PHENIX OPERATION FEEDBACK AND APPLICATION FOR THE FUTURE.

J GUIDEZ Director of Phenix plant from November 2002 to december 2007

Milestones in the French FBR development

→ FBR reactors in France

RAPSODIE : 40 MWth reactor

PHENIX : 563 MWth/250 MWe nuclear plant

SUPER-PHENIX : 3000MWth/1200 MWe nuclear plant

EFR Project

ASTRID Project

→ Background on PHENIX

Construction: 1963 to 1973

First Criticality: 31 August 1973

Grid connection: 13 December 1973

Commercial Operation: 14 July 1974

End of commercial operation : 06 March 2009

PHENIX ORGANIZATION

- **CEA is**
  - ✓ **the owner**
  - ✓ **the nuclear operator**

  of PHENIX plant

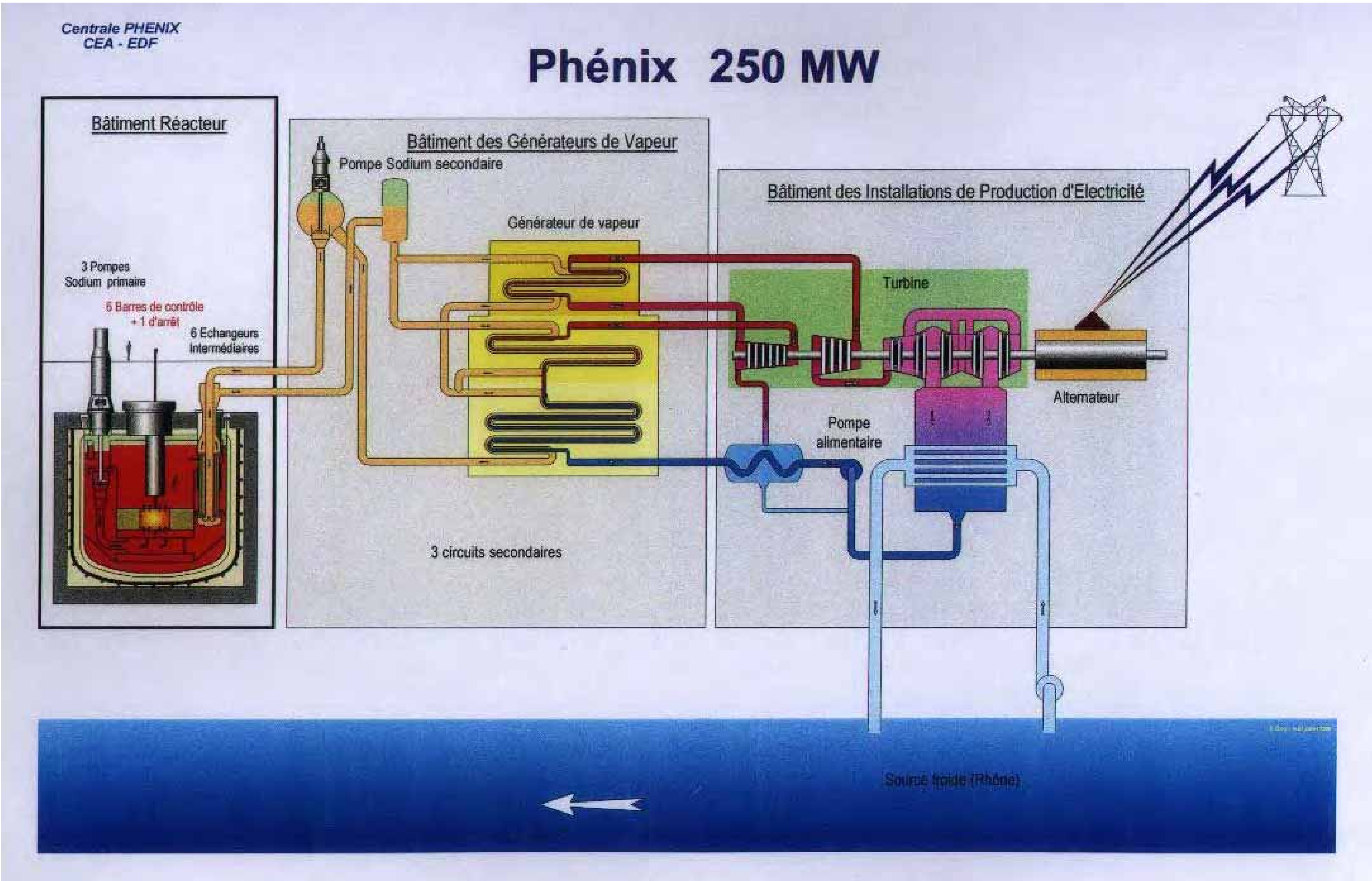
The plant is operated by an association composed of :

- ✓ **CEA for 80 %**
- ✓ **EDF for 20 %**

The total personnel of the plant is 280 with a same participation of CEA and EDF:

- ✓**210 CEA**
- ✓**70 EDF**

Plant Diagram



Reactor Block

Pool type primary circuit

3 primary pumps

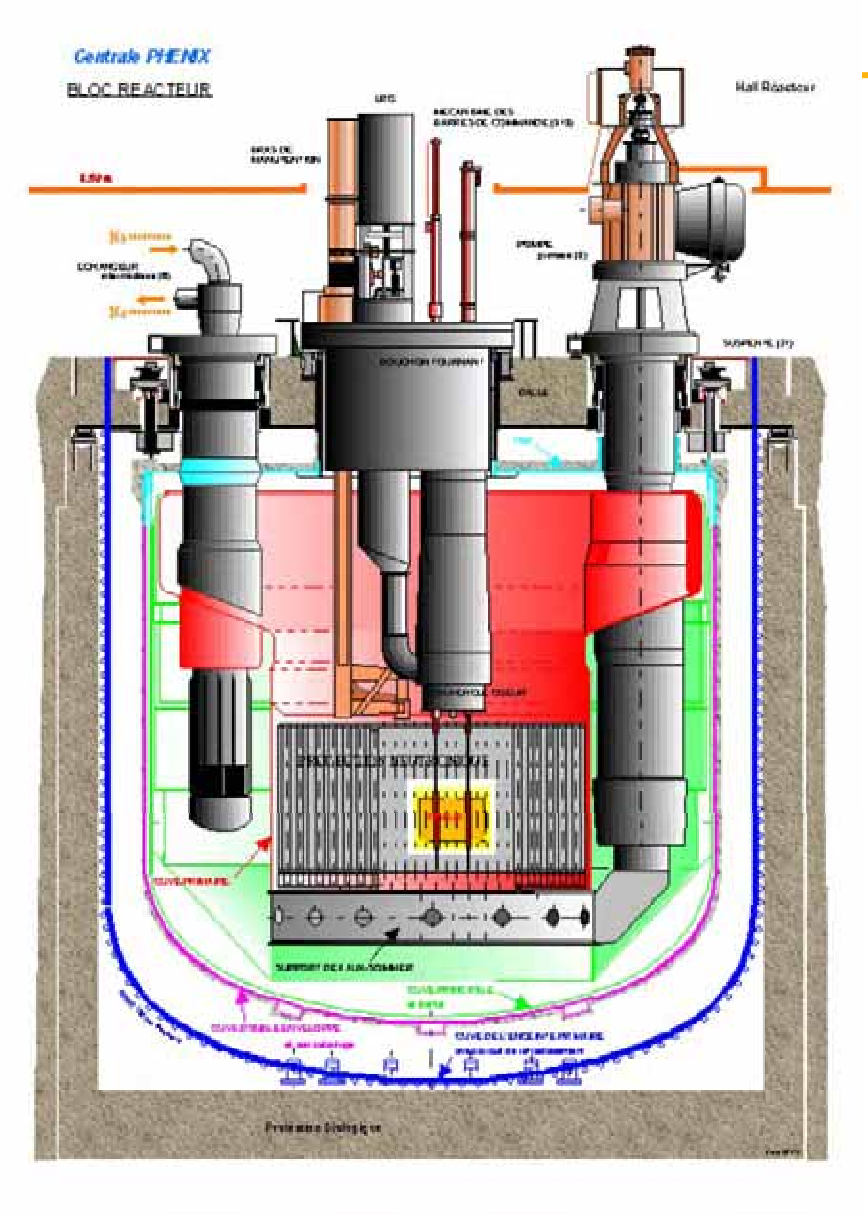
6 intermediate heat exchangers (563 Mwth)

7 Control rods:

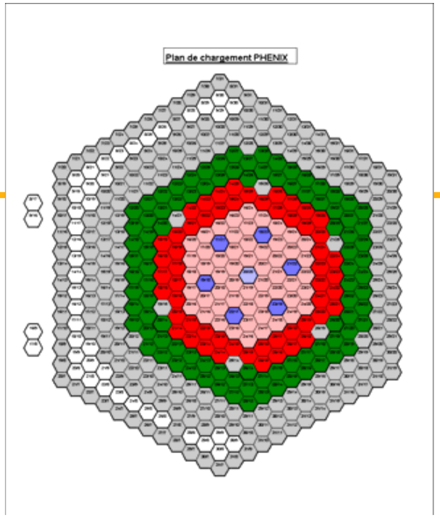
- 6 rods for power control, burn-up compensation and shutdown,
- 1 safety rod (shutdown)

temperatures :
400 - 560°C (563 MWth)

main vessel diameter :
11,8 metres



Reactor Core



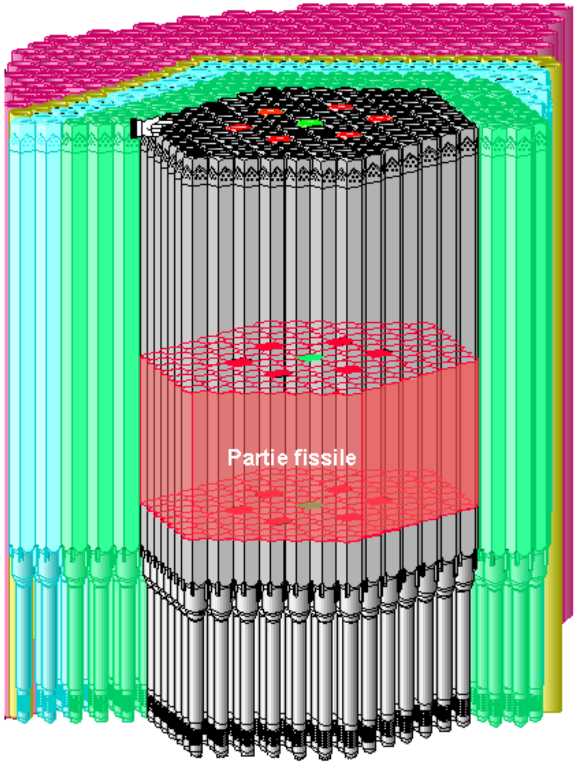
Driver fuel S/A : 217 pins, 6.55 dia., 1515 titanium stabilised stainless steel clad, wired spaced, ferritic wrapper

Mixed oxide fuel UPuO2

Pu total enrichment:

Inner Zone: 23 %

Outer Zone: 28 %



Nb of fuel SA: 106

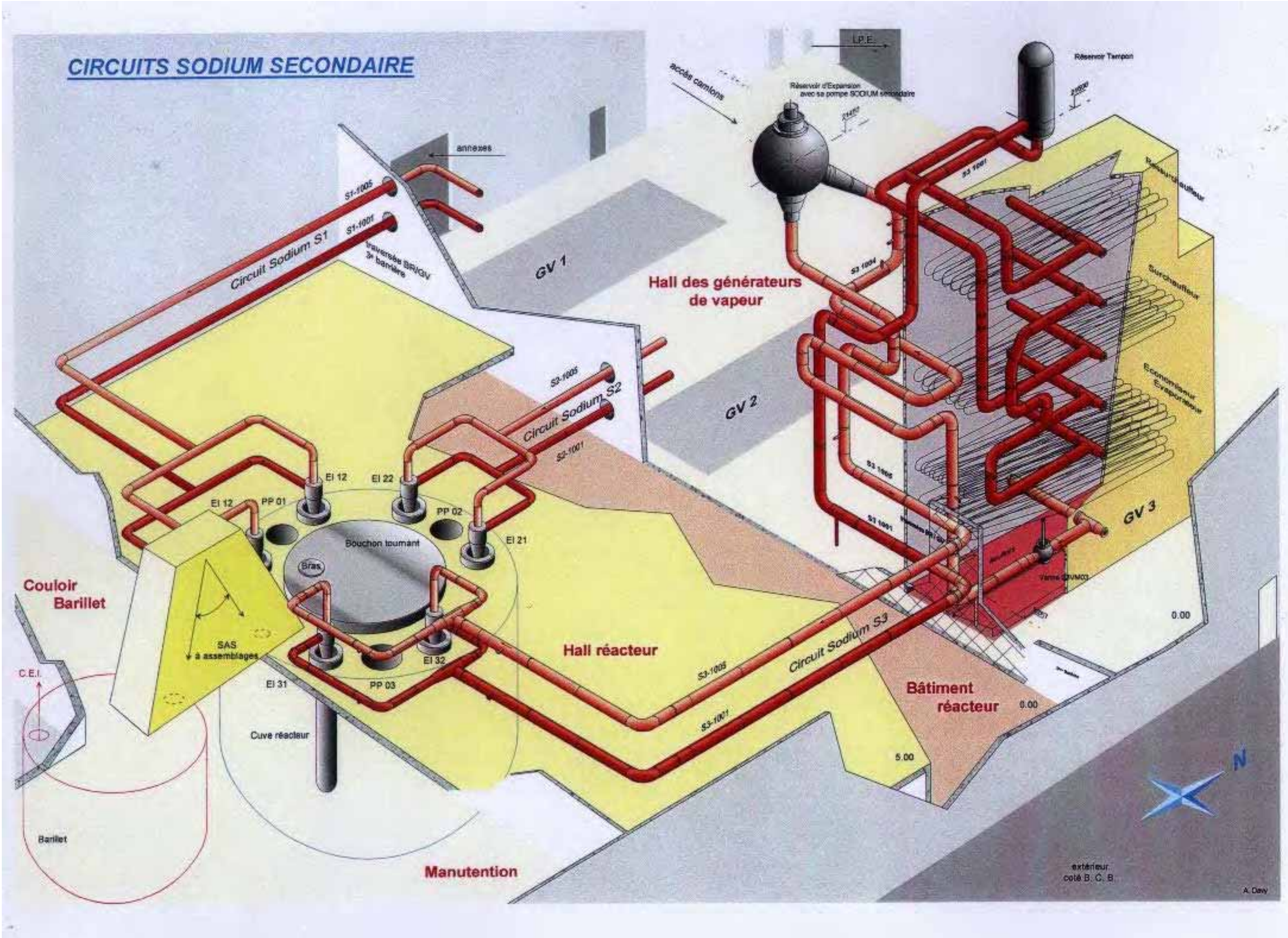
Nb of Breeder SA: 86

Max neutron flux :

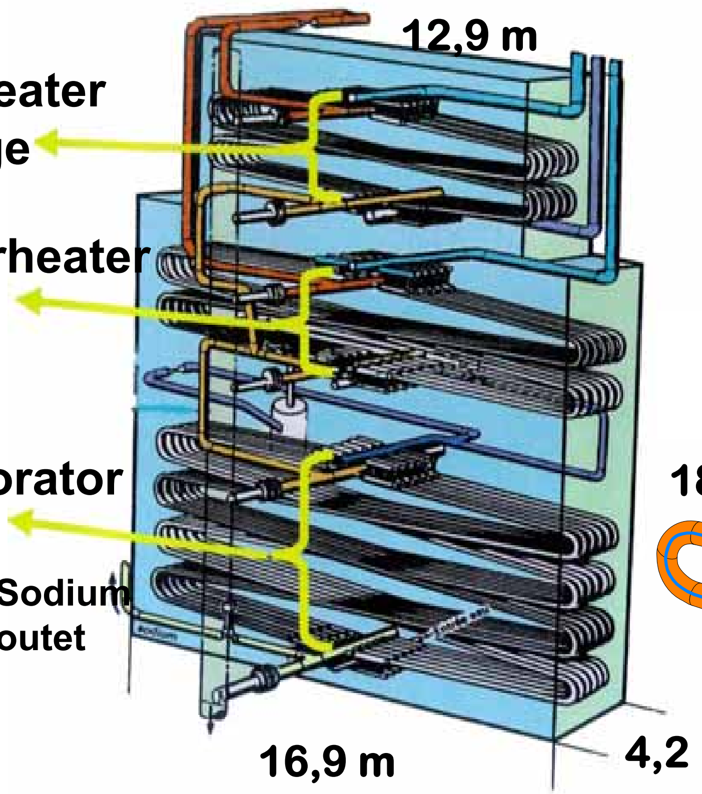
4.4×10^{15} n/cm2.s (at 350 MWth)

Secondary sodium loops

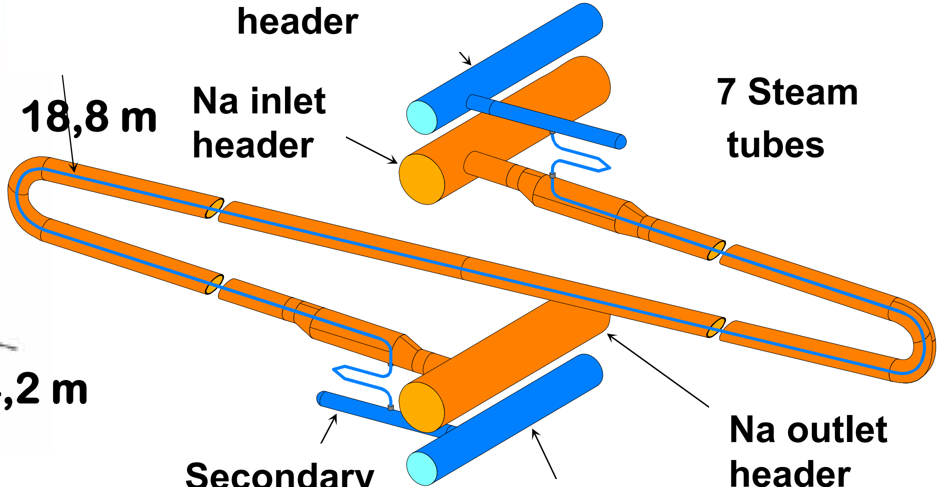
Temperatures:
350°C - 550°C



PHENIX Steam Generator Unit



Steam tubes and sodium shell



Superheater module

Steam conditions:

512°C

16,3 MPa

Main characteristics

THERMAL POWER	345 MW	563
GROSS ELECTRICAL OUTPUT	140 MW	250
NET ELECTRICAL OUTPUT	140 MW	233
CORE EXIT SODIUM T°	530 °C	560
CORE INLET SODIUM T°	385 °C	400
SG INLET SODIUM T°	525 °C	550
ECO-EVA OUTLET STEAM T°	360 °C	375
SUPERHEATED STEAM T°	490 °C	512
REHEATED STEAM T°	500 °C	512
SUPERHEATED STEAM PRESSURE	140 bar	163
REHEATED STEAM PRESSURE	20 bar	35
SG INLET OVERALL WATER FLOWRATE	500 t/h	750

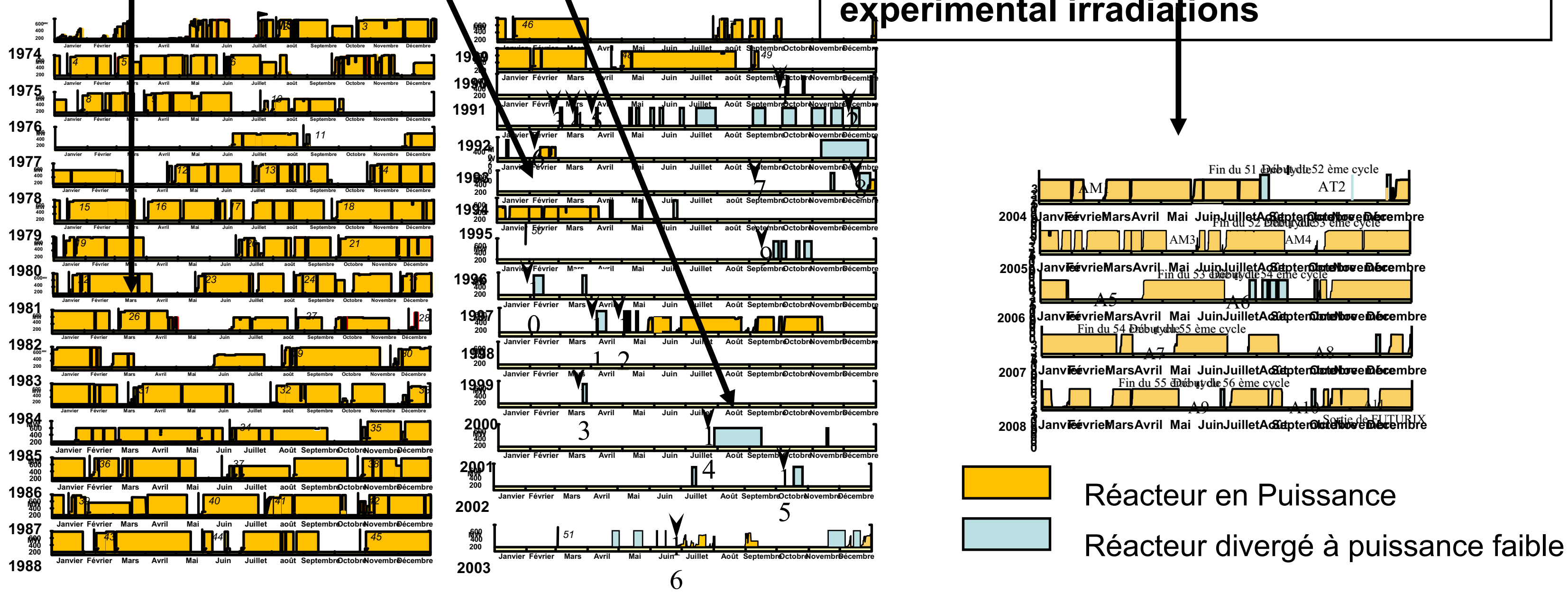
Operation diagram

1974-1990 Démonstration of Sodium cooled FBR technology with a reliable ans safe operation. Validation of components, fuel and materials.

1990-1993 : Investigations following four shut down by negative reactivity transients

1994-2003 : Time life extension. Upgrading of all the plant to new safety level.

2003-2009 :operation at two third of the power and with a new program of experimental irradiations



Availability rate

In the first period (1074/ 1990) the average value of Phenix availability rate is about 60% despite the necessary replacement and reparation of all IHX and primary pumps.

After its restart in 2003, the Phenix availability rate has oscillated between 69% and 85%, until 2009.

These values are high for a prototype and show the potentiality of high availability rate for this type of reactors

Sodium leaks

32 sodium leaks

from a few cm^3 to several liters

very few primary sodium leaks: 3 small leaks on plugging-meters:

most of the leaks located on welds of secondary loops and auxiliary circuits

Leak satisfactorily detected at an early stage

(significant corrosion due to delayed detection on one occasion: lead to improvement of detection system)

Consequences for the plant on availability but not on safety

Sodium leaks

Location of leaks:

- **23 on welded junctions (piping or other pieces)**
- **3 on flange assemblies**
- **2 on IHX tubes**
- **1 on a valve bellow**

Major causes:

- **Design and manufacturing (IHX, Plugging meters, junction Te…)**
- **Material (321 SS)**
- **Inert atmosphere keeping of circuits**

Sodium leaks

Remedial actions:

- improvement of design and fabrication
- junction Te replaced by mixers
- replacement of 321 SS hot parts of circuits
- separation wall between secondary loop and Water/Steam circuit in SG building

Improvement of detection through feedback:

- additional detection by monitoring of the electrical insulation of trace heaters
- equipment of circular welds with “sandwich” detectors
- Aerosol detection by flame spectrometer in secondary circuit separation cells

SODIUM LEAK on PURIFICATION LOOP n°1 (March 2003)

SODIUM LEAK on PURIFICATION LOOP n°1 (March 2003)

SODIUM LEAK on PURIFICATION LOOP n°1 (March 2003)

Disassembling of the leaking valve

AN EXAMPLE OF SODIUM LEAK (21st August 2007)

Amount of leak : approximately 1kg, confined in the insulation

No corrosion found on piping

Metallurgical examination: crack in a zone repaired in 1997

Cause: creep cracking due to local stress induced by repair

No other repaired welds on the secondary loop hot legs

Replacement of the elbow and straight part of piping

Solid Compound: sodium and insulation material

Sodium-water reactions

4 sodium-water reactions on reheater stages in 1982 and 1983:

- Cause: fatigue damage due to temperature fluctuations during start up phase (water ingress)
- All reheater units replaced
- Improvement of startup procedure, Leak detection and Shutdown sequence

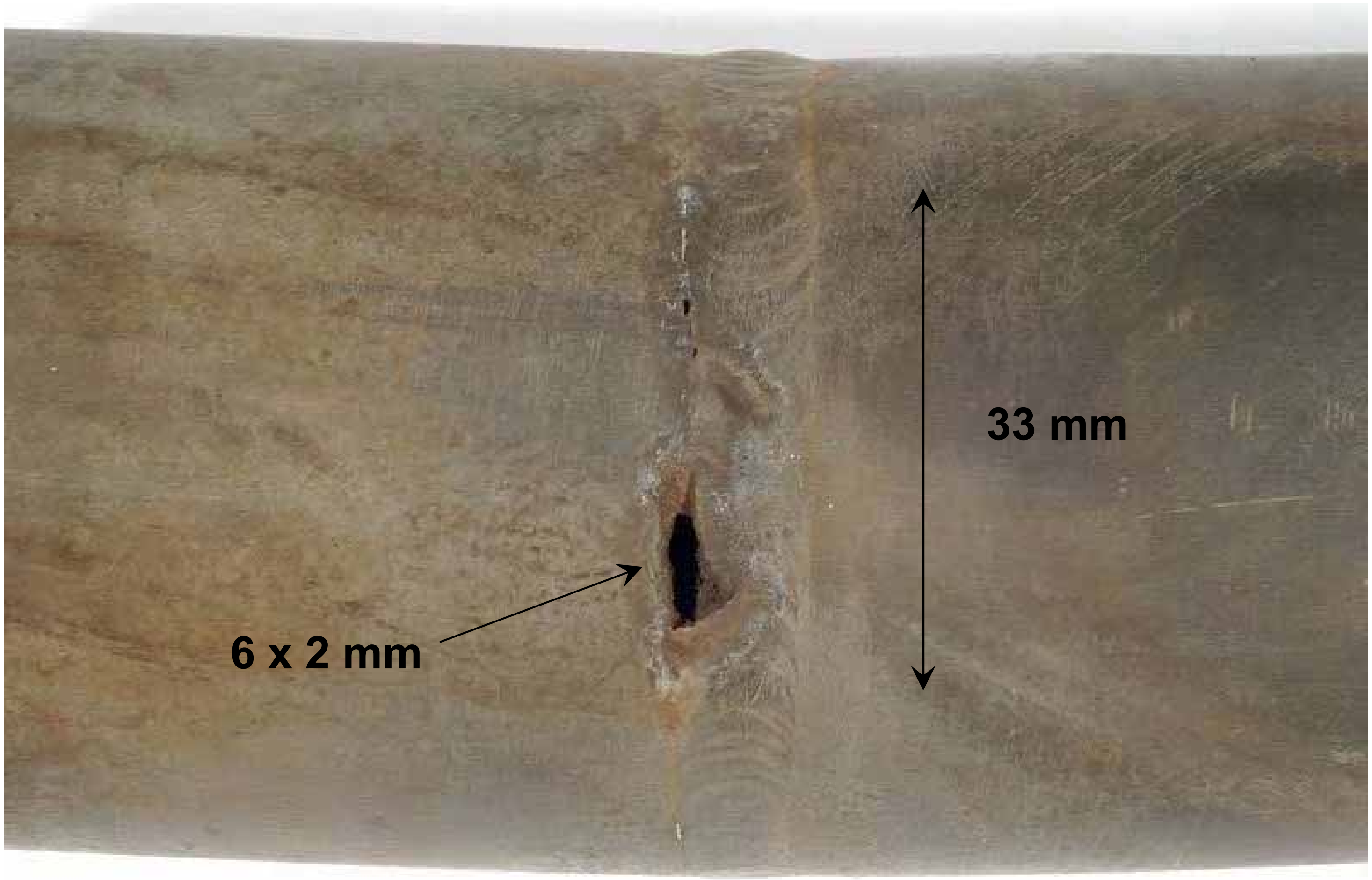
1 sodium-water reaction in 2003:

- Cause: welding defect on one reheater steam tube
- Replacement of the module

Sodium-water reactions: April 1982 event

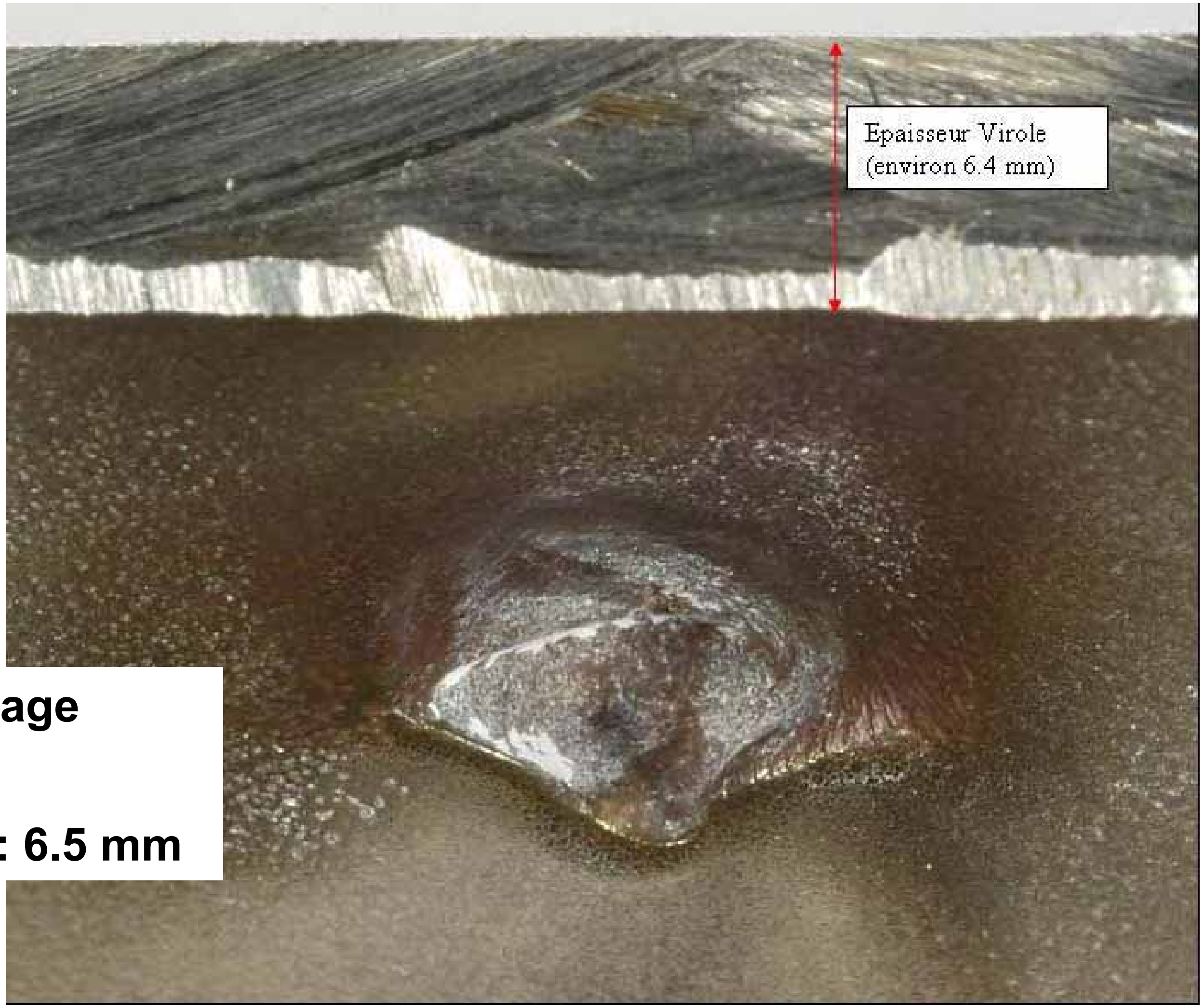
Steam tubes of SG2 reheater module n°12

Sodium-water reactions: Sept. 2003 event



Sodium-water reactions: Sept. 2003 event

Wastage on sodium pipe after cleaning

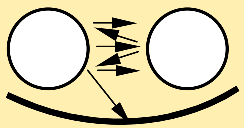
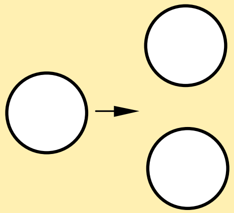
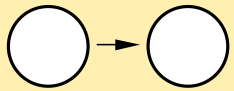
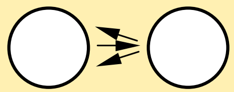
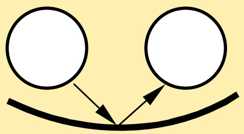


Maximum wastage depth: 4.5 mm

Pipe thickness: 6.5 mm

SODIUM – WATER REACTIONS

➢ Summary of sodium-water reactions

Na/H_2O Reaction N°	1	2	3	4	5
Number of leaking tubes	2	1	1	2	1
Wastage effect	Very important	Nil	Significant	Important	Significant
Scenario of the leaks					
Section of holes on sodium side (mm^2)	13 + 60 + 90	7,4	7	6 + 35	24
Duration of the leak (mn)	> 10	4	4	4	1,6
Estimation of the average leak flow (g/s)	20	12	5	12	20
Total quantity of water injected in sodium during the reaction (kg)	30 ± 8	3 ± 1	1,2 ± 0,3	4,1 ± 1,7	4 ± 1
Erosion on the Na shell	Yes on 1/4th of thickness i.e. 1,5 mm	No	No	No	Yes On 2/3rd of thickness i.e. 4,5 mm

Expérimental Irradiations

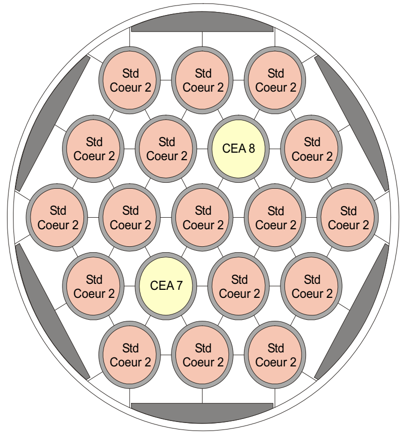
Very good conception of the reactor for experimental irradiations:

core characteristics, easy handling, hot cells for fabrication of the experimental components or for post-irradiation examinations

More than 200 experimental irradiations:

- **Behaviour of MOX fuel**
- **Cladding and structure materials**
- **Concept of heterogeneous reactor**
- **Test of other types of fuel (carbure , nitrure, ..)**
- **transmutation of minor actinides in homogeneous and heterogeneous mode**
- **New fuels and new materials for the reactors of fourth generation.**

Concepts innovants pour RCG: Combustibles nitrures et carbures en matrices inertes



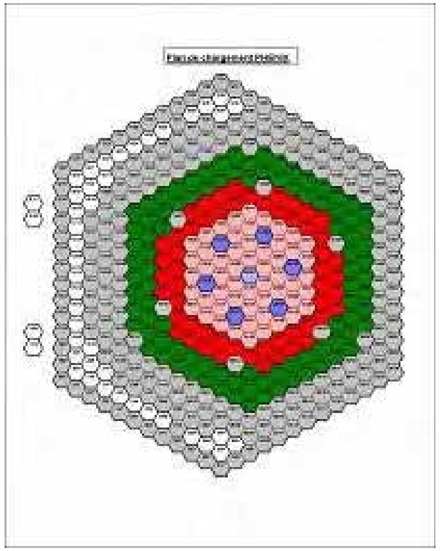
Expérience FUTURIX FTA
$(Pu_{0,50}, Am_{0,50})O_{2-x}$ - MgO 80%

A lot of these experiments was also achieved in the frame of international collaboration.

Fuel Performance

Constituant steel of hexagonal tube:

The initial type-316 led to deformation in excess of criteria, in the 40-50 dpa range. With the titanium stabilised steels it was possible to support about 80 dpa . At the end , the use of ferritic-martensitic steels allowed to support more than 150dpa.



Fuel pin material:

The same work of research was made on the fuel pin material. It allows , now with the 316-TI ,to reach about 120dpa. Research continue with ferritic-martensitic steel strengthened by an oxide dispersion (ODS)

MOX performance:

Gradually increasing burnup was possible with these new materials and gave a lot of informations on fission gas behaviour and fuel evolution at high burn up

PHENIX:FUEL BURN-UP INCREASE

Driver fuel max. Burn-up increase:

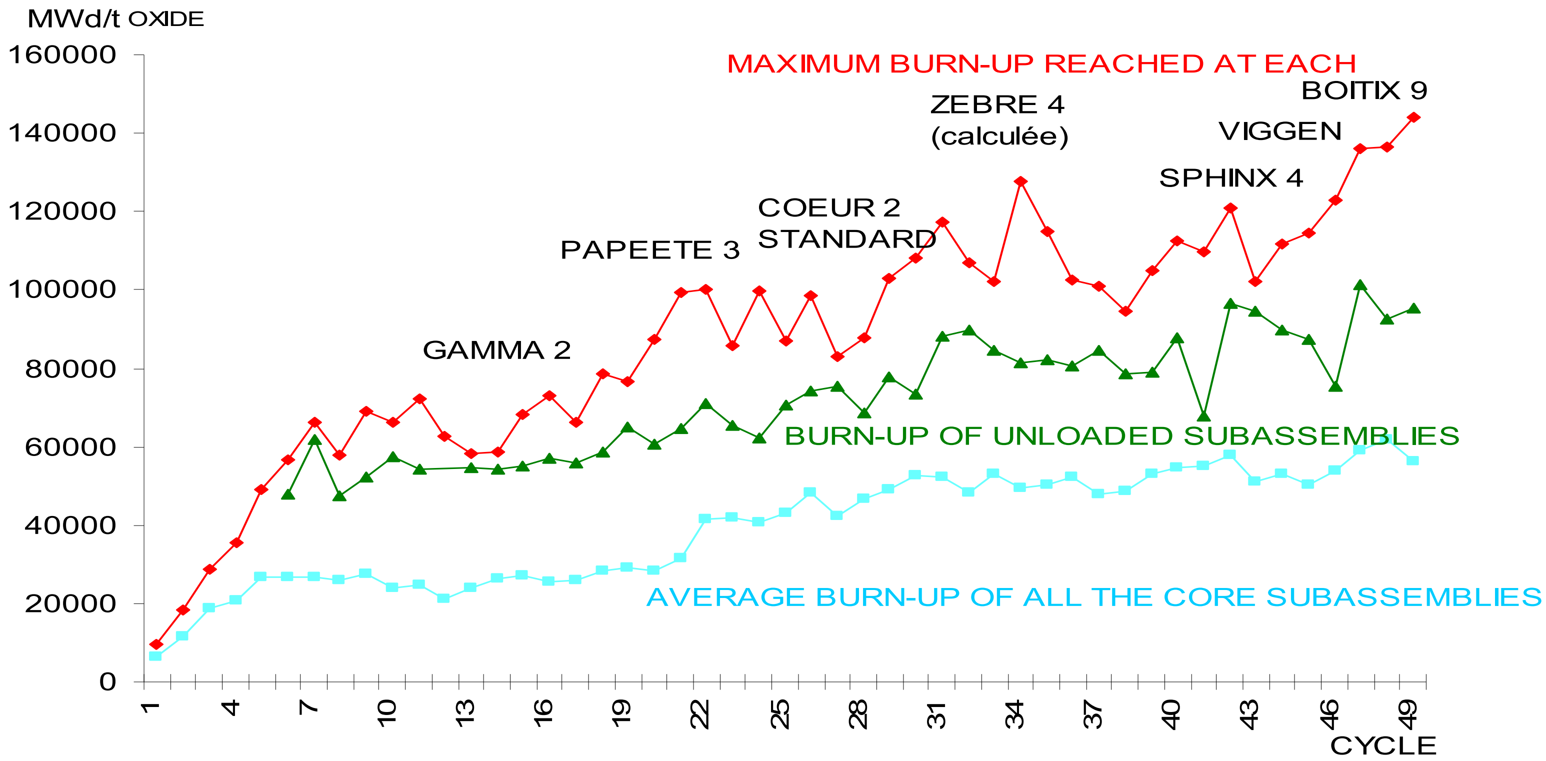
Inner core: 60000 to 90000 MWd/t.ox

Outer core: 75000 to 115000 MWd/t.ox

Max. Burn-up achieved:

160000 MWd/t.ox

17.4 at % 156 dpa



Fuel Failures

- 15 fuel failures with delayed neutron signals
- (8 of them on experimental sub-assemblies)
- 11 Gas leakers without neutron signal
- Detection and location systems has proved to be effective and reliable (Location is based on sodium sampling from every fissile S/A outlet)
- They allowed an early detection and monitoring of the failures with in most of the case a shut-down of the reactor before reaching the trip level
- Low contamination level of primary sodium
- (Cs 137: 1200 Bq/g)

FUEL TREATMENT

- From 1979 to 1992 , about 27 tonnes heavy metal, including four tonnes plutonium , were produced , by reprocessing of fuels irradiated in Phenix.(it means about four and a half Phenix cores)
- As early as 1980, assemblies fabricated with this recycled plutonium were loaded into the core.
- Thus, Phenix has demonstrated , at industrial level, the closure of a FBR cycle.
- The breeding ratio , planned initially at 1,13 , yielded, with the measurements during fuel dissolution operation , a value of about 1,16.

Primary components: pumps and heat exchangers.

Due to some initial default of conception, it was necessary to repair all these components.

The total number of handling operations has been 32 for IHX and 22 for primary pumps.

The possibilities of inspection and reparation of components have been demonstrated:

-Experience on large component handling.

-Optimization of cleaning and decontamination process.

-Knowledge of primary components contamination.

After corrections, the operation of these components has been reliable . This knowledge has been used for the conception of primary components for SPX1 and EFR.

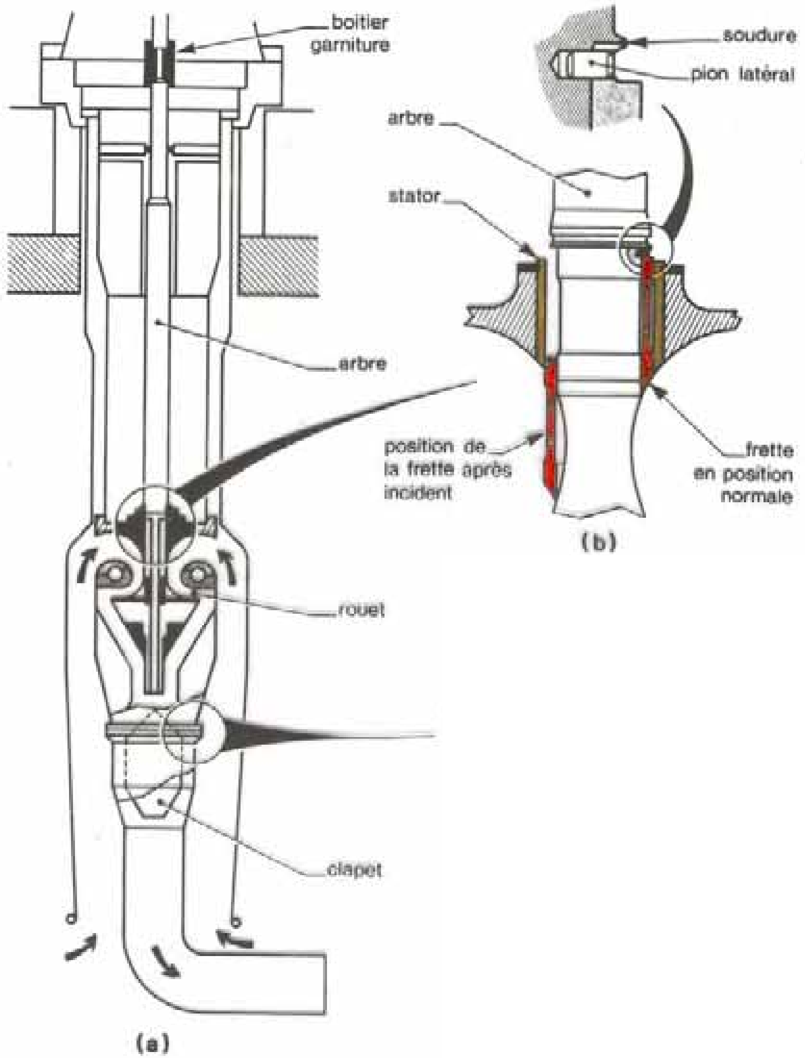
NB: the possibility for the plant to operate , at reduced power, with only two secundary loops available, has reduced the production losses during the components handling and reparation.

Hydrostatic bearing of pumps

slippage of reinforcements from hydrostatic bearing

Incidents in 1976 and 1981 on the primary pumps, and in 1987 on a secondary pump. Reinforcements slid down to the level of the pump impellers.

- ✓Mechanical incidents due to repeated expansion and contraction on the braces after the sodium thermal cycles during the trip transients.
- ✓Modification in the assembly of all the pump reinforcements

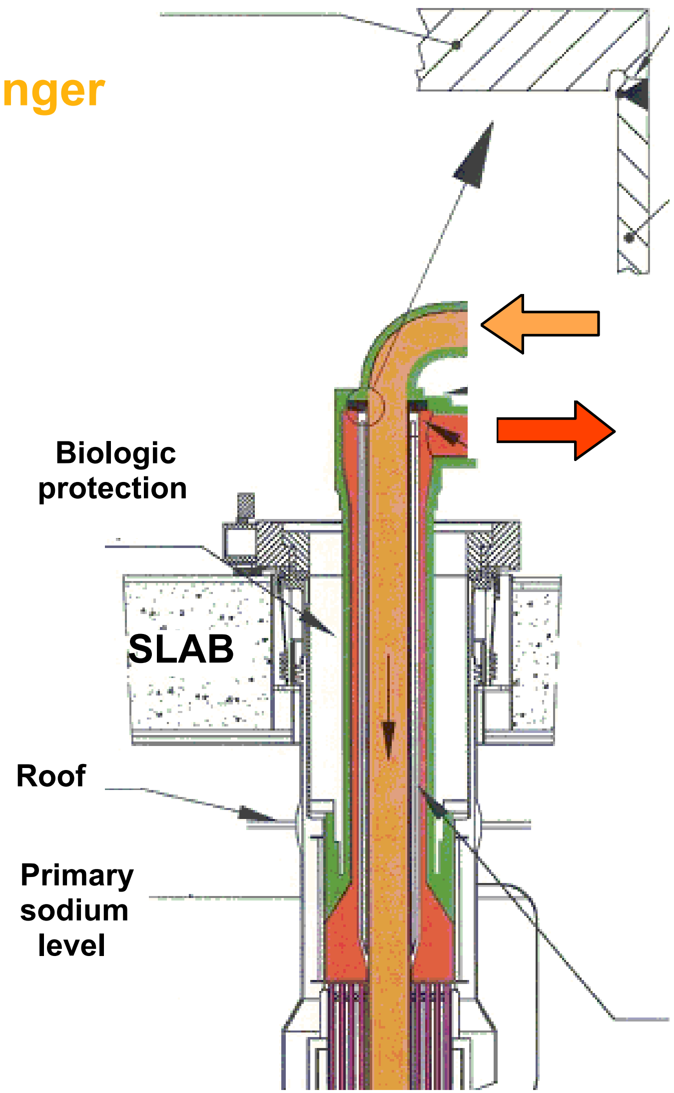


Events in 1976/1977 on all intermediate heat exchangers(1)

- **Crack in the top closure plate of exchanger**

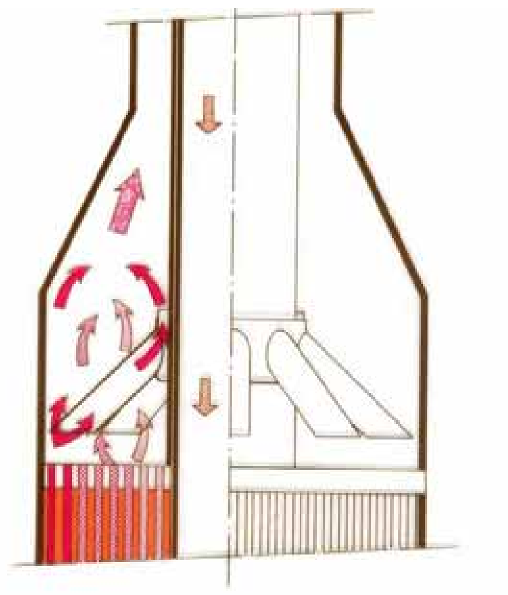
this plate connects the 2 shells forming the secondary sodium header

- difference of temperature arising between the 2 shells led to differential expansion between these shells
- this gave rise to high mechanical stresses and caused the weld connecting the inner shell to the plate to crack



Events in 1976/1977 on all intermediate heat exchangers(2)

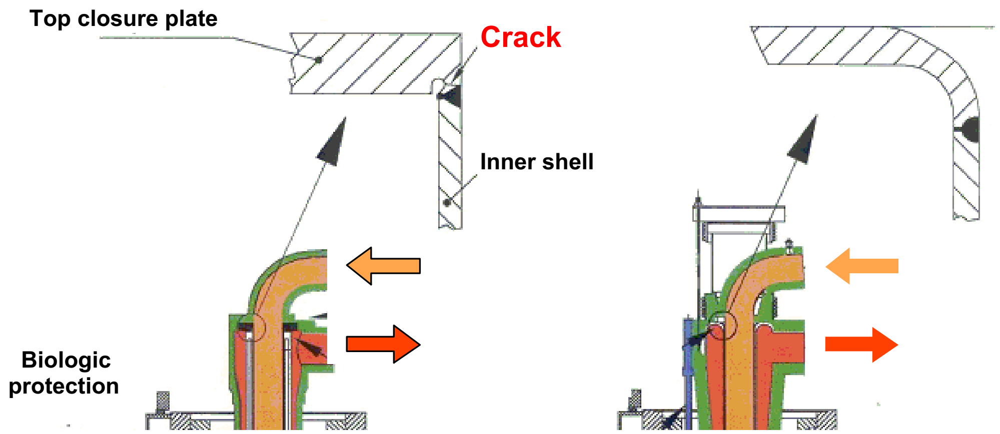
- **Crack in the top closure plate of exchanger**



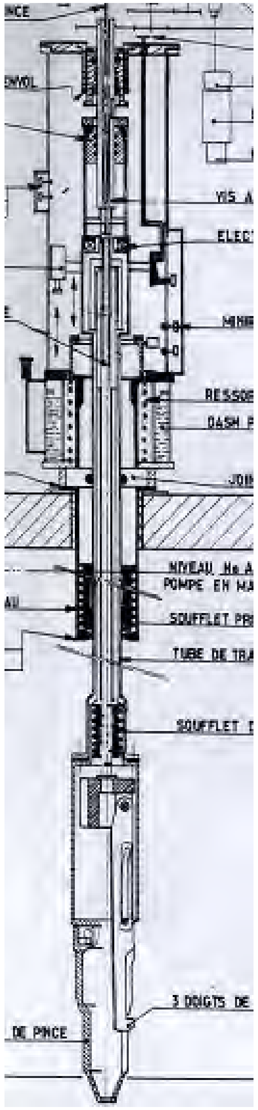
Modifications:

addition of a mixer at the secondary sodium outlet from the tube bundle

improvement of the flexibility of the IHX hot header between the top closure plate and the inner shell



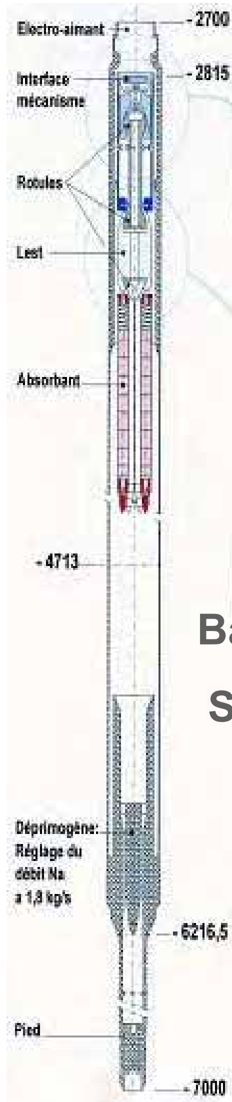
Primary component: the control rods



Satisfactory operation of the six control rods and their drive mechanisms.

Some improvements were carried out to take in account swelling problems and sodium aerosol deposition .

A new articulated control rod (called SAC)was added during the safety reevaluation work.



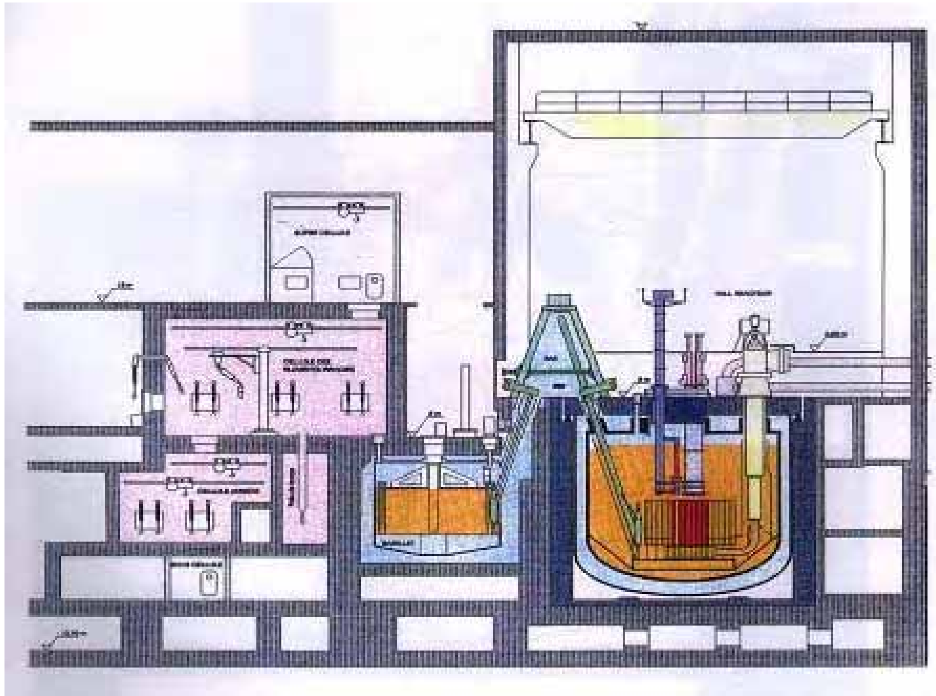
Barre SAC

Fuel assembly handling

Satisfactory running of fuel assembly handling operations.

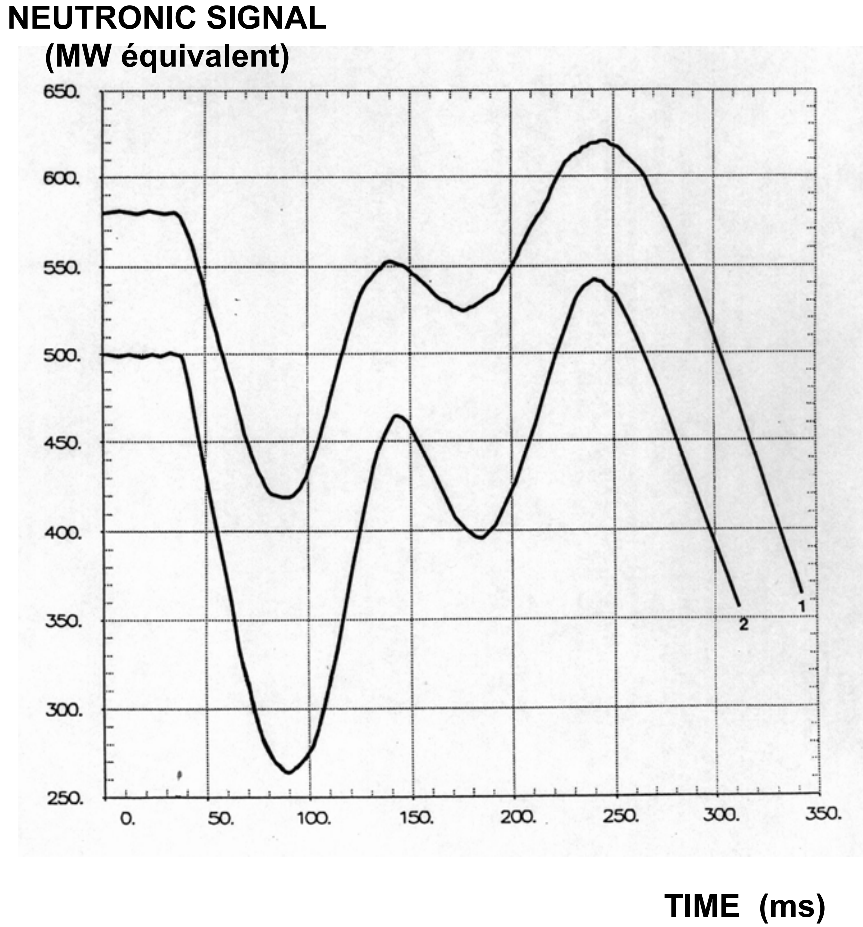
No incident.

But the handling operations require time (about one hour for a transfer)



Negative Reactivity Transients 1989-1990

- 4 trips due to negative reactivity transients in 1989-1990
- Extensive studies and testing to identify the cause of the transient
- International Expert committee
- 200 Man.Year - 500 documents
- Examination of all possible
- phenomena
- Safety analysis conclusions: no safety consequences for the reactor



Negative Reactivity transients 1989-1990

- Most of the explanations were eliminated
  - electrical perturbation
  - gas release through the core
  - core/control rods relative movement
  - oil ingress …
- Reference scenario
  mechanical (core flowering effect, initiator under study)
- Considerable reinforcement of reactor instrumentation (200 sensors)
- Fast data acquisition system for:
  - permanently monitoring of the reactor
- recording of any new event
- No new occurrence since 1990
- A new scenario proposed in 2006 is today under demonstration , by experimentation during the end of life test and by calculation.

PLANT LIFETIME EXTENSION WORK

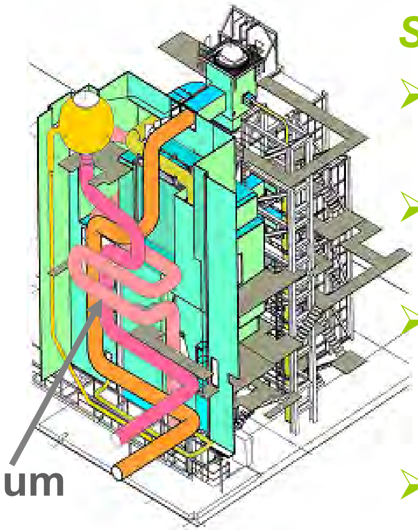
- 6 years of work in two phases from 1994 to 1997 and 1999 to 2003, separated by one operating cycle.

- 250 million € of studies and renovation works

- 5000 contracts entered into,
- 350 sub-contracting companies

- 4500 agents working for the sub-contractors (up to 700 per day)
- [PHENIX staff : 260 people + 50 backup CEA/EDF]

Life time extension / safety upgrading of the plant



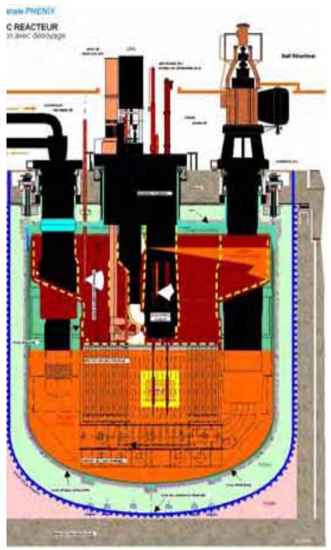
Circuit sodium

Safety reevaluation of the plant :

- **Seismic reevaluation and reinforcement of buildings and components.**
- **Replacement of all the parts at high temperature in 321 steel , by 316 steel**
- **Decrease risks of large sodium fire and consequencies of a sodium/water reaction**
- **New emergency cooling system**
- **New articulated control rod.**

Inspection of component ans structures :
dedicated inspection and maintenance.

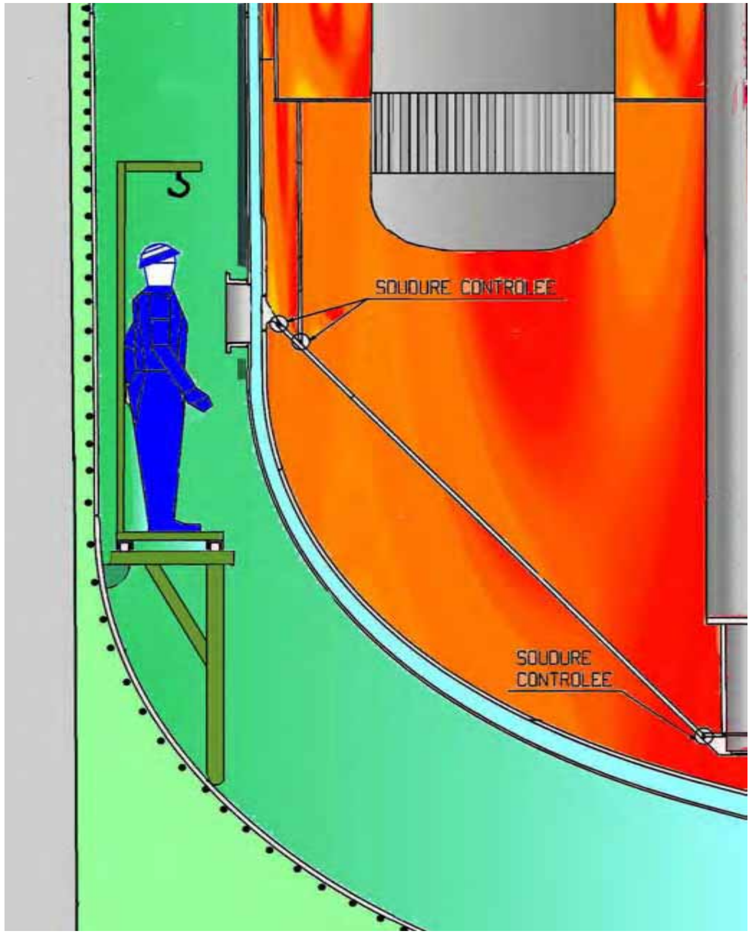
- **A lot of new methods of inspection was developed during this period**
- **Ultrasound inspections were used for welds in sodium**
- **Visual inspections were possible, by draining partially the sodium from the reactor block.**



CENTRALE PHENIX CEA-EDF

SPECIAL INSPECTIONS of REACTOR INTERNALS

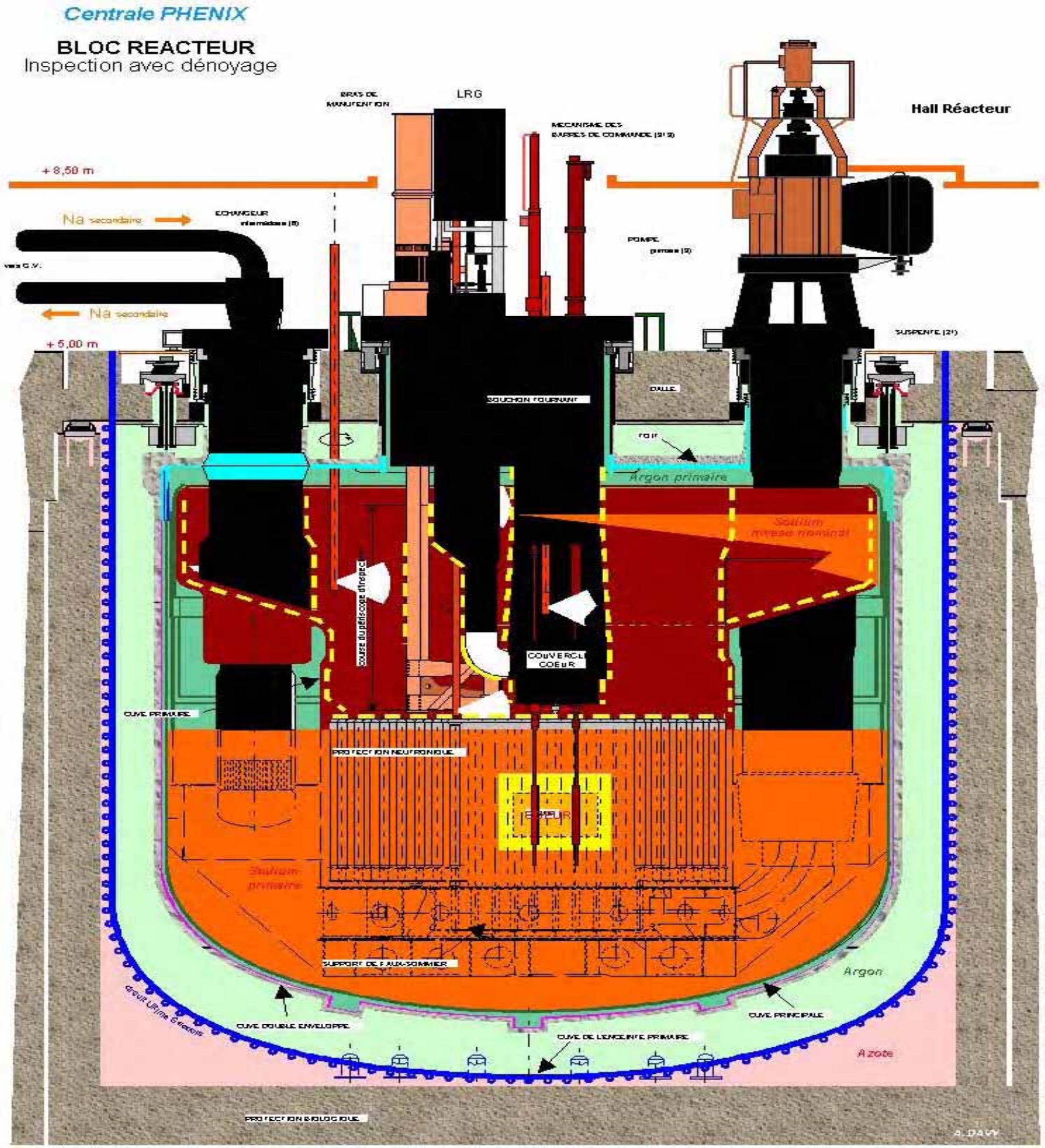
Ultrasonic inspection of the core support conical skirt carried out under sodium at 155 °C
Sept-Oct 1999



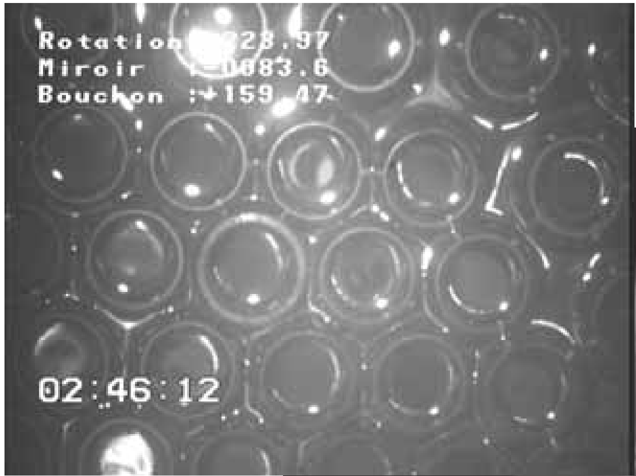
SPECIAL INSPECTIONS of REACTOR INTERNALS

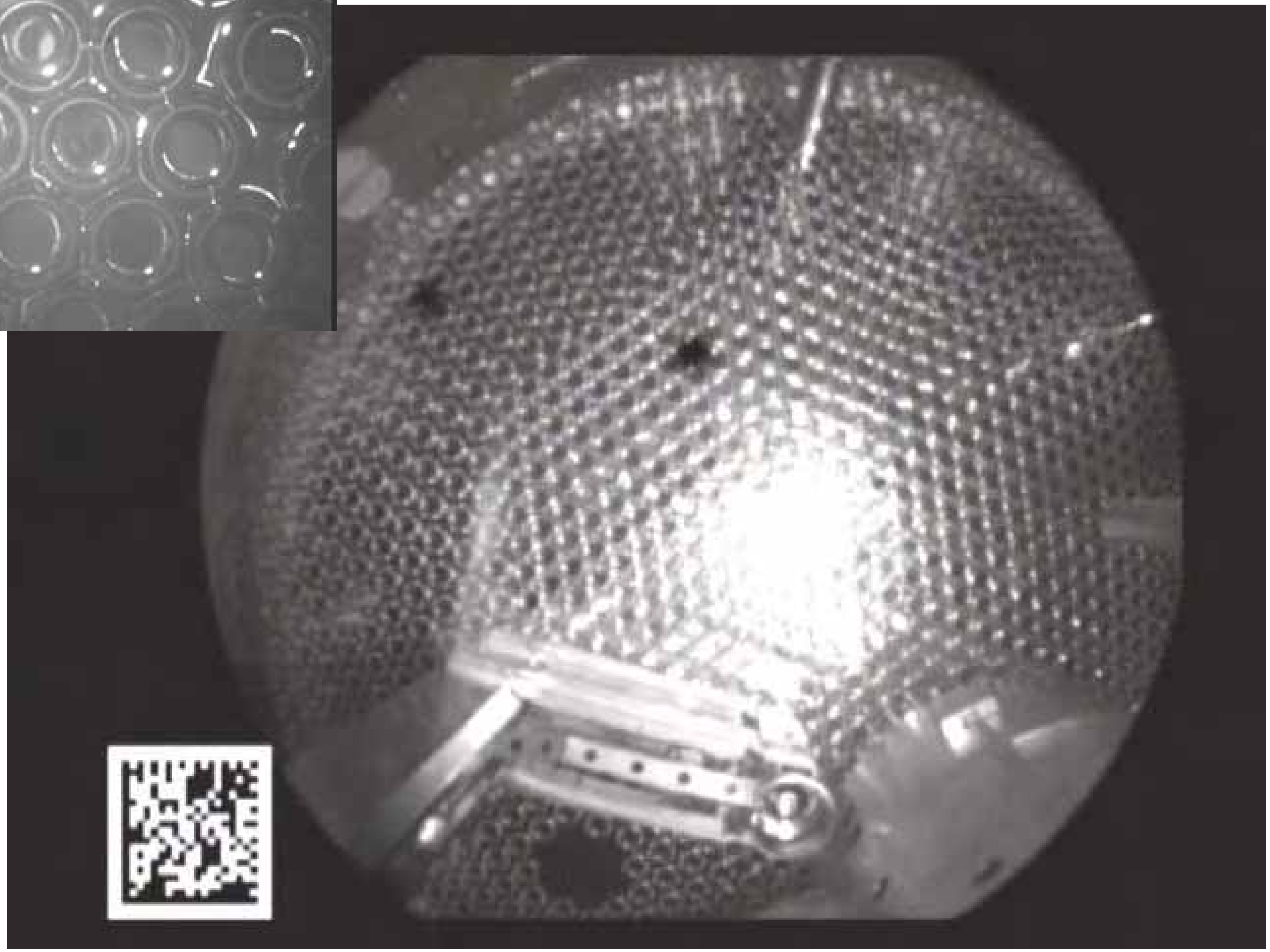
A visual inspection of the core cover plug and of the internal structures was made in March-April 2001

For this operation sodium was drained partially from the reactor block , ans special devices allow to provide lights and visualisation

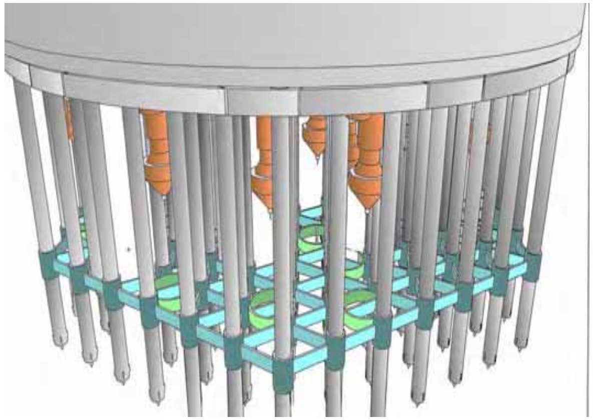


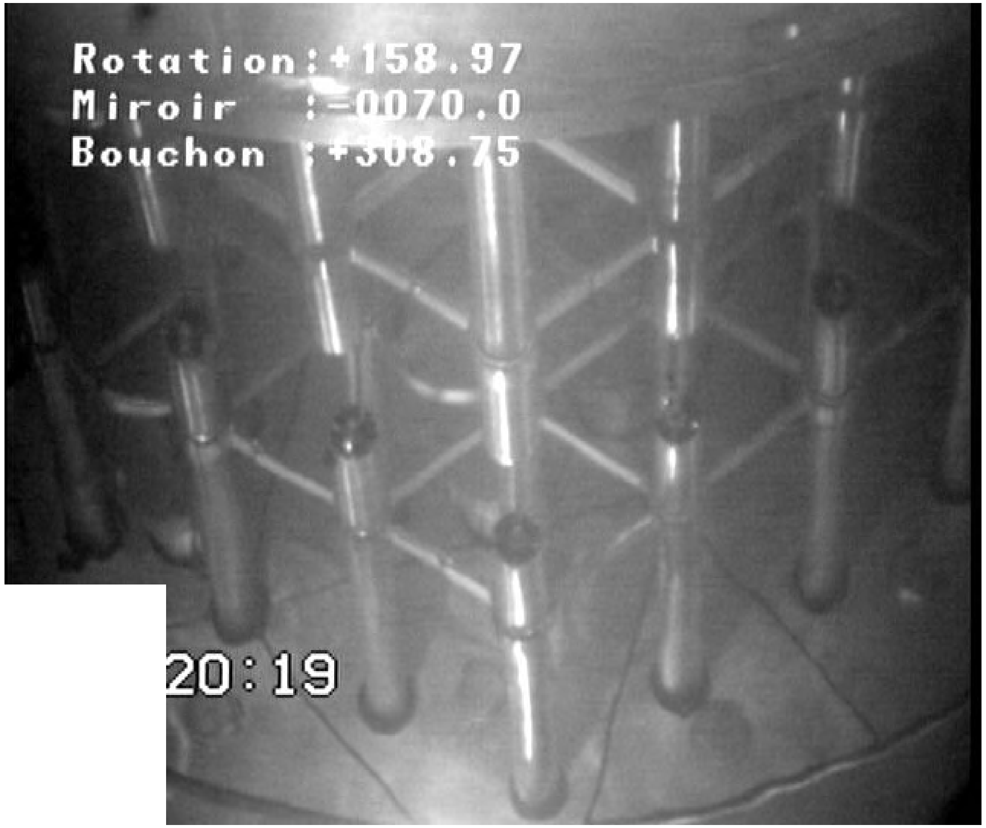
CORE S/A HEADS





CORE COVER PLUG BOTTOM GRID





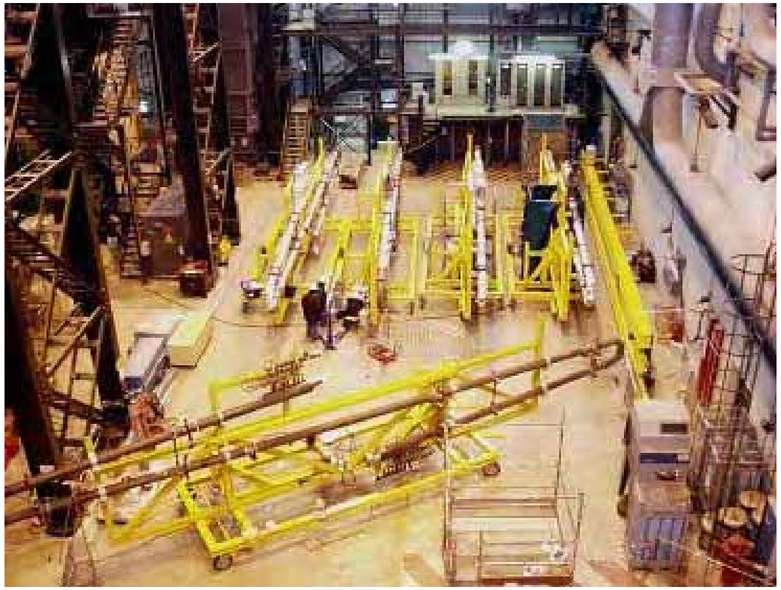
- Conclusions of the inspections:
- very good condition of reactor internals

Materials

Satisfactory overall feedback as regards AISI 316L steel ,used for the reactor block and intermediate heat exchangers , and more generally for all materials used in the primary part.

Some problems of stress relief cracking with welds of titanium-stabilized AISI321 grade (affecting welds at high temperature with stress relief treatment) . This steel was used in the secundary loops and on the steam generators. All the parts at high temperature have been replaced.

A final confirmation will be given by the end of life program.



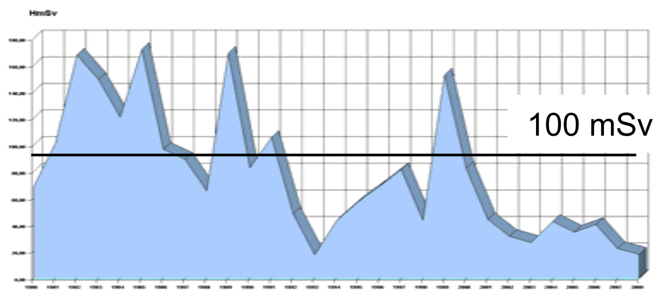
Dosimetry and environment

Advantages for RNR-Na, due to reactor characteristics.

➢ Radioprotection :

The dosimetry accumulated in 35 years for all the personnel is only 2,3 Sv .The average annual dose of an employee corresponds to the dose absorbed during a flight from Paris to Tokyo.

Dose cumulée annuelle

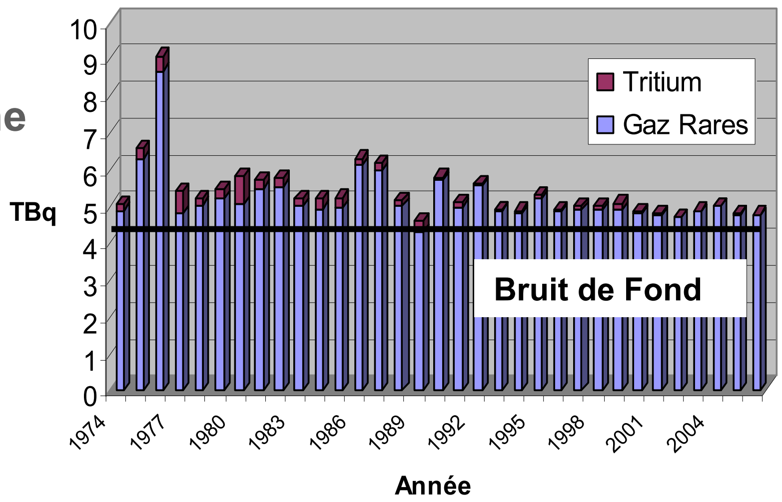


➢ Environment

Gazeous release very low(less than one TBq per year in average value)

Liquid radioactiv effluents production also very low (a few TBq/an on average).

Rejets radioactifs gazeux



Main objectives of Phénix end of life program

Tests

- ✓ Tools validation in the fields of neutronics, thermal-hydraulics…
- ✓ Safety demonstration: intrinsic safety features of sodium cooled FR, verification of calculation margins,
- ✓ Investigation of scenarios for Phénix negative reactivity transient explanation

Expertise

- Material's behaviour knowledge acquisition (material properties, damaging mechanisms, welded assemblies, modelling)
- Technology demonstration : validation of materials and components

Phenix end of life test program

1)Neutronics

1- Subassemblies reactivity worth measurements

- 1A – Substitutions of S/A in core central position.
- 1B – Substitution of a control rod by a gas volume

2- Control rod withdrawal

- 2A – Assymetrical control rod configuration (static)
- 2B – Control rod withdrawal and FACTO (dynamic)

3. Decay heat measurement

4. Control rod worth measurements by different methods

2)Thermalhydraulics

5. Reactor assymetrical thermal-hydraulic conditions (secondary pump trip)

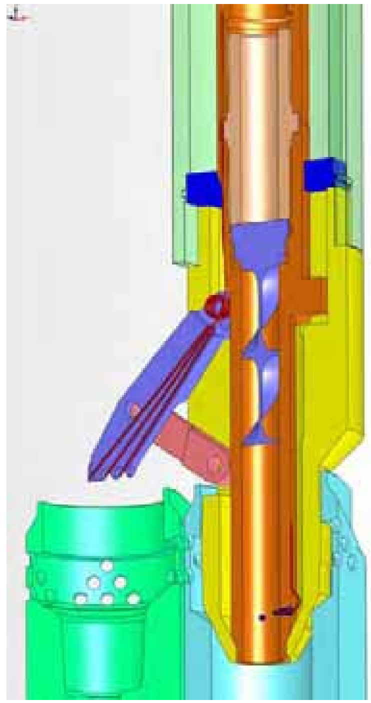
6. Natural convection (primary and secondary)

Phenix end of life test program

3)Negative reactivity transient :

measurement of core flowering effect , with a special device.

reproduction of a scenario with the DAC component (also with dedicated device)



4)Program of post mortem examination

After the end of life test , and during the dismantling, collection of samples of various materials will be made in several places ,to confort the knowledge on the mechanical evolution of materials after 35 years of operation.

CENTRALE PHENIX CEA-EDF

Conclusion on Phenix operating feedback

- In terms of industrial operation, this prototype demonstrated that it was possible to operate this type of reactor with a good availability rate.
- In terms of research the 200 experimental irradiation conduced in Phenix , allowed a lot of progress on materials, fuels, transmutation and other matters.
- In terms of technology , a lot of knowledge was accumulated in sodium technology, chemical matters, decontamination, repair methods, ..
- In terms of safety , a lot of knowledge was accumulated especially during the life time extension process , with a lot of new methods for inspection in sodium , and a lot of modifications driven by safety,that are guides for the future reactors.

Conclusion for the future

- Phenix , with other reactors as BN600 in Russia, has demonstrated the possibilities of sodium fast reactors and validated the choice of main options on fuel and materials.
- Phenix is the only reactor in the world, that reprocessed its fuel , manufactured new fuel with reprocessing produces and used it to demonstrate the overall breeding operation.That means the demonstration of possibility to provide electricity during several millenaries, only with the depleted uranium today available.
- The Phenix experience has also shown some specific advantages of the FBR: dosimetry , environment, possibilities of waste transmutation, ..
- In conclusion ,the Phenix experience provides a lot of necessary knowledge, on materials, component conception, sodium technology,..totaly necessary for the sodium FBR today in project or already under construction