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Studsvik Report

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BWR-STABILITY INVESTIGATION AT FORSMARK 1

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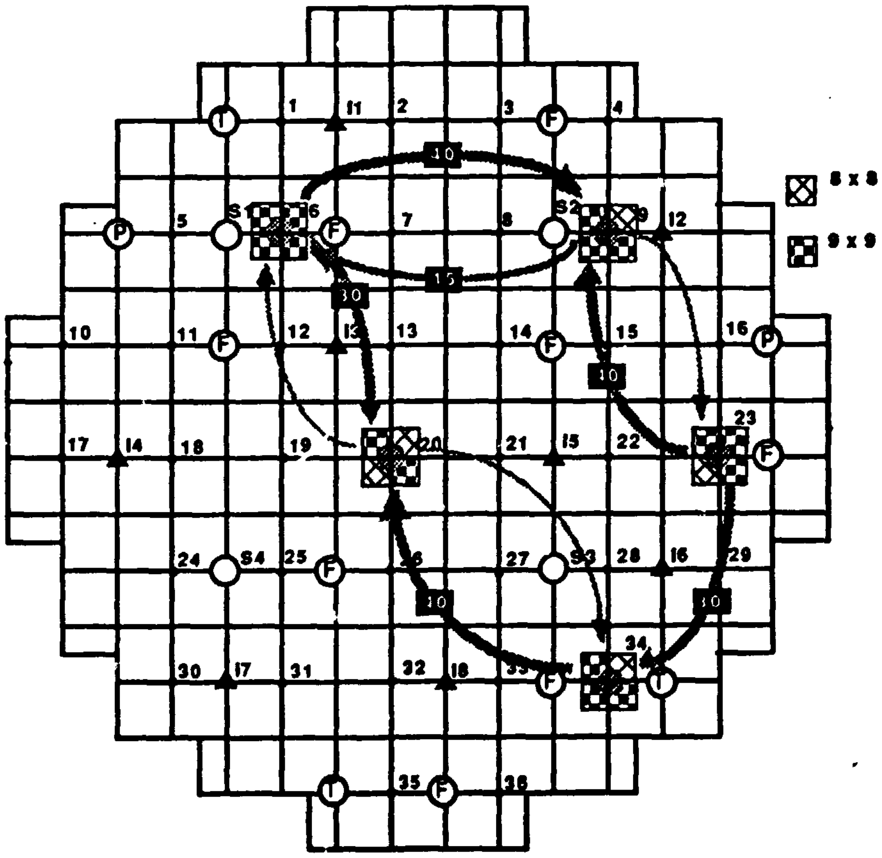

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ABSTRACT

A series of noise measurements have been conducted at Forsmark 1 during start-up operation after the revision summer -87. The main purpose was to investigate BWR-stability problems, i.e. resonant power oscillations of 0.5 Hz around 65% power and 4100 kg/s core flow, which tend to arise at high power and low core flow conditions.

The analysis was performed to estimate the noise source which gives rise to the oscillation, to evaluate the measure of stability, i.e. the Decay Ratio (Dr) as well as to investigate other safety related problems.

The result indicates that the oscillation is due to the dynamic coupling between the neutron kinetics and thermal hydraulics via void reactivity feedback. The Dr ranged between values of 0.7 and > 0.9, instead of expected 0.6 (Dr=1 is defined as instability). These high values imply that the core cannot suppress oscillations fast enough and a small pertubation can cause scram.
Further it was found that the entire core is oscillating in phase (LPRM's) with varying strength where any connection to the consequence of different fuel (8x8,9x9) being present simultaneously cannot be excluded.

This report elucidates the importance of an on-line BWR-stability surveillance system with functions like stability condition monitoring and control system diagnosis.

CONTENTS

1 ABOUT PROCESS IDENTIFICATION IN GENERAL

Noise analysis has been applied at Studsvik to nuclear power plants for over fifteen years. Within this area a fruitful international exchange in research results has taken place.

Noise analysis can be used for several purposes. One goal is to attain a better understanding of the dynamics of the process. Through establishing an adequate model of the process, a reliable estimation of its important parameters, which cannot be measured by direct methods, is possible. Another goal is the designing and construction of on-line measurement systems which signals, at a very early stage, any change in system dynamics - a task which can not be achieved by conventional methods. In Studsvik we have experience in both fields.

Recording a measurement signal in any process will reveal the characteristics shown in figure 1. There is a direct current corresponding to the physical quantity, superimposed by a noise signal. A noise signal has different possible origins, and most frequently it contains valuable information on the dynamics of the process.

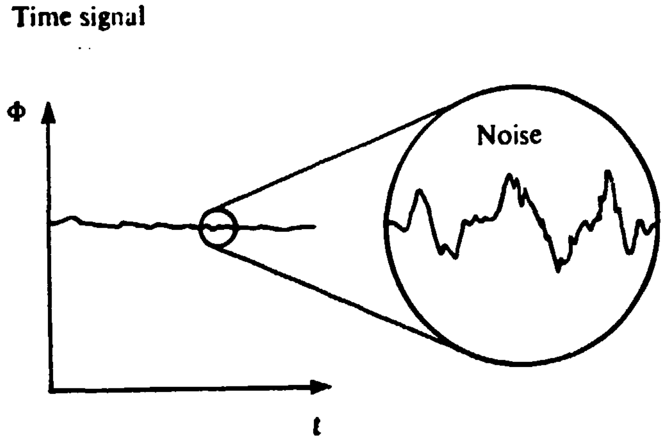


Figure 1 Sensor signal with a noise content.

The identification of process parameters is possible even if no preliminary mathematical knowledge on the process is available. Figure 2 illustrates the underlying principle. The process is treated as a black box with input signal u(t) and output signal y(t). The signals are sampled and logged into a computer where a general model structure is programmed. Then the output signal given by the model is compared to the output signal of the process. If the difference is zero, the model corresponds perfectly to the process. If there is a difference, however, this leads automatically to the correction of the model. The model obtained in the end can then be used to evaluate the dynamics of the process. The step response of the model can be determined and time constants and stability margins calculated.

All this is performed without disturbing the process itself. These estimated parameters can also be surveilled in an early warning system. Our software can also handle systems with multiple inputs and multiple outputs. This is very important when there is need to find cause / effect relations between different signals.

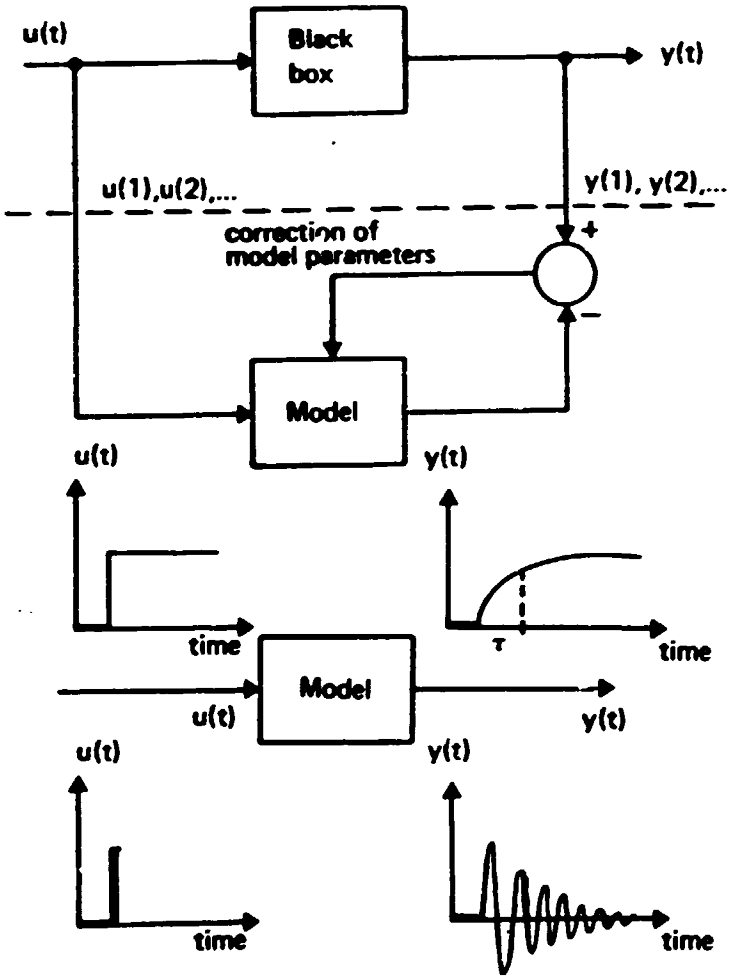
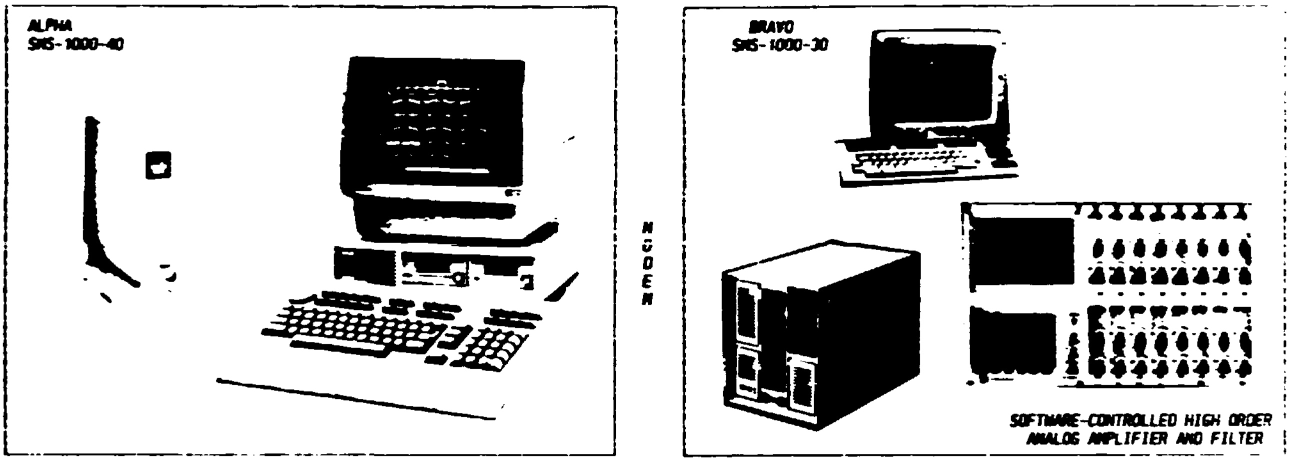


Figure 2 The idea of identification.

2 *PORTABLE COMPUTER SYSTEM FOR NOISE ANALYSIS*

For the purposes of noise measurement together with its concurrent analysis, a mobile computer system, shown in figure 3, has been purchased. The system consists of a PDP 11/73 computer with graphical terminals and an analog to digital converter. In addition, software controlled screening amplifiers and high order filters are included. The purpose of the latter is to make advanced signal conditioning and prevent electric interference with the object of the measurement.



ANALYSIS SITE (LAB)

MEASUREMENT SITE (POWER STATION)

Figure 3 The mobile noise analysis computer system.

3 RECENT PERFORMED ACTIVITIES

A listing of performed identification activities are given here. Reports are available which cover the mentioned subjects - just give us a call. All measurements can be performed during operation of the reactor and without disturbing the process.

REACTOR CORE VIBRATIONS IN MODE AND AMPLITUDE IN PWR.

HEALTH TEST OF COMPONENTS IN NUCLEAR REACTOR INSTRUMENT SYSTEMS.

- Response time calculation for temperature sensors.
- Calculation of lag and lead/lag filter time constants in a reactor safety system.
- Estimation of proportional band and integral action time of a controller.

THERMAL TIME CONSTANTS OF FUEL IN A RESARCH REACTOR.

ESTIMATION OF LPRM SENSOR VIBRATION IN A BWR.

THE INFLUENCE BETWEEN DIFFERENT COMBUSTION SIGNALS IN A FLUIDIZED BED.

INVESTIGATION OF BWR - STABILITY.

SUMMARY

A BWR type reactor has such design properties that instabilities may occur during adverse conditions. Power oscillations may occur at frequencies between 0.1 - 1.0 Hz and amplitudes may be relatively high according to data reported.
Reports of significance in this area include March-Leuba 1986, Suziki 1986, Danemoto 1984, Tagikawa 1987 and Upadhyaya, Kitamura 1979 and Reisch 1969.

Measurements to establish core stability properties have been carried out in two BWR units, Forsmark 1 and 2. The measurements on which the study was based, were taken during power ascension following the refuelling outage in summer 1987. The operating regions which occur during startup are the most risky from the standpoint of stability. Low coolant flow in the core and high power characterize the operational states until full power operation is achieved.

It was possible to calculate a Decay Ratio (Dr) by adapting a mathematical model, using a process identification technique. The Dr characterizes the stability margin and is a measure of how rapidly (Dr = 0.) or slowly (Dr = 1.) a disturbance is damped.

Dr calculations for the various states occurring during power ascension are shown in Figure 1. For the purposes of comparison, the Dr has been given for Forsmark 1 and 2. Forsmark 1 shows poor stability, i. e. Dr > 0.7 while Forsmark 2 does not exceed Dr = 0.7 in the measurements carried out.

It has been widely reported that poor stability, at a Dr of almost 1, leads to limit cycle conditions. During the limit cycle, there is an uncontrolled growth of the amplitude up to a given level even if no external disturbances are present. Moreover, limit cycle conditions are evident in the spectra, where the fundamental peak is very sharp and the harmonics appear at twice and three times the fundamental frequency.
The following is a summary of results for Forsmark 1:

1 The measurements and analyses clearly show that a core resonance phenomenon leads to those oscillations at - 0.5 Hz - which can be observed in both LPRM and APRM.

2 A Dr ≈ 1.0 was calculated at 65 % of full power and 4128 kg/s coolant flow. In this case, the core oscillations occured in the limit cycle as could be seen from the harmonics in the

spectra.

3 The LPRM signals oscillate in phase throughout the whole core.

4 However, the LPRM oscillations vary in strength in different parts of the core. The strongest oscillation is found in the environment of 9 x 9 fuel and the weakest in the environment of both 9 x 9 and 8 x 8 fuel.

5 The upper LPRM signals are influenced by the lower ones in the same probe due to the void transport upwards in the core which is a well-known phenomenon. In addition, a downward influence was observed from LPRM 3 to LPRM 4 in the actual operating region.

6 The Dr was calculated as a function of time using recursive process identification. A Dr > 0.75 was found during half of the total 1.8 hour test period.

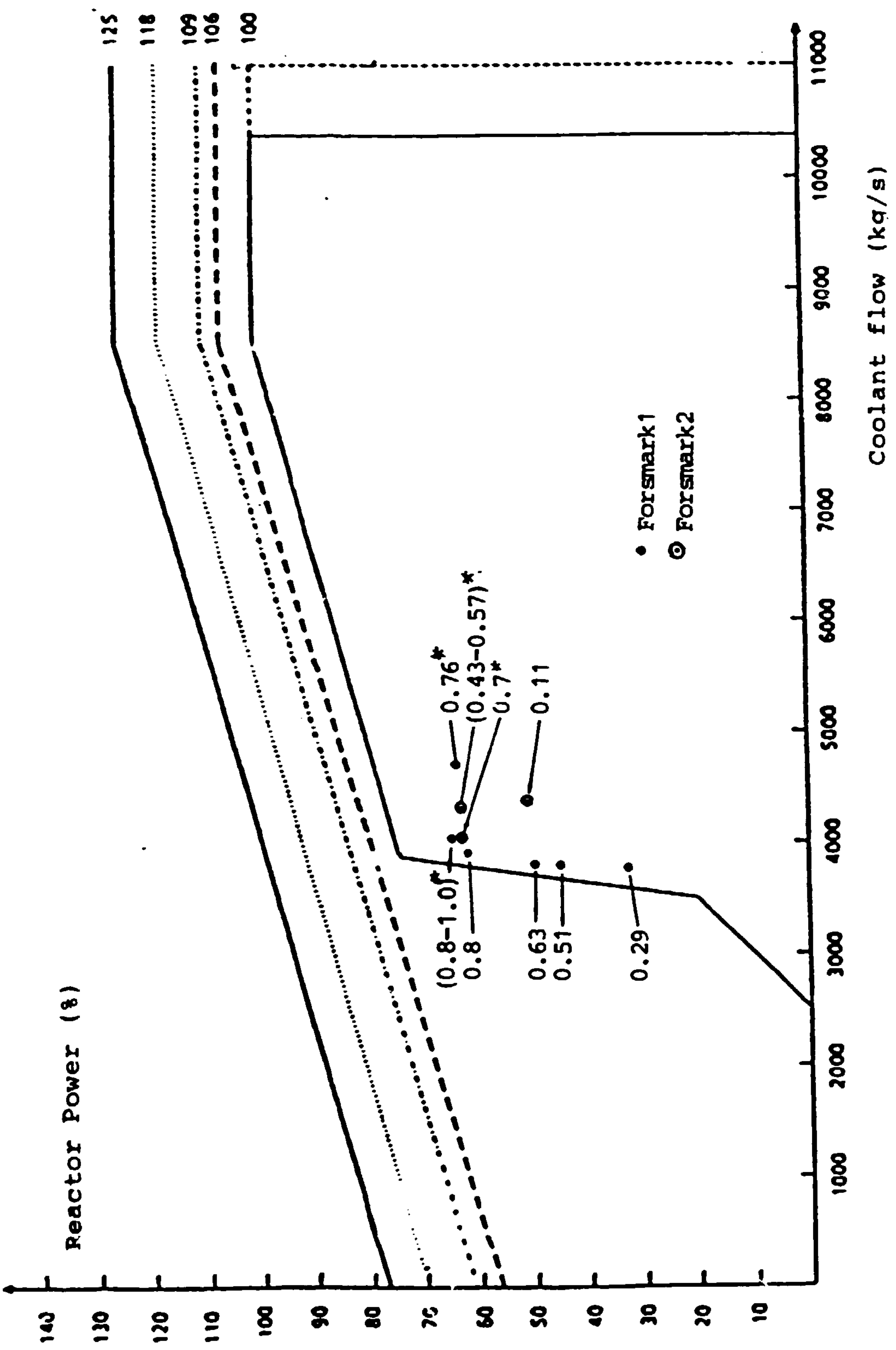


Fig 1 Operational diagram for Forsmark 1 and 2 with operating points and calculated Decay Ratio. It can be seen that the lowest coolant flow and the highest power lead to the poorest stability. The Dr marked with * were obtained during Power Control Mode, and the others during Pump Speed Control Mode.

1 BACKGROUND

There are three different kinds of instability which can occur during reactor operation.

i) Plant instability

ii) Global instability in the core

iii) Local instability in the core

Plant instability relates to reactor dynamics including control and turbine system. The control systems play a very important part and if properly designed, can have a stabilizing influence on the reactor. On the other hand, unsuitable design can accelerate non-desirable oscillations.

Figure 2 is a simplified diagram of global instability. This phenomenon is related to the properties of the dynamic system which occur during reactivity feedback of the voidage in the core.

In other words, the block diagram shows that:

- The nuclear power depends on the reactivity.
- The thermal power depends on the nuclear power. The thermal-dynamics of the fuel plays an important role.
- The void contribution depends on the thermal power transferred to the coolant.

The coupled systems that comprise the transfer functions Gr(s), Gf(s), Hv(s) and $\alpha(s)$ can become unstable or acquire oscillatory properties with poor damping under certain conditions. When large amplitudes are found, the transfer functions result in non-linear effects which in their turn lead to deformed sinusoidal signals. These deformations then give rise to harmonics in the spectrum. Figure 2 shows the interdependence of voidage, reactor pressure, steam flow and steam pressure.

Coolant flow and coolant temperature also affect void formation. Figure 2 is a simplified diagram which focusses on the physical quantities which can be measured with existing detectors.

Local instabilities are similar to the kind of instability just described but they occur at particular locations in the oscillations at various locations in the core. These phenomena may not be observed as easily in the APRM as in the LPRM due to the averaging qualities of the APRM.

The possibility of hydrodynamic instability occurring is evident from the feedback of the voidage to the cooling flow shown in Figure 2. This phenomenon is known to occur and has been observed in circuits with natural circulation and electrically heated rods. When steam is generated in the riser, the weight of steam per surface unit is greater in the downcomer and water flows into the riser - communicating vessel - see Figure 2. Beyond a critical power level, the flow rate oscillates in spite of the fact that the thermal output is constant. During oscillations with high power and large amplitudes, non-linearities deform the sinusoidal spectra and harmonics are formed.

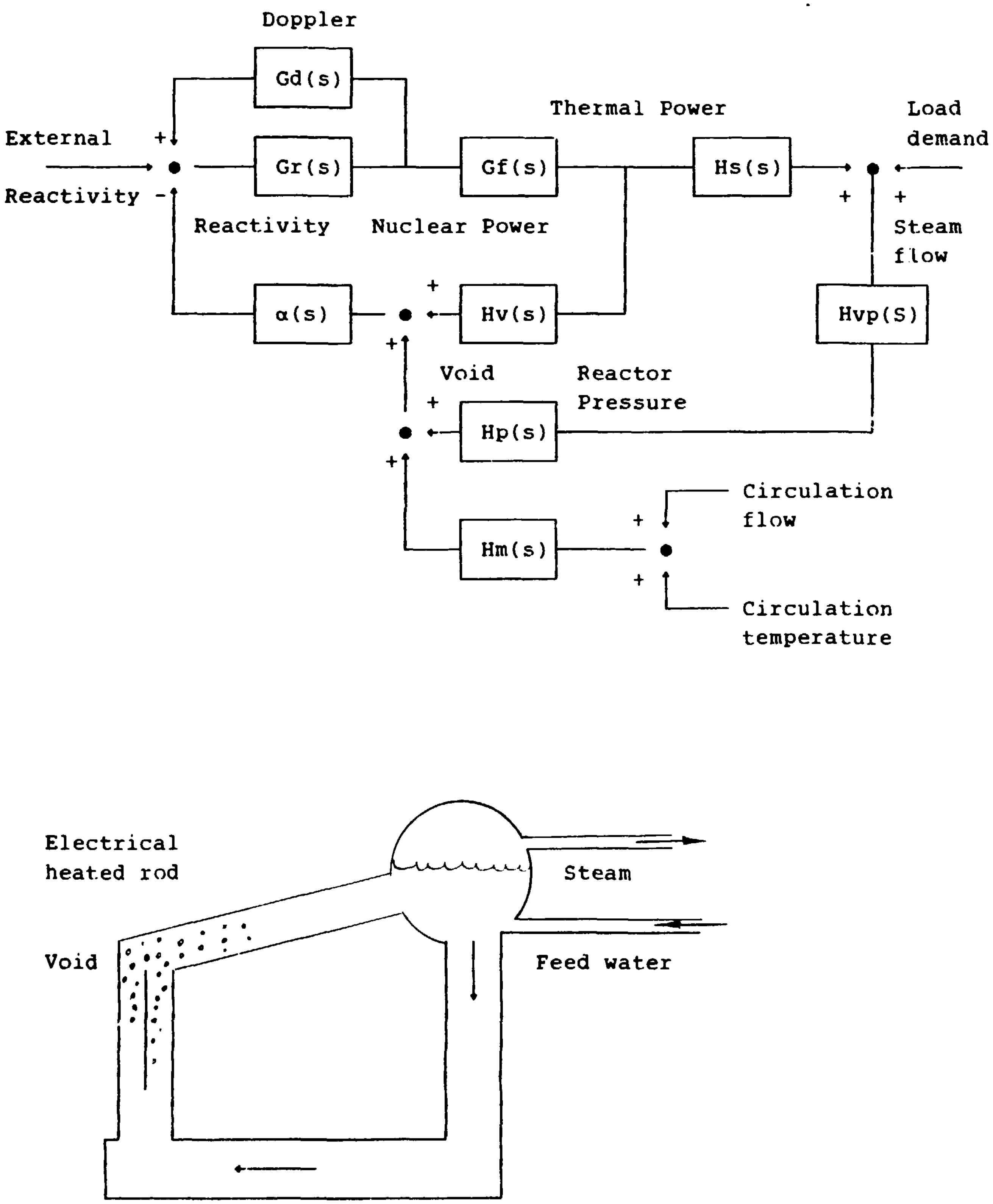


Fig 2 Block diagram of simplified BWR dynamics

2 STABILITY

Stability is a term used in reactor dynamics which has two different meanings. Two different sequences may occur in a unstable dynamic system:

1. The state variables (the physical variables which describe the dynamics of the system) increase monotonically without oscillations.

2. The state variables oscillate with growing ampitude.

Stability is always an inherent property in a linear system, i.e. it is independent of operating region or operational state.

On the other hand, in non-linear systems, stability is not an inherent property but a property which varies with each operating region and where certain states have good stability whereas others are unstable.

In non-linear systems, like linear systems, instability can be found with growing amplitudes or oscillating and growing amplitudes.

In addition, an oscillating state can occur in non-linear systems which is called the limit cycle. Uncontrolled growth of the oscillation amplitude takes place up to but not beyond a certain limit which is determined by the non-linear properties of the system.

A light water reactor is an example of a non-linear system. The operational states fall into regions of stable or unstable character (limit cycle). The boundary between these regions is not clearly defined but it is known from incidents at BWR power plants that reduced coolant flow at high power can cause limit cycles.

It is thus important, from the point of view of economics and safety to carry out on-line, real time monitoring of reactor stability.

3 MEASUREMENTS

Up to 32 signals were taken directly from the sensor connections and sampled by Studsvik's mobile computer system (PDP 11/73) via analog filters and isolation amplifiers.

The following signals were analysed to determine the global stability:

group (10*)

1 APRM
2 Reactor pressure
3 Coolant flow
4 Total feedwater flow
5 Steam flow 1
6 Steam flow 2

The following signals were analysed to determine the plant stability:

group (2A*)

1 APRM
2 Reactor pressure
3 Coolant flow
4 Coolant temperature
5 Feedwater temperature-1
6 Feedwater temperature-2

group (2B*)

1 Condenser level-1
2 Condenser level-2
3 Feedwater flow-1
4 Feedwater flow-2
5 Steam flow-1
6 Steam flow-2

The following signals in various fuel channels were analysed to determine the local stability.

group (3A*)

1 APRM
2 Reactor pressure
3 LPRM-062
4 LPRM-072
5 Channel flow
6 Coolant temperature

group (3B*)

1 APRM
2 Reactor pressure
3 LPRM-064
4 LPRM-114
5 Channel flow
6 Coolant temperature

The following signals were analysed to determine power oscillations in the core:

group (4A*)

1 APRM
2 LPRM-062
3 LPRM-092
4 LPRM-202
5 LPRM-232
6 LPRM-342

group (4B*)

1 APRM
2 Channel flow-1
3 Channel flow-2
4 Channel flow-3
5 Channel flow-4
6 Channel flow-5

group (4C*)	group (4D*)
1 Coolant flow	1 APRM
2 Reactor pressure	2 Channel flow-6
3 LPRM-061	3 Channel flow-7
4 LPRM-062	4 Channel flow-8
5 LPRM-063	5 Channel flow-9
6 LPRM-064	6 Channel flow-10

4 STABILITY DURING STARTUP

Stability during startup has been studied using a method whereby the reactor power signals (APRM) are adapted to a mathematical model of the type:

$$x(t) = \sum_{m=1}^{M} A(m)\, x(t-m) + e(t)$$

where $x(t)$ = The sampled signal
$e(t)$ = White noise
$A(m)$ = Model coefficients
M = Model order

The model describes the dynamics of the system. By disturbing the model (impulse disturbance) we can obtain information on the reactor's dynamics.

The response is used to determine the degree of stability by using another parameter called the Decay Ratio (Dr), defined as the ratio of two consecutive amplitudes during the decay of an oscillation, see Figure 3.

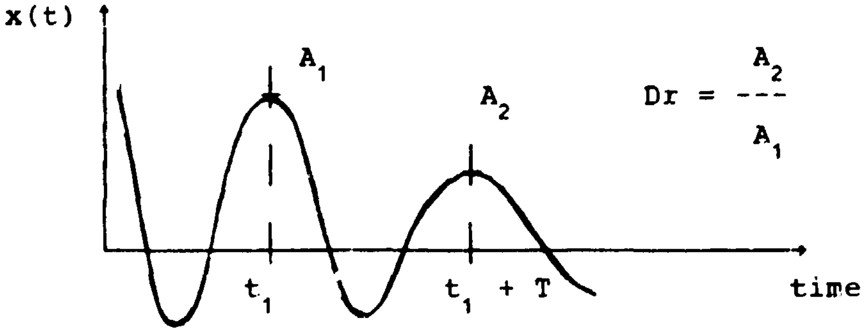
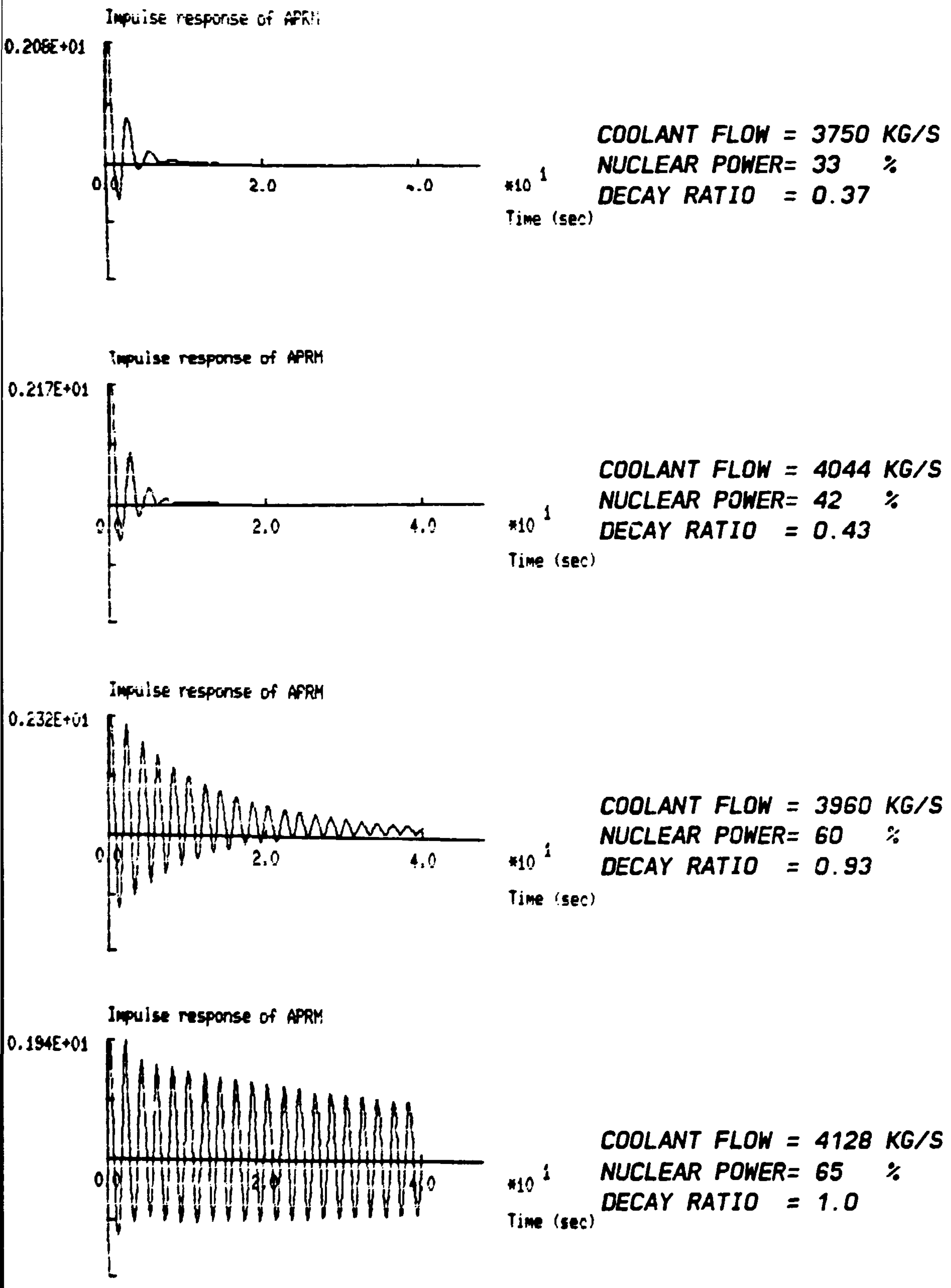


Figure 3 Definition of Decay Ratio (Dr)

Figure 4 shows how such a disturbance influences the reactor dynamics and the change that takes place when there is a power increase. The first two results demonstrate satisfactory stability since after two peaks the disturbances fades out. In these two instances, Dr is 0.37 and 0.43 respectively at powers of 33% and 42%. On the other hand the next two oscillations at 60% and 65% of reactor power have very poor stability properties with Dr=0.93 and Dr≈1.0 respectively. As can be seen from the diagram the last oscillation does not fade out after 40 seconds with the typical core resonance of 0.5 Hz.



COOLANT FLOW = 3750 KG/S
NUCLEAR POWER= 33 %
DECAY RATIO = 0.37

COOLANT FLOW = 4044 KG/S
NUCLEAR POWER= 42 %
DECAY RATIO = 0.43

COOLANT FLOW = 3960 KG/S
NUCLEAR POWER= 60 %
DECAY RATIO = 0.93

COOLANT FLOW = 4128 KG/S
NUCLEAR POWER= 65 %
DECAY RATIO = 1.0

Fig 4 Reactor power dynamics after disturbance of the model.

5 OSCILLATION IN THE LIMIT CYCLE

An oscillation state occurs in non-linear systems which is known as a limit cycle. This state is an oscillation with a stable amplitude. In other words if the system is stationary, the amplitude during oscillation will reach this limit amplitude.
On the other hand, if the system is disturbed so that the amplitude during the state exceeds the limit cycle curve, the state will fall and remain at the level of the limit cycle curve. Figure 5 shows thi: phenomenon. If a second order system is assumed, it is possible to describe the dynamics of the system with two state variables x_1 and x_2. The state space or phase plane can thus be given in the two-dimensional vector space x_1 and x_2.

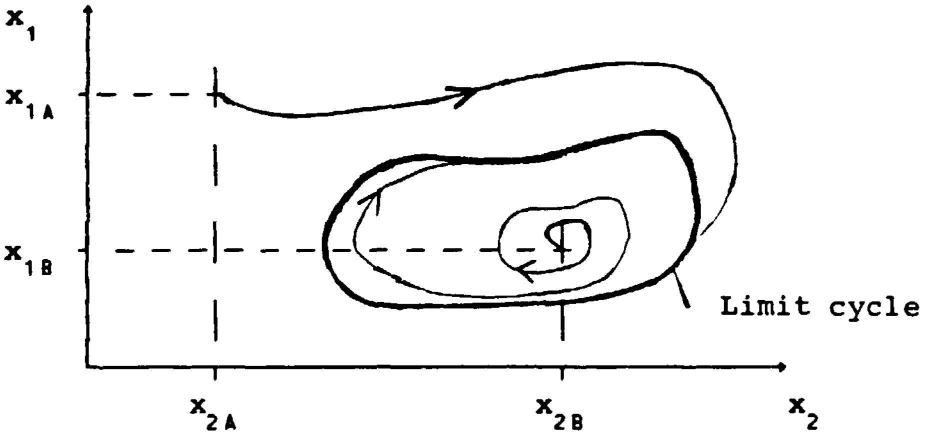


Figure 5 Phase diagram of a non-linear system with limit cycle dynamics.

An initial state at x_{1A}, x_{2A} leads to a stable approach towards the limit cycle curve while an initial state at x_{1B}, x_{2B} will grow in an unstable fashion during the oscillation up to the limit cycle curve contour.

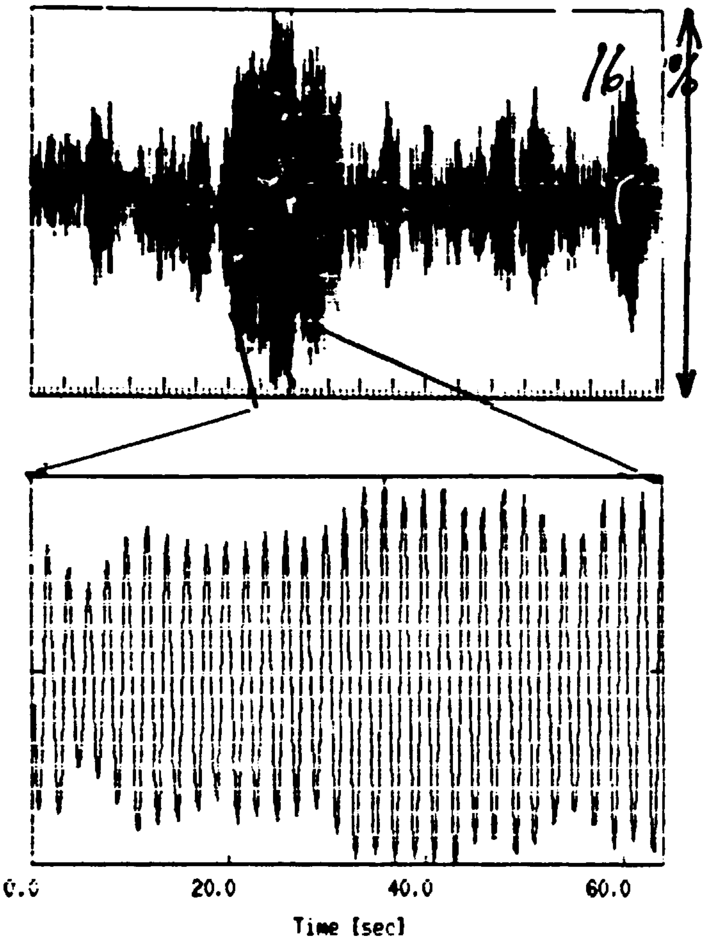
This process can be envisaged for systems with a higher order of numbers but the geometrical interpretation is not possible for orders > 3.

The oscillations of the APRM obtained during the actual measurements at F1 are due to the core resonance. The dynamic conditions are such that the void fraction and coolant flow through the fuel channels oscillate in phase.

High amplitude oscillations were found during some of the measurements. Figures 6 and 7 show the results before, during and after this test period.

It is interesting to see that the damping is poor, and the Dr is about 0.9 in all the cases.

The autospectrum for the three periods shows a sharp peak at 0.5 Hz. The greatest oscillation energy is found at this frequency. Another peak at 1.0 Hz can be seen in the spectrum for the high amplitude period. This extra peak (harmonic) is not as pronounced during the other test periods.



APRM SIGNAL WITH HIGH AMPLITUDE OSCILLATION.
REACTOR POWER = 65 %
COOLANT FLOW = 4128 KG/S

TIME EXPANSION OF THE HIGH AMPLITUDE OSCILLATION

APRM signal during operating conditions with poor stability.

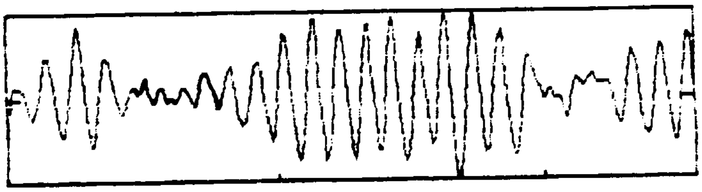
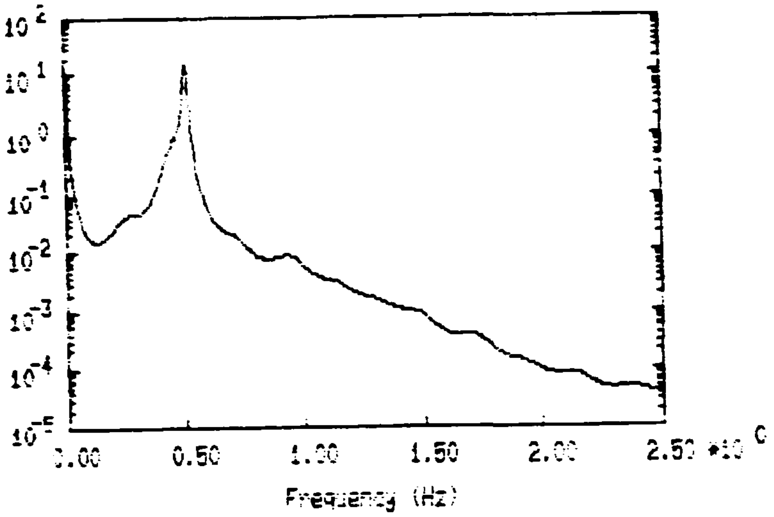
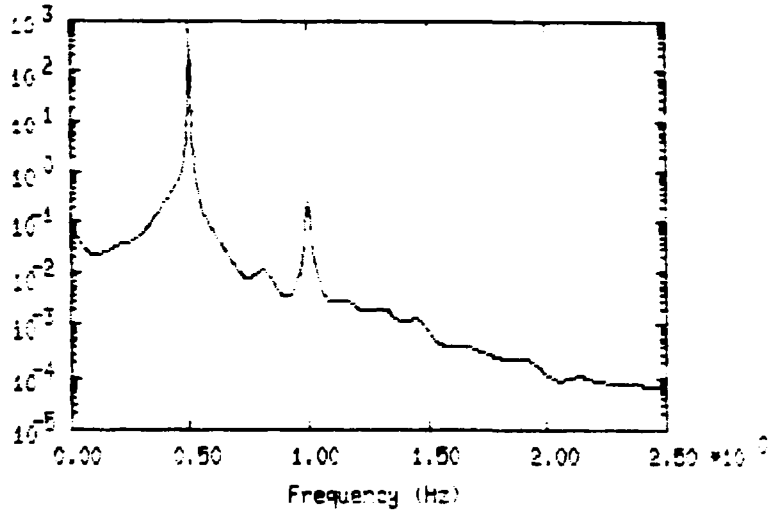


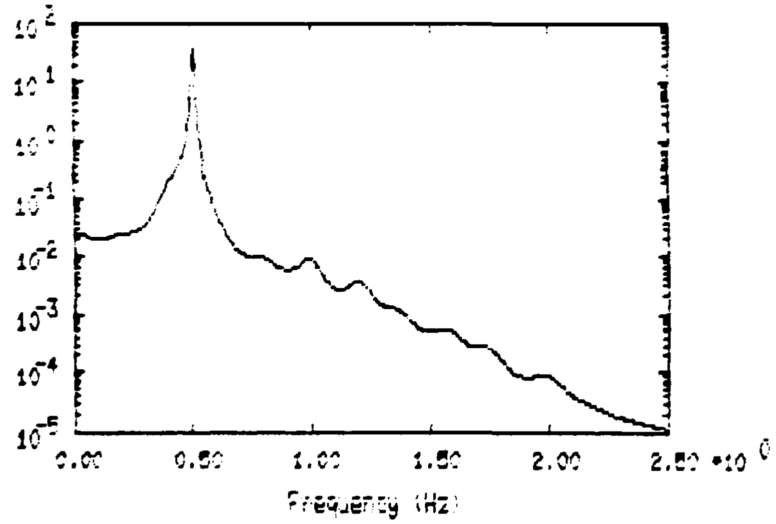
Fig 6 Reduction in oscillation and restart in the APRM signal.



AUTO POWER SPECTRUM OF APRM BEFORE THE HIGH AMPLITUDE OSCILLATION.
DR = 0.9



AUTO POWER SPECTRUM OF APRM UNDER THE HIGH AMPLITUDE OSCILLATION.
DR = 0.93



AUTO POWER SPECTRUM OF APRM AFTER THE HIGH AMPLITUDE OSCILLATION.
DR = 0.85

Fig 7 Autospectrum for APRM. Compare the results with the theoretical data for the limit cycle model.

These harmonics were predicted by March-Leuba et al 1986 by model calculations of BWR stability.

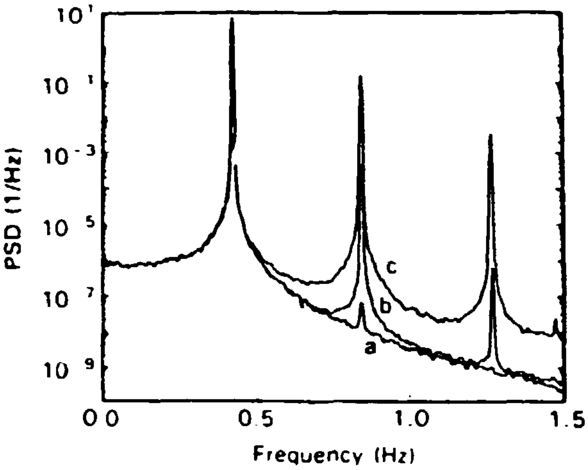


Figure 8 Auto power spectrum for the nuclear power signal. Taken from March-Leuba with accompanying text:

> In case a the model is barely stable and only the fundamental peak is clearly discernible at ~ 0.4 Hz. Case b represents a small amplitude limit cycle. Case c corresponds to a fully developed large amplitude limit cycle. The main difference between the stable and the unstable PSDs is the appearance of higher harmonics. These harmonics have a large magnitude, so they should be measurable in real-life experiments even in the presence of measurement and process noise.

It is interesting to note that the limit cycle model fits so closely to the measured data from Forsmark 1.

6 PHASE SHIFT

Another phenomenon which can be observed from the results is the sudden loss of oscillation energy in the LPRM signal and the cessation of the power oscillations at 0.5 Hz which sometimes occurs. Figure 6 illustrates the sequence. From this point, the power then starts oscillating again until the natural level is reached. This stopping in the power oscillations can easily be understood with the limit cycle model. For example, the reduction in amplitude can be explained by the loss of energy in the oscillating system due to an external distrubance which inadvertently comes into phase. For example, such disturbances may reach the fuel channels via the coolant flow.

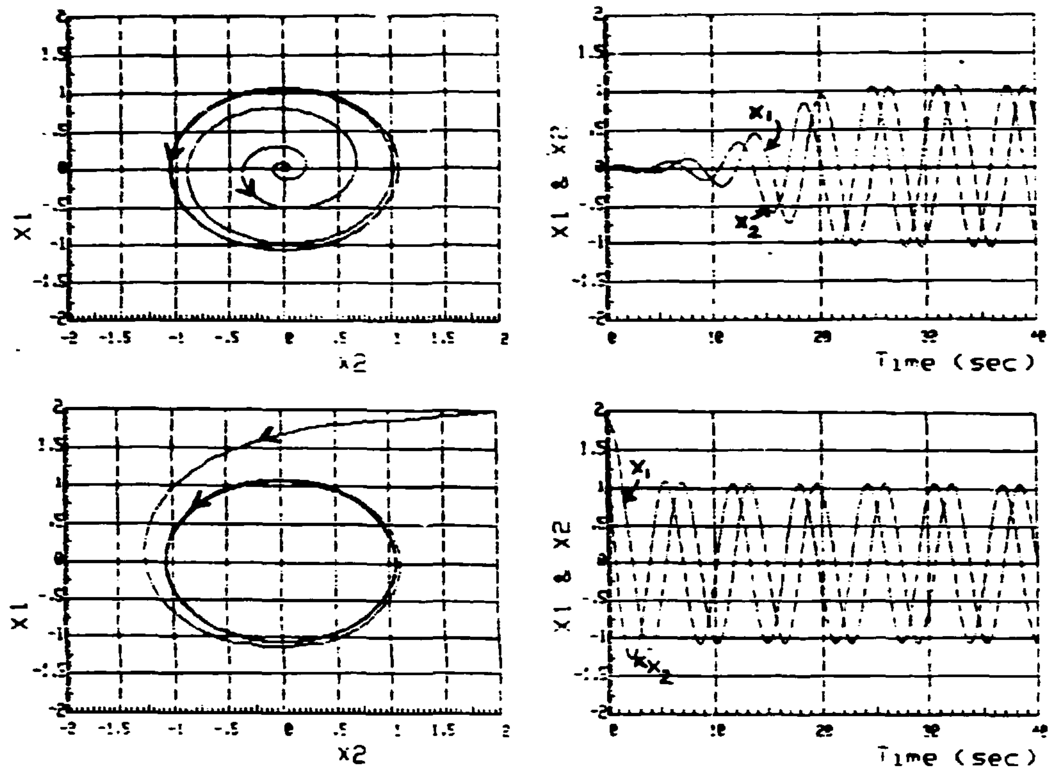
A disturbance in an oscillating dynamic system with limit cycle dynamics will generally result in a phase shift in the renewed oscillation. This relationship is illustrated in Figure 9 where a general 2-dimensional non-linear dynamic system is simulated. The equations describing the state of the system are as follows:

$$\dot{x}_1 = x_2 + x_1 (1 - x_1^2 - x_2^2)$$

$$\dot{x}_2 = -x_1 + x_2 (1 - x_1^2 - x_2^2)$$

The dynamics are such that the system has a limit cycle with amplitude 1. A sudden disturbance of the system, which leads to loss of energy, results in the sequence shown in Figure 9. The condition of the system reaches the stationary point. The system then starts to oscillate again, this time with a phase shift. If the new condition reaches this side of the stationary point, no difference in phase is found. Although the oscillation starts with a low amplitude the phase is maintained. On the other hand, if the condition exceeds the stationary point, a new oscillation starts which is out of phase with the original oscillation.

P Reibe, The Swedish State Power Board has demonstrated the existence of the phase shift between the oscillating periods of the measurement signals. The method entails reducing the original signal x(t) by its mean and multiplying the result by $\sin(2\pi f_0 t+\varphi)$, where f_0 is the oscillation frequency and φ its phase. When this is done, the in-phase oscillation will give positive results and the out of phase oscillation, negative. The analysis of APRM and LPRM signals by this method shows that Reibes phase shift holds true. See figure 10. The flux oscillations start and stop and start again, this time with a phase swing of 180 degrees. In principle, this phenomenon occurs at the same time in the whole core. The stop and restart of power oscillations with a phase swing of 180 degrees can be seen in the theoretical example. However, the mechanism responsible for the fact that the restart never occurs in phase or in an arbitraty phase cannot be explained at this point.



The simulation of limit cycle dynamics with various initial values. The state variables are shown in a phase diagram and as function of time.

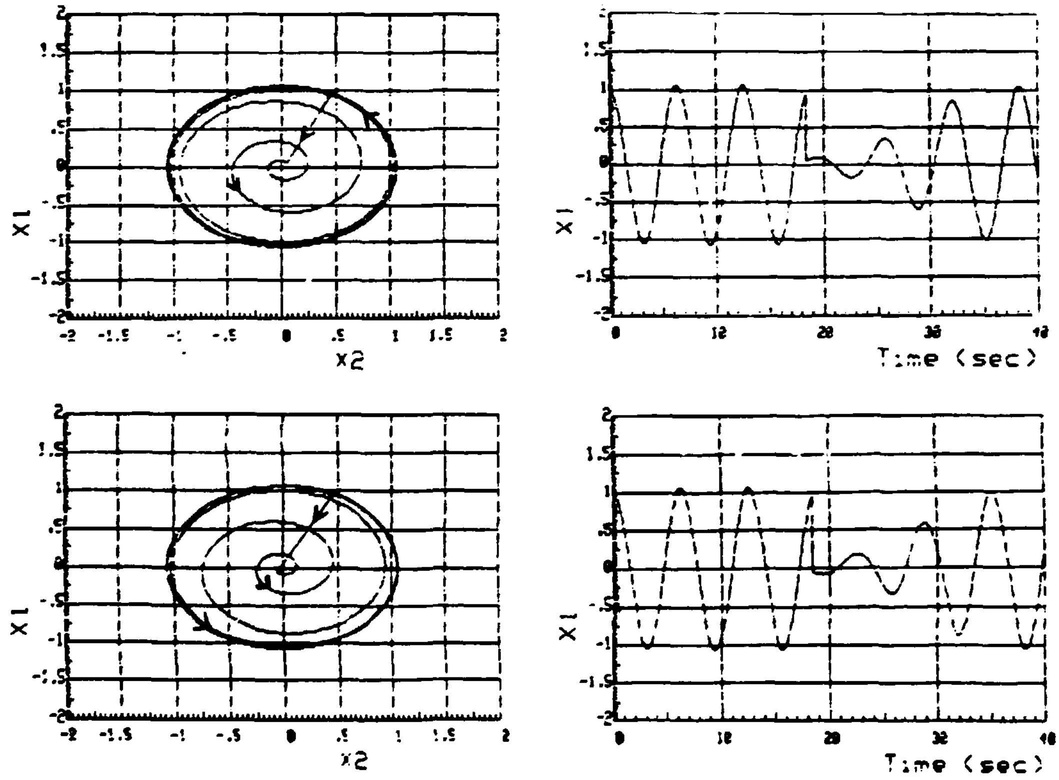


Fig 9 Disturbance of the limit cycle oscillation beyond and on this side of the stability point respectively. The oscillation after restart occurs out of phase and in phase with the original oscillation respectively.

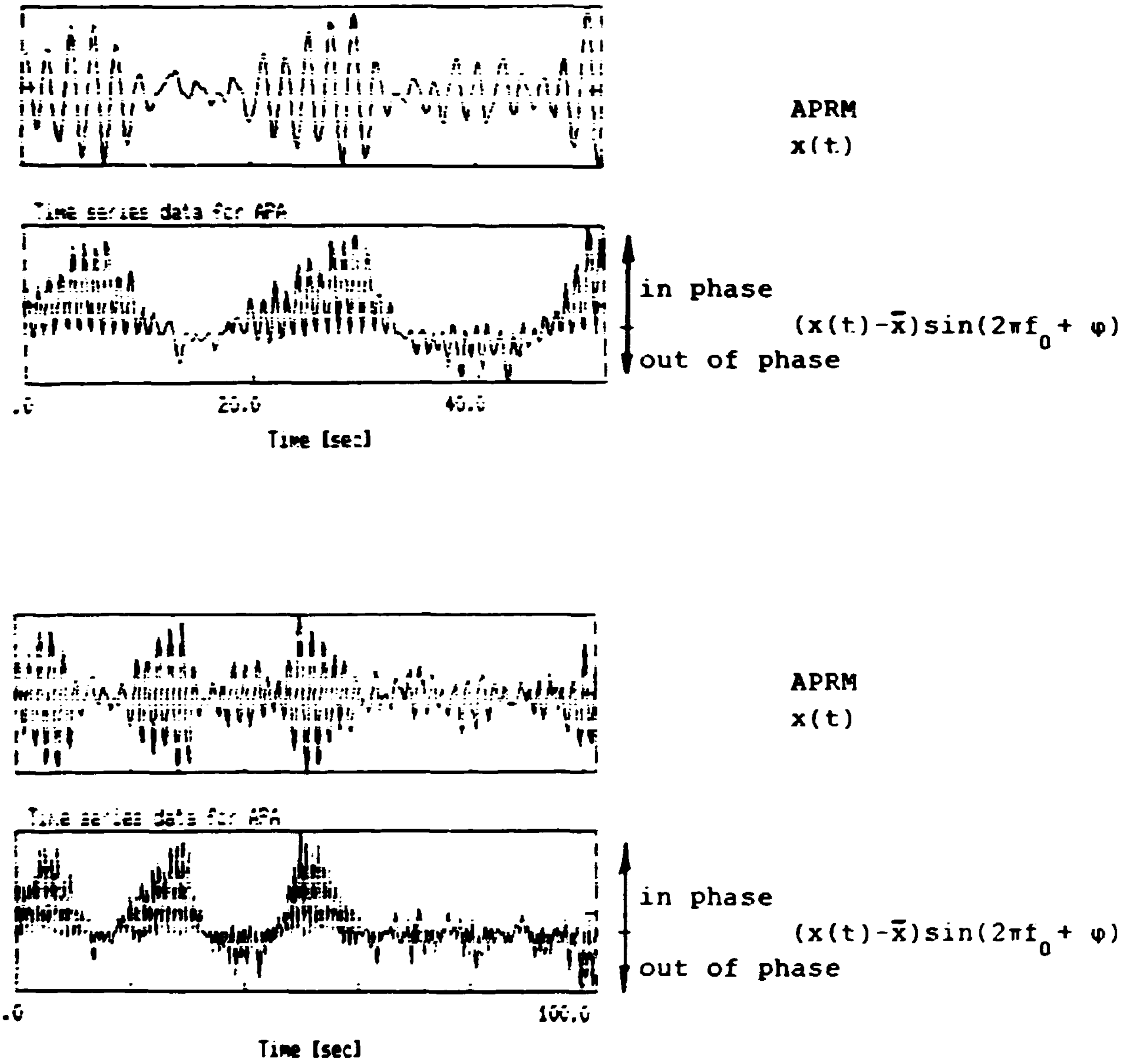


Fig 10 Test of in and out of phase oscillation in the APRM signal. Two time periods are shown where the phase shift occurs as soon as the 0.5 Hz oscillation of the APRM signal stops.

7 TEST OF POSSIBLE DISTURBANCES

A study was conducted to determine whether any of the registered signals are the cause of the cessation of oscillations in the LPRM and APRM signals. One basic idea was that a fluctuation in the feedwater flow or feedwater temperature affecting the core inopportunely when in phase would be able to suppress the oscillation. In view of the limitations on combinations of the data collected the following signal couplings were therefore analysed.

Feedwater flow - APRM

(local coolant flow x local coolant temperature) - APRM

The analysis shows that there is no coupling between the different signals. Neither the tests carried out using correlation functions nor those carried out by studying events on the time series data have shown a coupling.

8 GLOBAL STABILITY ANALYSIS

The assumed coupling between APRM (i.e neutron flux) - reactor pressure - coolant flow - steam flow-1 - steam flow-2 was analysed using Multivariate process identification. Besides producing autospectra this technique enables the classification of how much of each spectrum is derived from other signals, and shows how an oscillation distributes through a complicated dynamic system.

The principal result obtained is shown in Figure 11.

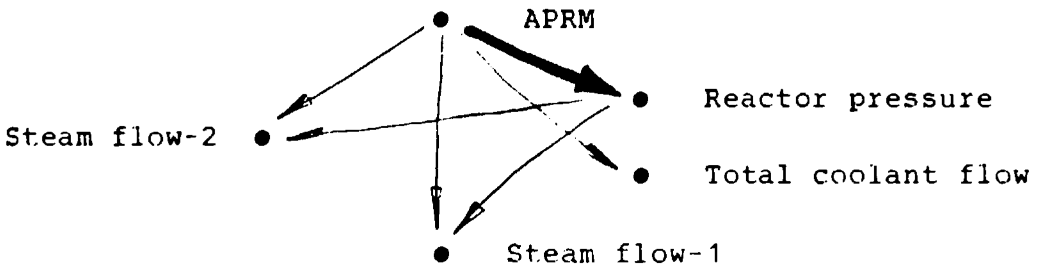


Figure 11 Dependency relations between the measured signals.

The neutron flux APRM has the strongest influence on the reactor pressure and affects the other signals to a lesser degree. In addition there is a dependency of the steam flow on the pressure.

The results of the multivariate analysis are shown in Figure 12. In the diagram, each spectrum is standardized and divided into inherent noise and contributions from the different signals. It can be seen that the inherent noise is the largest contributor and that the APRM signal with its resonance at 0.5 Hz affects all the other signals. This result supports the hypothesis that the poor stability is a core resonance phenomenon.

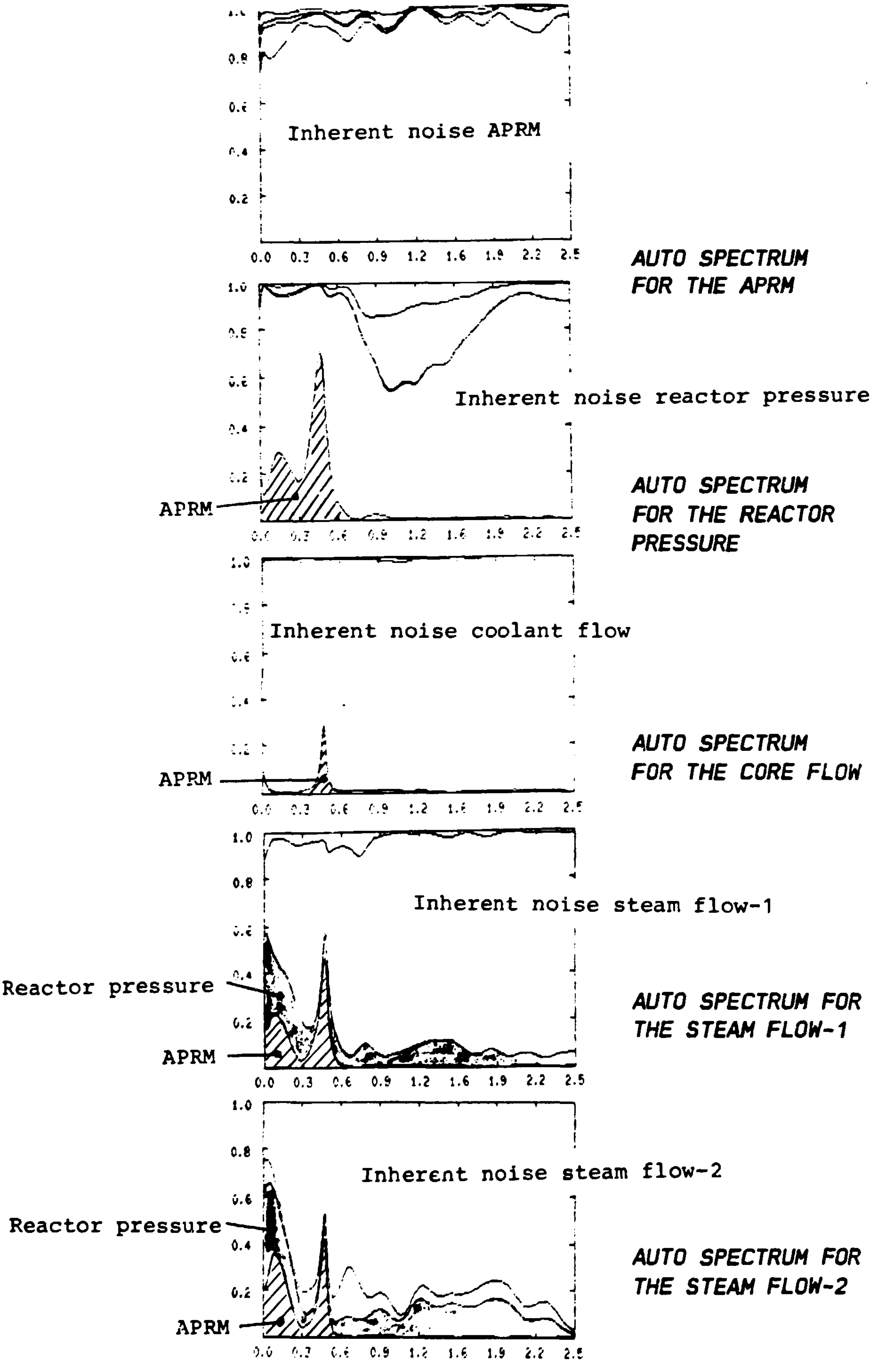


Fig 12 Multivariate analysis for the study of the coupling between process signals. Reactor power 64 %, core flow 4774 kg/s and the controller in power control mode.

9 LOCAL STABILITY

Local stability has been studied using LPRM and individual coolant channel flow together with reactor pressure, APRM and coolant temperature.

The spectra from these signals are shown in Figure 14. The resonance peak at 0.5 Hz is clearly seen for the APRM, reactor pressure, the LPRM signals and the local coolant flow, although the peak for this last signal is more rounded. The coolant temperature does not show a peak at 0.5 Hz. The influence of the signals on each another is shown in Figure 13.

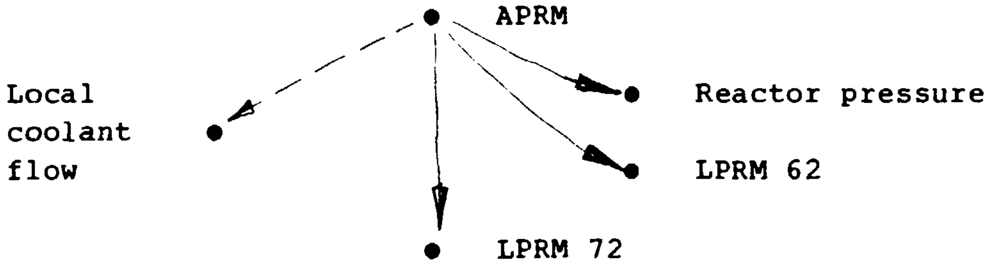


Figure 13 The influence of the signals on each other.

The results show that the APRM and LPRM signals are coupled to each other, and all signals have generally been found to oscillate in phase in the core. Previous results showing that the APRM influences the reactor pressure at the resonance peak at 0.5 Hz are also evident in this study. The study also shows that the local coolant flow is influenced by the APRM. No coupling between the local coolant flow and the local power signals can be seen in the results obtained, possibly due to the fact that the power measurement were not taken near enough to the coolant channel.

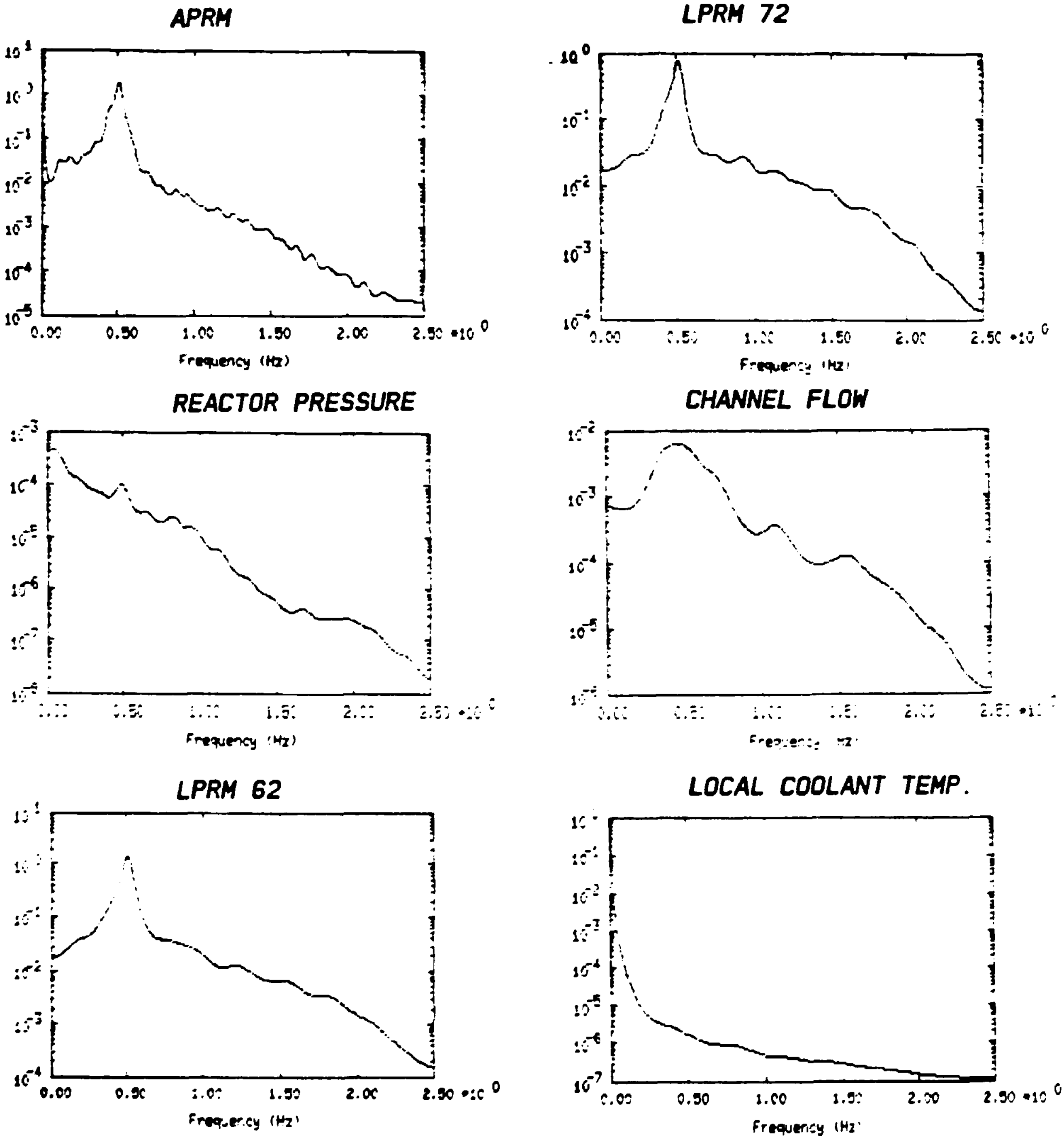


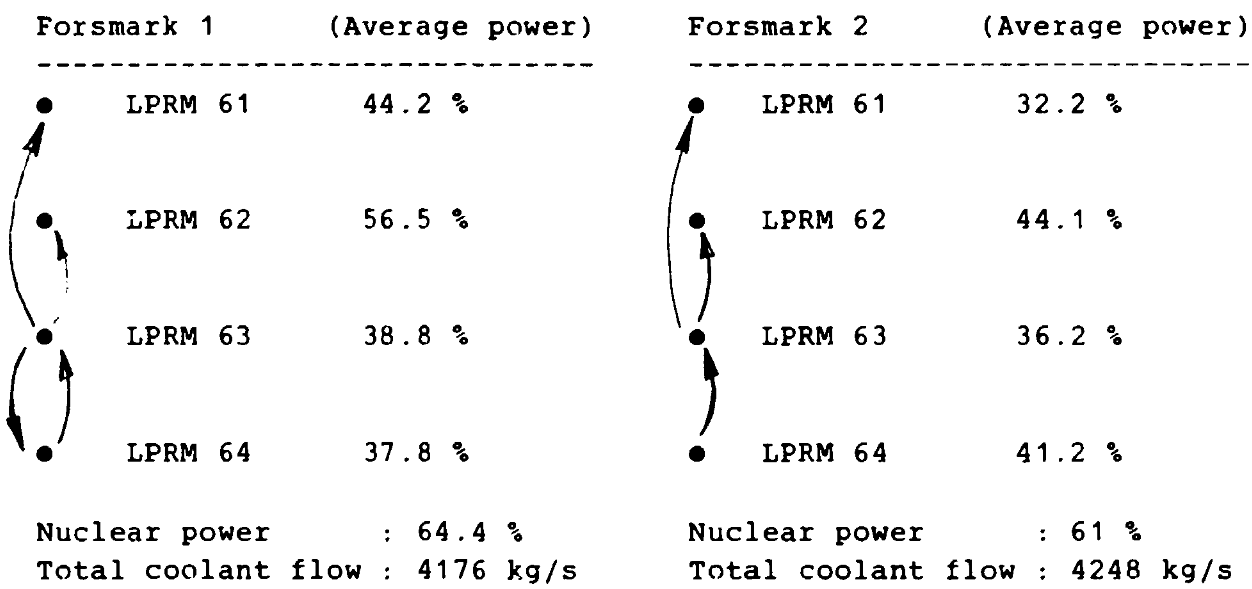
Fig 14 Auto spectrum for signals used to determine local stability.

10 STUDY OF THE DYNAMICS OF LPRM DETECTORS IN ONE STRING

The results obtained from the analysis of the total coolant flow, reactor pressure LPRM 061, LPRM 062, LPRM 063 and LPRM 064 are presented here.

Previous results showing that the LPRM signals and the reactor pressure have resonance peaks on a spectrum at 0.5 Hz hold true for the present study. This resonance is also found in the total coolant flow although the peak on the spectrum is not as sharp.

The new data obtained in this study concerns the relationship between the LPRM signals.



Forsmark 1	(Average power)	Forsmark 2	(Average power)
● LPRM 61	44.2 %	● LPRM 61	32.2 %
● LPRM 62	56.5 %	● LPRM 62	44.1 %
● LPRM 63	38.8 %	● LPRM 63	36.2 %
● LPRM 64	37.8 %	● LPRM 64	41.2 %
Nuclear power	: 64.4 %	Nuclear power	: 61 %
Total coolant flow	: 4176 kg/s	Total coolant flow	: 4248 kg/s

Figure 15 The relationship between the LPRM signals. Observe the difference in influence between LPRM 63 and 64 for Forsmark 1 and 2.

The diagram shows that information is transported vertically upwards through the core which is a well known phenomenon. The time sequence in the detectors is reproduced further up in the core due to the rising of the void. What is new is that LPRM 63 is the dominant noise source with influence downwards in the core as well, as can be seen in the results from Forsmark 1. Forsmark 2 does not show this coupling.

11 DYNAMICS ON THE HORIZONTAL PLANE IN THE CORE

The following LPRM signals were measured at the same level in the core in order to determine local power variations.

LPRM 62 - LPRM 92 - LPRM 232 - LPRM 342 - LPRM 202

Figure 16A shows that the different LPRM signals oscillate in phase during the operational state under consideration. The oscillation at 0.5 Hz is dominant. This phenomenon does not occur during more normal operating conditions since it is the local noise which dominates the global.

A multivariate analysis of the variables shows that detector 6 and detector 23 are the driving sources while detector 9 and 20 are mainly receiving sinks. Detector 34 acts as both a receiving sink and a driving source. Figure 17 shows the power noise exchange between the LPRM signals. In addition, the fuel environment of the detectors is presented. The strongest noise source is found in the environment of 9x9 fuel and the weakest is found in the environment of 9x9 and 8x8 fuel together. There is no distinct coupling between the signals in Forsmark 2 of the type seen from the Forsmark 1 signals.

As described above, the LPRM signals oscillate in phase with the fundamental 0.5 Hz on the horizontal plane. However, the same does not hold true for the channel flows which do not vary in phase for oscillations at 0.5 Hz, see Figure 16B.

During this operational condition, oscillations occur when the main recirculation pumps are operating at minimum speed. The relationships are similar to those of natural circulation and a tendency to hydrodynamic oscillations can occur between channels.

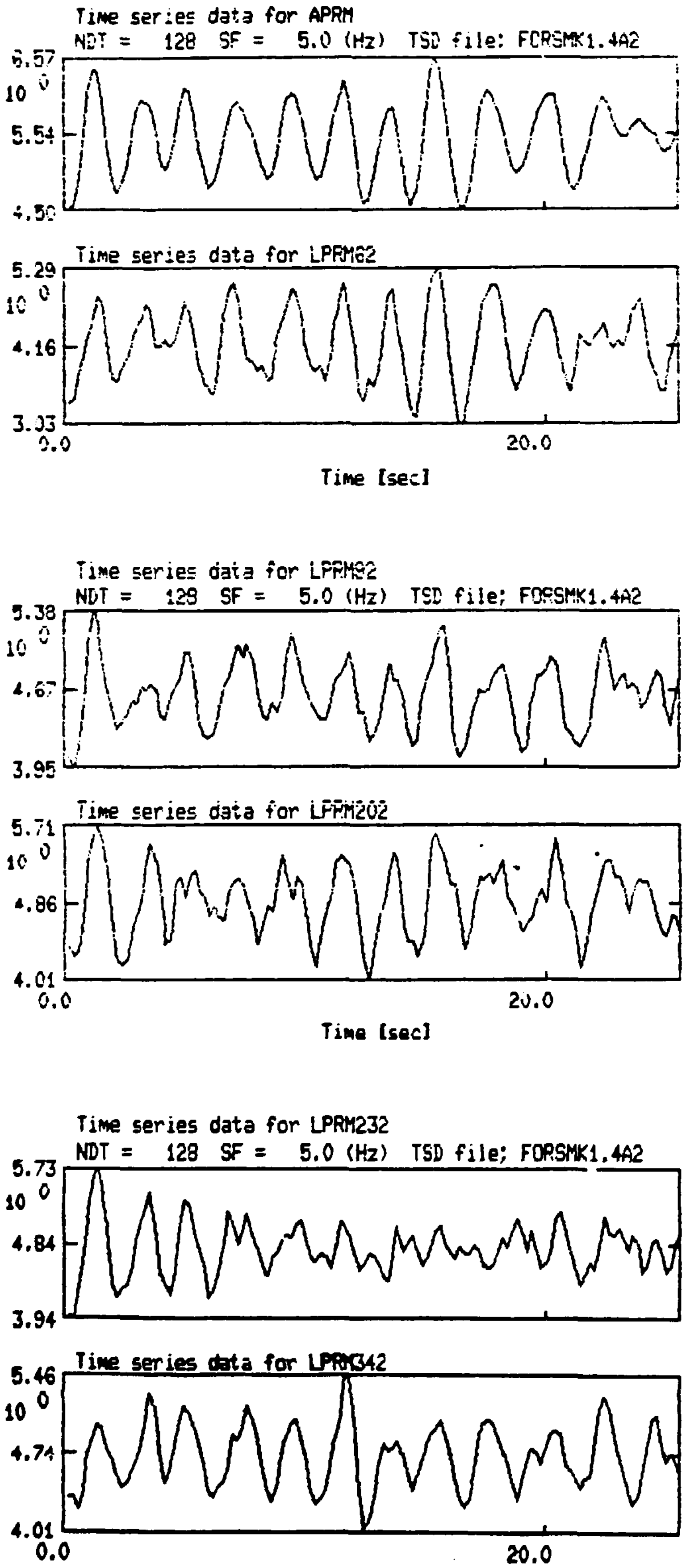


Fig 16A APRM and LPRM-62, -92, -202, -232, -342, recorded at the same time. The oscillation at 0.5 Hz is in phase between the different detectors in the core.

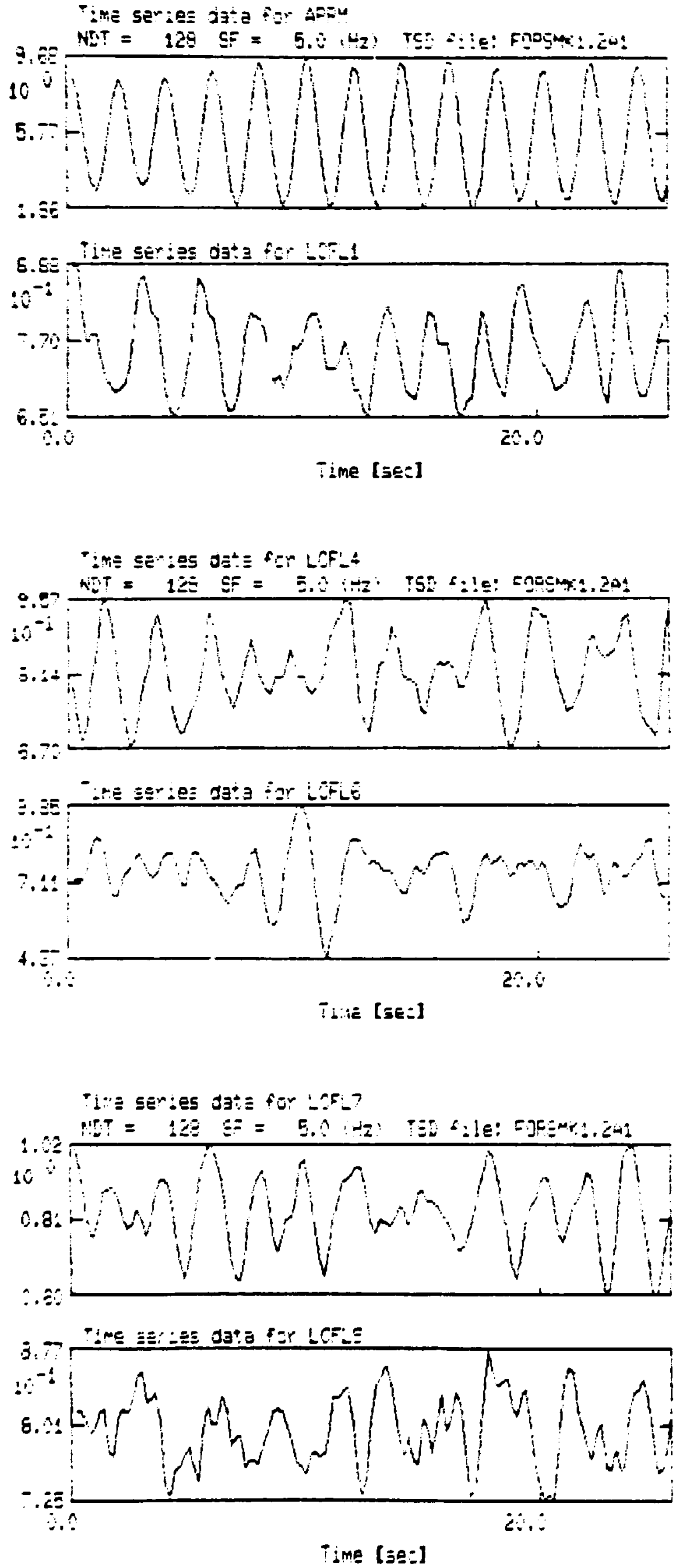


Fig 16B APRM and 5 channel flows recorded at the same time. Note that the channel flows are not in the phase.

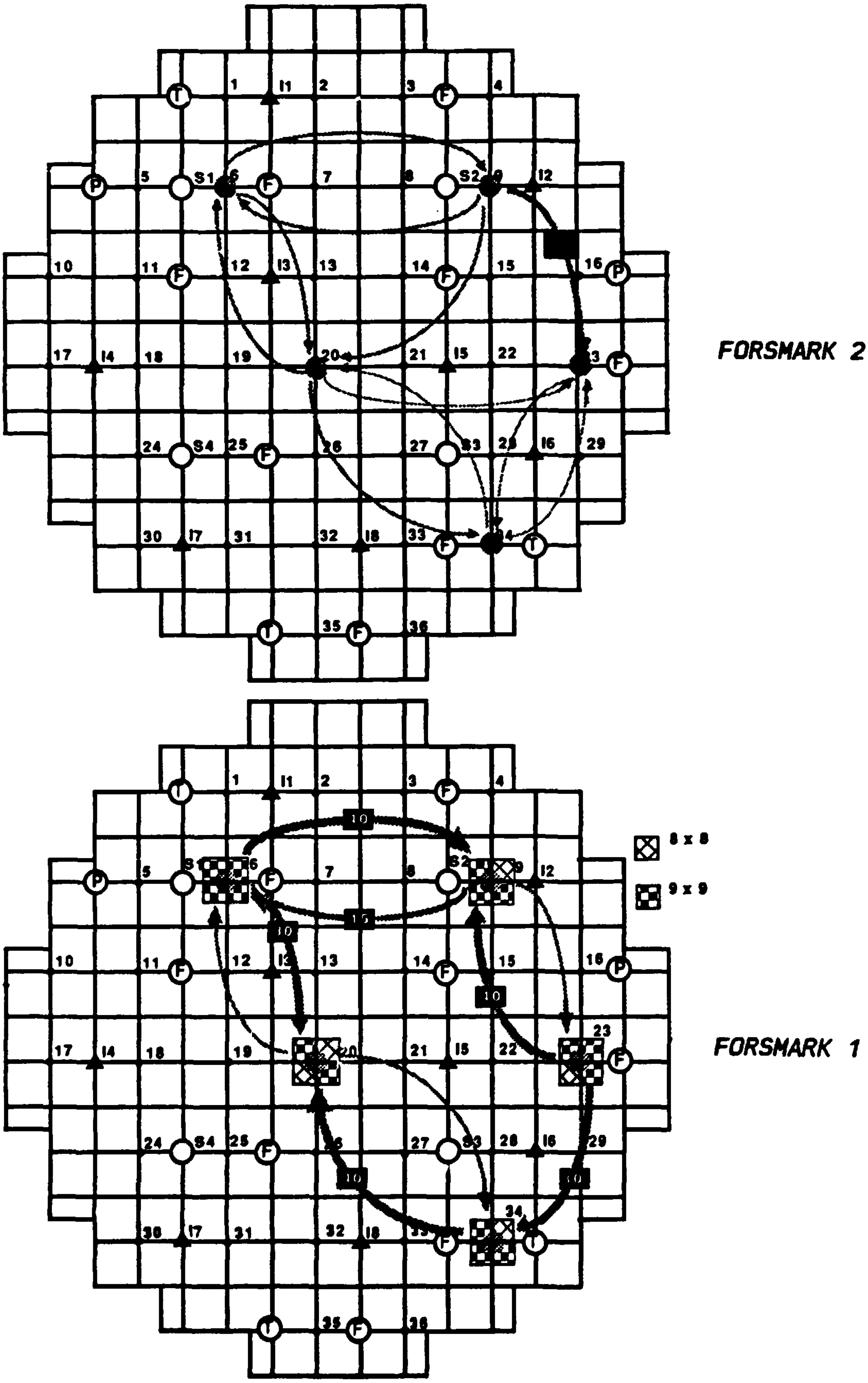


Fig 17 Coupling between different LPRM signals in the Forsmark 1 and 2 reactor cores. The thickness of the arrows and the numbers indicate the percentage contribution. Only 8 x 8 fuel is used in Forsmark 2 while Forsmark 1 has a mixture of 8 x 8 and 9 x 9 as shown in the diagram.

12 US-NRC BWR STABILITY CRITERIA

The US Nuclear Regulatory Commission (USNRC) has described the process for handling BWR stability issues in generic letter no 86-02 (Feb 1986). A copy of the letter can be found in Appendix A.

In general terms, it is stated that theoretical calculations of the Decay Ratio should be carried out for each core configuration. These theoretical estimates are judged to have a 20 - 25% uncertainty. In order to be on the safe side, i.e to prevent limit cycle oscillations, it is required that Dr be < 0.75 - 0.80. For cores which cannot fulfill the analytical criteria, operational limitations are instituted which provide for the detection and suppression of flux oscillations in operating regions.

A technical commentary on the generic letter has been written by March-Leuba, an acknowledged expert on BWR stability. The following extract has been taken from a paper presented at SMORN V, in October 1987:

> For this reason, United States utilities are required by the Nuclear Regulatory Commission to evaluate the reactor stability for every reload core unless plant technical specifications provide for monitoring of neutron flux oscillations in the so-called limit-cycle "Detect and Suppress" region. This region is defined by these specifications and commonly lies below the 40 % flow line and above the 80 % rod control line. Within this region, the reactor operator must monitor average and local power oscillations to detect instabilities. Should instabilities occur, they should be suppressed either by inserting control rods or by increasing recirculation pump speed.

In addition to these documents, it was learned during discussion with Japanese colleagues that the criteria in Japan require that the Dr be less than 0.40. It has not yet been possible to obtain a written document confirming this.

13 RECURSIVE CALCULATION OF THE DECAY RATIO

In Figure 19, the Decay Ratio is shown as a function of time for a 1.8 hr test period. The reactor power was 63% and the coolant flow 4500 kg/s when the measurements were taken.

To carry out the calculation, each sample was identified with a lattice filter algorithm. The Dr was then calculated from the impulse response at each 64th sampling. On the time scale, this means that the Dr was updated with a time interval of 12.8 seconds.

The results of the same APRM signal which was used to calculate the Dr are shown in Figure 18. The APRM mean values have been plotted on the graph and as an uncertainty estimate its variance for 64 samples. It can be easily seen that the reduction in stability at t=1300 s leads to less stable APRM signal. However, the correlation between stability in APRM and high Dr is not so simple that it can be read in the APRM amplitude.

The stability during the test period is also very poor. The Dr is over the NRC criterion of 0.75 for 50% of the measurement period shown.

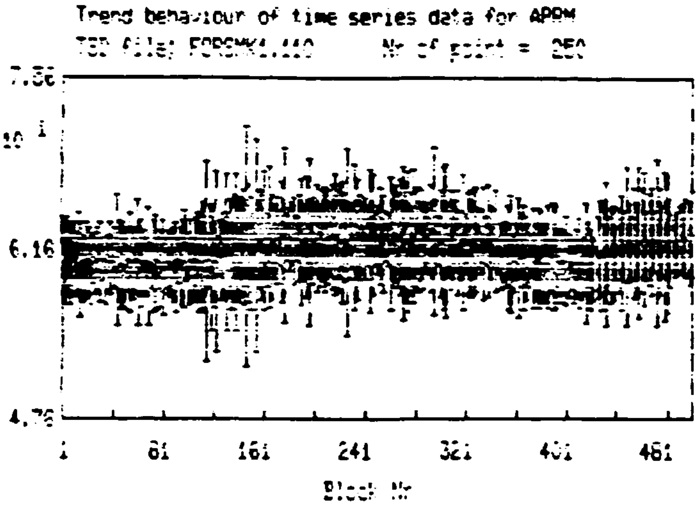


Fig 18 APRM mean and variance for every 64:th sample as a function of time.

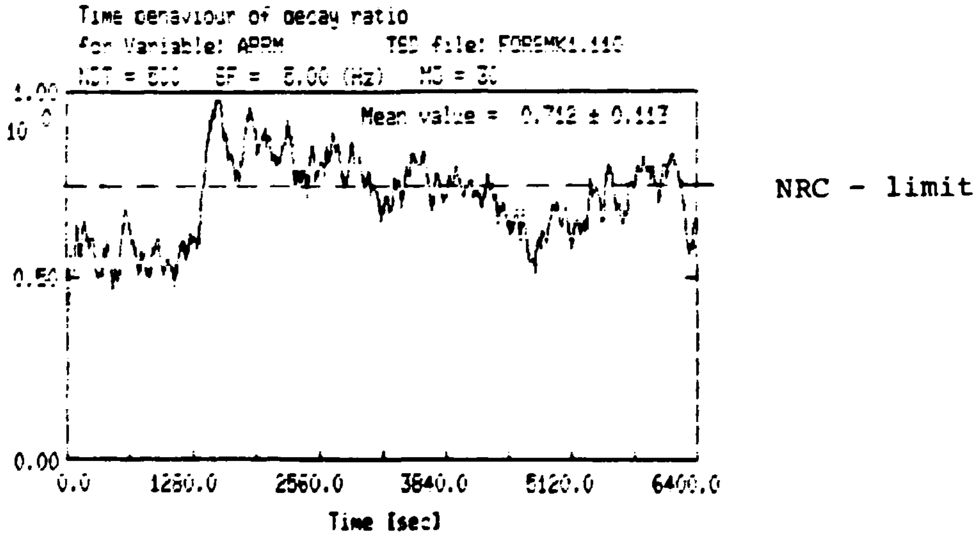


Fig 19 Decay Ratio as a function of time for the time series analysed.

14 CONCLUSIONS

Measurements to establish core stability properties have been carried out in two BWR units, Forsmark 1 and 2. The measurements on which the analysis was based, were taken during power ascension following the reguelling outage in summer, 1987. The operational states which occur during startup are the most risky from the standpoint of stability. Low coolant flow in the core and high power characterize the operational state until full power operation is achieved.

It has been possible to calculate a Decay Ratio (Dr) by applying a mathematical model to the power signals, using a process identification technique. The Dr expresses the stability margin and is a measure of how rapidly (Dr=0) or slowly (Dr=1) a disturbance is damped.

It has been widely reported that poor stability, at a Dr of almost 1, leads to limit cycle conditions. During the limit cycle, there is an uncontrolled growth of the amplitude up to a given level even if no external distrubances are present. Moreover, limit cycle conditions are evident in the spectrum, the fundamental peaks very sharply and harmonics are found at twice and three times the fundamental frequency.

The following is a summary of results for Forsmark 1:

1. The measurements and analyses clearly show that a core resonance phenomenon leads to those oscillations at 0.5 Hz which can be observed in both LPRM and APRM.

2. A Dr ≈ 1.0 was calculated at 65% of full power and 4128 kg/s coolant flow. In this case, the core oscillations occured in the limit cycle as could be seen from the harmonics in the spectrum.

3. The LPRM signals oscillate in phase throughout the whole core.

4. However, the LPRM oscillations vary in strength in different parts of the core. The strongest oscillation is found in the environment of 9x9 fuel and the weakest in the environment of both 8x8 and 9x9 fuel.

5. The upper LPRM detectors are influenced by the lower ones in the same probe due to the void transport upwards in the core which is a well-known phenomenon. In addition, a downward influence was observed from LPRM 3 to LPRM 4 in the actual operating region.

6. The Dr was calculated as a function of time using recursive process identification. A Dr > 0.75 was found during half of the total 1.8 hour test period.

15 FUTURE WORK

The measurements and analyses carrid out show that instability is a problem in Swedish BWRs. It is therefore important to increase the understanding of this phenomenon. The hypothesis which arose from the comparison of Forsmark 1 and 2 is based on core related instability, and possibly related to the presence of different kinds of fuel in the same environment (8x8 and 9x9). In order to increase the understanding of this problem, more measurements must be carried out to determine the importance of the role played by the fuel.

LPRM measurements taken at different locations in the core in cleaner fuel environments (9x9 or 8x8) must be carried out in order to establish the interactions observed in the studies.

It is also advisable to install a Decay Ratio monitor as quickly as possible in order to find out whether there are other regions in the operational diagram which are characterized by poor stability. Such an instrument should be accessible on-line and operate in real-time. The instrument should also provide the operator with early warning of deteriorating stability before the oscillations start.

Future measurements should also treat the role of the local coolant flow in the measured oscillations, e.g the coolant flow coupling between fuel channels.

It also is essential to have a feedback of experience of poor stability in BWR units abroad.

16 REFERENCES

1 J. March-Leuba et al. Non linear dynamics and stability of boiling water reactors: Part 1 - Qualitative Analysis. Nuclear Sc & Eng 93. 1986.

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3 S. Suzuki et al. Applicability of a multivariable Autoregressive method tc boiling water reactor core stability estimation. Nuclear Technology vol. 74. 1986.

4 Y. Takigawa et al. Caorso limit cycle oscillation analysis with three-dimensional transient code Tosdyn-2. Nuclear Technology vol. 79. 1987.

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6 B.R. Upadhyaya, M. Kitamura. Monitoring BWR stability using time series analysis of neutron noise. Transaction of the American Nuclear Society. Vol. 33. 1979.

7 F. Reisch, G. Vayssier. A non-linear digital computer model requiring short computation time for studies concerning the hydrodynamics of boiling water reactors. Nuclear Engineering and design 9 (1969).

APPENDIX A

L86-00175

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JAN 23 1986

RECEIVED
FEB 07 1986

TO: ALL LICENSEES OF OPERATING BWRs

GENTLEMEN:

SUBJECT: TECHNICAL RESOLUTION OF GENERIC ISSUE B-19-THERMAL HYDRAULIC STABILITY (GENERIC LETTER NO. 86-02)

The staff has been studying BWR thermal-hydraulic stability characteristics for several years under Generic Issue #B-19 - Thermal-hydraulic Stability. We have recently completed our review of this issue and the purpose of this letter is to inform you of our findings on the resolution of Generic Issue #B-19.

Specifically, we have recently completed our technical evaluation of topical reports (Refs. 1 and 2) by General Electric and Exxon which describe their analysis methods and have concluded the following:

> GE/Exxon methods for calculation of core stability decay ratio are uncertain by 20%/25% in predicting the onset of limit cycle oscillations (decay ratio =1.0). Thus a core having a calculated decay ratio of 0.80/0.75 may, in fact, be on the verge of limit cycle oscillations within permissible operating space. The result of this conclusion is that BWR 4, 5, 6s may not be able to show compliance with General Design Criteria 10 and 12 solely using analysis procedures to prove that thermal hydraulic instabilities are prevented by design. BWR 1,2,3s with conventional fuel designs and operating restrictions should have sufficient margin; however, licensees should examine each core reload to assure that it is typical of previously evaluated cores which have acceptable stability margin. For cores which do not meet the analytical criteria, we have concluded that operating limitations which provide for the detection and suppression of flux oscillations in operating regions of potential instability consistent with the recommendations of General Electric SIL-380, are acceptable to demonstrate compliance with GDC 10 and GDC 12 for cores loaded with approved fuel designs.

Many owners of BWR 4,5, and 6s have incorporated into their technical specifications provisions which enforce GE SIL 380 recommendations for operation of their plants. All BWR owners should review the need for such technical specifications in light of the approved stability criteria and the status of core stability design calculations for specific plants. Licensees are advised that the approved stability criteria are applicable to all operating reactors, and should be included in future safety evaluations in support of 10 CFR 50.59 determinations for all core reloads and other design or operating modifications which relate to core thermal-hydraulic stability.

This generic letter does not include any reporting requirements so that no OMB clearance is necessary.

Sincerely,

Robert M Bernero

Robert M. Bernero, Director
Division of BWR Licensing
Office of Nuclear Reactor Regulation

REFERENCES

1. G. A. Watford, "Compliance of the General Electric Boiling Water Reactor Fuel Designs to Stability Licensing Criteria", NEDE-22277-P-1, October 1984.

2. L. A. Nielsen, et.al., "Stability Evaluation of Boiling Water Reactor Core," XN-NF-691(P)(A), August 1984.

STUDSVIK/NI-88/12

BWR-STABILITY INVESTIGATION AT FORSMARK 1

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