APPLICATION OF PROCESS-MONITORING TECHNIQUES TO NEUTRON NOISE SIGNALS FROM SIMULATED-COOLANT-BOILING EXPERIMENTS

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Abstract

Within the framework of the research regarding the detection of boiling of the coolant in a pressurised water reactor, a new experimental set-up was developed that simulates boiling by blowing nitrogen bubbles into water. The aim of the experiments with this facility, which can be positioned next to the core of the IRI research reactor, is to investigate the performance of several-signal analysis and anomaly-detection methods.

It is shown that the signal-analysis techniques are all sensitive to the noise introduced by the blowing of bubbles. It is possible to detect bubbles even for small nitrogen flow rates using anomaly-detection methods. A comparison of different combinations of a signal-analysis technique and an anomaly-detection method has been made. It was found that autoregressive analysis followed by SPRT is the best combination.

Introduction

For safety reasons it is very important to continuously guard the operation of a nuclear power plant. Small deviations from normal operation are especially important as they can be the forerunner of large changes to come. In order to be able to detect these small changes, signals from all kinds of sensors are monitored and analysed. An example of a small deviation is the onset of boiling in a PWR. For studying the techniques and methods for detecting boiling, an experimental facility called SIMBOL was built. In this facility boiling is simulated by blowing nitrogen bubbles.

The great advantage of this new experimental facility is that anomalous behaviour is fully controllable in the sense that the starting time, the magnitude and the position of the simulated boiling can be adjusted independently and thus are precisely known quantities. The facility is placed next to the core of the IRI research reactor, called the HOR. It is equipped with self-powered neutron detectors for measuring the neutron flux. Neutron noise measurements were performed during experiments in which the magnitude of the ‘boiling’ was increased abruptly (step) or gradually (ramp).

In this paper, results from spectral and statistical analysis, performed on the measured neutron noise signals, are presented. Several signal-analysis techniques are applied to the neutron noise signals. These techniques do not, however, give a final decision about the state of the process under investigation; they mainly extract certain features of the measured signals. Therefore, anomaly-detection methods are applied to the results from signal analysis. These methods determine whether the system is in a normal (no ‘boiling’) or an anomalous (‘boiling’) state. Three methods are used: the extremes method, the distribution method and the sequential probability ratio test. The methods are compared on their ability to give a fast detection of an anomaly for a given false alarm rate.

Description of the experimental facility SIMBOL

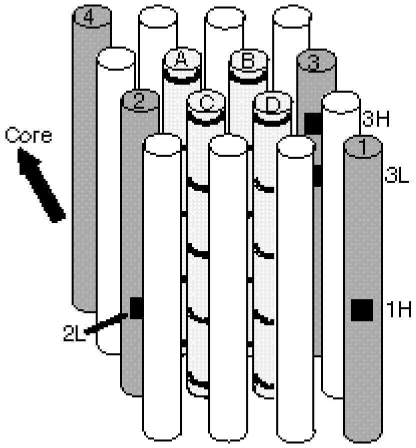
The SIMBOL facility was developed as a result of shortcomings of the former experimental facility NIOBE [1]. This facility was designed to evoke boiling of the coolant through electrical heating of three metal plates. With NIOBE it was impossible to determine the starting time and the starting position of boiling, which, however, is essential for doing research on the application of anomaly detection to reactor noise signals. Therefore, a new experimental facility was needed, leading to the design of SIMBOL in which boiling is simulated by blowing nitrogen bubbles into water. No heat is added in this facility. The disadvantage is that blowing nitrogen bubbles is different from boiling in the physical sense. Investigating this difference is beyond the scope of this paper. This is why the connection with boiling will be abandoned and the word “anomaly” will be used from here on.

SIMBOL consists of a simulated 4×4 PWR assembly (the core of the facility), a closed water circuit with a circulation pump, a nitrogen supply to the core of the facility via capillaries and a number of manually operated valves and gasflow meters to control the nitrogen flow. During experiments, the facility is placed next to the core of the IRI research reactor, called the HOR. The HOR is a pool-type research reactor of 2 MWth power with a maximum thermal neutron flux of approximately $2 \cdot 10^{13}$ cm $^{-2}$s^{-1}. The experiments are done without interrupting the normal operation schedule of the HOR.

The sixteen tubes in the core of the facility are positioned in a square case with inner dimensions of 52×52 mm^2. Each tube has a length of 554 mm and a diameter of 10 mm; the pitch of the assembly equals 13 mm. Figure 1 gives a schematic 3-dimensional view of the core of the facility without the square case. The innermost 2×2 tubes (the light-grey ones) of the assembly all have a ring of ten equally spaced holes on five different axial levels, resulting in twenty levels all together.

The bottom ring is located at 30 mm from the water inlet of the case and the subsequent rings are spaced 125 mm apart. The rings are numbered 1 to 5 from the top to the bottom of the tube. Each tube with holes is denoted by a capital letter from A to D as shown in Figure 1. The holes have a diameter of 0.2 mm. The position of the HOR reactor core is also indicated in the figure.

Figure 1. Schematic 3-D view of the core of SIMBOL
(not to scale)



Four detector tubes (the dark-grey ones in Figure 1) are available. Each tube contains two self-powered neutron detectors (SPNDs) at a fixed relative distance of 10 cm. Each pair of SPNDs can be moved in the vertical direction. Four SPNDs were used during the experiments. Their positions are shown in Figure 1. They are denoted by ND1H, ND2L, ND3L and ND3H, respectively, where ND stands for “neutron detector”, L for “low” and H for “high”. Table 1 gives the vertical distance between the SPNDs and the bottom ring (ring 5). Since subsequent rings of one tube are spaced 12.5 cm apart, ND1H is located 10.5 cm above ring 4, ND2L is located 2.5 cm above ring 4, ND3L is located 8 cm above ring 3 and ND3H is located 5.5 cm above ring 2.

Table 1. Vertical distance between centre of detector and ring 5

SPND	ND1H	ND2L	ND3H	ND3L
position	+23 cm	+15 cm	+43 cm	+33 cm

Each ring can be connected to the nitrogen supply through a capillary, causing nitrogen bubbles to escape from the ten holes into the water. A maximum of four rings can be connected to the nitrogen supply at one time. The nitrogen flow to a certain ring can be adjusted by manually operated valves, independently of the nitrogen flows to the other rings. The nitrogen flow can be measured by a flow meter.

The measurements presented here were performed without coolant flow. The natural circulation of water was prohibited too, meaning that the nitrogen bubbles were released in stagnant water.

Theory

In this section, three signal-analysis techniques and three anomaly-detection methods are introduced. The signal-analysis techniques are applied to a neutron noise signal from a SPND in order to extract certain features from the signal. The result of a signal-analysis technique is called a ‘time series’.

The anomaly-detection methods are applied to the time series in order to detect changes of one or more specific statistical parameters of the time series. Here, the three methods are designed to detect a change of the standard deviation. The methods distinguish only two states, namely the normal and the anomalous state. There are three quantities associated with anomaly detection, namely the false alarm probability (FAP), the alarm failure probability (AFP) and the average time to alarm (ATA). The FAP is the probability that a normal situation is present but an anomaly is detected. The AFP is the probability that an anomaly is present but none is detected. The ATA is defined as the average time interval between the occurrence of an anomaly and its detection. For practical purposes it is more interesting to know the false alarm rate (FAR: the number of false alarms per unit of time) and the alarm failure rate (AFR: the number of alarm failures per unit of time) than the corresponding probabilities.

In practical situations, it is usually demanded that the FAR be very small (< once a year), since it is very costly to have an unnecessary reactor safety shutdown. It is also very important to know the presence of an anomaly as soon as possible in order to be able to take countermeasures and to avoid undesirable situations. This means that the ATA must be as small as possible. The AFR is usually of less importance in practical situations. The ATA can be calculated by averaging over a large number of times to alarm (TA). The TA is the time interval between the detection and the occurrence of an anomaly. All these TAs must be determined using signals having the same characteristics and showing the same change in characteristics.

Signal-analysis techniques

In the present application of AR analysis a discrete signal at a certain time instant is predicted from a linear combination of successive signal values at earlier time instants. Burg’s method is being used for determining the coefficients of the AR model [2,3]. The difference between the actual signal values and the predictions is called the residual noise. A correct AR model yields white residual noise.

In this application, the coefficients of the AR model are determined using the neutron noise signal without nitrogen flow. It is expected that a change in the characteristics of the signal, caused by passing nitrogen bubbles, will cause a change in the prediction capacity of the model and will therefore affect the characteristics of the residual noise.

For the wavelet transform (WT), there is a direct coupling between the resolution in time and in frequency domain, giving it a constant optimum time-frequency resolution [4]. The WT is a convolution of a time signal and a dilated so-called ‘mother’ wavelet [5]. A ‘mother’ wavelet should be well localised in both time and frequency domain. A function which satisfies this criterion is the Gabor function [6]. The result of the WT is known as the wavelet coefficient. The so-called input order determines the central frequency of the WT [6]. By applying wavelet analysis to a neutron noise signal, a wavelet coefficient time series is obtained. This can be done for a set of input orders.

Fractal analysis is a general method for describing the self-similarity of data series. Curves that show self-similarity can be represented by a parameter called the fractal dimension [7]. For a data series the fractal dimension should lie between 1 and 2 [7]. By applying fractal analysis to a neutron noise signal a fractal dimension time series is obtained.

Anomaly-detection methods

For the extremes method a record of N successive time series values is considered and the number of values whose absolute value exceeds a certain predetermined threshold is counted. This threshold has been set equal to k ($k > 1$) times the standard deviation of the time series x under normal conditions (σ_0):

$$|x_i| > k \bullet \sigma_0 \tag{1}$$

An anomaly is declared whenever the number of values for which Eq. (1) holds exceeds m ($1 \le m \le N$), assuming that the standard deviation increases due to the anomaly. k, m and N are called the method parameters. In applying this method, the record of length N is shifted one time step at a time so that successive records overlap (sliding-window approach). This means that a record contains the last N-1 data values of the previous record, plus the momentary value. In this way, it is possible to make a decision about the state of the process every time step. It must be noted here that successive records are strongly correlated.

The distribution method is based on the Neyman-Pearson Lemma [8]. This lemma provides a method for determining the test that minimises the AFP for a given FAP. For detecting an increase of the standard deviation of a Gaussian distributed white noise signal e, the following test is obtained:

$$S = \sum_{i=1}^{N} \frac{e_i^2}{\sigma_0^2} \ge T \tag{2}$$

where T is the threshold of the test. S has a χ^2 distribution. An anomaly is declared when S exceeds T. The sliding-window approach is also used here.

The sequential probability ratio test (SPRT) was originally developed by Wald [9] for testing a normal hypothesis against an alternative one. Here, it is used for detecting a change of the standard deviation of a Gaussian distributed white noise signal *e*. From the basic equation of the SPRT method [9], the following recursive equation can be derived:

$$\lambda_i = \lambda_{i\,l} + \frac{\sigma_1^2 \sigma_0^2}{2\sigma_1^2 \sigma_0^2} e_i^2 \quad \ln \frac{\sigma_1}{\sigma_0} \tag{3}$$

where σ_1 is the standard deviation of the noise under anomalous conditions and λ_i is the so-called decision parameter of the SPRT method. This parameter is updated and compared with a lower threshold *A* and an upper threshold *B* every sampling period [9]. When λ passes *B* an anomaly is declared and when it passes *A* a normal situation is declared. After taking a decision, λ is reset to zero. As long as λ is in between the two thresholds no new decision is taken.

Although the distribution and SPRT method were derived for a Gaussian distributed white noise signal, they will also be applied to non-white time series having an unknown distribution, like the time series from wavelet and fractal analysis. For comparison purposes, it was decided to focus only on the detection of a change in standard deviation, although the average value of a time series can also change, as will be shown later.

A numerical and theoretical comparison has shown that the SPRT method is the best method because it gives the fastest response to a step in standard deviation (smallest ATA) of a Gaussian distributed white noise signal for a large range of FAR values. The distribution method is second best [10,11].

Experiments performed with SIMBOL

Experiments with different combinations of rings and various nitrogen flow rates have been performed with SIMBOL. During all the experiments the facility was positioned next to the core of the research reactor. In this paper, two measurements are discussed. Table 2 gives a short description of each measurement. The abbreviation Ms stands for measurement.

Table 2. Measurements performed with SIMBOL

Ms	Rings	Duration	Nitrogen flow rate
1	B2, B3, B4, B5	3840 s (1:04 h)	Stepwise increase (4 steps) from 0 l/h to approx. 6.5 l/h per ring. (Total flow rate: 0-26.1 l/h)
2	B5	900 s (15 min.)	Gradual increase from 0 l/h to approx. 22 l/h.

The neutron detector signals were first filtered using 8th-order low-pass filters with a cut-off frequency of 20 Hz. After filtering they were amplified using differential amplifiers. AC-coupling of the amplifiers, with a cut-off frequency of 0.04 Hz, was used. The nitrogen flow rate was measured using mass flow meters which return an output voltage proportional to the mass flow rate. The voltage signals from the flow meters were also low-pass filtered; no AC-coupling was used. Both the filtered and amplified neutron detector signals and the flow signals were recorded on magnetic tape. In order to analyse the signals with a computer, they were read from magnetic tape, filtered and amplified, if necessary, and were sampled with a sampling period of 30 ms. The flow rate and neutron detector signals were again filtered, this time using a low-pass frequency of 5 Hz and 12 Hz, respectively.

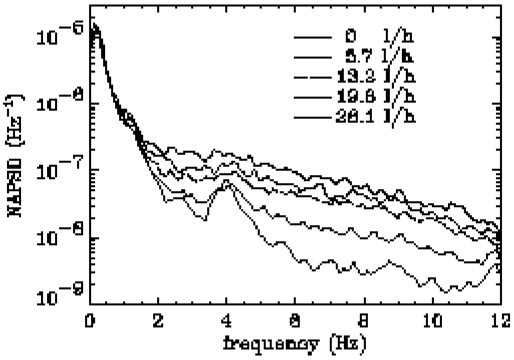
Analysis of neutron noise signals

Before the signal-analysis techniques and anomaly-detection methods are applied to the neutron noise signals, it is important to have a proper picture of the anomaly that is introduced by blowing bubbles. In this section, results of spectral and statistical analysis of neutron noise signals, obtained with the SIMBOL measurements, are given.

Spectral and statistical analysis

Figure 2 shows the normalised auto power spectral densities (NAPSDs) of ND3H of the first measurement for the five flow rate steps. The total flow rate of the first measurement as a function of time is shown in Figure 5(a).

Figure 2. Spectrum of ND3H for five different total flow rates (measurement 1)



For determining the spectrum, the signal was first normalised using the DC-value of the detector. It can be seen that the amplitude of the spectrum, for frequencies higher than 1.5 Hz, increases due to the blowing of nitrogen. The amplitude of the noise added by the bubbles increases with the nitrogen flow rate. The spectrum below 1.5 Hz does not change because the amplitude of the noise caused by the bubbles is much smaller than the amplitude of the global noise. The global noise is caused by reactivity fluctuations during normal reactor operation.

Figure 3 shows the probability density functions (PDFs) of the same neutron noise signal. The neutron noise signal was first filtered using a high-pass filter with a cut-off frequency of 1.5 Hz. It is clear that the standard deviation of the filtered signal changes due to blowing of nitrogen bubbles.

Figure 3. PDFs of ND3H for five different total flow rates (measurement 1)

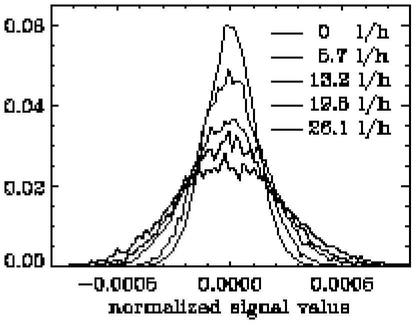
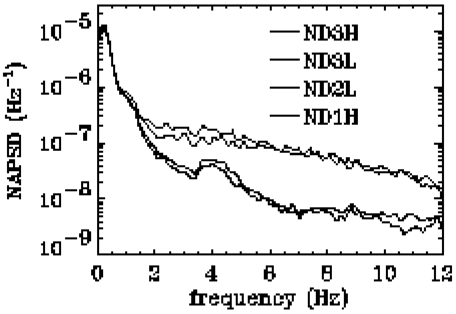


Figure 4 shows the NAPSDs of the four detector signals used in the first measurement in case of maximum flow rate. The spectra of ND3L and ND3H are different from the spectra of ND1H and ND2L. Comparing these spectra with the corresponding spectra for a flow rate of 0 l/h (not shown in Figure 4), it becomes clear that the spectra of ND1H and ND2L do not change visibly due to the bubbles, whereas the spectra of the detectors in string 3 do change. This can be explained by looking at the positions of the detectors relative to the stream line of the bubbles. In Figure 1 it can be seen that the bubbles which originate at the four rings of tube B pass along the detectors in string 3 at a very small distance (except the bubbles from ring B2 which do not pass ND3L). This is however not the case for ND1H and ND2L. This shows that, in principle, it is possible to localise the bubbles.

Figure 4. Spectra of neutron noise signals from four detectors (measurement 1, maximum flow rate)



Transit-time calculations were performed using the noise signals from two axially displaced SPNDs (ND3L and ND3H). It was found experimentally that the bubble rise velocity in the core is almost independent of the nitrogen flow rate and on the average equal to 31.4 cm/s. The void fraction is approximately proportional to the flow rate [12].

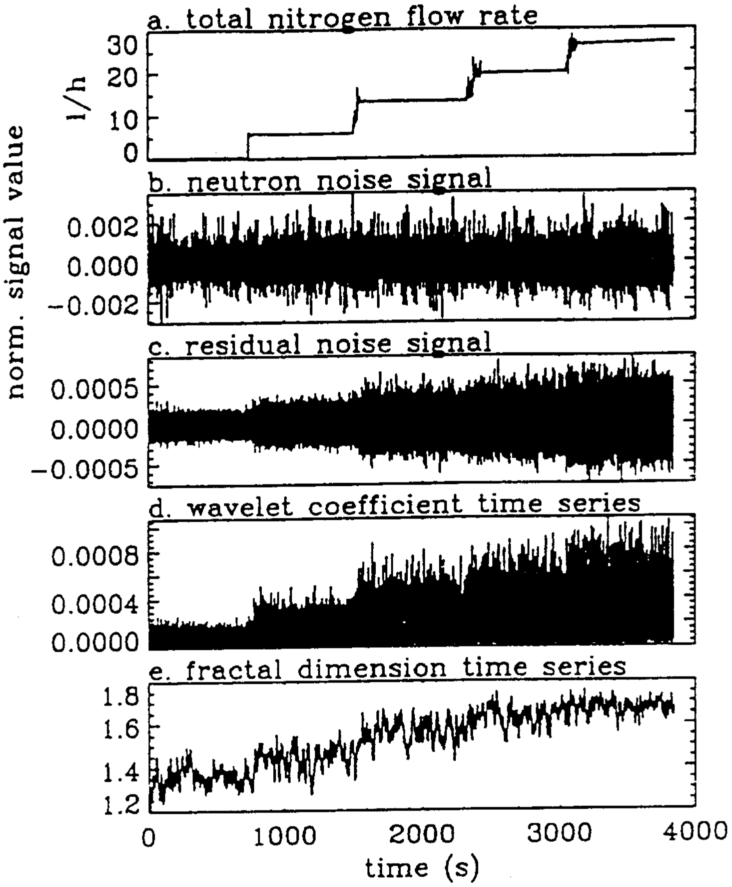
The effect on the reactivity of the blowing of nitrogen bubbles was too small to be detectable by control rod position. The DC-values of the SPND signals remained constant during the experiments.

Signal analysis

Three signal-analysis techniques were applied to the neutron noise signals. Figure 5 shows the resulting time series for the signal of ND3H at measurement 1. Figure 5(a) presents the total nitrogen flow rate and Figure 5(b) the neutron noise signal. The fluctuations at the start of the second, third and fourth step in nitrogen flow rate are due to the fact that the nitrogen flow rate is adjusted manually.

The neutron noise signal shows no visible change due to the presence of nitrogen bubbles. Figures 5(c) until 5(e) present the time series from the three signal-analysis techniques. For AR analysis an optimum model order of 40 was found, using Akaike's criterion [2]. The standard deviation of the residual noise increases 2.86 times when the total nitrogen flow rate is increased from 0 l/h to 26.1 l/h. For wavelet analysis many input orders were applied of which input order 7 was used here. This input order corresponds to a central frequency of 7 Hz. The average value and the standard deviation of the wavelet coefficient increase 4.10 and 4.09 times, respectively. The fractal dimension increases from an average of 1.36 to 1.67.

Figure 5. Results of applying signal-analysis techniques to ND3H signal (measurement 1)



These analysis results show that each of the three signal-analysis techniques is sensitive to the noise added by the blowing of nitrogen bubbles. The time series are used as input for the anomaly-detection methods.

Anomaly detection

Before starting the anomaly detection, the method parameters must be chosen. In practical applications it is usually demanded that the FAR must be smaller than or equal to a certain value. Here it is required that the number of false alarms encountered be zero. The false alarms are counted during a period in which no bubbles are blown. For measurements 1 and 2 the first 746.7 seconds and the first 229.4 seconds, respectively, are used for counting.

The parameters of the anomaly-detection methods are chosen in such a way as to achieve a false-alarm-free detection result demanding that the anomaly be detected as quickly as possible (ATA, in theory, as small as possible). For determining the parameters, results from theory and simulation are used [12]. For the SPRT method the standard deviation in the anomalous situation σ_1 is chosen equal to $1.1 \cdot \sigma_0$.

It is also possible to apply the anomaly-detection methods directly to the neutron noise signals. It was, however, impossible to detect the anomaly in this manner. This shows the importance of first applying signal-analysis techniques before performing anomaly detection [12].

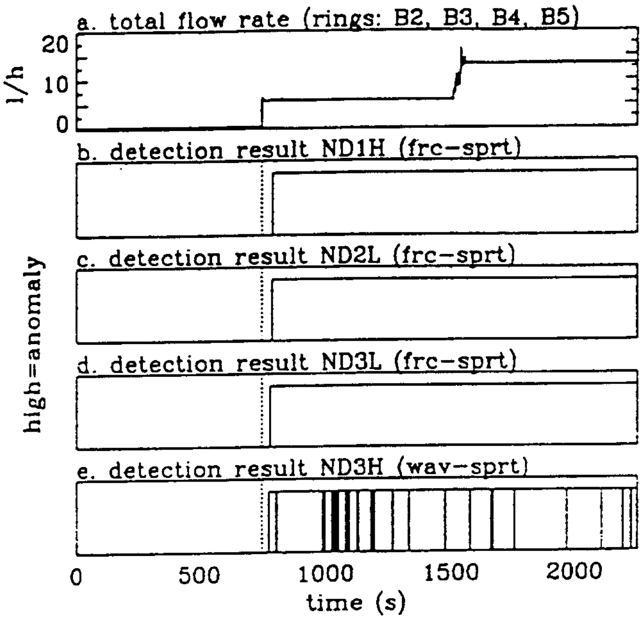
The goal of the anomaly detection is to detect the first step (Ms 1) or the gradual increase (Ms 2). Per neutron noise signal nine detection results are obtained. Table 3 shows the smallest TAs obtained per detector and it shows which combination of a signal-analysis technique and an anomaly-detection method gave the fastest detection. The TA is the difference between the start of the anomaly and its detection.

Table 3. Smallest TAs obtained per measurement and per detector

MS	Anomaly	ND	TA(s)	Method combination
1	Step from 0 to 6.6 l/h total N_2-flow rate (rings: B2, B3, B4, B5)	1H	43.29	frc-sprt
		2L	41.82	frc-sprt
		3L	34.44	frp-sprt
		3H	27.90	wav-sprt
2	Gradual increase of N_2-flow rate (ring: B5)	1H	247.27	wav-sprt
		2L	248.70	AR-x^2
		3L	247.59	AR-sprt/x^2
		3H	246.87	frc-sprt

The detection results obtained with measurement 1 show that with all detectors the step is detected. This is surprising, since only the spectra of the detector signals from string 3 show a visible change due to the blowing of bubbles (see Figure 2). This demonstrates the strength of the signal-analysis techniques in combination with the anomaly-detection methods in detecting small anomalies. The TAs obtained with ND1H and ND2L are, however, larger than the TAs obtained with ND3L and ND3H. It is remarkable that the step is detected much earlier for ND3H than for ND3L. By taking a look at Figure 6 one can see, however, that with ND3L a result without any alarm failures is obtained which is not the case for ND3H. It should also be noted that only approximately ¾ of the total flow passes ND3L because this detector is positioned above ring 3 but below ring 2.

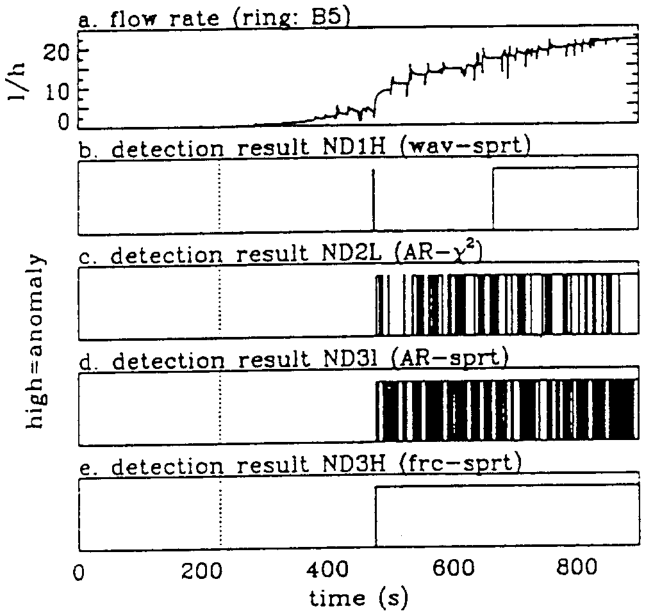
Figure 6. Detection results with four detector signals (measurement 1)



In the case of measurement 2, the anomaly is also detected for all four detectors. Again, ND3H is the first one to detect the anomaly. Figure 7 shows the detection results. The TA obtained with ND1H is rather questionable since after the first detection of the anomaly there is a long period during which nothing is detected (Figure 7(b)). The nitrogen flow rate shows a rather capricious behaviour owing to the non-linearity of the manually operated valves and the difficulty of adjusting the flow rate with these valves. At the point in time where the ramp is detected for the first time, the nitrogen flow rate equals 2.9 l/h (≈ 19 bubbles per second per hole).

Using the results from a series of measurements, it was possible to make a ranking of the method combinations. It was found that AR analysis in combination with SPRT gave, on the average, the smallest TA and is thus considered to be the best method combination. Regardless the signal-analysis technique, SPRT turned out to be the best anomaly-detection method. This is in accordance with what was found by theory and simulation (see the section entitled *Theory*). The extremes method and the fractal analysis technique gave relatively bad ratings.

Figure 7. Detection results with four detector signals (measurement 1)



When dealing with signal redundancy (several detectors measuring the same variable) or signal analysis redundancy (several signal-analysis techniques applied to one signal or to several redundant signals), as is the case here, it is useful to have a method which combines the outcomes of several signal-analysis techniques. Fuzzy logic provides a method for combining the outcomes and to come to one decision about the state of the process [13].

Conclusions and discussion

Experiments were performed with the SIMBOL facility which was placed next to the core of the IRI research reactor. In this facility a ‘boiling’ anomaly is simulated by blowing nitrogen bubbles. Results have shown that the presence of bubbles can be detected very well even for small flow rates.

The spectra of the neutron noise signals measured with self-powered neutron detectors show a clear change due to the blowing of nitrogen bubbles. The noise component which is added to the neutron noise signals increases with increasing nitrogen flow rate. In time-domain no change of the neutron noise signal is visible without first pre-filtering the signal.

The three signal-analysis techniques are all sensitive to the noise introduced by the blowing of bubbles. It was not possible to detect the anomaly without first analysing the neutron noise signals. After an extensive comparison of all the results obtained with anomaly detection, it was concluded that AR-SPRT is the best method, in accordance with what was found by numerical simulation. A nitrogen flow rate as small as 2.9 l/h (≈ 19 bubbles per second per hole) is detectable.

Localisation of the anomaly is also possible as was shown by spectral analysis. No conclusive explanation could be given for the fact that sometimes a far-off detector detected the anomaly earlier than a nearby detector. More research into this field is therefore required.

In order to learn more about the detection of actual boiling more research is needed to understand the connection between blowing nitrogen bubbles and actual boiling.

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