Fast Reactor Operation and Reactivity Control: Report on the Phenix Experience

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Fast Reactor Operation and Reactivity Control: Report on the Phenix Experience

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Abstract

Operation of the Phenix prototype fast reactor has resulted in 35 years of experience in controlling fast reactors. The self-stabilizing thermal feedbacks, the low spatial effects and the high thermal inertia provide wide safety margins and greatly facilitate reactor control.

It is recalled that there is no pressure and no phase change, that the use of boron type poison is not necessary to compensate excess reactivity, that there is no xenon or samarium effect in the case of reactor shutdown and that redivergence is always possible even during cooling. In practice, power is going to correspond to control rod position and remain stable. The control rods must be lifted from time to time to compensate for burn up.

Four automatic shutdowns related to negative reactivity transients occurred at Phenix in the 1990's. The last hypothesis – related to a core flowering due to the implosion of a sodium bubble along the periphery – is explained herein. At any rate, the core is compact in rated operation, (the sub-assemblies are in contact at the pad level), which prohibits significant variation in positive reactivity.

In conclusion, the Phenix reactor is shutting down in early 2009. At that time, neutronic end-of-life tests will be done to increase the knowledge gained from this fast reactor system, and to help prepare optimisation of the future Sodium Fast Reactors cores.

1. Introduction

The Phénix prototype sodium-cooled fast breeder reactor is located at Marcoule in the Rhone valley. Reactor construction work started in November 1968 and ended in 1973. The first divergence took place in August, and first grid connection in December 1973. The Phénix reactor reached rated power of 580 MWth (260 MWe) in March 1974.

As of 1979, the fuel cycle had become a closed loop. The irradiated sub-assemblies in Phénix were reprocessed and the recovered plutonium was reused to make new fuel for insertion into the core. The breeding rate (ratio of fissile atoms produced to the number of fissile atoms consumed) reached 1.16.

Throughout reactor operations, an ambitious experimental irradiation program was developed and conducted for R&D on materials, transmutation and future (Gen IV) reactor systems.

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Furthermore, operations at the Phénix plant have provided over 30 years of experience in controlling fast reactors.

2. **The Phénix plant**

2.1 Installation diagram

The option chosen by France for the Phénix and Super-Phénix type of power reactors was the integrated concept where the core, primary system pumps and intermediate heat exchangers are contained in one single sodium-filled tank. The produced heat is removed by a secondary system that is also a sodium system, and is sent to the steam generators.

The overall diagram presented in Fig. 1 shows the three main buildings:

- The reactor building with the nuclear reactor with the integrated primary system.
- The Steam Generator building with the secondary systems and the SG.
- The electricity generating installations building, with the turbine, generator, feed pump. The cooling source is the Rhone.

2.2 The reactor

The reactor block shown on Fig. 2 consists of an external safety vessel and a primary vessel joined to a slab. The installation contains the core on a diagrid, three primary pumps, six intermediate heat exchangers, one core cover plug holding the instrumentation (thermocouples…) and one rotating plug holding the control rod mechanisms and the transfer machine.

The vessel contains 800 tons of sodium with cover gas of argon at 40mbar pressure. The core fills a volume of 1.2 m^3. Sodium enters at a temperature of 380° C and goes out at a temperature of 530° C.

2.3 The core

The core, illustrated on Fig. 3, is comprised of approximately one hundred hexagonal-section fissile sub-assemblies, and approximately as many fertile sub-assemblies on the periphery. Six control rods are used to control reactivity. There is also a Complementary Shutdown System, with a safety control rod in the center of the core.

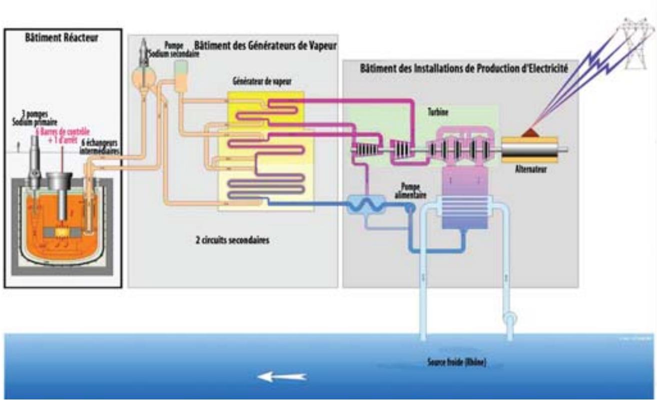

Fig. 1. Overall diagram

The fissile zone, diameter 1.5 m by 0.85-m height, is made up of mixed oxide (U-Pu)O2 with 23 to 28% plutonium enrichment. The structural hexagonal wrapper and the fuel pellet clads (217 per sub-assembly) are stainless steel.

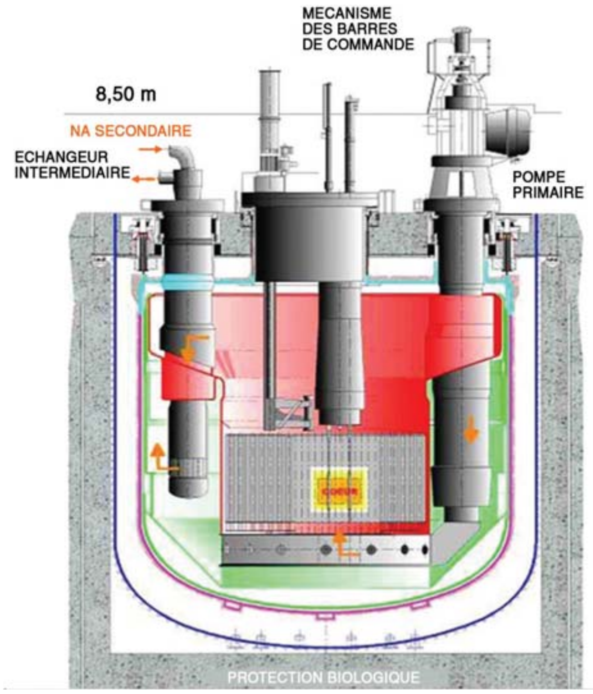

Fig.2. Reactor section

Maximum Linear power is 450 W/cm for a sub-assembly power of 5 MW and a clad temperature of approximately 650°C. The fraction of delayed neutrons, called effective Beta, is equivalent to 325 pcm (as a reminder, approximately 700 pcm for the PWR).

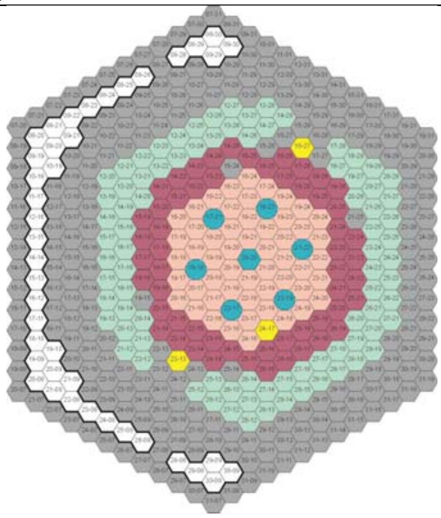

Fig. 3. Core section

2.4 Instrumentation

The instrumentation used to control and operate the reactor monitors the following parameters:

- Core temperatures
  Two thermocouples at the outlet from each fissile sub-assembly and one measurement of the core inlet temperature, with respect to each of the primary pumps.
- Neutronic measurements
  Three power ranges (in-vessel pre-start up channel in the lateral neutron shielding, intermediate range neutron measuring channels and under-vessel power range neutron measuring channels)
  Reactivity meter to measure the kinetic reactivity of the power core.
  Doubling time.
- Sodium flow rate
  Pump speed measurement (variable depending on operating characteristics).

2.5 Automatic shutdowns

To stop a chain reaction and make the reactor sub-critical, the 6 control rods and the Complementary Shutdown System are dropped, despite the fact that, at Phénix, one single control rod would be sufficient.

Two types of automatic shutdowns are possible: emergency shutdowns (AU), where the control rods drop gravitationally in less than one second, or the rapid shutdown (AR) with motorised drop of the control rods in approximately 45 seconds.

The primary shutdown stations are the following:

AU

- Core or sub-assembly heating (+6 %)
- Nuclear power (+6 % PN)
- Reactivity or doubling time (10±pcm ; Td = 10 s)
- Open clad failure
- Primary pump trip or Power/Flow rate threshold
- Earthquake (geophone).

AR

- Hydrogen detection, secondary pump, turbine shutdown, etc. …

Note on the role of the control rods.

In the fast reactors, the control rods have three roles:

- Safety: stopping the chain reaction and making the core sub-critical.
- Compensation for the loss of reactivity due to burn-up.
- Flattening of the power distribution during the cycle for large dimension Super-Phénix type cores.

3. **Operations and control**

3.1 Approach to criticality and divergence

In normal circumstances the approach to criticality starts from a cold state, which is 250°C. After lifting the Complementary Shutdown System rod out of the core, the approach to criticality takes place by lifting, in successive steps, the 6 control rods, with the neutron counting being done by the pre-startup chambers. Divergence then takes place on one rod, then the chain reaction is stabilized and the 6 rods are positioned at a given level to determine the critical value. This value is pre-calculated with a deviation which is most often less than a few millimetres from the measurement.

Nuclear heat gradually builds up the power and temperature by progressively lifting the control rods and acting on pump speed to adjust the sodium flow rate and the heating. After coupling to the turbine, power buildup continues based on the same principle, until the required operating power is reached.

Given the absence of poison due to the fact that there is no Xenon or Samarium effect, and given the low, stable temperature coefficient (≈ -3 pcm/°C), it is always possible to restart the reactor after unscheduled shutdown or trip, even during temperature transient.

The Neptunium effect, the only effect that exists (formation of the Pu239 from the captures in the U238), causes a delay of approximately 110 pcm over a period of one week (period of 2,3 days).

3.2 Power operation

One of the characteristics of fast reactors is that the neutrons have a significant free path (several centimetres). For a reactor the size of Phénix, the consequence is the absence of significant spatial effects, whether axial or radial. If load following has not been planned, it is however basically possible.

Another feature is the stability of the reactor in operation, for several reasons:

- Self-stabilizing thermal and power feedbacks.
- Low deformation of the power distribution over time (sufficient for Phénix to justify one single control rod curtain)
- Reactivity loss due to burnup is low, below 20 pcm per day, which is the equivalent of one approximately 1.5-mm lifting of 6 control rods.
- High thermal inertia of the sodium contained in the tank -800 t-.

4 Operating transients

Intrinsic variation in core reactivity, and thus in power, is related to the following three variables controlled by the operator:

- The TE core inlet sodium temperature, adjusted by the speed of the primary and secondary pumps.
- The ΔT heating of the sodium in the core, adjusted by speed of the primary pumps.
- The ρ_{bar} reactivity variation controlled by the movement of the control rods.

Starting with stable reactor operating conditions, any perturbations to any one of these three variables leads to a new state of equilibrium governed by the following equation:

$$k.dT_E + g.d\Delta T + h.dP + d\rho_{bar} = 0$$

with:

$k(pcm/°C) = \partial\rho/dTE$: core inlet temperature feedback coefficient

$g(pcm/°C) = \partial\rho/d\Delta T$: core heating feedback coefficient

$h(pcm/MW) = \partial\rho/dP$: power feedback coefficient

These k, g and h coefficients, related to the Doppler effect and to thermal expansion of materials, are all three negative.

Fig. 4 shows the changes in the power following three different types of steps, separated by approximately 2-hour intervals, in the following order:

- 1 –40-pcm reactivity step obtained by a 20-mm drop of the control rod into the core.
- 1 secondary flow rate step obtained by decreasing the speed of the secondary pumps by 10 %.
- 1 primary flow rate step achieved by decreasing the speed of the primary pumps by 10 %.

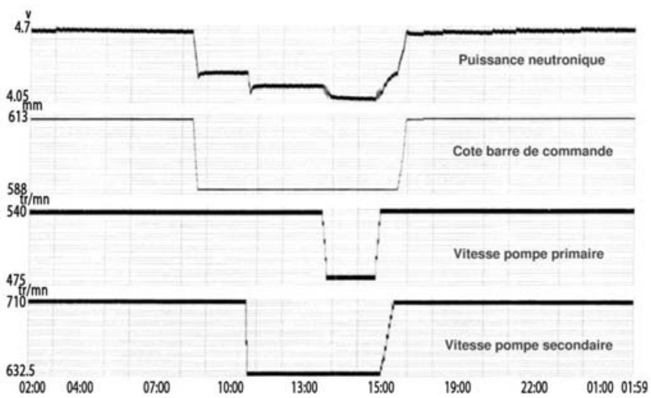

Fig. 4 - Reaction to variations in operating conditions

In each of these cases, the operator intervened on one and only one control variable at a time. Then, following these three steps, he put the reactor back in its original configuration by doing the opposite, on the three control parameters, concurrently. This type of test demonstrates the inherent stability of the fast neutron reactors.

As an example, it can be seen in this same figure, that before and after the test there is a gradual decrease over time of the power due to the burnup effect, compensated for by the operator solely through the use of the control rods.

On the Super-Phénix reactor, with rated power of 3000 MWth, fissile height of 1 m and a diameter of approximately 4 m, such testes have been performed and have shown the same self-stabilizing phenomena. From this perspective, load-following operation does not raise any insurmountable problems.

5 Comparison: Fast neutron reactors (FNR) and Pressurized water reactors (PWR)

Control of Fast Neutron Reactors differs from Pressurized Water Reactors in the following ways:

- There are no Xenon and Samarium effects. Only a low Neptunium effect (value ≈ 100 pcm over one week) must be taken into account.
- There is no need to use poison to compensate excess reactivity, unlike PWR (boron, consumable poisons …).
- High thermal inertia and the absence of pressurization contribute to reactor stability.
- Redivergence just after a shutdown is always possible, even during cooling.
- The reactor is only controlled through the use of the control rods which adjust the power level, compensate for loss of reactivity during the cycle and radially flatten the power distribution if necessary.

Basically, any constraints inherent to fast neutron reactors come more from the reactor structures (thermal gradient on the vessel supports, for example), then from the core.

6 Automatic shutdown due to negative reactivity transient

The Phénix reactor experienced 4 automatic shutdowns due to negative reactivity transient in 1989 and 1990. Despite the significant resources dedicated to research and testing, no satisfactory explanation was found at the time. Investigations showed that, other than an artefact, the most likely physical explanation was outward flowering of the core, prompted by a localized impulse, and followed by a return to the original configuration. This explanation would correspond with approximately -80 pcm for a homogenous radial movement of 1mm, to 3 to 4 mm of movement on the median plane. There has been no explanatory scenario for this flowering. However, since a variation in positive reactivity due to core compaction is physically restricted (the sub-assemblies come into contact at the plate level in rated conditions) the reactor was authorized to resume operation. These automatic shutdowns due to negative reactivity transients have never occurred since.

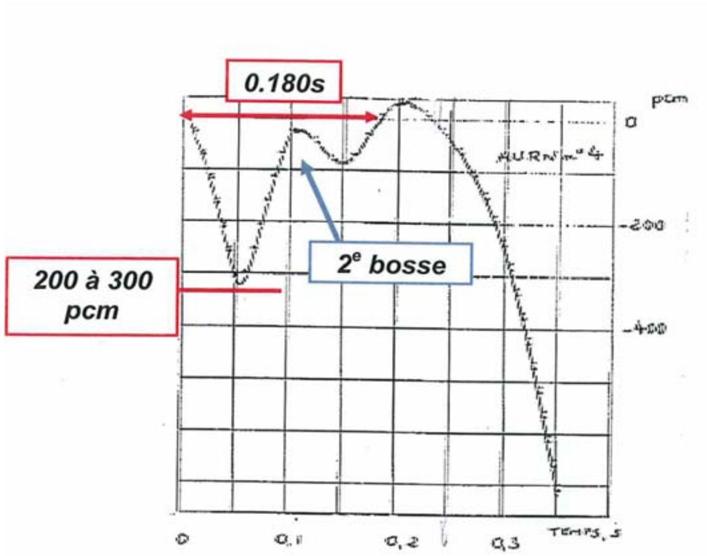

Fig. 5: Example of negative reactivity variation in an automatic shutdown due to negative reactivity transient

In the year 2000, we were concerned by the local flux modifications at the time of the conception of the ECRIX irradiations with the DMC carrier containing calcium hydride. Indeed, local thermalization of the neutrons leads to significant increase linear power rate in the adjacent radial blanket sub-assembly (R/B) pins, with the consequence of excess output and significant temperature buildup in these assemblies. Calculations, carried out for former R/B in contact with some other moderating sub-assemblies (DAC) containing much more moderator and still present in the reactor in 2000, showed that the temperatures reached had not led to risks of boiling and damaging the clads and that they could thus remain in the reactor.

In 2006, these elements were rediscussed to provide a scenario to explain the 4 automatic shutdowns. A statistics study showed that some of the R/B present at the automatic shutdowns, which have since been dismantled, had been irradiated much longer, and were thus much more charged in plutonium, prior to being placed in contact with DAC in a thermalized flux. They could, therefore, have risen much higher in temperature. In the event of local boiling of the sodium, the implosion of the bubble of vapour formed along the periphery of the core, could therefore have led to anflowering of the core along the shock wave, then to a return to normal. One of the major strengths of this scenario (other than the consistency with the measurements recording during the automatic shutdowns) is the timing coincidence between the presence of these irradiated R/B" adjacent to the DAC and the occurrence of these reactivity variations.

Calculations and studies were undertaken to quantify both the thermal aspect of the events (possibility of the appearance of a vapour bubble) and the consequences of an implosion in this spot (core flowering).

The combined thermal and neutronic studies showed that the effects were extremely three-dimensional, and that, for the face touching the DAC, temperatures of 700 to 800°C could be reached, for the highly irradiated R/B, in best estimate. This extremely high temperature gradient leads to a lower mix temperature at the outlet from the R/B and thus below the boiling values. However, it is difficult to estimate the accuracy of the calculations in such disturbed configurations.
These studies continue, to study the thermics of the DAC which lead to a few dozen kW power connected to the R/B.

It is hereby pointed out however that the studies conducted later on the reports on the in-cell dismantling of these DAC showed that samples of stainless-clad cobalt were found welded the length of their generatrix, which is the sign of a local high temperature rise in the DAC.

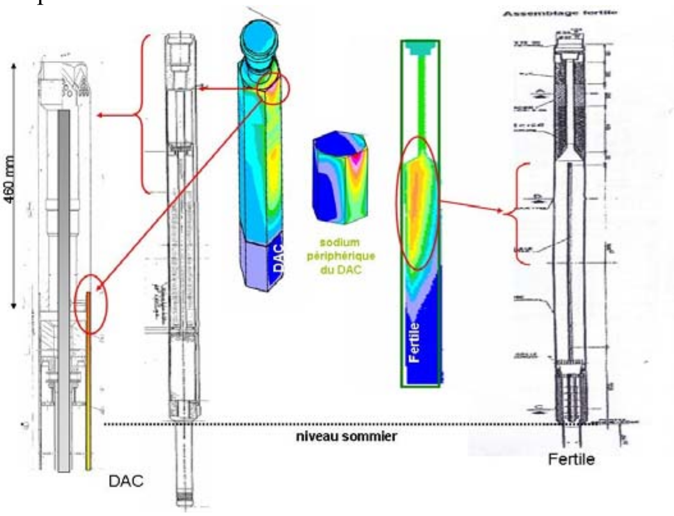

Fig. 6. Combined thermal calculation between the DAC and the R/B

The second part of the studies investigated the dynamic response from the Phénix core to a force-field from the implosion of a sodium bubble. The calculation presented is made with a 30-liter bubble (approximately twenty grams vaporized) imploding along the periphery at the DAC level.

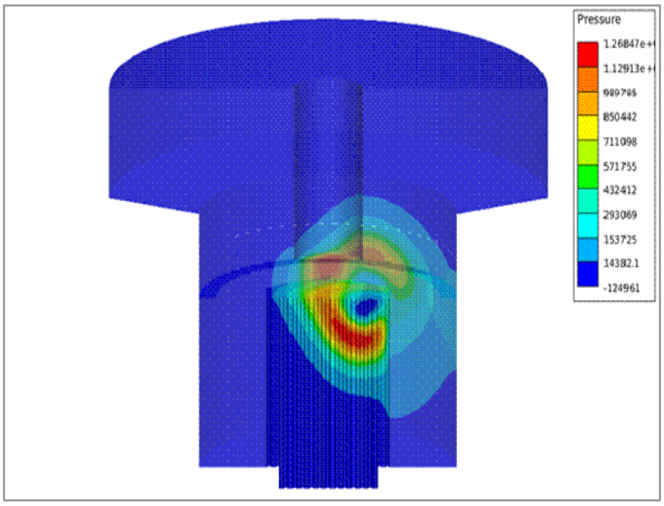

Fig. 7. Fluid mesh and pressure fields during the wave propagation

The enclosed diagram gives one example of the calculation of the movement of the sub-assemblies over time. The flowering of the core takes place with movement of three to four millimetres at the top in less than 0.1 second, and return to normal in 0.25 sec.

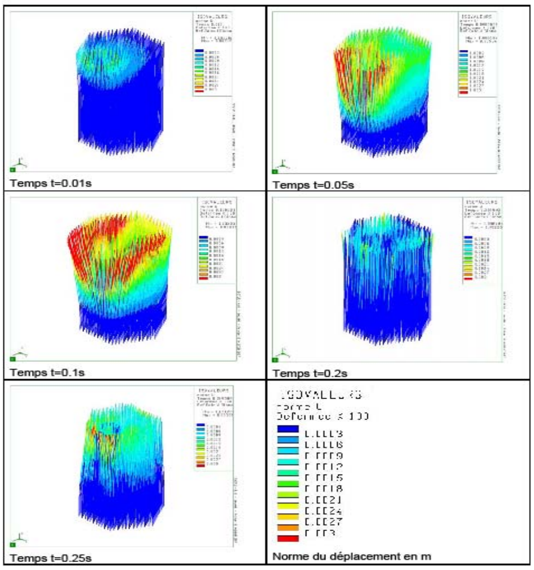

Fig. 8. Sub-assembly deformations over time

Precaution must be taken with any comparison to the negative reactivity automatic shutdown timed signal, for on the one hand there is a sub-assembly movement signal and on the other the overall reactivity signal. However, the values are of the same order of magnitude on the timed level (0.05 for 0.1 sec and 0.2 for 0.25 sec). However, the average movement level and the energy level are highly insufficient, in the assumptions used for this calculation (0.6 for 3 to 4 mm and factor 70 for the energy) Here too, this type of calculation is extremely complex and the results can vary depending on the assumptions and the calculating methods used, in particular for the added masses.

In conclusion, studies are continuing in the attempt to validate this new proposal for an explanatory scenario.

7 Conclusion

The feedback from over thirty years of operating experience with Phénix has shown that control of this reactor type is simple from both the neutronic and theoretical standpoints, and that there are wide safety margins.

Shutdown of the Phénix reactor is scheduled for 2009, and will entail a series of end-of-life tests which include tests devoted to neutronics in order to improve fundamental knowledge and the related validation of the neutronic computation codes. Another set of tests will be devoted to quantifying the core reactivity sensitivity to imposed flowering and to testing the thermics at the outlet of a configuration made up of a DAC joined to irradiated R/B assemblies.