Neutron Flux Oscillations at German BWRs

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Abstract:

Neutron flux oscillations are a well known phenomenon for Boiling Water Reactors (BWRs). The oscillations can occur in a specific region of power and core flow map. The oscillations themselves are caused by interdependencies between thermo-hydraulic parameters and the reactivity feedback. In the instability region these interdependencies can result in an insufficiently damped oscillation of the neutron flux with increasing amplitudes. It cannot be excluded that fuel rod cladding limits may be exceeded if these oscillations are not timely suppressed. During the specified normal operation a BWR should run in stable regions with adequate margins to the instability region. But, during transients the point of operation may enter the instability region.

Worldwide several events occurred since the 1980ies related to neutron flux oscillations. Countermeasures have been derived from these events. In the last years, neutron flux oscillations occurred again in some BWRs, especially in Sweden and Germany. The events showed that the combination of advanced fuel assembly design with high burn-up, spectral shift operation, and low leakage core configuration could result in fast increasing neutron flux oscillations following transients. GRS has evaluated these new events under specific consideration of potential out-of-phase oscillations and derived recommendations to prevent, detect and suppress these oscillations.

1. INTRODUCTION

Neutron flux oscillations are a well known phenomenon for Boiling Water Reactors (BWRs). The oscillations can occur in a specific region of power and core flow map. The oscillations themselves are caused by interdependencies between thermo-hydraulic parameters and reactivity feedback parameters such as the void-coefficient (fig. 1). The instability region depends on the core configuration, the operating regime, burn-up of the fuel assemblies, and the control rod positions as well as further influence factors like pressure drop in the one-phase and the two-phase flow regions within the core [1, 2, 3]. It can be calculated with specialised computer codes. These codes determine among other things two main coefficients limiting the allowed operating region, the DNB ratio (departure from nucleate boiling) and the decay ratio.

The DNB ratio describes the heat transfer between the fuel rod cladding and the coolant. During nucleate boiling the heat transfer takes place from the cladding surface to water and very small steam bubbles. The film boiling or so called “dry-out” occurs if the water film on the cladding breaks down and the heat is transferred mainly to steam. This increases the load on the cladding and it may fail if the film boiling continues for some time. The load on the cladding augments, if it is cyclic rewetted again by intruding coolant. Such a scenario can result from neutron flux oscillations. Therefore, the DNB ratio is limited for normal operation to ensure sufficient margin from dry-out conditions.

The decay ratio describes the dampening of neutron flux oscillations. An oscillations has decreasing amplitudes, if the decay ratio is less than 1. If the decay ratio exceeds 1 than the amplitudes of an oscillation rise until they are limited by physical effects or neutron absorption e.g. by control rods. Due to calculations for a Swedish BWR [1] the maximum power level for global oscillations is limited to about 250% of the rated power. In BWRs the decay ratio should be less than 0.8 for stable operation [2].

There are mainly two types of neutron flux oscillations: In-phase and out-of-phase oscillations. During the in-phase or global oscillations the entire core oscillates with the same phase. Out-of-phase oscillation types comprise oscillations of half a core each, i.e. the left half core has the maximum amplitude when the right half core has the minimum amplitude, and oscillations of parts of a core (local or regional oscillations). Out-of-phase oscillations have been observed during tests [4] and even during events e.g. at Caorso, Italy, 1984 [2] and at the Swedish power plant Ringhals 1, 1989 [1].

Fig. 2 illustrates allowed operation regimes and the excluded zone i.e. the instability region in the power-flow-map. In BWRs the power level is mainly controlled by the recirculation pump speed which governs the core flow and by the control rod positions. There are additional parameters influencing the power level, e.g. the feed water temperature. The pressure is kept constant in BWRs during normal operation. An operation in the instability region can result in an oscillation of the neutron flux with increasing amplitudes. It cannot be excluded that fuel rod cladding limits may be exceeded if these oscillations are not timely suppressed. The normal operation of a BWR should avoid the instability region. But, during transients the point of operation may enter the instability region.

2. OPERATING EXPERIENCES

After first events in the beginning of the 1980ies, a major event related to neutron flux oscillations occurred 1988 at the LaSalle NPP, USA [1, 2]. This was the first internationally reported event with oscillations following a transient during power operation. In LaSalle a trip of the recirculation pumps occurred followed by a loss of the feed water preheaters. Some minutes after start of the transient an in-phase oscillation developed. The transient was stopped by a scram at 118% reactor power.

In the following years several similar events were reported internationally including two events from German BWRs [2]. As a result of these events, several measures were taken against neutron flux oscillations. The measures included three stages: prevention, detection and suppression. The prevention comprises the calculation and experimental proof of the boundaries of the instability region to assure sufficient margin between the allowed points of operation and the exclusion zone. Additionally, preventive measures are taken in some plants if during transients the entering of the instability region is to be anticipated. The detection is performed by the incore neutron flux detectors which are combined in the average power range monitors (APRM). The APRM is used to generate the scram signal if the maximum allowed power level is exceeded.

The measures for suppression are manifold. Derived from the allowed control rod line additional sliding limit values have been established. The rod block line prohibits the further extraction of control rods out of the core, the single rod insertion line and the group (bulk) rod insertion line activate the insertion of control rods into the core. The group rod insertion is also called a partial scram. And above these lines a sliding scram exists in some BWRs to assure a scram at much lower power levels dependent on the core flow. In some instances this scram is delayed for some seconds to avoid unnecessary scrams during transients. In fig. 2 some of these lines are schematically shown.

3. LESSONS LEARNED AFTER RECENT EVENTS

For nearly nine years no events related to neutron flux oscillations were reported at German BWRs. But in November 2001 an in-phase oscillation occurred at Philippsburg-1 NPP after a feed water temperature transient [5]. The in-depth analysis of this event resulted in new lessons to be learned. A similar event occurred in the Swedish BWR Oskarshamn-2 in February 1999 [1]. In both events a scram terminated the neutron flux oscillation, but at the fixed scram setpoint at 120% and 132% power level, respectively. In both cases, control rod insertion was activated but too late to limit the oscillations effectively.

In the recent years the core design was further developed to achieve more efficiency. The three most important factors are the “low leakage” loading to minimize neutron losses, the “spectral shift” operation to control the axial power distribution, and new fuel designs with higher enrichment for higher burn-up.

The combination of these influence factors with very few control rods inserted during power operation and the use of high operational rod lines lowered sufficiently the margin between the operational points and the instability region. This resulted in the fact that for certain transients the end point was in the instability region and manual actions were necessary to leave this region. These events showed however that there is no sufficient time for manual control.

The operating experiences and calculations show that the fixed scram setpoint is sufficient to terminate safely in-phase oscillations before fuel rod cladding failures establish (see fig. 3). But, there is still no proof that cladding failures are excluded during out-of-phase oscillations. The measurements installed in most BWRs (APRM) cannot or not timely detect out-of-phase oscillations and thus cannot activate the suppression measures in time. During symmetrical out-of-phase oscillations the average power level does not change as long as the sum of the amplitudes is constant (see fig. 4). The average power level increases when the lower peak of the oscillation reaches zero power (there is no negative neutron flux) and thus the positive and the negative phases are asymmetric. But, even then the fixed scram setpoint may not be exceeded because the maximum amplitudes are limited due to physical and technical reasons. In addition, the neutron flux measurements are limited to about 150% nominal flux due to detector saturation effects [6]. Taking into account simplified assumptions, even the sliding scram line might not be reached during such an oscillation (fig. 4). Detailed calculations for real core configurations have to be performed to assess the influence of the detector saturation on the flux level indicated by the APRM during an out-of-phase oscillation.

The results of these analyses lead to following recommendations comprising measures in prevention, detection and suppression of out-of-phase oscillation. The operating regime should avoid operating points within the instability region. Prevention should be based on adequate calculations and tests to determine the boundaries of the instability region, sufficient margin between the operating region and the instability region as well as timely measures during transients to trigger countermeasures before entering the instability region and the development of oscillations. For specific transients, there may be a passing through of the instability region, but automatic measures should assure that the end point of each transient is outside the instability region. Manual control should not be envisaged at operating points inside the instability region.

The recent operating experience illustrates the necessity of early countermeasures. In recent events the staggered measures installed have been too slow to prevent the oscillations. The event analyses revealed that the measures were activated after the oscillations had started. For instances, it takes about half a minute for cold feed water to flow into the reactor pressure vessel after a preheater bypass event. This time can be used to insert control rods and to keep the operating point outside the instability region.

The detection measures installed in German BWRs are sufficient to detect and suppress in-phase oscillations before fuel rod cladding limits are exceeded. But the analyses revealed that out-of-phase oscillations may be not detected by using the APRM only. Thus, it cannot be excluded that fuel rod failures occur during out-of-phase oscillations. Actions should be taken to safely detect these oscillations and to derive countermeasures. Recently, supervisory control units have been developed and qualified which depend on local power range monitors. These control units are able to detect out-of-phase oscillations and to activate staggered measures including scram.

4. CONCLUSIONS

Neutron flux oscillations are a well known phenomenon in BWRs. After several events, measures have been taken to prevent, detect and suppress these oscillations in German BWRs and worldwide. The progress in core configuration, fuel design and neutron efficiency affects the influencing factors on the oscillations. The in-depth analyses of recent events revealed that the measures taken are sufficient to control in-phase oscillations in order to prevent fuel rod cladding failures. But, the control of out-of-phase oscillations still needs some developments in view of GRS. The prevention of neutron flux oscillations should be strengthened to avoid entering of the instability region by an adequate operating regime and activation of countermeasures at the beginning of a related transient before the oscillations have started. In addition, automatic control units should be implemented to detect out-of-phase oscillations and to trigger staggered measures limiting their amplitudes and their duration.

5. REFERENCES

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4. Analytis, G. T., Hennig, D., Karlsson, J. K-H., The physical mechanism of core-wide and local instabilities at the Forsmark-1 BWR, NURETH-9, October 1999
5. BfS, Quarterly Event Report , IV Quarter 2001 (in German)
6. Kraftwerk Union, Neutronenmesssystem fuer Siedewasserreaktoren, October 1979 (in German)

Fig. 1: Main influence factors on BWR stability [2]

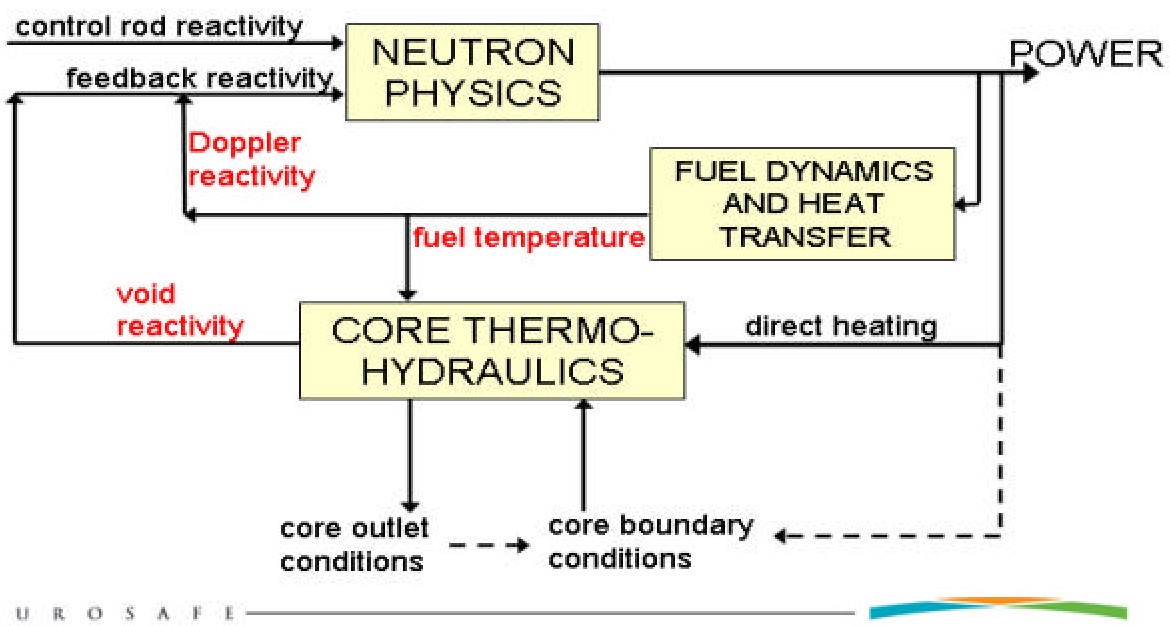

Fig. 2: Simplified power-flow-map

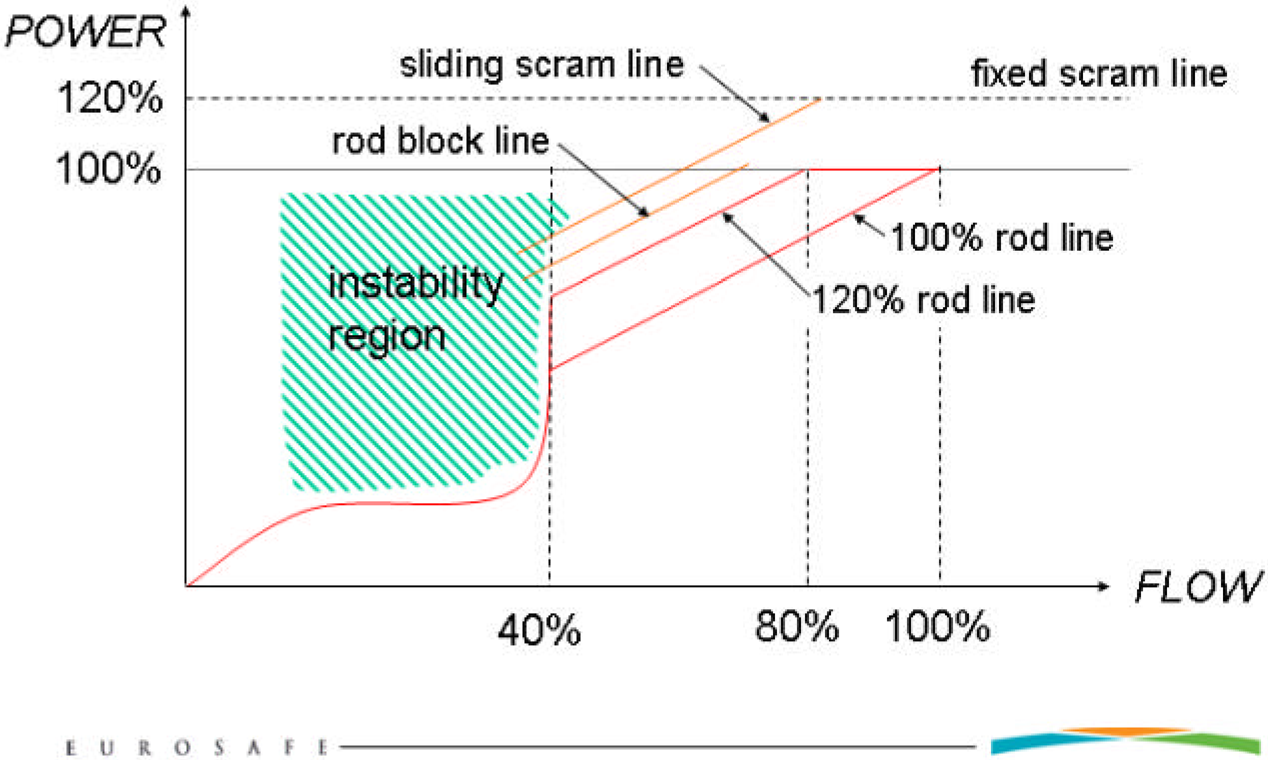

Fig 3: Simplified schematic diagram of an in-phase (global) oscillation

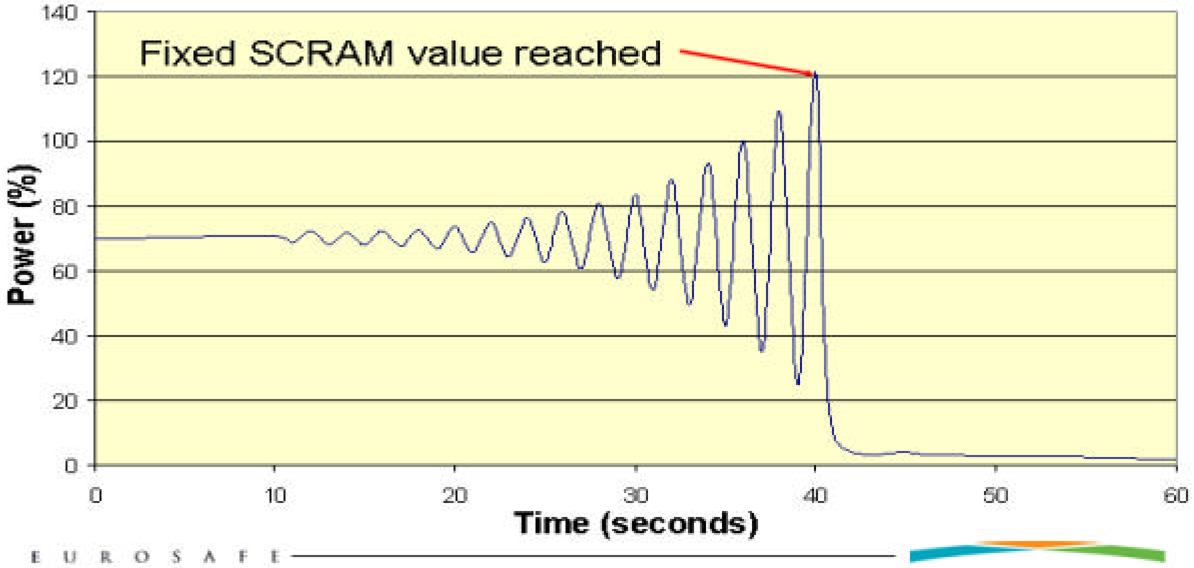

Fig. 4: Simplied schematic diagram for an out-of-phase (half core) oscillation (assumptions made: equal neutron flux core wide, saturation of local neutron flux detectors at 150%)