted in reactor shutdown during more than 12 years.



Examination of the circuit after a sodium leak located on a valve bellows

These leaks involved very different volumes of sodium. Some involved less than one gram (detected during inspection) and others were massive (BN 600, 2 leaks greater than 300 kg and one involving 1000 kg).

These sodium leaks can have many very different origins :

- Constructional defects,
- Design problems, such as the Monju thermocouple thimble,
- Materials problems, such as the example of 321 steel stress cracking,
- Thermal crazing at the mixing tee level, leading to through cracks,
- Corrosion following air intake into the circuits (one example),
- Operator error (for example, during thawing of the circuit and the corresponding expansion of the sodium),

Lessons have been learned from these incidents in terms of design, circuit operating procedures, leak detection and protection from sodium fires.

The two latter points have led to the following :

- Diversified, redundant detection instrumentation (bead detector, sodium aerosol detector, smoke detector, camera….),
- Need for rapid drainage of the sodium circuits,
- Sectoring around the sodium areas to limit the quantity of air available in the event of a possible fire,
- Insulation protection of the concrete floors and walls, covered with a metal plate,
- Possibility of nitrogen blanketing of the areas involved.

7. INTAKE OF AIR OR IMPURITIES

In a sodium reactor, avoiding the intake of air or impurities into the circuits is of utmost importance. Under certain conditions, these pollutions can start mechanisms of stress-corrosion cracking.
Outside of the many ongoing operational problems that this constraint entails, in particular for conservation of the circuits during drainage, there were three significant incidents in this area.

- Superphenix
  Significant air intake occurred in July 1990, in the primary circuit, due to a defective membrane on a compressor sending air flow to the reactor cover gas. A major purification campaign, through to September 1991, was required to restart the reactor.

- PFR
  Significant oil intake (approximately 17 litres) occurred in June 1991. This resulted in partial clogging of the pump filter, and was detected by temperature variations at the core outlet. An 18-month shutdown was required to recondition the reactor.

- BN 600
  In 1987, the BN 600 reactor underwent a brief transient at rated power. On 21 January, during 7 minutes, with the reactor at rated power, changes were noted in several parameters: sodium level, core reactivity, reduced power at the pumps….
  After analysis, the incident was attributed to the drop of a chunk of impurities from the reactor roof, formed at the top by contributions from poorly purified gas. These

impurities, which suddenly fell in a block, disturbed core hydraulics and neutronics.
This event then later caused several clad failures and reactor shutdown. Since this time, gas leaks in the core cover gas have been minimized, and more advanced purification takes place. This phenomenon has not occurred again since 1987.

Feedback from such incidents, for the future, has of course shown the need for proper surveillance of the quality of the inputs from core cover gas, and a pump design which precludes oil drops (intermediary recovery).

8. EXPERIENCE FROM FUEL AND CLAD FAILURES

Most of the reactors used uranium oxide and plutonium fuel, with excellent feedback experience.
However other fuels were used, such as enriched uranium (BN 600), carbide fuel (FBTR), and metallic fuels for the American reactors.

For all of these fuels, the progress made on clad materials has gradually led to eliminating clad failures and significantly increasing burnup.

On the subject of the KNK clad failures, these were due to the use of grids instead of spacer wires. Since that time, all fast reactors use spacer wires to separate the pins.

The following table summarizes the occurrence of clad failures :

	PHENIX	PFR	BN 350	BN 600	KNK II
Nombre de ruptures de gaines	15	21	grand nombre en début de vie	grand nombre en début de vie	5

In conclusion, this field is a strong point for this reactor type, and R&D seeks to make further progress in this field through the use of new cladding materials.

9. NEUTRONIC OPERATIONS AND CONTROL

Several characteristics intrinsic to the fast sodium reactor type result in straightforward reactor operations and wide safety margins :

- Self-stabilising thermal counter-reactions,
- The absence of any fission product poisoning phenomena,
- No use of neutronic poison for reactivity control,
- High thermal inertia from the volume of primary sodium;
- Very low fluid pressure.

There are no particular problems or difficulties to report from the operations of all the reactors.
However, core sensitivity to reactivity variations, during movement of the sub-assemblies, should be pointed out.

On FBTR, this led to positive reactivity variations through repositioning of the core at reduced power. These events have been explained and are reproducible.

At Phenix, core compacting is impossible (sub-assembly contact at the level of the sub-assembly wrapper tube plates level). However, radial outward movement is mechanically possible and leads to negative reactivity variations.

Such reactivity transients occurred at Phenix in 1989 and 1990. The investigations into the mechanism leading to the radial outward movement have developed explanatory scenarios which are currently undergoing validation.

10. MATERIAL PROBLEMS

The prototype aspect of these reactors served to validate the use of many materials, and to continually improve materials. One example is the move to ferritic steel for fuel sub-assembly wrapper tubes, which eliminated the swelling in the sub-assemblies. The example of the BOITIX experiment at Phenix reached a dose of 155 dpa.

The two biggest problems encountered in this area were the following :

- Use of 321 austenitic steel
  Used extensively at Phenix and PFR, this steel showed cracks over time corresponding to residual welding stresses, particularly in the hot areas.
  As a result, all the 321 parts at Phenix were gradually replaced. Many successive repairs were made to the PFR steam generators, and all the parts made of 321 on existing reactors are closely monitored.

Phenix : repair of the SG sodium inlet header

– The Superphenix drum
  Rapid cracking on the Superphenix drum led to abandoning this material (15 D3 steel) for use with sodium.

Today there is a range of approved materials, however, development of new materials remains one of the promising directions for improvement for this reactor type.

In particular, there are the oxide-dispersion steels (ODS), which could result in reaching a dose of 200 dpa for the clads, or the secondary circuit materials, with reduced expansion.
Qualification of these materials remains to be done.

11. SODIUM AEROSOLS

Convection movement of the reactor cover gas from the lower sodium hot areas near the sodium surface, to the colder zones carries sodium aerosols which can deposit on the upper parts of the reactor.

This phenomenon has led to several operating constraints. All the reactors the world over have experienced problems related to deposits of sodium aerosols.

Two particular events are cases in point :

– On BN 600 in 1997, significantly greater efforts were required to move the rotating plug.
  Analysis showed large deposits of aerosols on the bearings (and in the bearing cage). The system was disassembled and cleaned.

– Control rods
  On several reactors (PFR, KNK II, Phenix….), aerosol deposits led to partial blocking of the control rod.
  These incidents led to design changes, to improvement of the monitoring instrumentation and operating procedures, including, among others, periodic verification tests of the control rods performed on the reactor in operation.

12. CONCLUSION

Fast sodium reactors have now built up significant feedback experience in the fields of materials, design, sodium technology and operating modes.
Analysis of reactor availability factors has shown that availability has been affected by the difficulties inherent in the role as prototypes. However, once this burn-in work on initial design errors has been accomplished, these reactors show outstanding ease of use and reliability.

Operations with the BN 600, once steam generator problems and early fuel behaviour problems were solved, are an excellent case in point. Since 1990, the BN 600 has continuously displayed load factors around the 80% level.

Similarly, Phenix has made significant contributions to this reactor type, by successively modifying component design (heat exchangers, pumps …), operating procedures and core materials.
The reactor's average availability factor over the first 17 years of operation was 60%. Since the reactor started back up in 2003, after the renovation phase, availability factors have been 75, 86 and 78 %. Production losses are nearly exclusively attributed to the classical part of the reactor (electricity production installation).

This experience, applied to the design of future reactors, represents significant progress toward reaching the objectives of good performance, competitiveness and reliability assigned to this reactor type.