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THE PHENIX EXPERIMENTAL IRRADIATION PROGRAM

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In then years of industrial operation, nearly 120 000 fissile pins have been irradiated in the PHENIX fast breeder reactor ; of these, more than 10 000 may be considered as experimental pins tested in about 50 devices.

The PHENIX experimental program covers several fields of application, primarily including the linear power density, cladding temperature, burn up, integrated dose and residence time. The range of operating conditions studied for different types of cladding materials has led to significant improvements in fuel element design for commercial plants, and particularly for the SUPER PHENIX reactor.

Similarly, more than 10 000 pins pins containing fertile oxide have been or are being irradiated in the radial blanket rows surrounding the PHENIX core. The objective is to extend the limit conditions as well as the core residence time and the end-of-life linear power density. Various technological solutions using boron cardibe absorbers have been developed in specific experiments with the perspective of increasing the residence time under irradiation.

1. PHENIX OPERATING RECORD

The PHENIX operating record up to mid-1981 was presented in Brussels in 1982 [1] [2], and is updated here in a few figures after three additional years in service to July 1984, i.e. after a total of ten years of industrial operation beginning in July 1974 [3].

As of July 1984, PHENIX had accumulated 2255 equivalent full power days (EFPD), referenced to the nominal power rating of 250 MW_e (563 MW_{th}). The total gross energy output was 13.13 TWh_e (30.46 TWh_{th}), representing a net operating production of 12.22 TWh_e. The cumulative production curve is shown in Figure 1, and the plant power history in Figure 2.

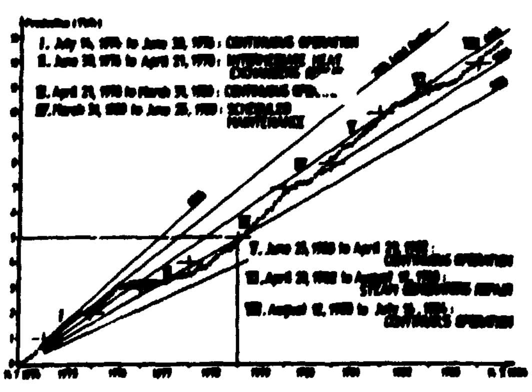

Fig. 1 - PHENIX operating diagram

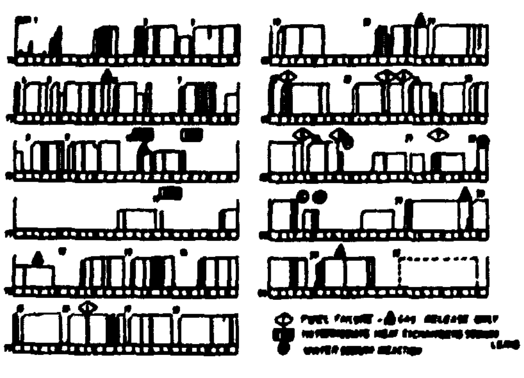

Fig. 2 - Phenix power history [3]

The cycle duration is now set at 90 EFPD.

The 32 cycles terminated at the end of 1984 represented 598 subassemblies containing more than 120 000 pins. A total of 330 subassemblies have been reprocessed, and the fuel cycle implemented in 1979 has been completed several times. The measured breeding gain has been 16 %, and 7 clad failures have occurred. The overall load factor* has been 59.3 % to date.

$$* \ \frac{\text{Total gross electric energy (MWh)}}{\text{Number of calendar hours x 250 MW}}$$

These highly satisfactory plant operating results are even more appreciable when it is considered that PHENIX is also a major fast neutron irradiation tool (the only such facility in France since RAPSODIE was shut down in 1982). As of the end of 1984, nearly 10 400 fuel pins had been irradiated in 10 capsules and 56 experimental assemblies ; of these, half have already been removed, while the others are still in the reactor.

2. EXPERIMENTAL IRRADIATION PROGRAM OBJECTIVES

Figure 3 shows the volume of experimental irradiations in PHENIX since 1978. Broadly speaking, three major experimental categories may be discriminated :

- experiments on material specimens in irradiation capsules,
- experiments on fissile pins in capsules and subassemblies,
- experiments on hexagonal wrapper tubes and fertile pins in subassemblies.

Except for a slight dropoff in pin experiments around 1979 corresponding to temporary emphasis on specimen irradiation tests, this diagram shows a regular and significant increase in the overall experimental volume, primarily due to qualification tests on fissile pins made from the selected materials.

At the end of 1984, the current and planned program can be broken down into the objectives indicated in Figure 4 :

- Development of fuel subassembly materials (primarily cladding and hexagonal wrapper materials) : this highly important area is covered by irradiating specimens, pins or complete subassemblies ;
- Research to obtain high performance characteristics (analysis of operating ratings at high temperatures, high linear power densities and high burn up) ;
- Design demonstration and optimization (qualification of LMFBR project studies) ;
- Specific studies (e.g. corrosion, thermal and mechanical characteristics, behavior during incident situations) ;
- Industrial demonstrations (industrial manufacturing process optimization) ;

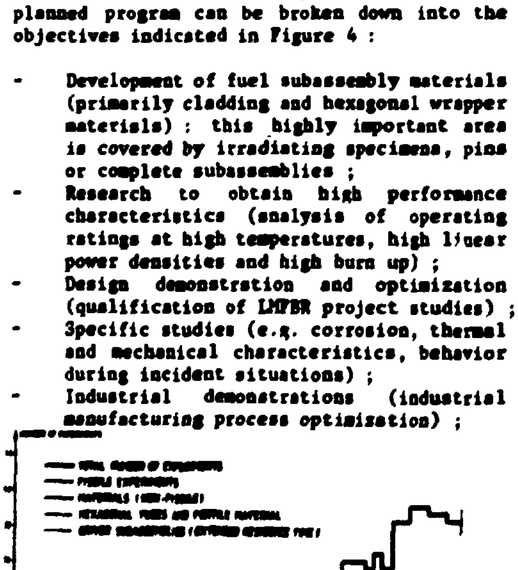

Fig. 3 - PHENIX experimental history

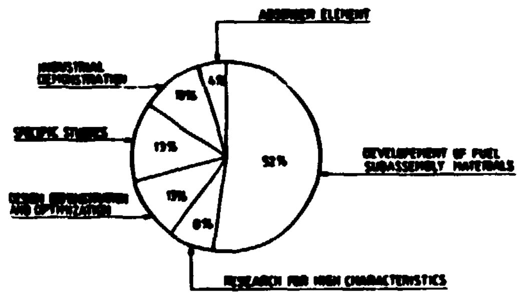

Fig. 4 - French program for the FBR experimental irradiations (in pile or programmed experiments ended after 1984)

- Absorber element studies (improvements for SUPER PHENIX and subsequent French LMFBRs).

3. PROGRESSION OF EXPERIMENTAL FISSILE PIN IRRADIATION CHARACTERISTICS

Figures 5 and 6 show the experimental irradiated fissile pin distributions for the following parameters :

- Maximum specific burn up ;
- Maximum displacements per atom in the clad material according to French standards (dpaF)*.

The current nominal values for driver core subassemblies [2] are :

- Inner core : 66 000 MWd/t oxide (7.8 at %) - 95 dpaF ;
- Outer core : 85 000 MWd/t oxide (9.4 at %) - 95 dpaF.

In actual fact, these nominal values do not constitute a technological limit, and many standard subassemblies are irradiated to 120 - 130 dpaF.

The following results have been obtained with experimental pins :

- Burn up: Nearly 2200 pins have sustained specific burn up exceeding 10.6 at % ; over 430 pins have exceeded 13 at %, and the maximum value reached to date is 117 300 MWd/t oxide (13.8 at %) ;
- dpaF: Over 4100 clads have been exposed to damage rates above 100 dpaF and, for nearly 1100, above 130 dpaF ; the maximum value reached is 146 dpaF.

A major advantage of the PHENIX reactor and its experimental environment that contributes to this progressive extension of performance limits is the possibility of reinstalling irradiated pins in new capsules, or even complete subassemblies (217 pins) in new hexagonal wrappers.

* 100 dpaF ~ 77 dpa NRT

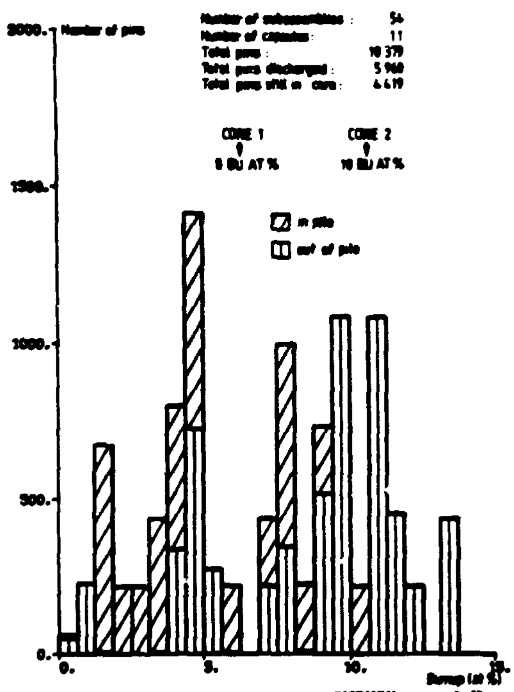

Fig. 5 - Specific burn up in PHENIX as of Nov. 1984 : experimental pins

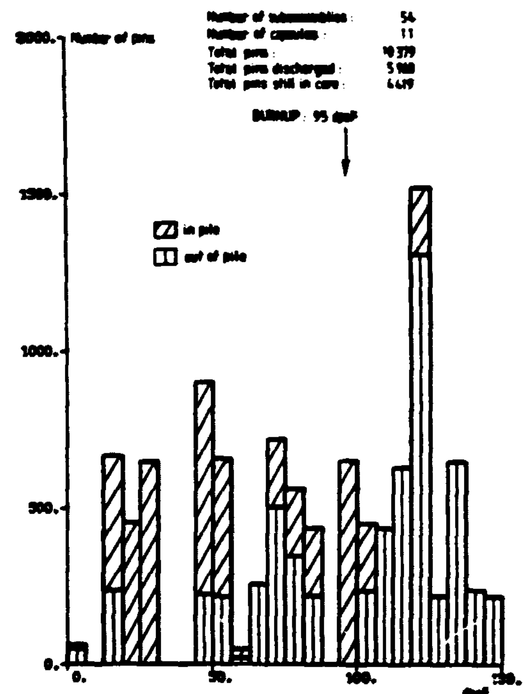

Fig. 6 - Dose (dpaF) in PHENIX as of Nov. 1984 : experimental pins

4. TRENDS FOR EXPERIMENTAL PINS

4.1 Pin cladding

The current standard austenitic steel clads are fully satisfactory for the nominal reactor performance characteristics, and are capable of accepting a 40 % increase in these limits in the near future.

Many other materials are being tested or are scheduled for qualification for high doses (up to 220 dpaF), mainly ferritic steels and nickel alloys. Certain grades should shortly allow production of new standard clads with appreciably improved performance due to a major increase in the irradiation swelling resistance. Clad failure tests are an integral part of the qualification process.

4.2 Hexagonal Wrapper Materials

Work is in progress at the same time on new materials for the hexagonal tubes to ensure coherent solutions for high-performance subassemblies. Swelling is a limiting factor here, especially for austenitic steels ; conversely, embrittelement of ferritic materials must be carefully analyzed when doses exceeding 180 dpaF are considered.

4.3 Severe Fissile Pin Irradiation Conditions

Two experiments are in progress, and a third is planned, with the objective of studying pin behavior at high cladding temperatures (above 650°C).

High linear power densities (above 450 $W.cm^{-1}$) are investigated by several experiments : three experiments now under way and a fourth currently in preparation cover the linear power range from 500 to 650 $W.cm^{-1}$.

High burn up values are studied in qualifying structural materials for high doses. A large number of irradiations are thus scheduled or in progress in this area, currently limited to doses of about 220 dpaF and to specific burn ups on the order of 180 000 MWd/t oxide (20 at %).

Finally, specific irradiations are conducted to study the conditions resulting from certain operating incidents, such as a mixed oxide core meltdown, or various natural clad failures to qualify clad failure parameter study programs in test reactor (SILOE).

4.4 Experimental Fertile Pin Program

This program covers approximately 1000 pins to date, in ten subassemblies, and is designed to investigate the residence time parameter, currently limited to 670 EFPD for the internal core positions (to avoid exceeding the 650°C clad temperature limit) and to 900 - 1160 EFPD for the more remote positions.

On a purely experimental level, noteworthy studies are in progress on the heterogeneous core, including irradiation of radial blanket subassemblies in the fissile core, and of special subassemblies with an intermediate fertile plate (which have been found fully satisfactory up to the highest burn up values reached in the core so far).

Future experiments are planned in the following areas :

- Data acquisition to improve thermal behavior models for fertile fuel ;
- Clad failure studies.

4.5 Experimental Absorber Program

This program is also much more limited than the fissile pin program. Nevertheless, it involves experiments with considerable impact on the optimization of future LMFBR core management procedures to ensure that the absorber element residence times are compatible with the long cycles planned for future cores. Two very different aspects are covered :

- Basic research supported by parameterized irradiations to provide a better understanding of the swelling and future properties of absorbant materials (boron carbide compounds) ;
- Qualification studies for the technological solutions adopted.

These irradiations are performed either in specific capsules, or in the actual PHENIX control rods to study their behavior in dynamic operation.

5. CONCLUSION

The PHENIX experimental irradiation program represents a substantial volume of work. For example, more than forty experiments were in the core during the 33rd PHENIX irradiation cycle at the end of 1984. This program ensures the implementation, optimization and qualification of new solutions for the future development of French LMFBRs in three significant areas : fissile, fertile and absorber elements.

The program has been made possible by the remarkable performance of the irradiation facility constituted by the PHENIX reactor, which at the same time continues its exemplary career as a nuclear electric power generating demonstration plant. The constant progression of the experimental program and its minimal interference with normal plant operation are proof of coherence and expertise in the basic technological options and their evolution. In this respect, they are an assurance of the harmonious development of the French LMFBR system, which is about to enter the industrial phase with the commissioning of SUPER PHENIX.

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