THE CEA PROGRAM ON BOILING NOISE DETECTION

G. LE GUILLOU, M. BRUNET, J.P. GIRARD, D. FLORY
CEA, Centre d'études nucléaires de Cadarache,
Département des réacteurs à neutrons rapides,
Saint-Paul-lez-Durance, France

I. INTRODUCTION

The research program on the application of noise analysis on boiling detection in a fast subassembly began 10 years ago at the CEA, mainly in the Nuclear Center of Cadarache.

Referring exclusively to the aspects of premature detection of the boiling phenomenon it can be said of this program :

- that it is organized around the following three detection techniques :
  - . acoustic noise analysis
  - . neutron noise analysis
  - . temperature noise analysis
- that its development is in conjunction with in-pile experiments 'PHENIX' or 'RAPSODIE' as well as 'ex-pile' (boiling experiments through electric heating).
- that the three detection techniques were developed independent of each other, but that they were regrouped during the execution of the most important experiments and with the 'Super Phenix' project.

The noise analysis system 'ANABEL' with which 'Super Phenix' will be equipped shows the industrial interest in detection methods based on noises.
One of the results of the CEA program today is the possibility to evaluate the potential capacity for boiling detection in the subassembly. But in order to obtain the necessary funds from the commercial nuclear plant operators it is mandatory to have successful demonstrations : this will be the objective of the future program.

II. GENERAL OUTLINE OF THE CEA PROGRAM

II.1 - The distinct development of the three detection techniques

a) The reasons

The three techniques having been developed by the CEA and which are based on acoustic, neutron and temperature noise analysis have attained a comparable results level.
However each technique has known a specific development program. There are three principal technical reasons for this :

1) Sensors and associated instrumentation
   very different technology levels at the beginning
2) Knowledge on the transmission functions between the sensor and the centre of the trouble
   very different knowledge levels at the beginning
3) Initiatory process of the trouble signal
   each technique has a specific process

b) Similarity in the acoustic and in the temperature noise development

In these two areas the development was largely determined by the introduction of specialised detectors (acoustic transducers or quick-acting thermocouples)

Moreover, the theoretical references related to the detection of boiling defect or to its transduction were purely hypothetical at the start of the program.

In both cases, the development of a special technique was required as well as the proof of its applicability on boiling detection - thus during the first years - the program has combined the development of detection techniques and of 'in-pile' and 'ex-pile experiments.

c) Neutron noise

This technique was very favoured at the beginning :

- the sensors were operational (ordinary ionization chambers)
- the theoretical equipment was extensive (sensor model, background noise, perfect knowledge of the transmission characteristics involved ...)

In short, the only unknown factor at the beginning were the boiling mechanism in a subassembly.

For the technique based on neutron noise an immediate start on the problem of boiling detection was possible :

- definition of the analysis methods
- compilation of background noise references ('RAPSODIE' and 'PHENIX")
- experimental identification of the boiling mechanisms.

II.2 - The CEA program is mainly experimental

This is a characteristic justified by the privileged position of the CEA : the availability of the two fast reactors 'RAPSODIE' and 'PHENIX'.

Three types of experiments have in particular contributed to the progress in boiling detection by way of noise analysis.

a) Analysis of the normal signals obtained in 'RAPSODIE' and 'PHENIX'

- Tests and development of the detection systems (especially in acoustic and temperature noise).
- evaluation of the on-line analysis methods of the signals (spectral analysis...)
- identification of the parameters of the background noise in the reactor.

b) Boiling experiments 'NABO I and II' in 'RAPSODIE'

'NABO' is a boiling subassembly and is γ-heated. Its hydraulic characteristics are very different from a real subassembly, 'NABO' in fact can be compared with a 'boiler'.

The boiling mechanisms observed through NABO are not very representative of real cases.

The objective with 'NABO' was the evaluation of the detection capacity of a certain way of boiling, in the reactor, through acoustic and neutron methods.

Three series of experiments took place with this subassembly, in 1974 (peripheral subassembly) then in 1975, (central subassembly and peripheral subassembly).

One can say that these experiments marked the turning point in favour of the detection techniques based on noise :

* no other conventional measurement device was activated by boiling
* in all cases the detection was very clear with neutron noise and, although to a lesser extent, with acoustic noise (because of construction reasons the detection by temperature noise was impossible).

c) Boiling experiments on experimental loop CFNa - GR 19

'CFNa' is an experimental loop which permits to study the exact thermal working conditions in a fast subassembly of the 'Super Phenix' type.
The pins are electrically heated, the most significant experiments have been performed with a geometric configuration of 19 pins :

- boiling by reduction of the flow rate (three experiments : 1976, 1977 and 1980)
- boiling by internal blockage (one experiment in 1977)

With 'CFNa' all stages of the cluster boiling mechanism could be observed in a significant configuration and under significant thermohydraulic conditions.
These experiments have contributed to :

- identifying the cluster boiling mechanisms
- establishing detection models (especially for neutron noise)
- identifying the specific boiling signals (acoustic and neutron noise *) or pre-boiling signals. (temperature noise).

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* Regarding the neutron noise this can be observed starting from the similarity between pressure and flow rate noises.

II.3 - Signal treatment methods

a) Methods used in laboratory

In laboratory, signal treatment systems were used.
Those systems are mainly specialized in the spectral analysis : APSD, CPSD, coherence, etc..
The results obtained in this way on boiling signals are :

- excellent as regards the neutron noise
- bad with respect to the complicated implementation of spectral methods and in regard to acoustics and temperature noises.

It is assumed nowadays that for these three techniques (acoustic, neutron and temperature) the pattern recognition associated with the simple techniques of time analysis (filtering and moments) will give excellent results for detection ; but this is still under development.

b) On-line methods used in the reactor

The CEA have developed suitable equipment for continuous on-line observation. For the three techniques this consists of an analog equipment which combines frequency filters and calculation circuits of efficient value.

These principles have been retained for the ANABEL (SPX 1) project with, in any case, the possibility of computer control.
Our real knowledge permits to define the pass band of the filter which suits to the boiling and the technique involved (acoustic, etc..)

c) The principle of the noise analysis system 'ANABEL'

We remind only the aspects concerning the boiling detection.

- Specific detection devices

* Acoustic : 6 'waveguide + accelerometer' channels which will eventually be replaced by sensors immersed in Niobate of Lithium.
* Neutron noise : 2 channels (ionization chambers under the vessel)
* Temperature noise : 221 subassemblies monitored by quick-acting thermocouples Na Inox.

- A hybrid system for treatment and detection

* Conditioning and analog detection
* Analysing or registration initiated by computer
* Computer control

- A software for the computer

* Normal supervision procedure (threshold management, spectral analysis control, periodical recording control).
* Possibility to apply experimental methods (without changing the normal procedure).

III - STATEMENT AND PRINCIPAL RESULTS

III.1 - The technique of acoustic detection

a) Acoustic transducers

The CEA have developed and produced high-temperature transducers which can be immersed in sodium.

Reference : Conf. Richland - Washington (1980) :
'Immersed Acoustic Transducers and Their Potential Uses in LMFBR'.
by J.P. Argous, M. Brunet, J. Baron.

b) Evolution in the ideas

At the beginning (1970 through 1978) the guiding principles were inspired by the following scheme :

- to characterize the loop boiling signal
- to study the background noise in the reactor.

Then it was realized that the results obtained in the loop could not be transposed to a reactor : the transmission function of the sensors differed from one case to another.

It follows therefrom that came the recent idea of the necessity to make demonstration experiments:

- NABO 'RAPSODIE'
- cavitation subassembly ('PHENIX', see figure 1)

Nowadays it is intended to utilize systematically the acoustic spreading of the cavitation to obtain signals to be controlled in the reactor.

c) Evolution in the methods of treatment

At the beginning of the program :

- power of the noise associated with the pass-band filtering
- spectral analysis.

Nowadays

- Counting the random emissions

- Supervision of the frequency bands which are in particular associated with the pattern recognition (see figure 2)

III.2 - Detection technique through the temperature noise analysis

a) The most promising detection technique

The CEA after a comparative study of the different boiling detection techniques have decided to encourage the program whose purpose is the analysis of temperature noises at the subassembly outlet.

This choice, in force since 1978, was made for following grounds :

1) It permits a premature detection, before boiling
2) It is the only one to detect the most likely anomaly, i.e. the small blockage without boiling
3) It permits to identify the subassembly involved
4) It makes it possible -in principle- to locate the defect inside the subassembly and to estimate its extent
5) Also in principle, it constitutes a follow-up means for the evolution of the deformations of the bundle during its life.

All these potentialities substantiate the great effort made by the CEA for about 5 years in order to develop these techniques.

b) Development of special equipment

All the advantages noted in favour of 'temperature noise' hold only true under the following indispensable condition: that the sensor has a fast reaction time. (less than 10 milli-seconds).

The CEA which develops and above all experiments the 'steel/sodium' thermocouple for about 10 years has gained a good experience in regard to the in-pile operation of this sensor.

It is difficult to select the right reference thermocouple:

But the drawbacks related to this problem are appearing at the very low frequencies, beneath those of the boiling phenomenon.

It is shown by figures 3 and 4 that 'chromel/alumel' and steel/sodium thermocouples give the same results in their common frequency ranges.

This fact proves the reliability of the steel/sodium technique.

Reference : Conf. Richland - Washington (1980)
'Temperature Measurements at the LMFBR Core' by J. Argous.

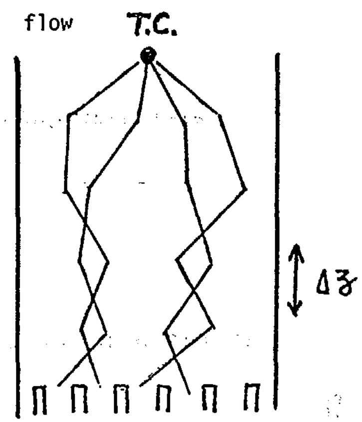
c) Development of the models and their effectiveness

It concerns here binding the measured characteristics of the signal to what occurs higher up in the bundle.

A 'Monte-Carlo' model was developed for calculating temperature fluctuations as per the D.FIRTH's (UKAEA) model.

The principles of this model are as follows :

- reversible way of liquid particles in a turbulent flow
- constant axial speed of the particles
- lateral speed with constant module and random phase



The theoretical results obtained through this model demonstrate that one can relate the measured characteristics of the signal to what happens higher up in the bundle. With our present knowledge it is assumed that we can relate the level of fluctuations (σ) associated with the dissymmetry factor (S) to the extent and the radial location of a blockage in the bundle.

This model has been proven to be correct during experiments in water.

- ANOMAT CEA Cadarache
- KFK Karlsruhe
- CEGB Berkeley (see the following reference)

Reference : 'Temperature fluctuations : an assessment of their use in the detection of fast reactor coolant blockages' by C.P. Greef in : Nuclear Engineering and design 52 (1979) 35-55

Figure 5 shows the excellent correlation calculation experiment obtained with this last experiment.

This model is in progress of proving itself on sodium experiments :

- CFNA CEA Cadarache
- ISIS Ispra
- ECN Petten
- KFK Karlsruhe
- RAPSODIE 'Têtacouple' experiment (CEA Cadarache)

Latter experiment 'Têtacouple' has as objective to follow the bundle deformations during its life.

III.3 - DETECTION TECHNIQUE BY NEUTRON NOISE ANALYSIS

a) Detection model

The physical analysis of the NABO ('Rapsodie') and above all the CFNA experiment has permitted the identification of the boiling mechanism in a sodium-cooled subassembly.

Consequently it has been possible to relate this mechanism to a detection model.

Reference : 'Chugging phenomena during sodium boiling. Application to flux and pressure noise analysis for bundle experiments' by J.M. Seiler 9th LMBWG Meeting - Rome (june 1980)

It was demonstrated that the main feature of the boiling mechanism was the appearance of a bubble whose volume oscillates around a frequency of some hertz.

The neutron detection model combines all the parameters and has as objective the evaluation of the detection threshold. (this threshold is expressed in units of reactivity).

For large reactors the problem is double :

- the vacuum sodium coefficient is small
- the neutron flux on the ionization chambers is not adequate

The following table gives the estimates for 'Super Phenix I' and for the sensitivity of detection which can be obtained (depending on the flux and the analyzing method of the signals)

				Bandwidth : 20 Hz	
NOISE ANALYSIS METHOD → / FLUX ON CHAMBERS ↓		INTER-SPECTRAL (2 SIGNALS) CPSD	DSP APSD	CROSSED EFFECTIVE VALUE (2 SIGNALS) "σ_{12}^2"	EFFECTIVE VALUE "$\sigma_{11}^2, \sigma_{22}^2$"
10^7 →	Sensitivity of detections in P C M (average conditions)	0.4	0.7	1	4
10^8 →		0.12	0.2	0.3	1.3
10^9 →		0.04	0.07	0.1	0.4

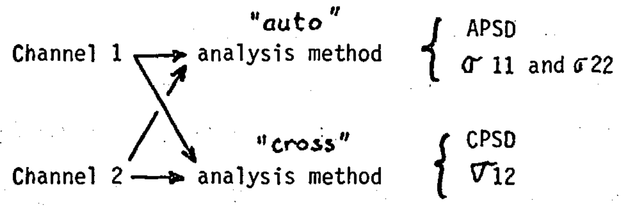


Figure 6 shows the results obtained with NABO and CFNa : note the appearance of a frequency peak characteristical for boiling.

b) Methods of analysis

At the beginning of the program (before 1978) the spectral analysis method was essentially used :

APSD or CPSD related to amplitude thresholds

Nowadays it is believed that the future is for the 'time analysis' (filtering and amplitude) in conjunction with the pattern recognition.

More and more it is tried to coordinate the neutron and acoustic detection techniques. Our program is based on this principle.

c) Necessity of a demonstration experiment

Only this type of experiment can bring, as in acoustic, a certain progress and mainly the confirmation of the effectiveness of this technique.

IV. CONCLUSION

It appears that the main effort has been experimental.

The three techniques developed by the CEA (acoustic, neutron and temperature noise) are complementary.

Nevertheless it seems that :

- the most likely anomaly (blockage of some sub-channels) can only be detected by temperature noise, which presents at the same time potentialities for locating and estimating the extent of the anomaly and the follow-up of the deformations of the bundle during its life.
- a certain number of gaps persist in the demonstration of the effectiveness of all the detection means envisaged, specially where those means are applied to the reactor. A demonstration experiment is then mandatory.
- as far as the acoustic noise is concerned, the main problems stem from reactor experiments : whether from background noise or from weakening of the signal.
- as far as the neutron noise is concerned, the most important problems are related to the weakness of the reactivity coefficients (sodium vacuum) and about the flux on the ionization chambers (we hope to improve this factor).

- the technique on temperature noise has yet to bring the proof of the qualities which are attributed to it. An important effort is in progress to design and to qualify this model.

Finally from the point of view of the signal analysis methods an integration is sought, through the application of the pattern-recognition, of the three techniques. (acoustic, neutron and temperature).

However, from a strict point of view of boiling defects, we can say that the noise analysis techniques (acoustic, neutron and temperature) seem to be the best promising ones. But it is very necessary to continue this development in order to show more precisely the efficiency of theses techniques on reactors.

PHENIX - EXPERIMENT "SIFFLEUR"

Detection of the cavitation through pattern recognition following the twp principal composants

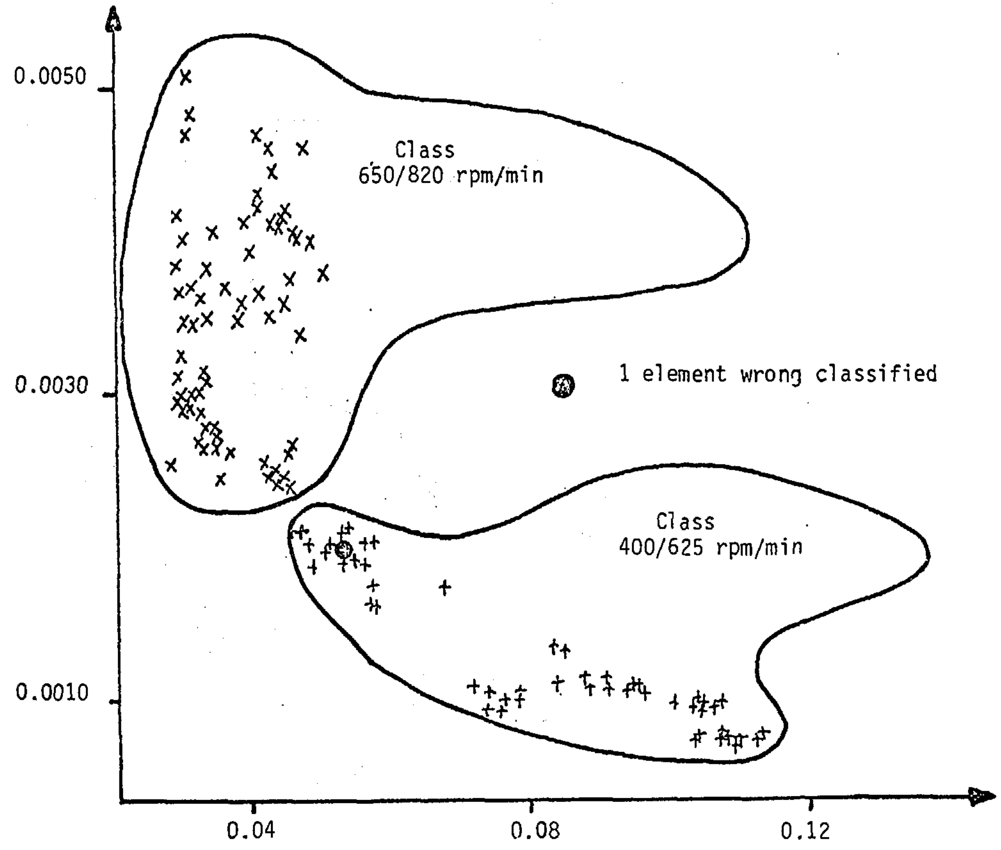


FIG. 1.

October 1980 (338)

PHENIX - EXPERIMENT "SIFFLEUR"
COUNT OF RANDOM EVENTS (SENSOR NR 12)

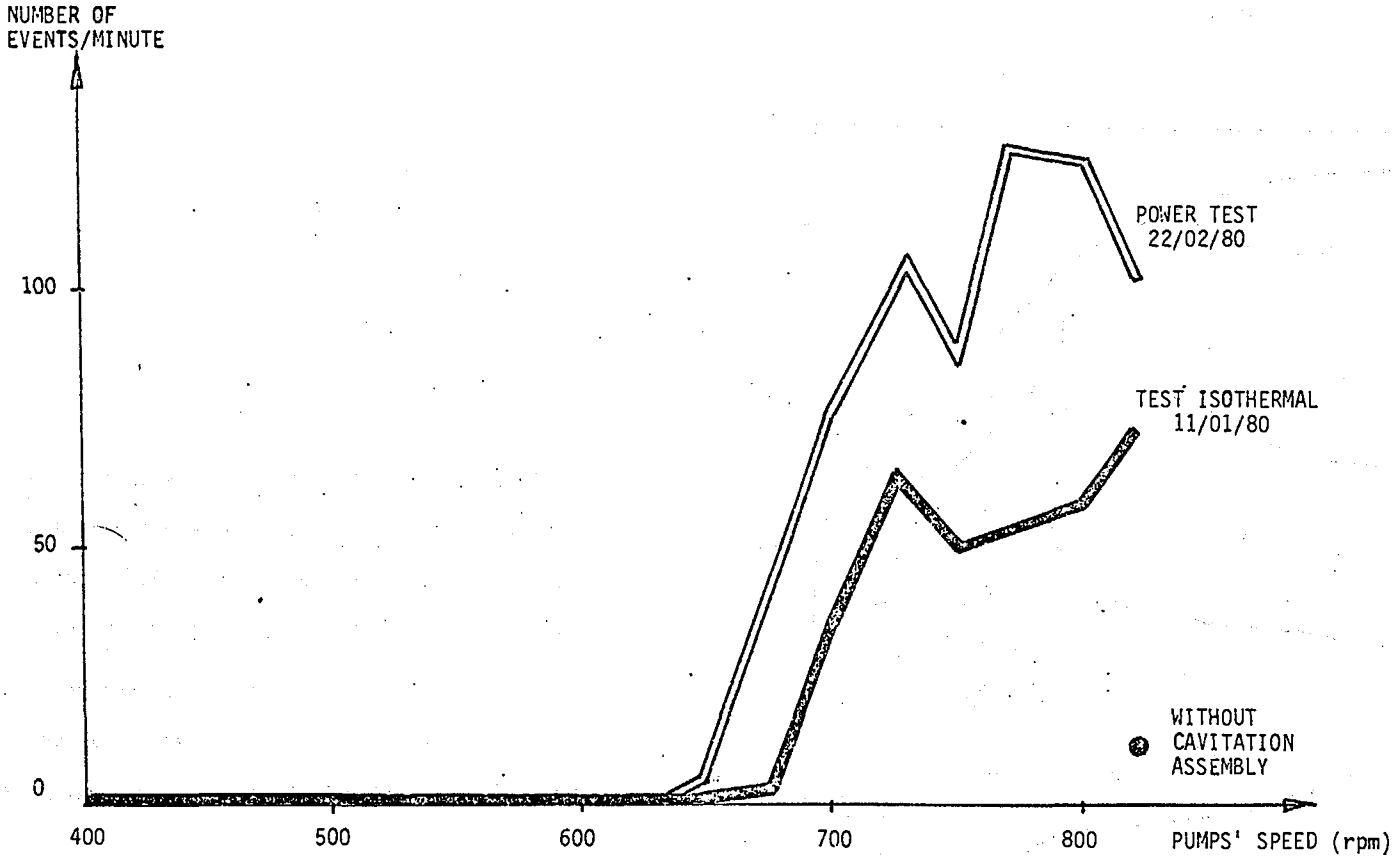
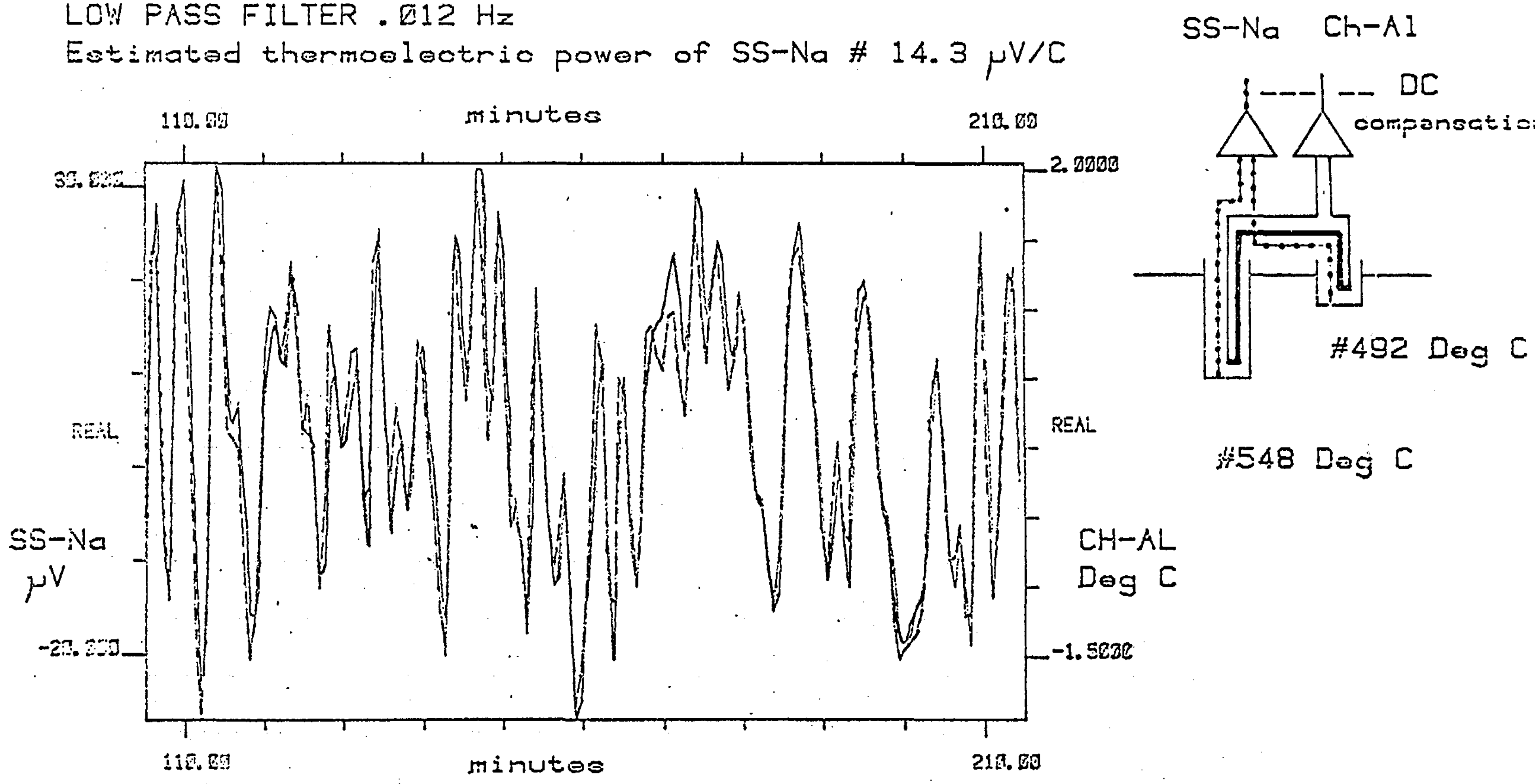


FIG. 2.

October 1980 (336)

MANUEL FIT OF BOTH SIGNAL FLUCTUATIONS
LOW PASS FILTER .Ø12 Hz
Estimated thermoelectric power of SS-Na # 14.3 µV/C

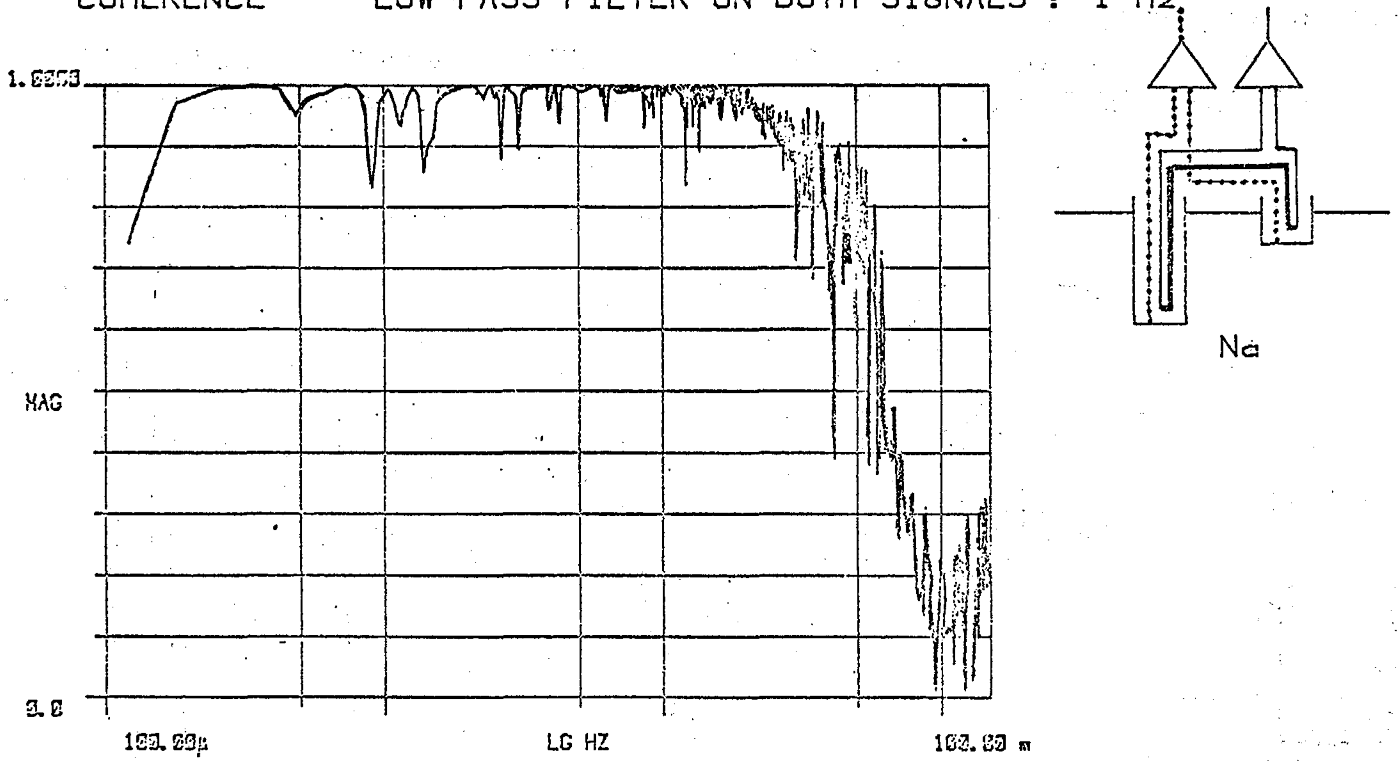


IN PILE LOW FREQUENCY COMPARISON OF STAINLESS STEEL-SODIUM
AND TYPE K THERMOCOUPLES - RAPSODIE 23/Ø2/1981

CEA/LEIS JP GIRARD

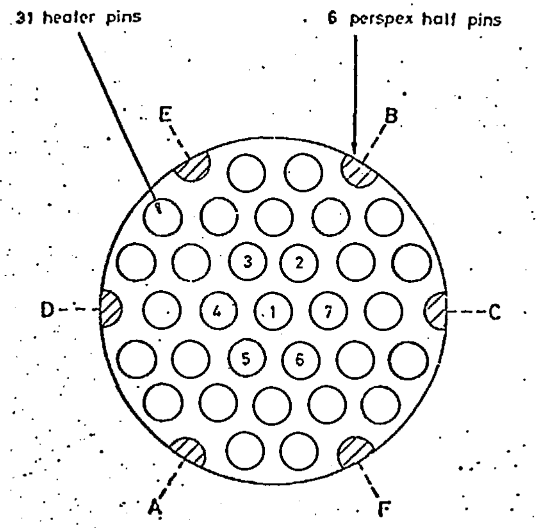
FIG. 3.

COHERENCE - LOW PASS FILTER ON BOTH SIGNALS : 1 Hz



IN PILE MEASURED COHERENCE FUNCTION BETWEEN STAINLESS STEEL
AND TYPE K THERMOCOUPLES
RAPSODIE 23/02/1981 CEA/LEIS JP GIRARD

FIG. 4.



"Greef" experiment

Pin 1-3-4 heated

Calculation/experience comparison with the "Brute" Model

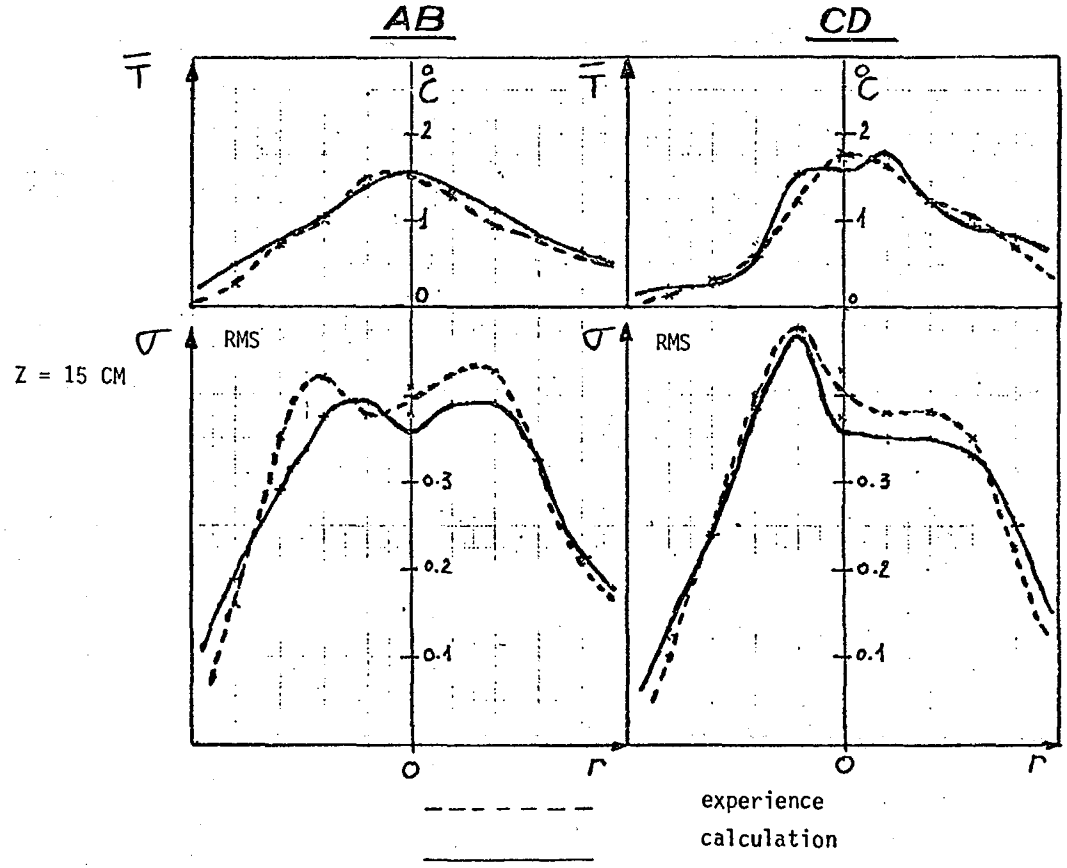
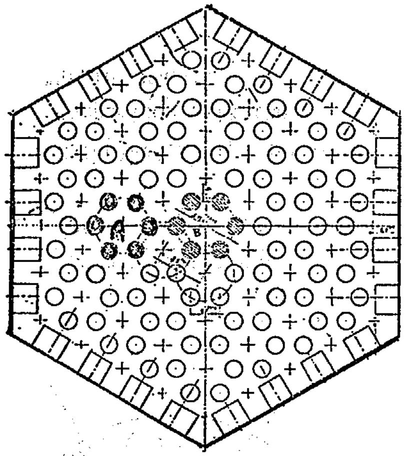


FIG. 5. 1



ANOMAT

Calculation/esperience comparison with the "Bruyant" Model (Fc : 30 Hz) Excentred Injection "A"

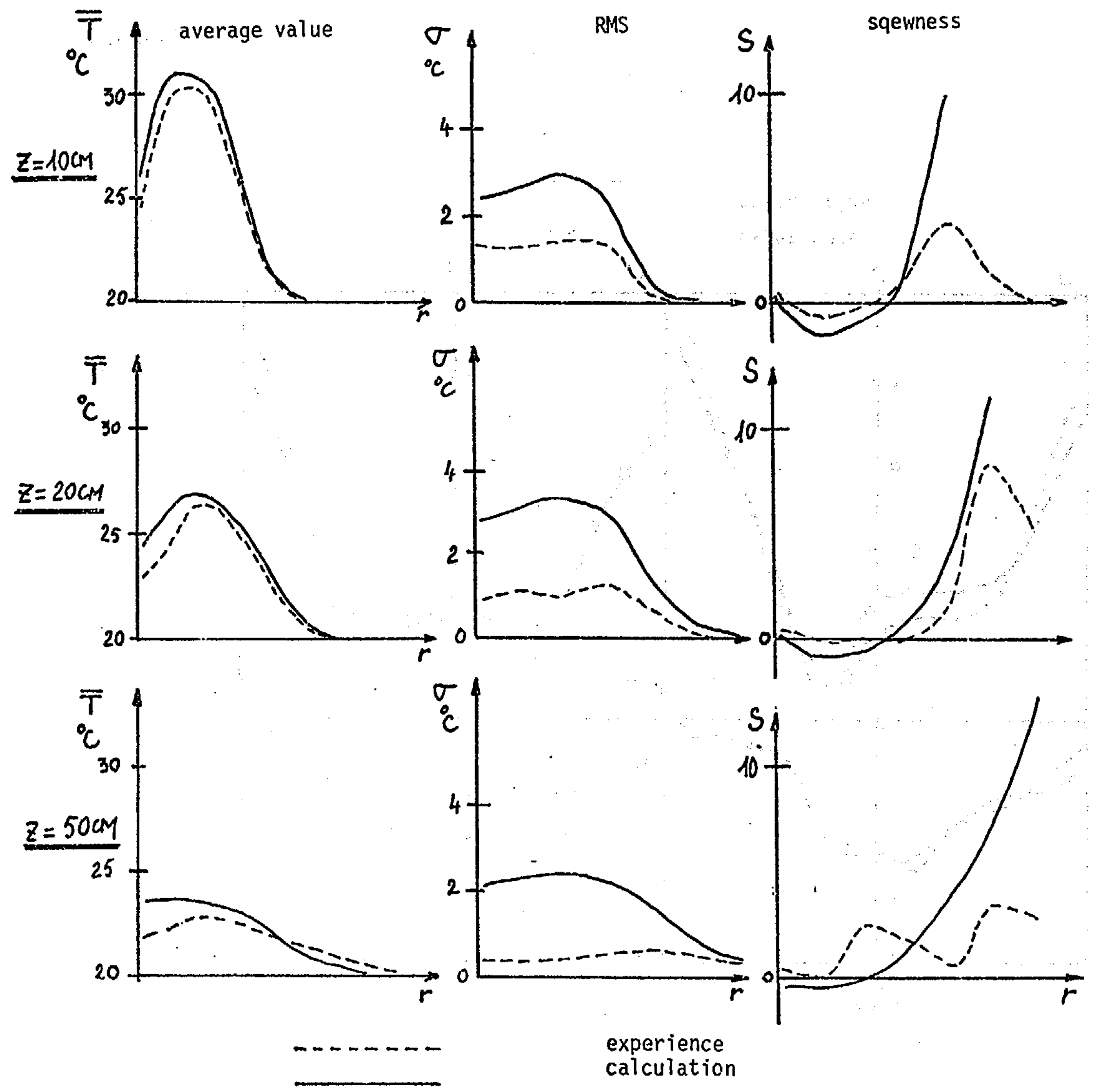


FIG.5.2.

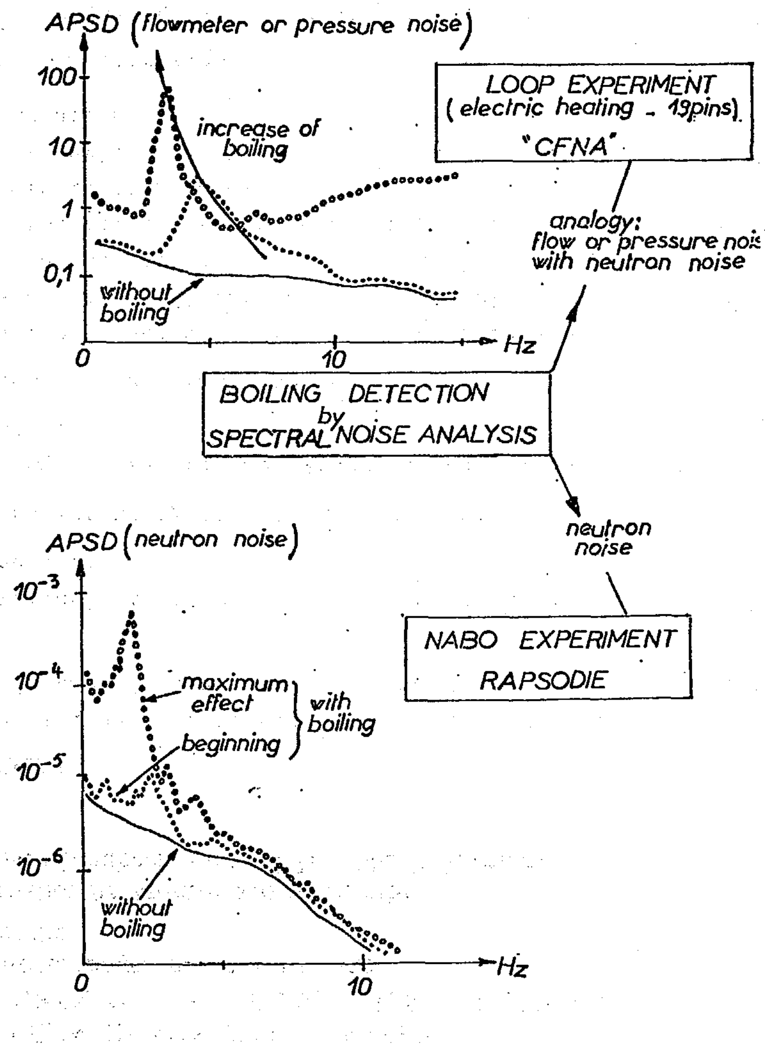

APSD (flowmeter or pressure noise)
100
10
1
0,1
increase of boiling
without boiling
0
10
Hz
LOOP EXPERIMENT
(electric heating - 19pins)
"CFNA"
analogy:
flow or pressure noise with neutron noise
BOILING DETECTION by SPECTRAL NOISE ANALYSIS
neutron noise
NABO EXPERIMENT
RAPSODIE
APSD (neutron noise)
maximum effect
beginning
with boiling
without boiling

FIG. 6.1

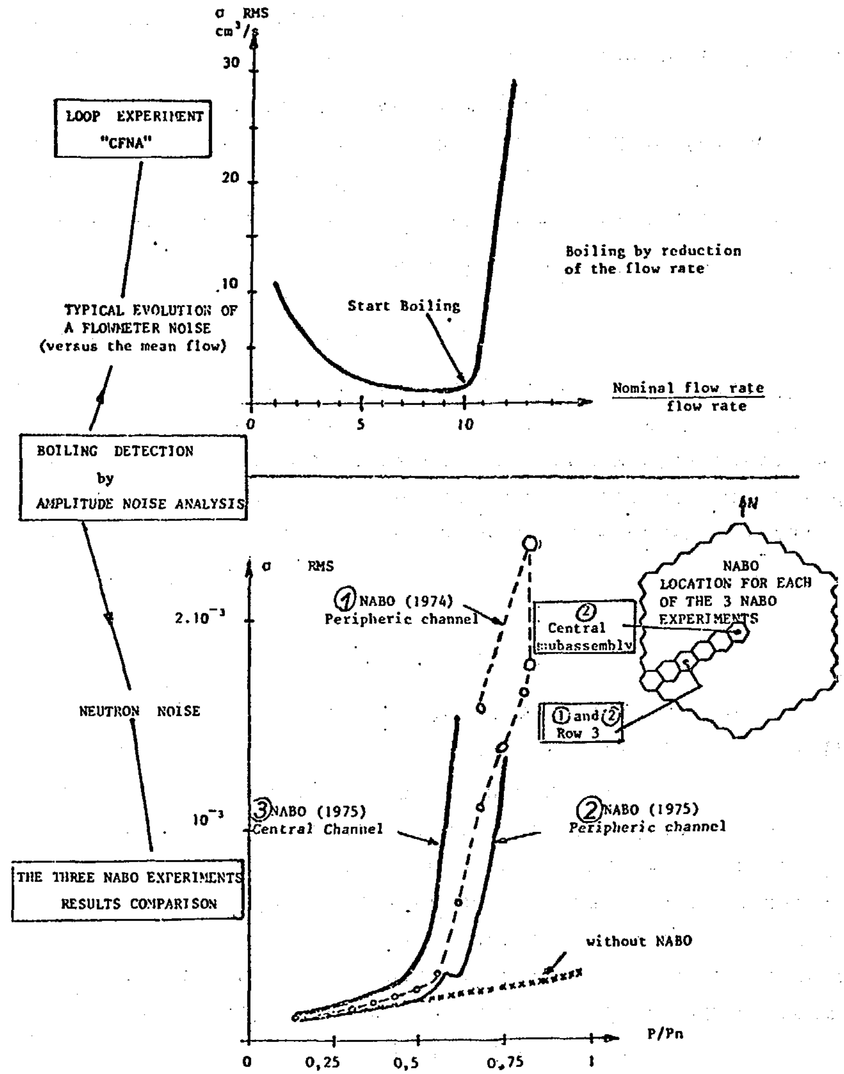

σ RMS cm³/s
30
20
10
LOOP EXPERIMENT "CFNA"
TYPICAL EVOLUTION OF A FLOWMETER NOISE (versus the mean flow)
Start Boiling
Boiling by reduction of the flow rate
Nominal flow rate / flow rate
0
5
10
BOILING DETECTION by AMPLITUDE NOISE ANALYSIS
NEUTRON NOISE
THE THREE NABO EXPERIMENTS RESULTS COMPARISON
σ RMS
2.10⁻³
10⁻³
① NABO (1974) Peripheric channel
② Central subassembly
NABO LOCATION FOR EACH OF THE 3 NABO EXPERIMENTS
① and ② Row 3
③ NABO (1975) Central Channel
② NABO (1975) Peripheric channel
without NABO
P/Pn
0,25
0,5
0,75
1

FIG. 6.2