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Review Article

BWR Stability Issues in Japan

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Abstract

The present paper reviews activates relevant to the boiling water
coupled neutronic and thermal-hydraulic nature, from the view
applications to the BWR stability solution methodology in Japan.

1. introduction

The core power oscillation phenomenon inherently exists in BWR
instability. The BWR instability is possible even at the normal pla
oscillations may threaten core fuel integrity due to the fuel claddi
(pellet-cladding mechanical interaction). Therefore, an accurat

indispensable for the safety of BWR core design and operatic understand the complicated BWR instability mechanism and to dev

The stability problem has become an important concern on safety (incident at LaSalle-2. It should be emphasized that the applied ar instability actually occurred. Therefore, GE and US BWROG (BV analysis models which can be adequately applicable to the actual (long-term stability solution methodologies with several modificatioı

Also in Japan, similar activities have been proceeded by the BV instability concern. Main goals in Japanese activities are as follov BWR instability mechanism, the power oscillation onset/growth, a the three-dimensional time-domain code; (2) to empirically defi design, and to assess the accuracy of calculation results by stabili (3) to establish the stability solution methodology, in which the sel to automatically exclude the operated core from possibly unstable

The present paper describes the BWR stability issues in Japan. R models, and codes applicable to the design analysis and stabili suppose that understanding the basis of the BWR stability issues stability solution methodology based on the advanced analysis m paper, an outline of the on-going research on the advanced BWR which employs the best-estimate analysis code and the statistical a

2. BWR Instabilities

The BWR instability can be subcategorized into the three ph oscillation); (2) core instability (global core power oscillation); an core oscillate with an out-of-phase mode).

2.1. Channel Instability

The channel instability is equivalent to the coolant density wave pressure drop is kept constant by any constraint [2, 3]. As shown region, which significantly affects the 2-phase pressure drop, cons at the channel inlet. Hence, the channel instability can be invokec relatively larger than the single-phase pressure drop, for such con rate, (2) lower inlet coolant subcooling, (3) down-skewed axial p spacers which tend to generate the larger pressure drop in the 2-p of the channel instability can be suppressed by many other stable fuel bundles in an actual core.

Figure 1: Schematic description for channel in

2.2. Core Instability

The coupled neutronic and thermal-hydraulic power oscillation ca the regional instability. In the first mode, the global core power (mode, the power in a half core oscillates in an out-of-phase mo oscillation is mainly driven by the negative coolant void feedbac conduction [2]. This power oscillation can be actually excited b oscillation, as schematically described in Figure 2. a range from 0 wave propagation velocity through the core fuel channel.

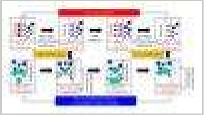

Figure 2: Schematic description for core instal

The core power oscillation becomes unstable under the lower corresponding to the density wave oscillation behavior. Large neg make the core state unstable. In addition, the past investigatio revealed interesting sensitivity with respect to the core power dist power shape, fuel bundles with high power peaking factors tend resulting in the core instability. The sensitivity regarding the ax described below. The down-skewed shape leads to the longer t density wave oscillation greater than the time constant in the fue the stable core power oscillation. On the other hand, the flat an influence of neutronics in the high void region of the core, inducinc void feedback.

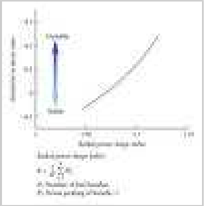

Figure 3: Sensitivity of core power shape to c

2.3. Regional Instability

The basic phenomenon dominating the regional instability is simil neutronic and thermal-hydraulic oscillation can be individually ex mode. Previous researchers proposed that the regional instabil harmonics (1st azimuthal mode) of the neutron flux distribution, fundamental mode (see Figure 4) [7]. Hashimoto derived the so- order to analytically represent the phenomenon, in stead of the orc

$$\frac{dN_m(t)}{dt} = \frac{\rho_m^s - \beta}{\Lambda_m} N_m(t) + \frac{\rho_{m0}(t)}{\Lambda_m} N_0 +$$

$$\frac{dc_m(t)}{dt} = \frac{\beta}{\Lambda_m} N_m(t) -$$

where

$$\rho_m^s = 1 - 1 / k_m$$

$$\rho_{mn} = \langle \phi_m^*, (\delta M - \delta L)\phi_n \rangle /$$

m is the order of the higher harmonic mode ($m = 1, 2, \ldots$); N, c, a neutron precursor, and delayed neutron fraction, respectively. Th original paper [8]. Physically, ρ_m^s represents the subcriticality of corresponding to the eigenvalue separation, and is a negative

Takeuchi et al. [9] pointed out that a smaller absolute value of
regional oscillation larger, which is correlated to the first term o
instability.

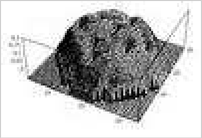

Figure 4: Sample of spatial neutron harmonic

As mentioned above, powers in two halves of a core oscillate
oscillations cannot be observed in the core-averaged power and i
hydraulic flow response via the recirculation loop is less sensitive t

3.BWR Stability Analysis Codes, Verifications, and A

Several stability analysis codes have been developed so as to in
and to apply on the BWR core design in Japan. The analysis cod
the frequency-domain code and the time-domain code. Features
of the time-domain code are summarized in Table 1, respectively.

Table 1: Features in frequency-domain and ti

3.1. Reduced-Order Frequency-Domain Codes

In general, the frequency-domain code employs the reduced-
mathematically simplify the phenomenological representation, and
the decay ratio, representing the stability degree of an oscillation,
on the system transfer functions. These features are favorable in
the physical phenomena are linearized for small perturbations to
transformation, which characterize the channel, core, and reg
employed in a representative frequency-domain code are the follo

(1) mass, energy, and momentum equations for 2-phase mi
(2) radial one-dimensional fuel heat conduction equations; a
(3) point neutron kinetics equations.

The thermal-hydraulic behavior in a core is modeled with the para
is accounted in each hydraulic calculation node. As for the reg
equation is replaced by the modal point kinetics equation as menti

Figure 5 shows a sample of verification result for the frequency-d
core design analysis. The code is able to derive good correlations
analysis as well as for the regional stability analysis, while the cod

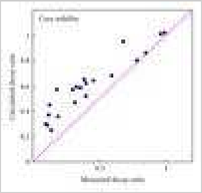

Figure 5: Sample of verification for the freque

3.2. Three-Dimensional Time-Domain Codes

As described above, the frequency-domain codes generally emplo
avoid mathematical difficulties in derivation of the system transfe
thermal-hydraulic phenomena in a BWR. The time-domain code,
physical models, like the spatial neutron kinetics model. In fac
straightforward, while it consumes larger computational time than
however, the significant advance in computation technologies has
employ the complicated three-dimensional and multigroup neutror
domain codes developed by Japanese organizations are listed in
codes is that the detailed spatial kinetics behavior in a core can be
and the regional stability can be evaluated using a single th
modification. However, users have to pay attention to the applied
simulated oscillation and decay ratio [15, 16].

Table 2: Three-dimensional stability analysis c

Furthermore, a simulator has been implemented on the recent ti
realistic dynamic simulation reflecting the actual core state inclu
consistent to the static core design [17, 18]. Figure 6 shows a sa
domain stability analysis code, SIMULATE-Kinetics, using the R
confirmed that the code is basically targeting on the best-estimat
approach applied in the frequency-domain code. The Ringhals
instability was observed, was accurately simulated as shown in F
simulation demonstrated that the observed regional instability is e
mode (1st azimuthal, N_1 defined by (3), and that modal reactivitie
regional event as shown in Figure 8.

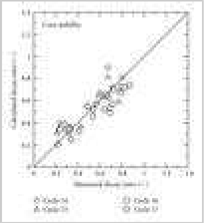

Figure 6: Sample of verification for the time-d

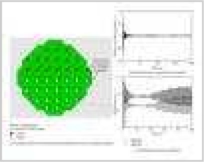

Figure 7: Simulated regional instability at Rin

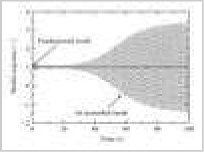

Figure 8: Modal parameter responses under si

A feature of the three-dimensional time-domain code is that it is a
cycle oscillation which is driven by the complicated nonlinear effe

del iberated mechanism in the formation of limit cycle oscillation. tend to increase the core-averaged void fraction and the negat neutron flux oscillation due to nonlinearity in the neutron kinet observed in the measured core power responses and/or in the nun is due to the above nonlinearities.

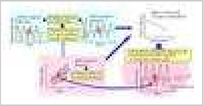

Figure 9: Mechanism in formation of limit cycl

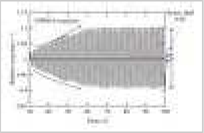

Figure 10: Average power shift in simulated R

As for another scientific interest on the regional limit cycle osci spectrum analysis of the measured core power responses [24], interaction in the modal reactivities defined by (4) plays an imp Ikeda et al. have numerically demonstrated that the nonlinearity averaged and regional power responses, respectively, as shown ir spectrum analysis to the simulated fundamental and higher modal

Figure 11: Harmonics excitations under regior

4. Current BWR Stability Solution Methodology

Since the instability incident at LaSalle-2 [26], GE, and US-BWRO(methodologies [27, 28]. Also in Japan, a similar stability solution stability margin must be ensured in the core design process, and equipped to exclude the BWR core from the unstable operation re 12 [29].The SRI system is activated to suppress the core powe tripped and the core goes into the preliminary determined stabilit determined by using stability design codes certified via the regul criteria (decay ratio is less than 0.8). Consequently, this methodo not possible in the operated core in Japan.

Figure 12: Outline of approved stability soluti

5. Research on Advanced BWR Stability Solution Me

The current stability solution methodology is effectively contribu However, considering the recent occurrences of BWR instabilities may be indispensable for the future stability solution methodo modifications in the existent BWR plants as the extended core t designs [33 - 35]. An approach to resolve this concern is that suf

the plant operable region is limited by the wider stability exclusi
current conservative stability analysis code, as shown in Figure
economical loss by consuming longer time for the plant startup op
region are generally allowed to adopt few continuous withdrawals
This is because the continuous-withdrawal operation induces signi
condition, possibly removing the core into the prohibited stabilit
operations, which must be conducted slowly and intermittently to
under the higher power condition to attain the target control rod p
the overall plant startup time tends to become longer in the BWR p

Figure 13: Plant operable region for the powe

In order to reasonably enhance the operable region even unde
organized by several Japanese industrial and academic organiza
stability solution methodology based on the best-estimate code sy
the original regulatory criterion with respect to the BWR instability
design limits (SAFDLs) are not possible" , not prevention from th
applicable SAFDLs on the BWR instability, the PCMI and the mate
no significant affect on the fuel integrity, because temperature res
small as shown in Figure 14. Therefore, occurrence of the core co
for the fuel failure under the BWR instabilities. So as to accurat
under the BWR instabilities, the research group is applying an a
plant simulator, TRAC-BF1/ENTRÉE [13], and the 2-fluid/3-field
described in Figure 15, TRAC-BF1/ENTRÉE provides the pin-by-pi
subchannel thermal-hydraulic behavior and BT onset on the loca
conditions supplied by the TRAC-BF1/ENTRÉE.

Figure 14: Fuel temperature responses under

Figure 15: Outline of TRAC-BF1/ENTRÉE and I

The research group is also investigating the possibilities to intro
[39] so as to establish the reasonable conservatism in the stabili
best-estimate code system. The research, in particular, currently
identification ranking table (PIRT) applicable to BWR instabilities i
on the existent stability PIRTs [40 - 42]. This is the basis of the
stability analysis.

6. Conclusions

Many efforts have been paid to research on BWR stability issues
industrial organizations have developed and improved the BWR sta
the reduced-order frequency-domain and three-dimensional time-c
to the BWR stability design analysis, while the latter one has
phenomena related to BWR stability. The current stability solutio

stability exclusion region is successfully preventing the occurrenc suppose that the future application of the extended core power u solution methodology in order to reasonably minimize the stabili currently proposing to apply the best-estimate analysis code with will allow better evaluation of the stability exclusion region, and w the extended core power uprate.

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