HIGH TEMPERATURE FISSION CHAMBERS: STATE-OF-THE-ART

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Abstract

In the control and the surveillance of fast breeder reactors, high temperature fission chambers able to operate in extremes of temperature and gamma dose perform two essential functions:

- In-vessel integrated neutronic control;
- Clad failure detection by integrated detectors.

In addition, they can be used for example to:

- Measure the weight of the control rods;
- Monitor the insertion of new sub assemblies (SAs) and withdrawal of irradiated SAs;
- Eventually monitor the neutron flux in Boiling Water Reactors (BWR).

Since 1970, a major research development and qualification programme has been undertaken in France by the CEA in very close collaboration with the Philips Photonics France, and the staff of PHENIX and SUPERPHENIX fast breeder reactors.

This programme has resulted in the development of:

- Dedicated manufacturing processes for fission chambers to cope with the specific conditions in fast breeder reactors;
- A complete range of detectors to cover all other possible applications.

This paper reviews:

- The detectors in their dedicated applications;
- The main problems encountered, studies made and solutions found;
- The detector qualification status;
- The performance of the detectors in the French fast breeder reactors.

Introduction

To prevent a main core accident in the reactors, the reactor protection instrumentation must provide fast, continuous and reliable data on the reactor conditions. Some of the best detectors for this purpose are high-temperature fission chambers.

Several types of fission chambers have been specially developed for:

- Neutron monitoring and control in the PHENIX and SUPERPHENIX reactors and also for the European Future Reactor (EFR) project;
- Surveillance and protection on the clad failures using fission chambers integrated in the vessel;
- Specific measurements such as reactivity weighting control rods and monitoring the insertion and withdrawal of irradiated material sub assemblies.

Such fission chambers could also be used wherever conditions are particularly harsh, for instance as in core detectors in a Boiling Water Reactor (BWR).

Since 1970, a major development programme for the French fast breeder reactors has been conducted and managed by the French Atomic Commission (CEA) in close collaboration with Philips Photonics. The programme aimed to develop, manufacture and qualify a new family of high temperature fission chambers and associated electronics able to cover a wide dynamic range.

This paper reviews the programme, advances in detector manufacturing technology, and detector performances in the French fast breeder reactors.

High temperature fission chambers and associated electronics

In fast breeder reactors, the high temperature detectors are used for:

Neutron monitoring

- *Start-up system at PHENIX:* at shutdown state, the counting rate under the vessel is very low (only the electronic noise); to monitor conditions at shutdown and during the first stage of start-up, a detector integrated in the vessel, near the core, is needed.
- *Auxiliary neutron monitoring system for SPX*: during core loading and also during the neutron measurements, an auxiliary neutron detection system in a central channel of the core has been used in view of monitor the reactivity and to protect the reactor; three fission chambers (type CFUX14) were used in this system from 1985 to 1990.
- *Integrated neutron monitoring system for EFR project*: a neutron monitoring system in the core cover plug is needed for the EFR reactor project for which no neutron guides are forecast; about nine fission chambers (type CFUC07) would be needed for the reactor protection and surveillance instrumentation to cover the core from shutdown to full power.

Cladding ruptures detection

The design concept of “clean sodium” adopted in France for FBR reactors demands the immediate detection of a clad failure and to shutdown the reactor before there is any fuel loss in the primary circuit.

In addition to the conventional sipping system, an experimental system is used in the SPX reactor, since 1985, to detect the clad failures with integrated detectors: eleven fission chambers (type CFUC06) in the vessel; eight of which are located behind the eight Intermediate Heat Exchangers (IHX).

Other applications

- *Reactivity weighting control rods*: these measurements are extremely important for safety; the “rod drop” method can be used as on FBR, using high temperature fission chambers in vessel, as well on PWR reactors, with ex-core detectors.
- *Monitoring sub-assemblies* during their insertion / withdrawal to detect any spurious handling.
- *In-core neutron monitoring:* the eventual monitoring of the neutron flux in-core of other reactors such as BWRs.

Associated electronics

The detector is, of course, only one part of a measuring system for one channel. An electronic system is also necessary. Therefore, a considerable effort was devoted to the design of an electronic system that could cover a wide measuring range from start-up to full power, with the fission chambers operating in the three modes: pulse mode, fluctuation (Campbelling) mode and current mode.

It is also tested in reactor.

Detector challenges and technical solutions

The development of high temperature fission chambers started in 1970, from a collaboration between the CEA/DEIN and Philips Photonics.

Three detector types were developed, mainly for pulse mode operation:

- **CFUE** type (sensitivity 0,01c.s-1/nv – ∅=7mm);
- **CFUD** type (sensitivity 0,1c.s-1/nv – ∅=36mm);
- **CFUC** type (sensitivity 1,0 c.s-1/nv – ∅=48mm).

Several prototypes of each type were manufactured and tested in experimental reactors at Saclay and Fontenay, France.

The goal was to obtain a reliable high sensitivity detector able to operate in very harsh conditions (temperature, neutron and gamma flux) over a wide dynamic range. The signals from these detectors had to be transmitted down cables (cable to withstand the same conditions) to the electronic measuring equipment with no significant signal degradation.

For more than ten years, several tests were made in experimental reactors and in PHENIX FBR. These tests enabled us to define the best detector technology, and provided a better understanding of what happens to detectors in severe conditions. This allowed some detector parts to be improved, securing long-term reliability in harsh conditions.

Environmental influence on detectors

High temperature around 600°C

High temperature has a large influence on detector components, causing:

- A reduction in insulation resistance of ceramic insulator;
- Produces spurious discharges on the surface of the ceramic insulators at high voltage, generating pulses similar to neutron pulses;
- Outgassing of the chamber's metal body, which contaminates the filling gas;
- Combination of some gases such as nitrogen by the materials of the chamber;
- Weakening of the metal body and electrode support structure, making it difficult to use a small electrode spacing.

High neutron and gamma flux

The high neutron and gamma flux aggravate the high temperature effects, causing:

- Increased parasitic current in the cable and on the insulators;
- Increased outgassing and gas combination.

Technical solutions used

Designing a low sensitivity fission chamber is fairly straight-forward because only two uranium coated electrodes are required. High temperature fission chambers (filled with pure argon with a sensitivity between 0,01 and 0,1 $c.s^{-1}$ per nv and a collection time less than 100 nsec should be possible. The difficulties arise with increasing sensitivity; for instance:

- The area of uranium layer must be increased. In addition, more than two electrodes with are needed and the design of the mechanical assembly starts to become difficult;
- The electrode spacing must be increased (owing to mechanical considerations), so the detector must be filled with a mixture of argon and nitrogen to maintain a collection time < 100 nsec.

To meet the desired characteristics (see Figure 1):

- Special alumina ceramic feedthroughs and seals were designed and tested at high temperatures and high gamma flux;
- Different metals were evaluated. Our final choice was Inconel 600 for the electrodes and detector body. The external cable shield was kept as traditional stainless steel;
- High immunity parasitic and mineral insulated cable was chosen and tested in pulse mode at high temperature and high gamma flux; the cable was sealed at both ends by specially designed feedthroughs;
- To avoid spurious breakdown pulses and reduce the leakage current seen by measuring electronics in current mode, a “guarded” design with two cables (one cable for HV, one cable for signal) was adapted for CFUX14, CFUC06 and CFUC07. However, since 1986, considerable improvements have been made in reducing breakdown pulse noise. For the future, a new design with high sensitivity wide dynamic range fission chambers will use only one cable for both (HV and signal);
- Special vacuum and gas treatments were developed to reduce outgassing of metal parts and to prevent gas combination. A mixture of argon and nitrogen can be used in our detectors to reduce the collection time in pulse mode. The CFUC07 was filled with this mixture and tests results indicated high reliability and no change in collection time. The nitrogen did not disappear;
- Special electrode assembly was developed and tested under high temperature and exposed to shocks and vibrations.

Tests and qualification

To evaluate the performance of the high temperature fission chambers and cable during the development phase, the following tests were made to characterise the prototype detectors.

Preliminary laboratory tests

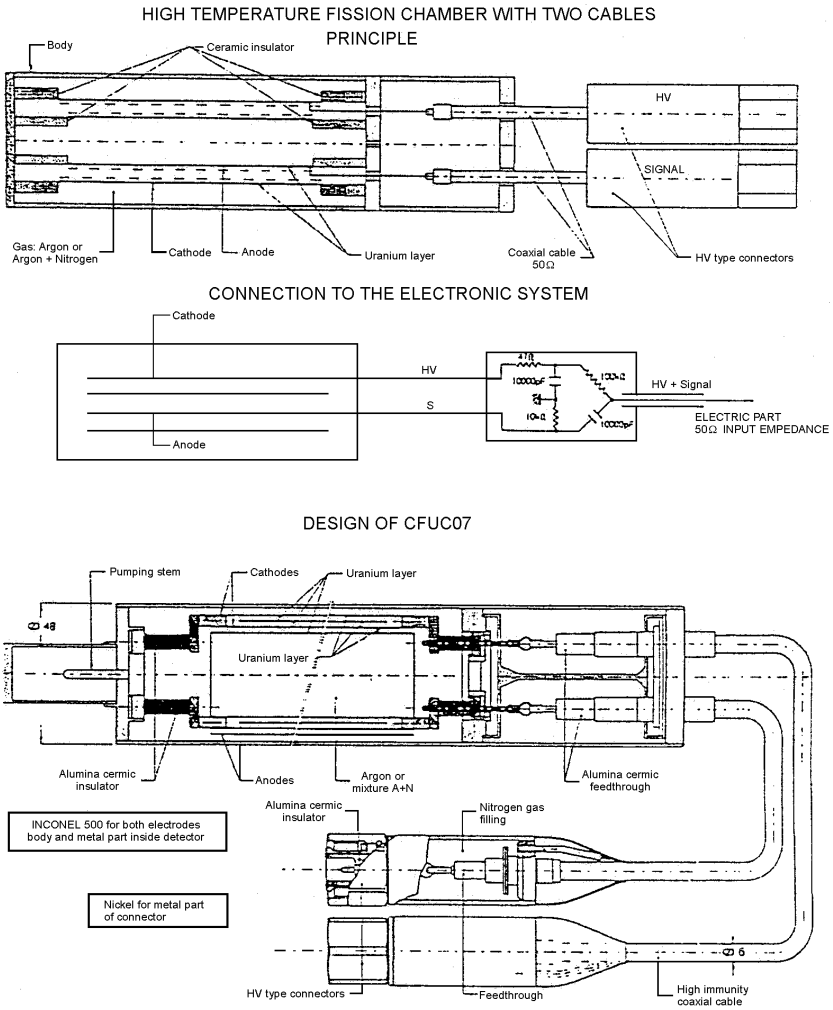
These are performed systematically on all detectors before operation in the PHENIX or SPX reactors and comprise:

Electrical and thermal tests

The insulation resistance and capacitance of each cable were measured over a wide temperature and the absence of breakdown pulses under high voltage confirmed.

For example, the CFUC07 and its cables were tested 16 hours at 650°C and no deterioration of its main characteristics were observed.

Figure 1.



Neutron tests with RaBe source

These tests were performed to characterise the pulse shapes from a fission chamber exposed to a low neutron flux (4 to $5 \times 10^{+3}$ n.cm^2.s^{-1}) and to enable the chamber's sensitivity to be evaluated.

Complementary tests

High gamma flux tests

The influence of gamma radiation was determined in pulse mode operation and the sensitivity to gamma radiation was measured in current and fluctuation (Campbelling) modes. These tests were performed at Saclay in the gamma irradiator PAGURE (^{60}Co), with dose rates up to several kGy.h^{-1}.

Neutron tests in an experimental reactor

These tests verified the linearity of the fission chamber response over all three operating modes (pulse, Campbelling, current) and confirmed the overlapping zones between these modes (overlapping zone).

For these tests, the ULYSSE experimental reactor at Saclay was chosen because it can deliver a neutron flux, constant over several decades.

Experimental qualification tests

Several prototypes underwent extensive endurance tests in the laboratory and in experimental reactors to help us in our choice and to confirm the chosen manufacturing technology for the application.

For example: one prototype of a CFUC07 fission chamber was tested in the laboratory at 600°C for 10 000 hours with no detectable degradation in its main characteristics (for an earlier prototype, the nitrogen disappeared completely in less than 2000 hours under the same conditions).

Another prototype was tested in the MELUSINE reactor at Grenoble during three or four months, at an average temperature of 565°C and under a neutron flux ranging from 8.10^{+10} to $1.8.10^{+11}$ $n.cm^{-2}.s^{-1}$. After a neutron fluence of about 7.10+17 $n.cm^{-2}$, the charge collection time and the discrimination curve for the new prototype were unchanged.

Cables and associated electronics

Special coaxial cables manufactured by Thermocoax Company were integrated with the detectors. These cables generally include a mineral insulator (magnesia), a metal sheath (stainless steel, copper and iron) and a copper core (with zirconia). The cable diameter is 4 or 6 mm and the characteristic impedance is 30 or 50 Ω.

Several tests were performed to evaluate or to measure breakdown voltage, transfer impedance, attenuation coefficient and insulation resistance as a function of temperature.

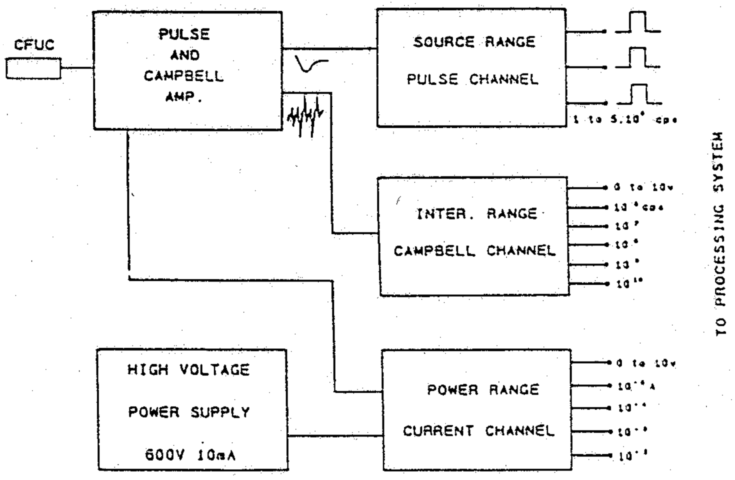
Similarly, special (organically insulated) cables with high immunity to parasitic signals were used to make the long (150 to 300 m) connection between the detector and its associated electronics.

A special electronic system able to operate in all three operation modes (pulse, fluctuation and current) was also developed for the CFUC07 sensor.

Particular emphasis was given to:

- Decreasing the background noise for the Campbelling mode to improve the transition between the pulse and fluctuation modes;

- Automatic changeover operating modes.



Experience in reactors

Several different high temperature fission chambers have been tested and operated in PHENIX and SPX reactors for the purposes indicated in the section entitled *High temperature fission chambers and associated electronics*.

Implementation in reactor

- *PHENIX – CFUC06.* One chamber in each of the two channels (SS8270 - 7082) located in the lateral shielding. One in a lateral channel, near one of the intermediate heat exchangers.
- *PHENIX – CFUC07, CFUE22 and CFUE42.* One of each chamber in channel SS8270, just above the CFUC06.
- *SPX – CFUX14.* Three chambers located in a movable device in the central channel (30/30) of the SPX core.
- *SPX – CFUX06.* Eleven chambers: eight located behind the eight intermediate heat exchangers and three surrounding one of the exchangers.

Operation in reactor

Today, only the three CFUX14 have been withdrawn from the SPX reactor, and this was for maintenance of mechanical support – the chambers themselves were still fully operational. All of the other chambers (in or out of core) continue to operate.

The neutron fluence received by each chamber depends on its position in the vessel (in or out of core and distance from the core centre).

So far, the detectors have been operated between five and fifteen years depending on the chamber type. The operating temperature ranges between 180°C (when reactor is shutdown) and 550°C (when reactor is at full power).

The following table shows the main parameters of this reactor experience.

High temperature fission chambers: Operational conditions

	CFU PHENIX	**C06 SPX**	**CFUX14 SPX**	**CFUC07 - CFUE22 and CFUE42 PHENIX**
Integrated neutron flux (n.cm^{-2})	2 x 10^{+13} to 3 x 10^{+18} (*)	5 x 10^{+8} to 2 x 10^{+11} (*)	6 to 15 x 10^{+17}	3 to 4 x 10^{+16}
t x T (sec x C)	1 to 2 x 10^{+11}	1,5 x 10^{+11}	8 to 11 x 10^{+10}	7 to 9 x 10^{+9}

(*) Following the position or regard to the centre of the core.

Operational characteristics

Generally, the operational behaviour of a fission chamber is characterised by two main parameters:

a) The slope and the length for the high voltage plateau [N(c/s)=f(HV)] in pulse or Campbelling mode and for the saturation plateau [I(mA) = f(HV)] in current mode;

b) The discrimination curves of counting rate as a function of discrimination voltage [N(c/s) = f(HV)] in pulse mode.

a) Plateau gradient [(DN/N) / DV] (% / volt)

CFUC06 at PHENIX

	1981	**1987**	**1995**
P(Mw)	**588**	**100**	**350**
Pulse mode	0,021	0,03	0,060

CFUC06 at SPX

1984	**1996**
Factory with a neutron source	**1500**
0,037 ± 0,0043 (*)	0,0363 ± 0,0180(*)

CFUX14 at SPX

	1986	**1986**	**1989**	**1989**
P(Mw)	**3000**	**307**	**490**	**1470**
Pulse mode				
Campbelling				
Current mode	0,037	0,042	0,032	0,042

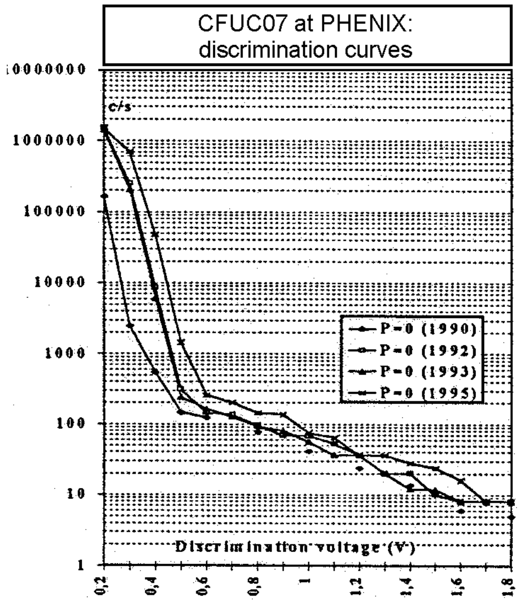
CFUC07 at PHENIX

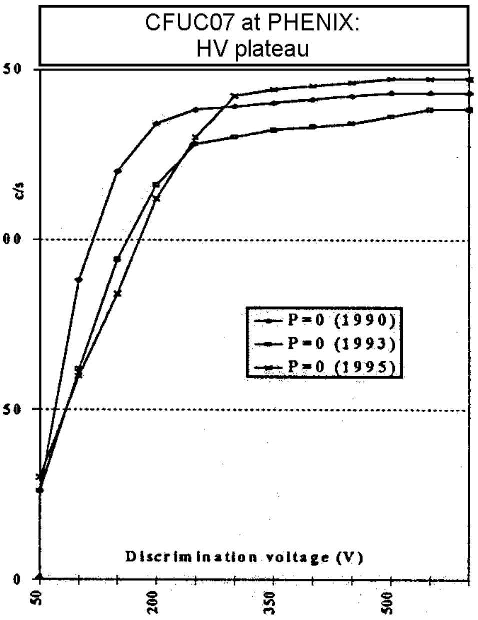
1991	**1993**	**1995**	**1995**
10KW	**350**	**350**	**10 KW**
0,019			0,022
0,047	0,055	0,018	0,047
0,012	0,012	0,014	0,013

In each case, the length of the plateau is equal to or higher than 250 volts.

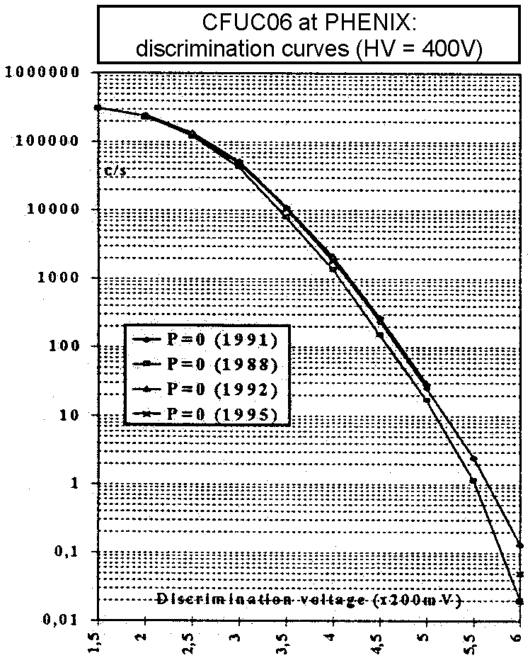
b) Discrimination or saturation curves - reactor shutdown (P=0 Mw)

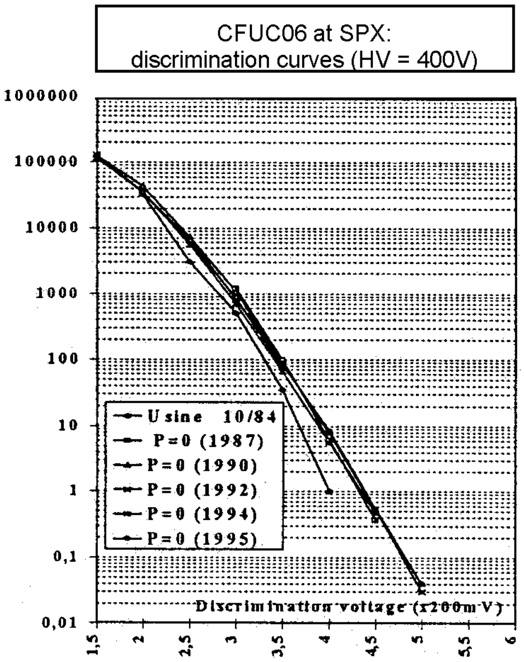
These curves describe the conditions in the measurement channel (sensor, cable and electronics) as a function of the time and indicate possible operational problems.





(*) Average value on 11 detectors: the statistical fluctuations of the counting rate explains the spread between the two results (#900 c/s in factory and 1 to 100 c/s in reactor).

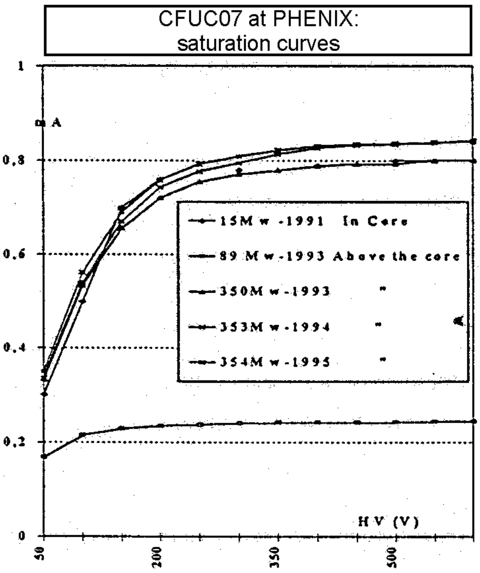




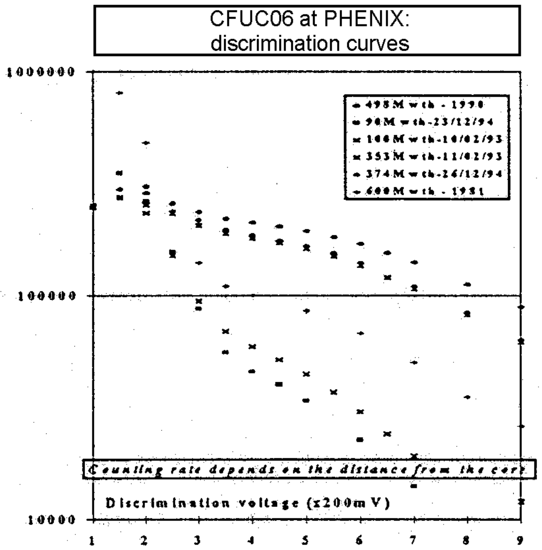
Over the indicated period, the main characteristics of these fission chambers have remained constant.

c) Discrimination or saturation curves in operation

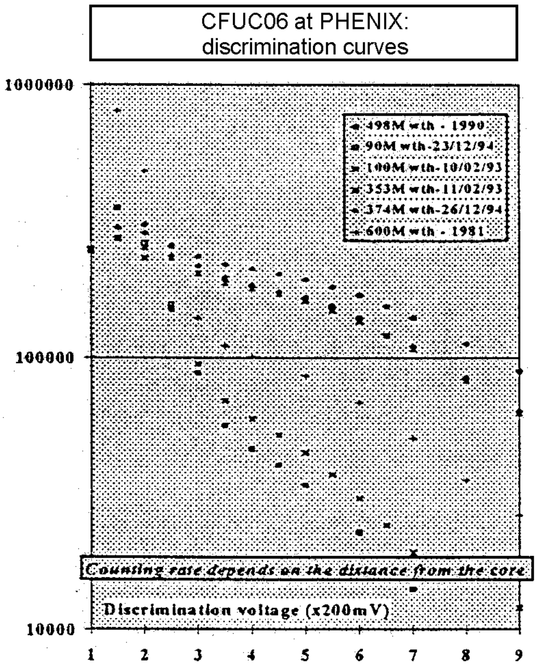
In operation, the discrimination curve (in pulse mode) or saturation curve (in current or Campbelling mode) indicate a possible change of the condition of the measurement channel and especially the in the behaviour of the detectors.



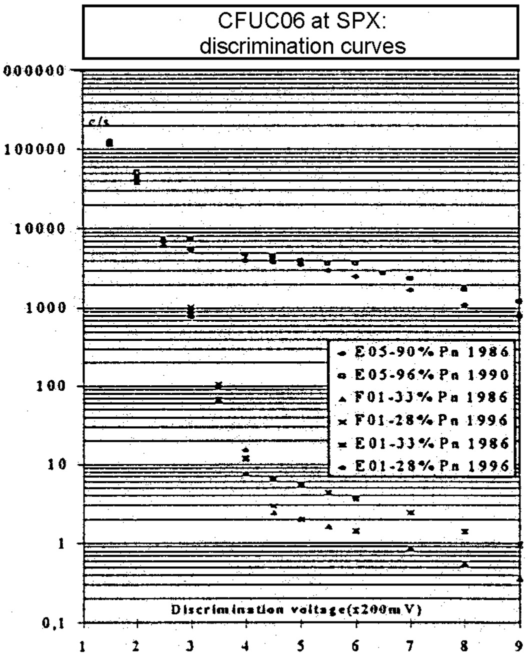
CFUC07 at PHENIX:
saturation curves



CFUC06 at PHENIX:
discrimination curves



CFUC06 at PHENIX:
discrimination curves



CFUC06 at SPX:
discrimination curves

Throughout the long test period and operating in real conditions, no problems have occurred.

The operational parameters such as the slope of the current plateau (or Campbelling plateau) have remained constant.

Particularly in pulse mode operation, no spurious pulses or breakdowns were observed, even at high temperature (>500°C). during a voluntary scram, the counting rate immediately assumed its proper shutdown value; for the high dynamic fission chamber with the three operation modes, the automatic reversal to pulse mode from current mode (via the Campbelling mode) occurred perfectly.

Conclusion

Now, this twenty-year programme has been fully completed, except for the CFUC07 endurance qualification test in the PHENIX reactor. Today, reactor instrumentation designers have at their disposal a complete range of sensors able to operate in very harsh conditions (high temperature and high gamma dose) with a large range of sensitivity. Such detectors are now in operation in the French fast breeders, but could be also used in BWR or HTR reactors for in-core neutron monitoring, handling operations, control, surveillance and many other operations.

A future development programme could complete these studies; for example, the development of a CFUC08 chamber (similar to the CFUC07 with only one integrated cable); the initial results of the first development phase of a such detector, driven by Philips Photonics, were quite positive.

However the development of a new prototype is presently postponed.

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