2 INSTABILITY IN BWR NPPs

2.1 GENERALITIES

2.1.1 Basic Phenomenology and historical perspective

Two-phase flows may exhibit unstable behaviour under particular conditions. Nature provides at least an interesting example of such behaviour in geysers which represent highly unstable flow of water and steam.

Towards the end of the 1930's, attention was drawn in the literature to a phenomenon that was observed in two-phase flows in certain components of industrial plants, notably boilers. This is nowadays called "Ledinegg" instability and refers to a mechanism which may induce recursive flow changes between an upper and a lower limit, of a periodic nature. The mechanism triggering this instability is commonly referred to as the static Ledinegg instability.

However, the particular thermalhydraulic instability phenomenon which is of prime concern with respect to BWR NPPs operation is of a different type; the interest for it rises from the fact that it can cause periodic oscillations in flows through boiling channels which may escalate to very large amplitudes, under adverse conditions. Since the 1950's, considerable theoretical efforts and experimental studies have been devoted to its exploration.

Initially, the phenomenon was considered rather complex. Then after a number of years and following in depth experimental and theoretical analyses, the problem seemed to be solved: with the adoption of uranium oxide pellet fuel having a long thermal time constant, the void reactivity feedback results attenuated, preventing it from becoming regenerative.

No oscillation incident took place for several years of BWR operation. Since then, a number of fuel modifications have been imposed and core power densities have also been increased.

The first indications of "new" stability problems came in the late 70's and during the 80's. Even in the early 90's many operating BWRs experienced oscillation occurrences.

From a physical point of view, the removal of thermal power by boiling water in a vertical channel, in a closed or in a loop configuration, may cause instability in the operation owing to density changes and the related thermalhydraulic mechanisms. Furthermore, in a BWR plant the cooling fluid is also a moderator; so, an oscillation in the core void content results in a variation of the neutron flux and of the generated power that, in turn, affects the void. Coupled neutronic-thermalhydraulic systems may show stable or unstable behaviour: in the former case the effect of any disturbance occurring during a steady state condition is damped in time, while in the latter case the disturbance is amplified and there is the possibility to reach self-sustained oscillating conditions, called “stable-limit-cycle”.

The instability is a well known drawback in boiling water reactor technology that complicates the very low pressure operation and is mitigated only at nominal design pressure. The stability of nominal operating conditions is assured, but this may not be the case in some off-normal situations including, pump trip, ATWS (Anticipated Transient Without Scram) or during start-up or shut-down.

Parameters affecting BWR stability have been identified through the use of more or less sophisticate predictive models and computational tools; proper countermeasures have been taken at a design level, essentially keeping low the pressure drops in the two-phase region inside the core and downstream them, and increasing them in the single-phase region of the loop.

2.1.2 Technical considerations

The signal analysis aiming at characterizing the stability of BWR cores shows the multiple nature and the complexity of the involved physical phenomena. A more precise idea of the present situation can be obtained from a few preliminary considerations connected with general capabilities and limits of the numerical tools currently adopted for stability analysis.

Thermalhydraulic systems codes able to predict plant behaviour within wide ranges of parameters variations have been developed and qualified; on the other hand, fully 3-D neutron kinetics models have been developed able to calculate neutron fluxes averaged into cells having volumes of the order of 0.001 m^3, when the fuel history and the thermalhydraulic boundary conditions are supplied.

In order to appreciate the current difficulties in predicting the occurrence and the evolution of instabilities in BWR plants, the following items should be considered:

a) periodic time variations of core related quantities, neutronic and thermalhydraulic parameters, are affected by the overall system behaviour including recirculation pumps, feedwater heaters, turbine, pressure drops, electronics of the control systems, etc., that cannot be modelled in detail, including individual feedback;
b) typically, a BWR core consists of several hundreds of individual coolant channels (up to 900), characterized by different burnup histories, inlet pressure drops, number of fuel rods (in some cases), different fuel types and power axial profiles: in principle, each channel can be the origin of core oscillations and can sustain such oscillations;
c) few parameters, like gap conductance, which affect the thermal response of the fuel rods might be known with a poor degree of accuracy.

Some limitations at item a) can be solved within the domain of current code capabilities with an accurate modelling effort, after revealing the relations among the relevant reactor systems (e.g. detailed modelling addressing item c). Qualified 3-D thermalhydraulic models of lower and upper plena and the possibility to nodalize each channel separately are necessary for item b) and are beyond the development level of present generation codes; however, important advancement have recently been demonstrated in this direction.

2.1.3 Safety relevance

Design parameters, like nominal pressure and pressure losses in single and two-phase regions, can be properly selected to reduce the impact of the problem on reactor operation. However, the large variety of situations expected during the life of the core, also depending on the range of fuel burnup, requires a prudent analysis and the evaluation of a set of design parameters preventing the occurrence of instability in most of possible BWR plant operating conditions.

So, there is the need to understand the effect of relevant parameters upon the involved physical phenomena, to detect these phenomena and to mitigate or suppress the possible instability occurrences, using the safety margins adopted in the design.

In terms of safety, the concerned variables in an instability occurrence with high oscillation amplitudes are the neutron flux and the rod surface temperature: the control of the first of the above quantities may prevent any undesired excursion of the second one. An additional problem arises since thermal cycling may also induce greater than normal fission product release from pellets.

Frequency, amplitude and Decay Ratio (DR) can be used to characterize oscillations. In case of an instability event in a BWR, the frequency of oscillations is of the order of 0.5 Hz, directly connected with the fluidodynamic of the system[1]. In the worst situation, the oscillation amplitude may grow with speed fixed by the DR. As a consequence of this and since heat flux is proportional to the 3rd to 4th power of the temperature difference between the wall and the coolant, cladding temperature changes are expected very small, unless dryout takes place.

Large-instantaneous reactivity insertions, including RIA (Reactivity Initiated Accidents) may be considered as a limit situation for instability or may be induced by the instability event itself. Even in this limit cases, the reactor power might achieve unacceptable values in time periods of the order of seconds, more than required for effective insertion of rods.

As a summary, safety concerns can be raised in each of the following situations, excluding rapid reactivity insertions (like RIA, void collapse, rod ejection and so on):

- lack of intervention of control rods: the case of ATWS originated oscillations may be included in such a scenario;
- undetected (local) oscillations that may bring local power beyond licensing limits also causing unacceptable rod surface temperature increases; the problem in this case is to detect the oscillations early enough.

Off-normal conditions can be originated from instability and the instability can be originated from off-normal conditions. In any case, the reliability of SCRAM and the efficiency of instrumentation, ensure the BWR plant safety in

[1] This frequency value is correlated with the steam bubble velocity in a hydraulic channel (the concentration wave propagation velocity) or with the mixture transit time.

case of instability; although some concern may exist in relation to regional and local instabilities. Specific Emergency Operating Procedures (EOP) and operator guidelines during planned events may have also a role in this connection.

2.2 PHENOMENOLOGY OF BWR PLANT INSTABILITY

Stability in BWR has been a topic of great interest in actual plants and fuel design. It has been an important area for BWR thermalhydraulic engineers, who have been developing the understanding of involved phenomena and the numerical tools necessary for the analysis.

Over a period of several years there have been approximately thirty instability events in commercial BWRs. In-reactor core tests have been performed to study stability behaviour; a few unplanned events occurred during normal operation, essentially start-up processes or recirculation pump trip transients.

The event of LaSalle-2 plant in March 1988, that caused high neutron flux SCRAM, attracted again the attention toward this topic. Since the US NRC issued notices and asked the BWR utilities to take a long term action to solve the stability problem, international interest on this topic has grown significantly.

One of the NRC major concerns was the so-called out-of-phase oscillation: one of the first events that occurred was in the 1984 at the Caorso plant. Since that time, it has been observed on a number of occasions[2].

2.2.1 Qualitative evaluation

Several instabilities events occurred in BWR plants have been analyzed, some of them were inadvertent events and others were induced intentionally as experiments. Instabilities were identified as periodic oscillations of the neutron flux via instrumentation readings.

The flux peak reached the SCRAM set-point, which is the 118% of the rated level, in the most extreme case related to the LaSalle-2 BWR NPP. In this case neutron flux behaved in-phase at all azimuthal and radial locations of the core.

[2] For more detailed information on tests and events see [2]

In some instability, neutron flux oscillations were out-of-phase at different locations in the core; a diagonal symmetry line could be identified in the majorities of cases. In one case [6] a rotating travelling wave was identified.

Some core flow measurements indicated cyclic oscillations of coolant flow at the unstable condition which was synchronized with neutron flux oscillation. In some reactors, channel flow instrumentation signals showed correlations between the channel flows and local neutron flux levels around the channel.

Some of the instability events arose under natural circulation conditions, which are encountered with all recirculation pumps at zero speed; others developed under the condition of rather small core mass flowrate owing to reduced recirculation pump speed. Though there are some unique features in each instability event, there are many characteristics common to all instability events. Since many parameters are interrelated in the BWR plants, the effect of each parameter must be identified separately. Some general characteristic of BWR plant instabilities are as follows.

- All instability events arose under low flow conditions, in most cases at less 40% of the rated core flow. Thus coolant flow is a key factor of instability.
- When instabilities have been observed, core power was less than the rated power because of the partial core flow condition. In most cases, when core power was reduced by control rod insertion, the core became stable. In some other cases, an average power increase induced an unstable condition or made wider the oscillation amplitudes. Thus it is clear that the higher the core power is (within an identifiable parameters range), the more susceptible the core becomes to instability.
- Most instabilities reached the limit-cycle condition for the neutron flux. Limit-cycle amplitude depends on the “how much” unstable the core condition is.
- Axial power shape affects the instability. A bottom peaked power shape appears more likely to induce instability. However, like in other cases, the effort axial power shape on oscillations must be considered in the context of the composite core state.

- Although the average core power is the same, higher radial power peaking makes a core more unstable. In addition, rather high power core channels in the peripheral region, were found in out-of-phase oscillation cases.
- Pressure drop distribution inside the vessel with main regard to losses at geometric discontinuities (e.g., core inlet and outlet, separators, etc.) has a noticeable effect on stability: the increase in pressure drop at core inlet is stabilizing; the opposite occurs for drops in the core outlet region including separators, if the other conditions are kept constant. Separators, owing to their distance from the core may introduce other frequencies in the oscillations.
- In some cases, when inlet subcooling increased, the core became less stable because core power becomes higher and axial power shape becomes more bottom peaked if inlet subcooling increases. There is direct thermalhydraulic effect by inlet subcooling but the tendency can vary depending on operating conditions. As mentioned before, higher power conditions and bottom peaked axial power distributions, make the core less stable. Therefore, the independent effect of coolant subcooling might not be clear from the real plant experience and must not be confused with the power effect or other factors.
- Frequencies in all the observed plant oscillations varied from 0.2 to 0.6 Hz. These happen to be in the frequency range that is typical of density wave oscillation. Other instability phenomena may have the same or different resonance frequency ranges.
- BWR fuel rods have thermal time constants ranging from three to eight seconds, making the fuel mechanical duty induced by local temperature variations during a transient milder, even for large amplitude oscillation.
- When a specific analysis has been carried out, correlations between LPRM signals have been found; in some cases the concerned LPRM were in opposite zones of the core. This observation might bring to exclude the possibility of undetectable single channel oscillation; i.e., proper analysis of an LPRM signal related to an assigned radial position in the core, may reveal instability in the different radial position in the core, thus making easier the neutron flux oscillation detection. However, stability conditions may be strongly different among the various channels of a core.

- Complex relationships may exist between stability boundaries and system related parameters like fuel burnup.

Most of the characteristic described above may be interpreted and understood if those instabilities were considered to be thermalhydraulic density wave oscillations coupled with neutron kinetics feedbacks (as in the section 2.2.2). The main driving force for density wave oscillations in a boiling channel comes from the phase lag between the response of the two-phase pressure loss and single phase pressure loss. In a boiling channel, when the ratio of two-phase pressure loss to single phase pressure loss becomes larger, the feedback gain becomes larger, and the channel becomes less stable. Low flow, high power, high radial power peaking and bottom peaked axial power shape, all increase the two-phase pressure losses and make thermalhydraulic conditions less stable, consistent with plant experience.

As already mentioned, some control systems may have the potential to influence stability or, in extreme situations, to trigger the instability; in the latter case, the system can be modified to be less susceptible to instability by adjusting control parameters that are not part of the system hardware and are independent upon core design and not of fundamental concern.

In general terms, though density wave mechanism can be used to characterize the instability phenomena in BWR plants, several plant related parameters connected with hardware, boundary conditions, operational characteristic, BoP[3] (Balance of Plant) configuration, etc. and different fundamental thermalhydraulic and neutronic phenomena, may have an influence upon instability occurrence and evolution.

2.2.2 Classification of instabilities

There are several types of thermalhydraulic instabilities which may occur also simultaneously in a boiling water reactor; each of these types can be classified to the appropriate physical mechanism or mode of oscillations.

[3] The Balance of Plant in this work refers to components and systems, inside and outside the nuclear island, necessary to transform the thermal energy into electrical energy with optimized overall efficiency and, by hardware and software, to control the entire plant performance.

Lahey and Moody [7] classify thermalhydraulic instabilities into the two broad categories, of static and dynamic. The static instabilities can be explained in terms of steady state laws, while explanation of the dynamic instabilities requires the use of the time dependent conservation equations, and if the case, the servo system analysis based on control theory concepts. In the case of the use of the static laws, only the onset of instability can be characterized, not the system behaviour. Examples of static instabilities are 'flow excursion or Ledinegg' and 'flow regime relaxation'. Examples of dynamic instabilities are 'density wave', 'pressure drop oscillations', 'flow regime induced instability' and 'acoustic instabilities'.

In actual BWR operation, thermalhydraulic instability may be coupled with neutronic feedback. Since the origin of the oscillation may be either the neutronics or the thermalhydraulics, two main classes of feedback can be identified:

1) neutron feedback;
2) thermalhydraulic feedback.

Although no mechanism exists preventing the combination of the various identifiable instability modes, the thermalhydraulic density wave instability coupled with the neutronics feedback, is commonly referred to as the dominant mechanism triggering and sustaining instability in commercial BWRs. Two arguments support this conclusion:

a) inherently, the density wave instability mechanism couples the destabilizing effects of the thermalhydraulic feedback and the neutron feedback;
b) density wave related theoretical models and considerations allow a satisfactory explanation of the largest majority of the phenomena detected at the onset and following reactor instabilities.

The last argument might not be fully valid when complex system codes are applied for the simulation of the unstable reactor situations. In such case different mechanism modelled in the code may have a role in the prediction of instability scenarios.

2.2.2.1 Classification of density wave instability

In a generic thermalhydraulic system, density wave is a dynamic instability also referred to as channel (or parallel channel) instability. The physical feedback mechanism is based on thermalhydraulic characteristics. Two main modes of oscillation are single channel and parallel channel. For the parallel channel mode, when two channels are involved, the flow in one channel increases, while the flow in the other channel decreases: this mode is the out-of-phase instability. During out-of-phase oscillations, the channel void fractions follows trends opposite to the response of the flow, so that the pressure drops tends to remain the same across both channels.

The two modes of oscillation that are commonly recognized for density wave instabilities in a BWR plant are core wide oscillation and regional mode; these also referred as in-phase or out-of-phase mode respectively. In the core wide oscillation the power and inlet flow of the largest majority of core channels oscillate in phase since they behave as a single channel. In the regional oscillation, the power of a region of the core oscillates out-of-phase with respect to the power of other regions; the inlet flows to the different regions are also out-of-phase with respect to each other. If only two halves of the core are involved, these behave as two parallel channels.

A summary of the classification of the types of density wave instabilities based on their physical mechanism and modes of oscillations has shown in table 2-1:

Table 2-1: Summary classification of density wave instabilities

PHYSICAL MECHANISM	OSCILLATION MODE
Pure Thermalhydraulic	Single Channel Instability
	Parallel Channels Instability
Coupled Neutronic and Thermalhydraulic	Single Channel Oscillation
	Core Wide Oscillations (in-phase)
	Regional Oscillations (out-of-phase)

2.2.2.2 Physical mechanism of density wave oscillation with neutronic feedback

Complementary information in some cases related to different values of the parameter ranges, may come from the analysis of the fundamental density wave mechanism. In this paragraph the evidence resulting from BWR plants measurements is considered.

Coupled neutronic thermalhydraulic instabilities, such as core wide and regional oscillations, are considered to have their root in the density wave mechanism and in the significant delay in the neutronic feedback that it causes. The density wave mechanism and the neutronic feedback which relates to the mode of oscillation are discussed below.

In the assumption of imposed pressure drop across the boiling channel[4], the density wave causes a delay of a change in the local pressure drop along a fuel channel that may be caused by a change in inlet flow. Because this delay, the sum of all local pressure drops may result in a change of the total pressure drop which has delay from the change in the inlet flow. The coolant in commercial BWRs flows upward through the core, and variations in density in the bottom part of the channel travel upward with the flow. For example, if the inlet flow is decreased while the channel power is kept constant, there is an increase in the voiding in the channel that will travel upward as a packet, forming a propagating density wave. This packet of voids produces a change in the local pressure drop at each axial location, which is delayed axially by the density wave propagation time. In two-phase flow regimes, the local pressure drop is very sensitive to the local void fraction and is very large at the outlet of the channel, where the void fraction is greatest: thus, the change in the pressure drop over a significant length is delayed with respect to the original perturbation. Such delay is the basis for the instability.

[4] Three main types of boundary conditions can be distinguished: constant pressure drop, variable pressure drop, and constant channel inlet flow. The last one is the most stable , the first one is the most unstable especially if single channel oscillations are considered. The second one is typical of core wide oscillations, mostly with recirculation pump tripped or a low speed.

If the inlet flow is perturbed sinusoidally, the local pressure drop changes are also sinusoidal (within the linear range of the flow to pressure drop relationship), but they are delayed in the two-phase region with respect to the perturbation. The total two-phase pressure drop across the channel can be envisaged as the sum of a series of delayed sinusoids (the local pressure drops) and, thus, also has a sinusoidal time relation that is delayed with respect to the flow perturbation. When the total pressure drop is imposed to be constant as the boundary condition, the change of the two-phase pressure drop has an effect of the feedback perturbation to the single phase region. If the two-phase pressure drop perturbation delays 180º to the inlet flow change and the magnitude becomes larger, the channel flow becomes less stable. The critical point at which the channel flow instability starts is when the change of the two-phase pressure drops equals the change of the single phase pressure drop with the opposite sign at a particularly frequency. In this case, the channel has an effective flow resistance of zero at that frequency, so that any perturbation sustains itself.

For pure thermalhydraulic density wave instability, only flow is involved, and the power generation term in the fuel is assumed constant. In BWRs, the power generation is affected by the reactivity feedback and therefore, depends upon the core void fraction. Thus, when a void fraction oscillation is established in a BWR, the power oscillates according to the neutronic feedback.

The neutronic feedback involves:

1) the neutron dynamics, which affects and is affected by the power generation in the fuel;
2) the fuel dynamics, which affects and is affected by the heat flux from the fuel to the coolant;
3) the channel thermalhydraulics, which characterized the void fraction response to changes in heat flux and includes the thermalhydraulic feedback from the remaining parts of the system through massflow rates, fluid temperatures, pressure and void fractions;
4) the reactivity feedback dynamics, which relate the void fraction distribution to a reactivity value that affects and is affected by the neutron dynamics.

A flow diagram showing the above depicted feedback system is shown in the figure 2.1.

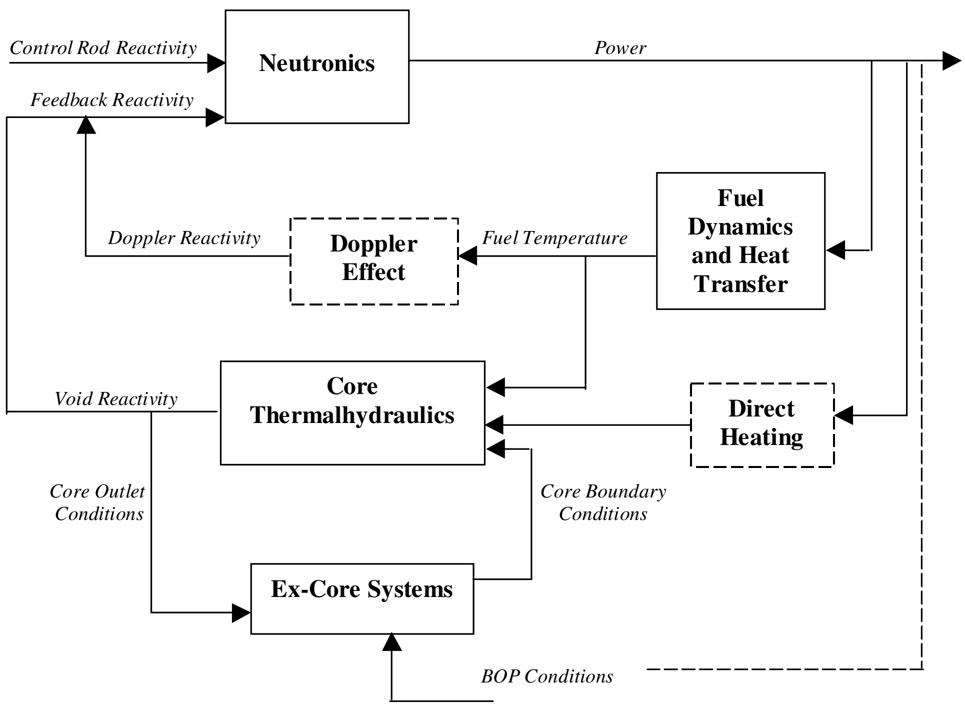

Figure 2.1: Example of possible idealization of thermalhydraulics and neutronics feedback following density waves in BWR plants

2.2.2.3 Relevance of basic phenomena to BWR technology

Since the BWR channels are vertical, buoyancy effect are bound to exercise some influence on the flow stability.

The need for a flow stabilizing orifice at the inlet of each core coolant channel increases the pressure drop over the core, and thereby also the power required for the forced recirculation of the coolant. This provides an incentive to avoid excessive inlet orificing, introducing a certain conflict between overall economy and flow stability.

All the core coolant channels in a BWR (including their inlet orifices) operate in parallel between a common lower plenum and a common upper plenum, therefore, the pressure head is the same for all of them. The channels also have the same inlet subcooling, provided that all the recirculation pumps are working.

Yet, the operating conditions differ between the channels, as regards both channel power and axial power distribution and thereby also flow resistance. Hence, the coolant flows differ between the channels. It follows that even the coolant transport times will differ somewhat between the channel and thereby also the natural frequencies for any purely thermalhydraulic fluctuation which may be present in these flows, owing to the "density wave phenomenon". For the same reasons, the stability margins will also differ between the individual channel flows. Accordingly, such flow fluctuations will be of an incoherent nature. This topic is usually referred to as "parallel channel stability".

2.2.2.4 Parameters affecting density wave oscillations with neutronic feedback

In order to observe which parameter governs the onset and the time progression of the instability, must be considered two general possibilities that can be used for changing the stability margin in a BWR. These are:

a) destabilizing the density wave mechanism: i.e., the characteristics of thermalhydraulic density waves, mostly frequency, may be varied in such a way to bring to increase or to decrease oscillation amplitudes in different quantities (obviously, increasing amplitudes versus time, means destabilizing);
b) increasing the neutron feedback gain: e.g. inserting control rods leads to change in power profile that also affects the neutronics feedback.

Most parameters affect reactor stability in the direction either stabilizing or in destabilizing at BWR operating conditions. The sensitivity of both in-phase and out-of-phase modes to all parameters are similar, because the basic mechanism involved are similar.

2.3 MODELING FEATURES AND ASSESSMENT

The main objectives of BWR stability analyses can be summarized as follows:

- to assess the stability margin in reactor plant, including normal and off-normal conditions;
- to predict the transient behaviour of the reactor when an unstable condition occur;
- to help in design and to assess the effectiveness of countermeasures adopted to prevent and mitigate the consequences of instabilities.

Such objectives can be attained only through a realistic simulation of relevant physical phenomena and instability mechanism.

A wide variety of codes and models exist that may be used to address the instability issues, ranging from sophisticate system codes, able to calculate an overall plant behaviour, to very simple models. All of them have the capability to deliver similar results to quantify stability (e.g. decay ratio), although their reliability may be different.

In fact, the objectives in the development and the level of approximation and of qualification, including the reliability of results, are different in various cases. Multipurpose codes solving multidimensional equations both for neutronics and thermalhydraulic are available; on the other hand, simplified codes based on 1D Homogeneous Equilibrium Model (HEM) are still used in the same frame. Furthermore, in some cases qualification for BWR stability applications may include tens of applications to basic experiments, separate effect loop tests and BWR plant occurrences; in other cases, it may be simply planned from predictions presently available.

As a general remark, computer codes adopted for BWR stability analyses should be suitable to predict real plant evolution. Available models cover the whole range of phenomena observed in power reactors and experimental loops. This means that they are able to provide physical understanding of the evolution of meaningful quantities describing the transient behaviour of unstable boiling systems. It can be observed that the range of phenomena shown by models includes, but is even wider and denser, that one observed in experiments and reactor occurrences.

In summary, the available models are adequate to give a qualitatively correct simulation of observed phenomena. Limitations and shortcomings are due to limits in practical applications, dictated by computational convenience or resulting from historical reasons.

2.3.1 Basic models

2.3.1.1 General description of available modeling techniques

Modeling BWR stability requires simulating both thermalhydraulics and neutronics together with their mutual interactions. This involves the definition and the solution of partial differential equations describing basic phenomena and to link them by the required feedback effects.

Four main interacting blocks can be noted:

- *core thermalhydraulics*, which affects power production by fission and is often the trigger for instability mechanism;
- *neutron kinetics*, which is directly responsible for the attained power level, as a consequence of the external and the feedback reactivity perturbations;
- *fuel dynamics and heat transfer*, which act as a filter of power perturbations and introduces times delays between power production and coolant flow heating;
- *ex-core system* (including BoP), which impose external boundary conditions to the core channels, thus influencing its stability.

Available codes for BWR stability analyses make use of specific models for simulating each one of the mentioned blocks, but the adopted simulation techniques and the level of detail in the description depend on the purpose of the analysis. In particular:

- when stability to small perturbations is investigated, *linear* models are adopted for representing the systems and their mutual interactions in the *frequency-domain* (linear stability analysis);
- when the interest is focused on the behaviour of the reactor after the occurrence of instabilities, *non-linear* representation of the various blocks is adopted to obtain a system response in the *time-domain*.5

2.3.1.2 Models for linear stability analysis

The dynamic behaviour of boiling water reactors and boiling systems in general, can be assumed to be linear for small deviations around steady operating conditions. This makes it possible to study stability of BWRs using locally linearized equations.

An assigned operating condition can be considered *linearly stable* if the system reacts to external perturbations of small amplitude showing the tendency to converge toward the initial state. Eventually, damped oscillations of relevant parameters are observed in the time-domain; the degree of damping can be taken as a measure of the margin to stability, since less and less stable systems are attained when oscillations tend to indefinitely maintain their initial amplitude. Beyond this limit, the system tends to amplify external perturbations, diverging from the initial state.

As a consequence, *linear analysis* can quantify the stability margin of operating conditions under small perturbations, also providing estimates of the critical value of parameters at which neutral stability can be observed. On the other hand, since the nonlinear effects which come into play at finite oscillation amplitudes are not considered, these methods are not suitable for predicting the system behaviour beyond the stability threshold.

Figure 2.2 schematically summarizes the various steps to be completed in the linear stability analysis of BWRs.

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[5] The codes are usually subdivided, following a generally adopted classification, in two classes:

- *frequency-domain codes*, whose purpose is the linear stability analysis of BWRs or other boiling systems; they are based on linearization and Laplace transform of the governing equation

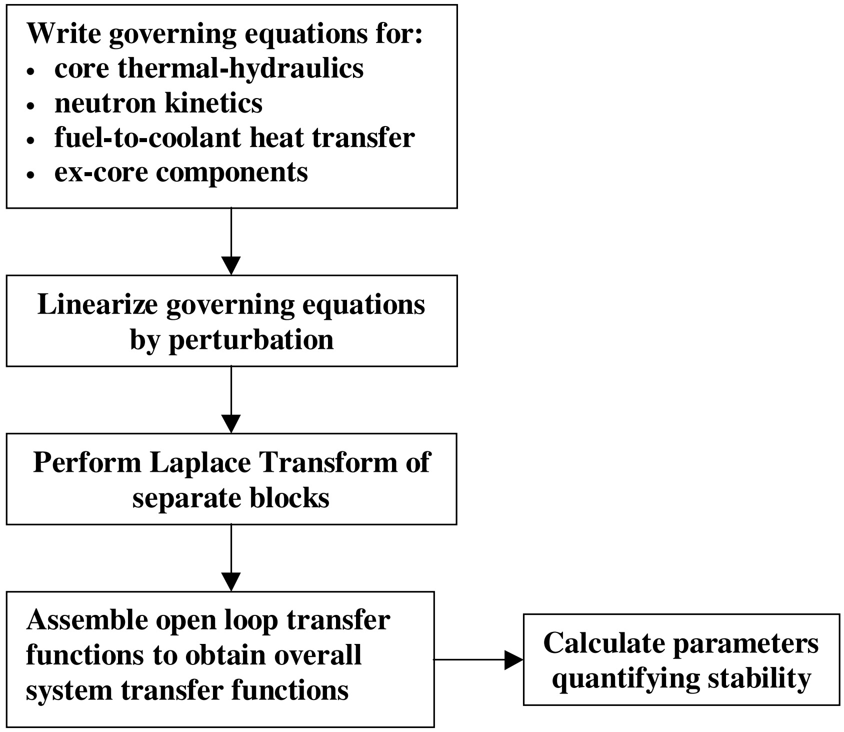

Figure 2.2: Procedure followed in linear stability analysis of BWRs

2.3.1.3 Models for describing non-linear behaviour

Figure 2.3 reports a general classification of non-linear models for the description of the dynamic behaviour of BWRs and other boiling systems as resulting from the available literature[2]. Two main classes are identified:

a. *Simplified Phenomenological Models*, mainly addressing only a few of the basic phenomena involved in BWR stability or even considering most of them but using some simplification at the mathematical or physical level;

b. *System Codes*, aiming at the detailed simulation of the BWR plant, in some cases using up-to-date descriptions for each relevant phenomenon.

The objective of phenomenological models is generally to provide understanding of the basic physical mechanisms involved in BWR behaviour beyond neutral stability, making use of concepts drawn from the theory of non-linear systems. The simplifications introduced in their development allow a more

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• *time-domain codes*, which include analysis tools specifically developed to simulate the transient behaviour of plant systems; these codes have the capability to deal with non-linear efficient discussion of the basic physical features of the system, neglecting complicated and relatively irrelevant aspects which could mask the overall system response during instabilities.

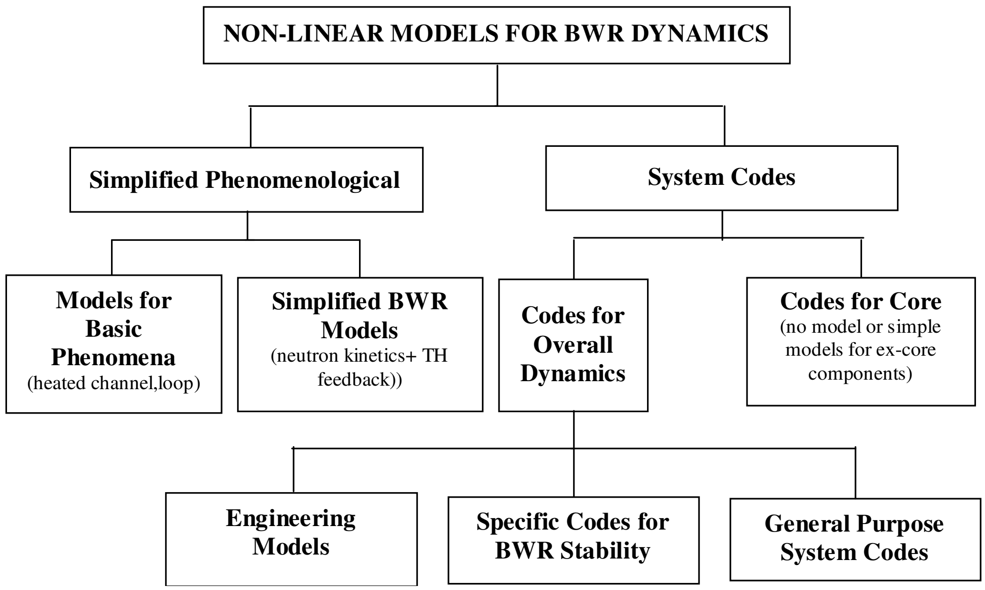

Figure 2.3: Classification of non-linear models adopted in the stability analysis of BWRs

2.4 PLANT MONITORING, PREVENTION AND MITIGATION OF INSTABILITIES

The plant systems allow characterizing the core status during stable and possibly also unstable operating conditions. The output of such system, i.e. monitoring system, is indispensable to depict the transient scenario, should an instability event occur, but also to prevent the occurrences of the same instability events. Before introducing further details, the definition of a monitoring system and of a (core) monitor considered here should be specified:

the monitoring system includes any subsystem, component and related software used to characterize or to control a generic core condition. The (core or stability) monitor makes use of parts of the monitoring system and consists

features of BWRs and are based on simulation techniques.

of a specific hardware and software components, finalized to the monitoring of the core stability.

2.4.1 Instrumentation capabilities

The reactor core of BWR plants is typically monitored in the power range by a number of in-core detectors, from which average power signals are derived for the reactors protection system, and by measurements related to the mass flowrate. More detailed information about capabilities and developments in neutron flux instrumentation can be gathered by the OECD/CSNI Specialist Meetings [8].

2.4.2 Neutron flux measurements

The neutron flux and power density distribution in the reactor core is monitored by a specified number of in-core detectors. These Local Power Range Monitors (LPRM) are arranged in radially distributed instrumentation guide tubes, which contain the detectors at four axial levels.

Typical numbers of installed guide tubes are about 20 in small cores and between 30 and 44 in large cores. Thus the total number of available LPRM's in large cores is in the range of 120 to 176. The four axial layers of detectors are usually named with labels from A to D from bottom to top. The detector signals are regularly calibrated, usually once per month, by a diverse measuring system consisting of movable ion chambers, the TIP-system (Traversing In-core Probe). The calibration procedure is based on measured detector values and a thermal heat balance of the reactor core.

In the operating range of neutron fluxes including core power from a few percent to full power, neutron detectors are constituted by a miniaturized gamma compensated fission chambers (CIC, Compensated Ionization Chamber). Among other things, the CIC are characterized by response times much smaller than the envisaged periods of oscillation of interest for instabilities.

By summarizing, local detector readings in several groups, e.g. 3 or 4 or even 8 signals for the average value of reactor power are generated (APRM's[6]) which are input for the reactor protection system. The design and the safety requirements determine the total number of in-core detectors and the specific manner of grouping to average values. The convention for APRM assignment varies from plant to plant.

The LPRM's give the most direct indication of neutron flux oscillations if instabilities occur. This has been confirmed by stability experiments approaching the stability boundary. The "summed up" APRM signals are prone to suffer from cancellation in case of regional oscillations, due to the spatial distribution of local detectors. The indicated component of the APRM signal is determined by the non-symmetric location of LPRM's and the non-linear behaviour of neutron flux during oscillations. Some plants, e.g. GE-BWR/2 type, have a quadrant-based APRM system, which is not affected by these cancelling effects for regional oscillations.

2.4.2.1 Measurement of other physical parameters

In view of stability considerations all measured parameters related to the mass flowrate through the reactor core are relevant. An evaluation of the total core mass flowrate may be obtained by measuring the pressure drop across the lower core plate. Additional information is available from the pump speed, especially with respect to the operational conditions, In external loops plants, the flowrate is measured in the external piping. In jet pump reactors the flowrate is measured over the jet pump diffuser. Some BWR plants of ABB-design have a peculiarity that the mass flowrate is directly measured at the inlet orifice of a few individual fuel assemblies.

Measurements of absolute pressure in the steam occupied region of the BWR plant and of feedwater conditions (mostly, mass flowrate and temperature), might have direct interest for a complete characterization of the reactor stability. Core inlet subcooling is directly affected by the values of the mentioned parameters.

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[6] Average Power Range Monitors

2.4.3 Use of the capability of the monitoring system

There are many factors which may affect the BWR core stability. Those parameters may affect the stability differently, depending on the reactor operational conditions and its operating history. As a consequence, the stability boundary may drift over a long period of the reactor operation or under certain operational conditions. Accurate theoretical predictions of the stability boundary necessarily require extensive calculations using complex computer codes involving detailed models of neutron kinetics and thermalhydraulics (so, in the current practice, stability boundaries are defined according to the operational experience). However, it should also be noted that reactors may not always be operated in the way which has been assumed in the stability prediction calculations.

In general, there are three approaches considered for the prevention and the mitigation of instabilities. There are advantages and disadvantages in each of the three approaches. At the same time, however, there are some points which must be addressed as a concern whether or not it can cover the whole stability problem area. Table 2-2 summarizes the features, functions and problems for each approach. Licensing requirements are important in this connection, e.g. GDC 12 of 10 CFR 50 Appendix A.

Table 2-2: Summary of main features of different approaches as a measure for prevention and suppression and mitigation of instabilities

<table>
<tr><th>APPROACH</th><th>TRIGGERING</th><th>ACTION</th><th>AUTO / MANUAL</th><th>ADVANTAGE DISADVANTAGE</th><th>CONCERNS</th></tr>
<tr><td rowspan="3">Prevention</td><td rowspan="3">entering the exclusion region</td><td rowspan="3">scram or SRI control rod block</td><td rowspan="3">automatic</td><td>less burden on operator</td><td>exclusion region determined by code prediction</td></tr>
<tr><td rowspan="2">system modification</td><td>risk for setting too much conservative or no conservative exclusion region</td></tr>
<tr><td>state of stability not known</td></tr>
<tr><td rowspan="2">Detection & suppression</td><td rowspan="2">detection of oscillation</td><td rowspan="2">scram or SRI</td><td rowspan="2">automatic</td><td>less burden on operator</td><td>risk for false alarm</td></tr>
<tr><td>system modification</td><td>stability not checked</td></tr>
<tr><td rowspan="2">Stability monitor</td><td rowspan="2">detection of reduced stability margin</td><td rowspan="2">scram, SRI or manoeuvring the reactor control system</td><td rowspan="2">manual</td><td>possible to know the stability state</td><td rowspan="2">May not be able to cope with rapid variations of core conditions, e.g. entrance to unstable region after ATWS</td></tr>
<tr><td>no system modification</td></tr>
</table>

Prevention and detection and suppression approaches principally assume that automatic measures are taken against the instability, thus placing no burden on the reactor operator. The major concern in the prevention approach is that there is no checking of the actual stability condition during the reactor operation, since the exclusion region (see section 2.4.4.2) is based on the code prediction.

Eventually, the stability may be checked independently also considering that the stability boundary may vary depending on various factors. Past instability experience also indicates that the reactor may not always run under conditions assumed by stability calculations. Inadvertently introduced undesirable factors affecting the stability cannot be excluded. An example of such a case is inadequate mechanical constraints of a fuel channel box to a lower tie plate, leading to water leakage and thus abnormal two-phase flow condition in the channel.

Consequently, the exclusion region could be set too conservatively or too generously. A too conservative exclusion region would reduce the flexibility of the reactor operation, possibly affecting the economy, while too generous exclusion region could bring about the risk for a reactor scram. As explained later, the exclusion region could be checked more systematically and frequently with stability monitor.

In the detection and suppression, on the other hand, the instability is detected using a simple algorithm based on checking the amplitude and frequency of the neutron flux oscillation. The frequency information can be used to distinguish the power oscillation due to the core instability from others. This approach is not dependent on the shift of stability boundary during the reactor operation. One problem is that the detection is practically possible only when the reactor has entered the unstable region, thus requiring rather quick actions to prevent the reactor from further excursion into more serious situations. Accordingly, very high reliability is required in the method for detecting the instability. The detection level must be set up very carefully so as to assure the instability detection while minimizing the risk for false detection. It must also be pointed out that this frequency alone to distinguish oscillations may be inadequate in some cases, for example, pressure oscillations at BoP level may occur near the core resonance frequency.

Either approach requires system modifications which may be very costly.

An early warning and avoidance approach is accomplished using the stability monitor. The stability monitor alone, however, cannot be connected to a safety system due to the fact that it requires complex signal processing calculations. The response time also restricts using a stability monitor as a safety system. The stability is determined by noise analysis which requires an accumulation of information over a certain time period to get a sufficient statistical accuracy in the result. In spite of these restrictions, however, monitors are still expected to play an important role for plant monitoring and prevention and mitigation of instabilities.

2.4.4 Control systems

The core operational conditions in BWR plants are represented in a Power/Flow map (figure 2.4), in which, allowed parameter conditions are kept by the power limitation and the reactor control and protection systems.

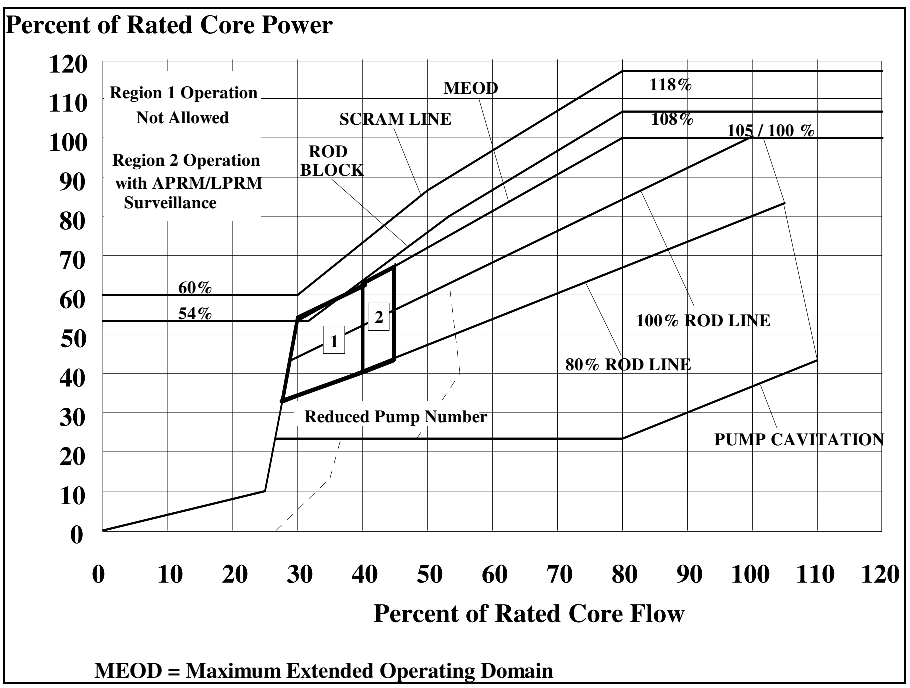

Figure 2.4: Typical BWR operating Power/Flow map (the thick lines identify the region not allowed for normal operation).

The BWR plant control and protection system including the power limitation system is a portion of the BoP. they are constitute essentially by control systems and logics for turbine speed, for reactor pressure and downcomer level, for feedwater conditions (also interacting with downcomer level), for recirculation loop and/or recirculation pump speed and for control rod insertion.

2.4.4.1 Power/Flow map

The operating conditions of a BWR core are commonly represented in the Power/Flow map (figure 2.4). This map relates the core thermal power to the core mass flowrate. The minimum mass flowrate is determined either by natural circulation conditions or by the minimum speed of internal or external recirculation pumps. Under specified assumptions or changes of control rod configuration or mass flowrate, the related changes of operational parameters define specific lines in this Power/Flow map. For instance, the 100% rod line or load line corresponds to a control rod configuration such that the nominal thermal power will be generated at nominal pump speed.

Starting at these nominal conditions, the power will follow the 100% rod line by reducing the mass flowrate; in this connection, one would have to account for dependence of the feedwater temperature (also affected by the power level) on the core inlet subcooling. A control rod insertion will reduce the power and lead to a rod line below nominal value. On the contrary, a control rod withdrawal will increase the power and lead to a rod line above nominal value.

The operational domain is described by an area in the Power/Flow map which determines a maximum allowed power value for each value of mass flowrate. In many BWR plants in US and Nordic countries, the operating domain was extended above the 100% load line, such that 100% power can be reached with about the 80% of rated core flow. The operational domain is defined by the MEOD-boundary (MEOD=Maximum Extended Operating Domain).

The nominal procedures of BWR power control in the operating region are based on the change of mass flowrate by pump speed control, keeping control rod configuration constant. Optimized core operation strategies for fast power changes and load-follow aspects, take into account also adjustments of control rod movements within power control.

2.4.4.2 Power limitation and protection system

The operational domain of the Power/ Flow map is based on the safety analysis. In accident analysis, it must be ensured that the operational conditions include sufficient safety margins for transients with respect to safety limits of fuel design.

Usually the safety limits is established for the MCPR (Minimum Critical Power Ratio), to exclude fuel rod failures. An increase of power above the allowed operational limit values is not only terminated by the reactor scram of the protection system, but in advance, by additional action of the power limitation system.

Typically, the following lines activating functions are available:

- a sliding line blocking rod withdrawal within the control system;
- a sliding line initiating automatic control rod insertion within the control system;
- a sliding line of power limitation set point;
- a sliding line of neutron flux scram set point;
- a fixed high neutron flux scram set point (at about 120%).

The first measures taken are intended to avoid a further power increase by withdrawing control rods. If the neutron flux scram set point is reached, the reactor scram is activated to shutdown the reactor.

2.4.5 Means to measure and quantify the stability of reactors

The main parameter currently adopted to characterize the oscillations is the Decay Ratio (DR), which can be defined as the ratio of consecutive amplitudes of the oscillation [2] (for more information see section 4.6). The Decay Ratio alone, and more specifically a unique value of the DR, might not be sufficient to characterize the stability status. However, a stable system has a DR lower than 1.0 whereas a constant oscillation with constant amplitudes is characterized by a Decay Ratio equal to 1.0.

In the following section the effect of instability in a BWR neutron flux and other process parameters is discussed and the basis of stability monitors is reviewed.

2.4.5.1 Effect of instability on process parameters

The stability boundary of a BWR core can be approached in stability tests. These give information on the starting phase of neutron flux oscillations, on the specific form of core wide or regional oscillation and on the limit-cycle oscillation with small amplitudes. The available measurements provide detailed information on indication from LPRM's and APRM's of the neutron flux oscillations.

When the core oscillates in the core wide or fundamental mode, all LPRM signals in a plane orthogonal to the reactor axis are in phase. By averaging these signals, a shape similar to this of the LPRM is obtained in the APRM signal. When the instability is incipient, the neutron flux is purely sinusoidal in time. As the limit-cycle is developing, the neutron flux can rise up to high values in the peaks but in the valleys it is limited. Thus the initial sinusoidal signals become distorted due to this non-linear behaviour.

When the core oscillates in the regional or out-of-phase mode, the LPRM signals from opposite locations in a radial plane show a 180° phase difference. If the APRM detectors were fully symmetrically distributed in the core and the oscillations were pure sinusoidal, then the APRM signals should completely cancel and should not indicate any oscillation. However, the non-linear behaviour of neutron oscillations introduces higher harmonics of the fundamental frequency, which is typically around the 0.5 Hz. This frequency of the oscillation will not be completely suppressed in the APRM signal and will be present together with frequencies of higher harmonics.

2.4.5.2 Stability monitors

The primary purpose of the stability monitor is to provide the reactor operator with an early warning of the reduced stability margin. The practical importance during operation is related to load follow strategy, where a great interest exists to achieve a sufficiently high power in low flow conditions with minimum pump speed. In fact, only in this case it is possible to quickly reach again nominal power by increasing pump speed. However, the studies demonstrated that the monitor is useful also for validating the exclusion region as well as getting a better understanding of the stability characteristics. The further operational experience should contribute more data on the accuracy of these stability monitors before their integration into protection system. A specific aspect still under discussion is the accuracy obtained under transient conditions in the reactor core.

The theoretical basis of BWR stability monitors is the signal analysis technique of LPRM and APRM signal [11] and the methods of monitoring BWR stability are based on the analyses of these and of other signals like mass flowrate or pressure drop measurements.

The stability monitor is composed of hardware for signal preconditioning, data sampling unit, signal processing software and mass storage device such as hard disks, information display system to present the stability state, output unit which can be connected to an alarm generating device and so forth. These essential components and their basic function are briefly described hereafter.

<u>Measurement signals and hardware signal preconditioning</u>.

With the different types of instability in mind, it is important to monitor all the LPRM strings together with the APRM signals. This provides the possibility of detecting local channel instability as well as regional out-of-phase instability.

The monitor may include information on core flow, so that one can identify the reactor operational state.

Neutron flux noise signals contain a wide spectrum of dynamics information related to the core. Namely, they carry information on the core stability, plant control system, pressure and other process variable disturbances, some types of in-core anomalies such as in-core guide tube vibrations, and so forth. In order to delete additional signal components that are not related to the core stability, high frequency components of the signals are often suppressed using a low pass filter prior to data sampling. Such filtering with a hardware system is called signal preconditioning.

<u>Data sampling and signal preprocessing.</u>

After the preconditioning, the noise signal are sampled an A/D converter with a predefined data sampling interval. The sampling frequency is selected to be 5 to 15 Hz, so as to cover the signal dynamics related to the core stability.

The sampled data are subjected to mean and amplitude calculation, to roughly check the signal conditions as well as to identify the reactor operational state.

Process identification.

The BWR dynamics model is obtained by applying various methods for the process identification. Time series model identification using ARMA(Auto Regressive Moving Average) or AR (Auto Regressive) model is a tool to obtain the core dynamics model (and so also the DR).

From the signal processing point of view, there are two different procedures for the model identification: one is the batch processing and other the recursive processing. In the case of batch processing, the measurement data series are once collected in the data buffer and then processed blockwise. In the recursive approach, the identified model is updated in such a way that the model obtained one sample before it is modified based on the information obtained by the newly sampled data. This method permits a more effective way of signal processing and a more frequent updating of the DR. However this approach requires a fast signal processing technique and a potential problem is the possibility of numerical instability.

Estimate of stability parameters and diagnostic checking

The stability parameters of DR, resonance frequency, amplitude and spatial power oscillation phase are estimated with use of the identified dynamic model. The results are checked carefully. This is important because various characteristics with respect not only to the stability but also to the whole plant dynamics are reflected on the identified model. Hence there is a risk that the estimated stability parameters get disturbed by characteristics that are not concerned with the stability.

There are three important parameters to characterize the monitor performance, i.e. accuracy, response time, and robustness. Various signal processing techniques are involved in the stability monitor to estimate on the stability parameters in real time.

Elaborate methods for the respective items and their suitable combination constitute the essential part in order to achieve a high performance of the stability monitor. Concerning the identification of the mode of instability, the stability monitor must be prepared for using methods for detecting and distinguishing global, local, and regional instabilities. This is accomplished in combination of hardware and software techniques.

2.4.6 Current strategies for prevention and mitigation of instability

The methodologies and solutions concepts to protect against adverse consequences of instabilities are following two complementary strategies: the prevention approach and the detection and suppression approach both provide the basis for protection system design. The objective of all solutions is to provide automatic protection against oscillations occurring in the plant. The broadest analysis of different strategies has been performed by the GE-BWR owners group to work-out long term stability solutions [12]. Other implemented solutions have been developed by vendors or utilities on the basis of specific plant conditions.

It should be noted that the proprietary nature of relevant information prevents the possibility to discuss in detail what specific steps can be taken from the points of view of the fuel vendor or of the core reload designer, to deal with the stability issue. Just to mention some examples, improved fuel design may be achieved by modifying spacers, fuel outlet pressure drop, void coefficient and by introducing PLR[7]; reload design can be improved by controlling through the loading patterns the eigenvalue separation of the out-of-phase mode (i.e. by a proper control of the radial power distribution achieved through individual fuel bundle positioning).

2.4.6.1 Design aspects

The design criteria require that the reactor and the associated protection system is designed such that power oscillations are not possible, or can be readily detected and suppressed without exceeding specified fuel design limits. The prevention approach demonstrates compliance by calculating decay ratios for allowable operating conditions and restricting operation by defining exclusion areas, if necessary, so that potentially unstable Power/Flow conditions are not encountered. Alternatively, the detection and suppression approach satisfies criteria by using plant instrumentation. The typical detection and suppression system monitors LPRM or APRM signals, and, when oscillating signals reach a predetermined level, initiates an automatic suppression function that may be a scram or an insertion of a preselected group of control rods to reduce power (SRI= selected rod insertion).

2.4.6.2 Implemented strategies

An overview of implemented strategies that are of general interest to cope with the BWR stability issue, is given below.

2.4.6.2.1 Regional exclusion

The basic approach uses an exclusion region and a restricted region in the Power/Flow map of possible operational conditions. The exclusion region is determined by analytical methods and lies in the range of low flow rates and high power. This region may be confirmed by operational measurements during the start-up phase after refueling. The stability behaviour near the boundary or within these regions may be supervised by a stability monitor, which informs the operators on the stability conditions in the actual operating state and gives and early warning that the stability margin is decreasing. The exclusion region is kept administratively (i.e. by operator checks) or may be enforced by automatic safety functions like a control rod withdrawal block, an automatic insertion of selected rod groups or even by a reactor scram. In some plant, the sliding neutron flux trip line is lowered in the low flow region and in addition the scram is initiated undelayed. Usually it is preferred to perform a predefined power reduction and to avoid the initiation of reactor scram. In order to limit these countermeasures to the low flow region the actions are combined with measurements of the total core flowrate, usually pressure difference measurements across the lower core plate.

2.4.6.2.2 Quadrant APRM

In some GE plants, only BWR-2 design, quadrant specific APRM signal exist. Therefore, an oscillation detection algorithm evaluating these APRM signals can detect regional oscillations and activate an automatic safety function.

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[7] Partial Lenght Rod

2.4.6.2.3 Power reduction derived from recirculation pump trip or loss- of feedwater preheater

As the operational region of low flowrate and high power is entered during transients like recirculating pump trip or pump-trips combined with a loss of feedwater preheater, some countermeasures to prevent the instability are directly combined with such events. Therefore, in some plants, an automatic power reduction is performed by selected rod insertion if such plant transients occur.