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BWR Stability Analysis: Assessment of STAIF with Input from MICROBURN-B2

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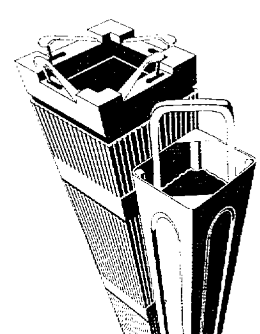

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BWR Stability Analysis: Assessment of STAIF with Input from MICROBURN-B2

Prepared: ______________________ 11/15/99
D. W. Pruitt — Date
Safety Analysis Methods

Prepared: ANR ______________________ ________
Y. M. Farawila — Date
Farawila et al., Inc.

Concurred: ANR ______________________ ________
D. J. Denver, Manager — Date
Commercial Operations

Concurred: ______________________ 11/15/99
for J. F. Mallay, Director — Date
Regulatory Affairs

Approved ______________________ 11/15/99
R. E. Collingham, Manager — Date
Safety Analysis Methods

Approved ANR ______________________ ________
O. C. Brown, Manager — Date
BWR Neutronics

Approved: ANR ______________________ ________
R. L. Feuerbacher, Vice President — Date
Engineering

lmk

U.S. Nuclear Regulatory Commission
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ABSTRACT

The boiling water reactor stability analysis program STAIF, coupled with the core simulator program MICROBURN-B, has been approved by the NRC. This report presents an enhanced version of STAIF coupled with the new core simulator MICROBURN-B2. Code enhancements, as well as an expanded qualification database, are presented to demonstrate the capabilities of the code version. This version includes a higher level of automation and integration with the core simulator. This results in improved quality for the analysis of the global and regional modes, as well as the density wave stability in a heated channel.

This report supports SPC's request for approval of the enhanced STAIF version as coupled with MICROBURN-B2 or other equivalent core simulators.

Nature of Changes

Item	Page	Description and Justification
1.	All	This is a new document.

Contents

Tables

Figures

1.0 Introduction

The STAIF computer program is a best estimate code used to predict the stability of reactivity coupled density wave oscillations in a boiling water reactor (BWR). The program incorporates a linearized, small perturbation, frequency domain model of the reactor core and vessel recirculation system. The program predicts the stability of the core-wide power oscillation mode as well as the regional out-of-phase mode. The program also calculates the hydraulic stability of flow in a single fuel assembly under the idealized conditions of constant heat flux and pressure drop.

The STAIF program is used to predict the core-wide and regional stability of BWRs with jet pumps and internal recirculation pumps. It was previously approved by the Nuclear Regulatory Commission (NRC) for applications with the MICROBURN-B steady-state core simulator (References 1 and 2). This report presents STAIF changes that were made to accept input from the recently approved steady-state core simulator MICROBURN-B2 (Reference 3).

The advances made with MICROBURN-B2 provided an opportunity to refine the models in STAIF. These refinements include the selection of hydraulic correlations that improve the consistency between the steady-state core simulator and STAIF, [

]. These code enhancements are detailed in Appendices A, B and C respectively.

The quality of STAIF predictions are demonstrated by making comparisons of predicted and measured decay ratios for hydraulic loop tests of current BWR fuel designs as well as integral reactor data for jet-pump and internal pump reactors. The measured decay ratio database has been expanded from that presented in Reference 2 to better reflect current fuel and cycle designs. The jet pump data include both stable and oscillatory state points from the Peach Bottom Unit 2 and Washington Nuclear Power Unit 2 BWRs. The internal recirculation pump data include stable and oscillatory state points for European reactors [

].

2.0 Summary

The STAIF code has been enhanced and modified to accommodate input from the recently approved steady-state core simulator, MICROBURN-B2 (Reference 3). The resultant code system was then qualified against an expanded experimental database (Sections 3 and 4), which included recent stability measurements from the Karlstein test facility as well as from boiling water reactors operating with current fuel designs manufactured by Siemens and other fuel vendors.

The hydraulic assessment of the enhanced code system included the original hydraulic stability tests reported in Reference 2 for the ATRIUM™*-9 fuel design with full-length heater rods [ ]. Also, the experimental database has been expanded to include ATRIUM-10 fuel designs with two different inlet orifice restrictions (AT10-S1 and AT10-S2). The comparison of the STAIF calculations with the experimental test results are presented in Figure 2.1. The mean difference between the calculated and measured decay ratios is [ ] with a standard deviation of [ ]. These statistics show approximately the same mean as the approved MICROBURN-B methodology but one half the standard deviation.

The reactor assessments have been extended to include data from recent operating cycles using current fuel designs and fuel management strategies. In addition, the number of measurements in the 0.5 to 0.9 decay ratio regime was increased. The database has been extended from [ ]. The comparison of the MICROBURN-B2/STAIF calculations with the reactor measurements are presented in Figure 2.2. The statistical comparisons are nearly the same as the approved MICROBURN-B methodology with a mean difference between the calculated and measured decay ratios of [ ] and a standard deviation of [ ].

These results for the MICROBURN-B2/STAIF code system show that the system accurately predicts both the hydraulic stability as well as the global and regional modes of BWRs. Therefore, the MICROBURN-B2/STAIF code system is a qualified extension to the approved MICROBURN-B/STAIF based licensing methodology. Extrapolating on this experience, STAIF

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* ATRIUM is a trademark of Siemens.

analysis is possible using data from other qualified BWR simulators, provided that such data meets the quality standard according to the SPC Work Practice guidelines.

Figure 2.1 STAIF Qualifications with Hydraulic Tests

Figure 2.2 STAIF Qualification with Reactor Data

3.0 Qualification with Hydraulic Loop Data

The revised hydraulic correlation sets (Appendix A) are shown to accurately represent density wave phenomena through thermal hydraulic testing without neutronic feedback. This was accomplished by running stability tests in a hydraulic loop using electrically-heated full scale bundles. Code assessments have been performed against hydraulic stability tests performed in the Karlstein (Germany) test facility from December 1992 through June 1999. The description of the test facility, procedures and bundle designs tested in 1992 were described and benchmarked in Reference 2. This section presents the bundle description for the 1999 tests as well as the benchmark calculations for all of the Karlstein hydraulic stability measurements.

3.1 *1999 Karlstein Test Bundle*

A series of stability tests were conducted in June 1999 on the ATRIUM-10 type bundle design. This design is a 10x10 rod array with 8 part length fuel rods and a square water channel replacing 9 full length rods. Specifically, the bundle data for [

]

The heater rods are designed with variable electrical resistance to produce a bottom-peaked axial power shape [

].

While both the 1992 and 1999 test bundles are prototypic of fuel bundles for reactors with respect to flow area and spacer grid design, there is one exception. [ ]

[

]

3.2 *1999 Karlstein Test Results*

The 1999 test series consisted of 7 test groups. [

] For each group the subcooling and pressure were fixed using loop controls. The operating conditions were then varied by changing the bundle power and allowing the flow to achieve a new equilibrium state. In some tests, a pseudo-random binary signal was used to perturb the power level. The data acquisition system recorded the data at a [ ]. The recorded data included the power, inlet flow rate, inlet temperature, system pressure and pressure drop across the inlet.

The analysis of the test data was performed with the ANNA™ program (Reference 4) to determine the decay ratio and frequency at various selected test points. [

] It is found through this parallel analysis, however, that the decay ratio from both time series is in very good agreement.

The various data recordings [ ] were reviewed to assure that steady-state conditions were attained over the sampling period. This review resulted in usable recording periods of [ ]. The ANNA™ univariate autoregression analysis used [

]

[

]

3.3 *Qualification with Hydraulic Loop Data*

The steady-state bundle conditions from the 1992 tests (Reference 2) as well as those from the 1999 tests were used as input to the STAIF code to determine the calculated channel decay ratios. The comparison of these calculated decay ratios and those determined from the test data are presented in Tables 3.1 through 3.4 and Figure 3.1 for the 1992 tests and Table 3.5 and Figure 3.2 for the 1999 tests. These comparisons show that the hydraulic decay ratios are well predicted by STAIF with a mean difference of [ ] and a standard deviation of [ ].

Table 3.1 Qualification with [ ] Bundle (STS-18.1) Tests

Table 3.2 Qualification with [ ] Bundle (STS-18.3) Tests

Table 3.3 Qualification with [ ] Bundle (STS-18.2) Tests

Table 3.4 Qualification with [ ] Bundle (STS-18.4) Tests

Table 3.5 Qualification with ATRIUM-10 (AT10) Bundle (STS-49-1) Tests

Table 3.5 Qualification with ATRIUM-10 (AT10) Bundle (STS-49-1) Tests (Continued)

Table 3.5 Qualification with ATRIUM-10 (AT10) Bundle (STS-49-1) Tests (Continued)

Figure 3.1 STAIF Qualification with 1992 Karlstein Hydraulic Tests

Figure 3.2 STAIF Qualification with 1999 Karlstein Hydraulic Tests

4.0 Qualification with Boiling Water Reactor Data

The qualification base for the MICROBURN-B2/STAIF version has been expanded over that used in the original safety analysis report and approval of STAIF (Reference 2). The qualification base retains the stability tests conducted at Peach Bottom 2, [ ] as well as the Washington Nuclear Power Unit 2 instability, but also adds more recent stability measurements at higher decay ratios for several reactors loaded with 9x9 and 10x10 fuel designs. This section describes the qualification of the MICROBURN-B2 / STAIF code system with this data.

The input requirements for STAIF are illustrated in Figure 4.1. This is a simplification of the input processing in the previously approved version (Reference 2) due to the fact that the coupling code, MB2STF, has been eliminated as a separate code in favor of incorporating its functions directly in STAIF. This eliminates redundancies and file transfers and allows the level of automation to be raised another step. As Figure 4.1 illustrates, the input for STAIF includes the MICROBURN-B2 input and core follow calculations up to the time of the test, test specific core operating conditions (core power, flow, inlet enthalpy, pressure and control rod pattern) and the test-specific recirculation system conditions (recirculation loop flow splits and pump speeds). STAIF reads the detailed 3-D core state (neutronic and hydraulic) from MICROBURN-B2 files and condenses the bundle-by-bundle representation in MICROBURN-B2 to macro-channel representations for the stability calculation.

[

] This user-selected channel grouping is subject to a code imposed minimum channel resolution based on the safety evaluation report for the previous version (References 1 and 2):

1) No single channel can be associated with more than 20% of the total core power generation.

2) A minimum of three channels for every significant bundle type that accounts for more than 25% of the reactor power.

3) A separate hot channel for every significant bundle type generating more than 25% of total power.

The input files required by STAIF are:

staif.recirc Contains the recirculation system volumes, areas, lengths, inertias, pressure loss coefficients, and recirculation pump characteristics. [ ]

rodex.inp [ ]

stf.case Contains the nodal neutronics parameters from the MICROBURN-B2 solution at the test conditions. [ ]

hyd.case Contains the bundle hydraulic parameters. [ ]

staif.inp Contains control parameters for the STAIF solution and the initial flow splits for the recirculation system. [ ]

The calculational steps used in simulating each of the reactor tests follow this procedure:

1. [ ]

2. [ ]

3. [

4.

]

This calculational process assures that the MICROBURN-B2 / STAIF code system effectively models the specific state-point conditions and provides insight into the behavior of the global and regional modes.

4.1 *Qualification with Previous Stability Test Results*

This section presents the qualification of the MICROBURN-B2/STAIF code system against reactor data used for the previously approved methodology. [

]

4.1.1 Peach Bottom Unit 2

Several stability tests were conducted at the BWR/4 plant Peach Bottom 2. Tests near the end of Cycle 2 (April 1977) utilized pseudo-random and periodic pressure perturbations to induce reactivity response, as detailed in Reference 6. Follow-up tests were conducted for Cycle 3 resulting in a series of low-flow tests documented in Reference 7. All these tests were performed near minimum pump speed with both recirculation loops operating.

Comparisons of STAIF stability predictions and the test data are presented in Table 4.1. In all cases the global mode was the least stable of the two oscillation modes with the eigenvalue separation varying between [ ]. Since these tests [

].

4.1.2 Washington Nuclear Power Unit-2

On August 15, 1992, a BWR/5 operated by the Washington Public Power Supply System (WNP2), developed a global limit cycle during the pump upshift maneuver, which required the reactor operators to scram the reactor. The instability occurred at an operating state point below the 80% rod line that had previously been considered to be a stable operating point on the power flow map. Investigation of this event identified that the instability was primarily due to the highly peaked power distribution at the time of the pump shift (References 8 and 9).

Post event analysis of the reactor instrumentation for the event indicated that prior to the pump upshift the plant was operating at a decay ratio above 0.80. As the flow control valve was closed, the reactor became unstable and reached a maximum decay ratio of 1.07 prior to establishing a limit cycle.

The MICROBURN-B2 / STAIF calculations for the global instability resulted in a global decay ratio of [ ] and a regional decay ratio of [ ]. It is interesting to note, that the regional decay ratio for the instability event was [

]

4.1.3 [ ]

Stability tests were performed for the [ ]reactors as part of the initial commissioning tests. These tests were performed on the minimum pump speed and natural circulation flow lines. As one of the purposes of these tests was to assess the high decay ratio plant operating characteristics, the power was adjusted to obtain data above the rated rod line.

The stability tests were conducted by maneuvering to the power/flow condition of interest and [

]

The stability test results and qualification calculations for [ ] are summarized in Table 4.2. These tests correspond to two power levels on the minimum pump speed line and three different power levels along the natural recirculation flow line. Starting at approximately the rated rod line, the reactor power was increased at natural recirculation flow until a reactor limit cycle was obtained. For [ ], the limit cycle oscillation was established for the regional mode. Again, as in the Peach Bottom 2 stability comparisons, the four stable operating points were determined by PRBS testing and, consequently, the measured decay ratios correspond to the global mode. For the unstable point, the code predicted a regional decay ratio of [ ] and global decay ratio well below unity in agreement with the observed behavior.

4.1.4 [ ]

Stability tests at the [ ] plant were performed [ ] exhibited a preference to the regional mode of instability. The core has [ ] bundles, and the mixed core configuration for Cycle 3 contained [ ]

For the BOC-3 stability measurements the reactor was maneuvered to minimum pump speed (600 rpm) with all pumps running. The [ ] pumps were then turned off one by one until natural circulation conditions were obtained. The tests were then essentially repeated by reversing the procedure by turning the pumps on, one by one, until all pumps were again operating at minimum pump speed.

The plant was stable at minimum pump speed flow and the [ ] The measured neutron flux oscillations were of the preferred out-of-phase mode. The decay ratio and frequency for the test points estimated from the flux noise measurements as well as the STAIF qualification calculations are presented in Table 4.3. As in the [ ], STAIF correctly identifies the mode of the oscillations as regional.

4.2 ***Qualification with Recent Reactor Stability Measurements***

Subsequent to the stability tests performed in the early 1980's, many of the reactors in Europe have obtained access to noise analysis systems so that the stability margins can be easily assessed and verified. This capability not only allows the utility to determine the current stability margin but also helps to assess the trend in stability margin with changing fuel designs and operating strategies. These measurements differ from stability tests in that typically the reactor is being maneuvered through the regions of interest with hold times only long enough to collect the noise data and usually the measured noise signals are not retained. Consequently, the MICROBURN-B2 calculations typically simulate the reactor operating history prior to the measurements where xenon dynamic calculation option is selected to better define the reactor state point.

4.2.1 [ ]

Stability measurements at [ ] were conducted by reducing the flow from rated conditions to that of minimum pump speed and recording the neutron noise data for analysis. For Cycle 6, this data was collected and analyzed for both minimum pump speed and natural recirculation conditions. The stability measurements and qualification calculations from [ ] are presented in Table 4.4

4.2.2 [ ]

Stability measurements for [ ] were made during the reactor startup shortly following a reactor scram. For Cycle 12, this was at approximately 3000 MWd/Mt cycle exposure, while for Cycle 13 it occurred at beginning-of-cycle during the initial reactor startup. The stability measurements and qualification calculations from [ ] are presented in Table 4.5. Of particular interest is the comparison of [ ] For both cycles, STAIF correctly identifies the dominant mode. [ ]

4.2.3 [ ]

Stability measurements for [ ] were made by reducing the flow from rated conditions to minimum pump speed and recording the neutron noise data for analysis. The stability measurements and qualification calculations from [ ] are presented in Table 4.6

4.3 *Summary of Boiling Water Reactor Stability Comparisons*

New reactor stability measurements, since the original safety analysis report and approval of STAIF, were added to the qualification base for the present version of the code system. The MICROBURN-B2/STAIF qualification calculations for these new measurements as well as the repeated reactor qualification calculations from Reference 2 are plotted in Figure 4.2. These comparisons show that the MICROBURN-B2 / STAIF code system predicts the measured data with a mean error of [ ] and standard deviation of [ ]. It also shows that the code system retains the previous version's capability of correctly identifying the global and regional modes of oscillation.

Table 4.1 Peach Bottom 2 Stability Test Qualification Results

Table 4.2 [ ] Stability Test Qualification Results

Table 4.3 [ ] Stability Test Qualification Results

Table 4.4 [ ] Stability Test Qualification Results

Table 4.5 [ ] Stability Test Qualification Results

Table 4.6 [ ] Stability Test Qualification Results

Figure 4.1 STAIF Input Diagram

Figure 4.2 STAIF Qualification with Reactor Data

5.0 References

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Appendices A, B and C are proprietary in toto.

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