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Author: **José March-Leuba**

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NRC Monitor : **T. L. Huang, Office of Nuclear Reactor Regulation**

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Prepared by
Instrumentation and Controls Division
OAK RIDGE NATIONAL LABORATORY
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
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## SUMMARY

This report documents the main conclusions and recommendations derived from our review of the Boiling Water Reactor Owners' Group (BWROG) long-term solutions of the stability issue as described in NEDO-31960 and its Supplement-1 (references 1 and 2). Overall, this review is very positive. Our main conclusion is that all three of the proposed solution types (I, II, and III) are technically sound and, in our opinion, any of them will solve the stability issue if properly applied.

Although not specifically related to the stability issue, the fact that implementation of a new reactor protection function will most probably result in an increased number of challenges to the reactor protection system may lead to a new safety problem unless the number of unnecessary challenges is minimized by design. It is recognized that the normal function of these solutions is to provide an automatic protection action (i.e., a scram or a runback) if either oscillations are detected or the exclusion region is entered; however, the implementation of this function must be performed carefully in order to minimize the number of unnecessary actuations while maintaining a very high probability to perform the intended safety function.

Detailed recommendations, including some qualifiers and reservations, are specified in the main text of this report. A condensed summary of these recommendations follows:

1. Approve the overall licensing methodology described in NEDO-31960 and its Supplement 1 for Solutions I-A, II, and III. This methodology includes the treatment of uncertainties and the selection of initial conditions and calculation parameters. The approval should be conditioned to assure plant-specific consistency with the axial (2.0) and the radial (end-of-cycle Haling) peaking factors assumed for the core power distribution calculation parameters.

2. Do not approve Solution concepts I-B and I-C because of its lack of detailed development and/or interest by the BWROG.

3. Do not approve Solution concept I-D at this time until the final evaluations that NRC has requested have been performed. This recommendation does not imply a rejection of Solution I-D; the approval of Solution I-D depends on the details of calculations that have not yet been performed by the BWROG.

4. A select rod insert (SRI) is an acceptable automatic protection action for any of the approved solutions (I-A, II, or III) as long as a full scram takes effect if either the oscillations do not disappear or the reactor does not exit the exclusion region within a reasonable period of time (a few seconds). The exclusion region must be examined prior to each plant operating cycle to assure consistency with the axial and radial power peaking distribution assumed in the exclusion region boundary calculations.

5. The BWROG must establish a criteria to limit radial and axial peaking factors during startup operations to those values considered for the analyses of the exclusion region.

The main technical issue of significant relevance that still remains to be solved is the reload-dependent confirmatory analyses required to assert the applicability of the previous-cycle safety settings and, in particular, the applicability of "old" exclusion regions to new types of fuel and loading

patterns. The BWROG is aware of this problem and is currently developing a methodology for these cycle-dependent confirmations that is based on a "response surface" approach. The goal is that these confirmatory calculations should be expected to be positive most of the time; major setpoint changes should only be expected following significant fuel design changes. The documentation of this reload-confirmation methodology is expected in Supplement 2 to NEDO-31960 that should be published in the spring of 1993. Supplement 2 will also contain a correlation to estimate the loss of critical-power-ratio margin as a function of the power oscillation amplitude. This correlation is necessary to confirm the setpoints required for Solution III as well as the nonprotected region for Solution I-D.

## BACKGROUND

Following the March 1988 instability event in the LaSalle BWR, the BWROG initiated a task to investigate actions that industry should take to resolve the BWR stability issue as an operational concern. Through analysis,[3] the BWROG found that the current plant protection system, that is based on a scram on high average power range monitor (APRM) signal, may not provide enough protection against out-of-phase modes of instability; thus, the BWROG decided that a new automatic instability suppression function was required as a long-term solution and that this function should have a rapid and automatic response which does not rely on operator action.

The BWROG does not plan to solve the stability problem on a "generic" basis, but it has proposed three different options instead. It will be up to the individual licensees to choose which solution will be implemented in their reactor. The options currently being considered by the BWROG are:

I Exclusion Region. A region outside which instabilities are very unlikely is calculated for each representative plant type using well-defined procedures. If the reactor is operated inside this exclusion region, an automatic protective action is initiated to exit the region. This action is based exclusively on power and flow measurements, and the presence of oscillations is not required for its initiation. Four concepts of type I have been proposed by the BWROG:

- I-A Immediate protection action (either scram or SRI) upon entrance to the exclusion region.

- I-B Same as I-A, but the exclusion region can be bypassed if a stability monitor is operational and detecting sufficiently stable conditions (for instance, decay ratio less than 0.6)

- I-C Protection action is taken if two conditions are satisfied: (1) the reactor is operating inside the exclusion region (defined similarly as in Solution I-A), AND (2) an APRM oscillation (of small amplitude) is detected.

- I-D Some small-core plants with tight inlet orifices have a reduced likelihood of out-of-phase instabilities. For these plants, it is claimed that the existing flow-biased high APRM scram provides sufficient protection. In addition, administrative controls are proposed to maintain the reactor outside the exclusion region.

II Quadrant-Based APRM Scram. In a BWR/2, the quadrant-based average-power-range monitor is capable of detecting both in-phase and out-of-phase oscillations with sufficient sensitivity to initiate automatic protective action to suppress the oscillations before safety margins are compromised.

III LPRM-Based Detect and Suppress. Local power range monitor (LPRM) signals or combinations of a small number of LPRMs are analyzed on-line by using three diverse algorithms. If any of the algorithms detects an instability, automatic protective action is taken to suppress the oscillations before safety margins are compromised. Two different options have been considered by the BWROG: Solution Concept III, and Solution Concept III-A. The main differences between the two is in the hardware implementation: Solution III requires a new Class 1E computerized system, and Solution III-A may use newly designed digital replacements of the APRM amplifier cards that will require a smaller number of LPRM detectors. Conceptually, the algorithms are (or may be) similar in both solutions.

## CONCLUSIONS AND RECOMMENDATIONS

### Positive conclusions

1. Overall, the BWROG has done an excellent job of addressing the stability issue in operating reactors. The BWROG has recognized that a problem exists, and they have attempted to solve it in a technically competent manner instead of performing analyses that would defend inaction.

2. The three proposed solution types (I, II, and III) are technically sound and, in our opinion, any of them will solve permanently the issue if properly applied.

3. The solutions can be implemented in existing reactors in a relatively straightforward manner without compromising their intended function.

4. The analyses techniques proposed by the BWROG in their licensing methodology appear to be sufficient to verify the effectiveness of these solutions in the lead plants.

5. The proposed BWROG procedures to generate input data for exclusion region calculations appear to be sufficiently conservative enough. Even though these procedures do not call for absolutely bounding values for all parameters, the conservatism is derived from the fact that reasonably bounding values are used for all parameters at the same time. In the real world, forcing one parameter towards its bounding limit is incompatible with having other parameters at their limit. The conservative nature of these procedures is verified through the use of transient confirmatory analyses under expected operating conditions, which include startup, pump runbacks, and loss feedwater conditions.

6. The application of Solution II to Oyster Creek has shown that the quadrant-based APRM scram provides sufficient protection for either in-phase or out-of-phase oscillations in a BWR/2.

7. The three proposed algorithms for Solution III appear to be able to detect oscillations in a manner reliably enough that automatic suppression action can be taken by the protection system. The good detection sensitivity of the period-based algorithm allows for fairly tight scram setpoints; therefore, this solution does not need to rely heavily on difficult calculations to show sufficient safety margin under a wide range of conditions and fuel types.

8. The arguments presented in NEDO 31960 about the expected oscillation modes are convincing, although they are not absolutely bounding in the case of the single-channel oscillation. We agree that the most likely oscillation modes will be either in-phase (or corewide) or out-of-phase (or regional). Higher order regional modes are not likely, because of their increased eigenvalue separation. We however have some minor reservations with respect to the single-channel type of instability (see reservation 10 in the next section and recommendation 12).

Reservations

1. Even though there are only three general types of solutions (Solutions I, II, and III), at least seven possible implementations (Solutions I-A, I-B, I-C, I-D, II, III, and III-A) have been proposed at one time or another. A more general type of solution that would apply to all reactors would have been preferable.

2. Some solutions (especially Solution I-A, regional exclusion with scram upon entry to the region) will most probably be implemented with margins as tight as possible to avoid unnecessary scrams. This approach might result in cycle-dependent implementations that would require new safety-system setpoints based on cycle-specific data for each reload. This is not a desirable feature in a long-term solution.

3. Solution I-B (exclusion region with bypass based on stability monitor) has not been developed in detail, and it appears to have been abandoned by the BWROG. If solution I-B were still under consideration, we would have reservations with respect to the ability of stability monitors to measure the decay ratio of the out-of-phase instability mode with sufficient accuracy to allow a bypass of the exclusion region scram. For example, in the Ringahls-1 tests,[4] the measured decay ratio was about 0.7 at 70% power and an instability was observed at 72.5% power. This event clearly casts a shadow on the viability of Solution I-B as an option.

4. Solution I-C (delta APRM flux scram) has not been developed in detail by the BWROG. If some licensee would want to pursue this option, we would have to look in more detail at the scram setpoint. The methodology used to estimate this setpoint should be similar to the one used for Solution III, including uncertainties and failed LPRM signals.

5. Solution I-D (small cores with tight inlet orifices) relies too strongly on decay ratio calculations that predict that the oscillation mode is very likely to be corewide. In this solution, the flow-biased scram does not appear to give significant protection against out-of-phase instabilities should they occur. Although these calculations will be documented in Supplement 2 of NEDO 31960 (due spring 1993), it is expected that there will be an area within the exclusion region where the flow-biased scram does not provide protection for out-of-phase oscillations.

6. We have some concerns about the methodology to estimate the stability of the out-of-phase (or regional) mode of oscillation. The BWROG proposes to use an acceptance region defined in a two-dimensional plane with the FABLE-calculated corewide and hot-channel decay ratios as coordinates (see Fig. 5-1 of reference 2, NEDO-31960/S1). The applicability of this acceptance region to determine whether a reactor condition is likely to oscillate in-phase or out-of-phase may impact the approval of Solution I-D. The two main concerns that we have about the methodology that defines core-channel decay ratio acceptance criteria are:

   6.1 Core-channel decay ratio acceptance criteria were developed by using test data and other calculations. In all these benchmark cases, the actual radial and axial power shapes were used with FABLE to estimate the core and hot-channel decay ratio. The BWROG, however, proposes to distinguish between in-phase and out-of-phase oscillation modes based on this acceptance criteria but using the conservatively defined "procedure" power shapes as inputs instead of the best estimate shapes. Although we agree that the procedure power shapes result in a conservative exclusion region, they may bias the results towards the in-phase mode of oscillation by using nonconsistent axial power shapes (flat for corewide and extremely bottom peaked for the hot channel). In summary, the data base used to develop the acceptance criteria do not envelop the conditions for the intended use (i.e., cannot distinguish accurately between in-phase and out-of-phase modes).

   6.2 The out-of-phase mode of instability is a function of how strong the flow feedback is, and that is represented qualitatively by the channel decay ratio in the acceptance criteria. However, the out-of-phase mode is also a function of the eigenvalue separation between the fundamental and first azimuthal neutronic modes. The eigenvalue separation is not included in the acceptance criteria, which represent only "typical" loading patterns and core sizes. It is conceivable that other loading patterns might result in different acceptance criteria.

7. Reducing the number of false positives (i.e, scrams when it was not required) for Solution III (LPRM-based detect and suppress) is crucial for the solution to work; however, the BWROG may take this false-scram avoidance to such an extreme that the solution will not work. Minor problems with electronic noise, controllers out of tune, or many other unknown parameters may result in failure to scram when required, if this solution is not carefully designed. This is the reason we recommend (as proposed by the BWROG) that several diverse algorithms be implemented simultaneously for Solution III.

8. Solutions III, I-C, and I-D depend partly on a correlation that relates the change in critical power ratio (CPR) caused by a neutron power oscillation. It is not clear that such a correlation exists or how many independent parameters it must contain. The BWROG has been working towards developing this correlation and is trying to define it in a conservative manner. BWROG expects to complete this correlation development in February 1993. The correlation documentation will be included in the Supplement 2 to NEDO-31690 that is expected in the spring of 1993.

9. The applicability of the delta-CPR correlation (see paragraph 8 above) to new fuels or fuels from different vendors is not clear. This point is being addressed by the BWROG, and a formal position is expected in Supplement 2 to NEDO 31960.

10. Reactor operators have a large degree of freedom to chose control rod patterns and power distributions during startup at low powers. Some of these "achievable" power distributions may result in instabilities outside the exclusion region, even if the reload confirmation procedures were successful. Criteria must be set by the BWROG to assure the operator that the reactor is within the limits where the Solution I exclusion region is applicable.

11. Under normal conditions, single-channel instabilities are not probable, because these conditions are likely to induce an out-of-phase instability before the single-channel instability develops. This argument, however, is based on the fact that many channels of the same type are loaded, and therefore, if one channel is close to instability, many channels will also be unstable and are likely to produce a global out-of-phase oscillation. This is not the case, however, with lead use assemblies (LUAs), where perhaps only one channel of that type is loaded. If this LUA had stability characteristics quite different from those of the rest of the core, a single-channel instability in the LUA could be possible. For this reason, we are recommending that the thermohydraulic stability of all LUAs be determined (see recommendation 13).

Recommendations

1. Approve the overall exclusion region calculation methodology as described in NEDO-31960 and its Supplement 1. The results of these exclusion region calculations may be used as part of the implementation of Solutions I and III.

2. Approve the overall treatment of uncertainties described in NEDO-31960 as it applies to the selection of initial conditions for exclusion region calculations and its confirmatory runs.

3. Pending review of the specific reload confirmation procedures that should be outlined in a second supplement to NEDO-31960, approve Solution Concept I-A for implementation in any BWR line with the following design objectives:

    3.1 Specific reload confirmation procedures must be developed so that for every reload, the licensee can either (1) confirm the applicability of old exclusion region settings, or (2) set a new exclusion region boundary.

    3.2 Favor implementations of Solution I-A that are not expected to change the exclusion boundary setpoints on a cycle-by-cycle basis. Confirmatory calculations should be expected to be positive most of the time; major setpoint changes should only be expected following significant fuel design changes.

    3.3 Select rod insert (SRI) may be used in conjunction with Solution I-A, but a full scram must take effect if the reactor does not exit the region within a reasonable period of time (of the order of a few seconds).

4. Do not approve Solution Concept I-B at this time. Solution I-B has not been developed in detail by the BWROG. If a licensee chose to implement Solution I-B, they would have to resolve the question of whether a noise-based stability monitor can provide adequate protection against instabilities in the out-of-phase mode.

5. Do not approve Solution Concept I-C at this time. Solution I-C has not been developed in detail by the BWROG.

6. Do not approve Solution Concept I-D at this time until lead plant confirmation analyses are performed, documented, and reviewed. It is expected that Supplement 2 to NEDO 31960 (due spring 1993) will contain confirmation analyses for the Duane Arnold plant that will allow a detailed review and a final decision on the acceptability of Solution Concept I-D. This recommendation does not imply a rejection of Solution I-D; the approval of Solution I-D depends on the details of calculations that have not yet been performed by the BWROG.

7. Approve Solution Concept II for implementation in BWRs with quadrant APRM scram (i.e, in any BWR/2). Oyster Creek has already submitted technical specification changes that implement this solution (see Ref. 5).

8. Approve Solution Concept III for implementation in any BWR line with the following design objectives:

   8.1 To avoid unexpected problems, several diverse algorithms must be used to detect oscillations. Automatic protection action must initiate if either of the algorithms detects oscillations (i.e., the algorithm outputs are connected by a logical OR, not a logical AND).

   8.2 The three algorithms described in NEDO-31960 and its supplement may be used in Solution III. These three algorithms are (1) high LPRM oscillation amplitude, (2) high-low detection algorithm, and (3) period-based algorithm. Preferably, all three algorithms should be used.

   8.3 The licensees that implement these algorithms must demonstrate by analyses the validity of the scram setpoints selected. These analyses may be performed on a representative-plant basis when applicable but must include an uncertainty treatment that takes into account the number of failed sensors permitted by technical specifications.

   8.4 The scram setpoints should be selected such that at least one of the algorithms has a large probability of detecting the oscillation and initiating protective action to prevent violation of any fuel safety criterion.

   8.5 If the algorithms detect oscillations, an automatic protection action must be initiated. This action may be a full scram or an SRI. If an SRI were to be implemented with Solution Concept III, a full scram must take effect if either (1) the oscillations do not disappear in a reasonable period of time, or (2) the reactor remains inside the exclusion region as defined by the general regional exclusion methodology of Solution I-A.

9. The LPRM groupings defined in NEDO 31960 to provide input to the Solution III algorithms appear appropriate for the intended oscillation-detection function. These LPRM groupings are: the oscillation power range monitor (OPRM) for Solution III or the octant-based arrangements for Solution III-A. The minimum requirements for operable number of LPRM detectors set in NEDO 31960 appear appropriate.

10. Approve the overall treatment of uncertainties described in NEDO-31960 as it applies to the selection of oscillation contours and failed LPRMs for Detect and Suppress Concepts (Solution III).

11. Implementation of Solution III will require the documentation of the selection of the bypass region outside which the detect and suppress action is deactivated.

12. The BWROG must establish a criteria to limit the actual radial and axial peaking factors during startup operations to those values considered for the analyses of the exclusion region. This criteria must be based on parameters or information readily available to the operator in the control room. Defining this criteria must be part of the reload confirmation analyses.

13. Establish a procedure to review the thermohydraulic stability of lead use assemblies (LUA). Solutions I and II do not protect the reactor in the case of a single-channel instability, and the protection for Solution III is limited. These instabilities are not likely if many bundles of one type are loaded in the core, but they could be possible if the wrong type of LUA were to be loaded. Thermohydraulic stability analyses must be required during LUA review if Solutions I or II are used.

## REFERENCES


1. General Electric Company, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology*, NEDO-31960, May 1991.

2. General Electric Company, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology*, NEDO-31960 Supplement 1, March 1992.

3. General Electric Company, *Fuel Thermal Margin During Core Thermal Hydraulic Oscillations in a Boiling Water Reactor*, NEDO-31708, June 1989

4. B-G Bergdahl and R. Oguma, "BWR Stability Investigation in Ringhals-1 Measurement Data from October 26, 1989," *Proceedings of The International Workshop on Boiling Water Reactor Stability, Holtsville, N.Y., 17—19 October 1990*, pp 142—159, OECD/NEA/CSNI Report No 178, October 1990.

5. Oyster Creek Nuclear Generating Station, *Technical Specification Change Request No. 191*, Docket No. 50-219, October 9, 1991.

## APPENDIX A

## LAPUR AUDIT CALCULATIONS OF Solution I EXCLUSION REGION CALCULATIONS

### AUDIT CALCULATIONS

A series of audit calculations were performed with the LAPUR code to verify the results presented by the BWROG that were based on FABLE/BYPSS calculations. All relevant input data used in the FABLE/BYPSS was made available for this review, and we set up LAPUR input decks that were representative of the conditions modeled by FABLE. The main result of these calculations is presented in Table A.1 and Figs A.1 and A.2. We observe that the maximum difference between LAPUR- and FABLE-calculated decay ratios is 0.09. This can be considered as excellent agreement and representative of the differences in modeling of both codes.

This type of code-to-code benchmark is not as good as a code-to-data benchmark, but it assures that gross modeling errors or systematic errors in the preparation of the input decks have not occurred. Furthermore, it ensures that "data fudging" is not taking place to obtain desired results, because all the data has to be made available and is evaluated for expected value ranges.

Both codes, LAPUR and FABLE, have been benchmarked against data from actual stability tests with satisfactory results. In general, it is recognized that this type of frequency-domain codes has an accuracy better than 20%. Thus, if a decay ratio of 0.8 or smaller is calculated, it is highly probable that stable reactor operation will result. Decay ratios larger than 0.8 result in smaller probabilities of stable operation. Note, however, that large errors are possible if the proper data are not used as input to the code. The 20% error quoted above is for detailed test benchmarks where extreme care is taken to reproduce the exact axial and radial power shapes, core pressure drops, and reactivity coefficients; calculations using approximate descriptions of the core operating condition are likely to result in larger errors.

The axial power shapes assumed in the BWROG analysis are: (1) fairly uniform (end-of-cycle Haling) shape to calculate the corewide decay ratio, and (2) strongly bottom peaked (2.0 peaking at node 3/24) to calculate the hot-channel thermohydraulic decay ratio. It is well known that the high-power channels (maybe 25% of the total number of channels) have the most influence in the stability of the reactor. This is due to the fact that the adjoint flux and density reactivity coefficients are higher in the high-power channels. Furthermore, hot channels tend to have bottom-peaked power shapes, that may be more unstable. To test the validity of the uniform power shape assumption, we ran two cases to determine corewide stability boundary: (1) with all channels having the same Haling power shape and (2) with a graded axial power shape, so that the hot channels have a bottom-peaked shape (2.0 at node 3/24), but the core average is the same as in case (1). The chosen power shapes are drawn in Figs. A.3 and A.4 for a BWR/3 and BWR/5 respectively. The out-of-phase and hot-channel decay ratio calculations were based on the graded power shapes of Figs. A.3 and A.4. The out-of-phase decay ratio was calculated by LAPUR assuming an eigenvalue separation of \$1.00 between fundamental and first harmonic neutronic modes. This \$1.00 value is a representative, but not bounding value of the eigenvalue separation. These results show that the uniform (Haling) power shape is more conservative at lower flows, but the use of bottom peaked graded shapes results in higher decay ratios at higher flows.

**Reload Confirmation Procedures**

The main technical issue of significant relevance that still remains to be solved is the reload-dependent confirmatory analyses required to assert the applicability of the previous-cycle safety settings and, in particular, the applicability of "old" exclusion regions to new types of fuel and loading patterns. The BWROG is aware of this problem and is currently developing a methodology for these cycle-dependent confirmations that is based on a "response surface" approach. The goal is that these confirmatory calculations should be expected to be positive most of the time; major setpoint changes should only be expected following significant fuel design changes. The documentation of this reload-confirmation methodology is expected in Supplement 2 to NEDO-31960 that should be published in the spring of 1993.

Of particular concern is how the reload procedures will be used to evaluate startup power distributions. For example, the root cause of a recent instability event in a BWR/5 has been determined to be the extreme radial (1.92) and axial (up to 1.87) peaking factors during the startup. This extreme power distribution was apparently not covered by the standard exclusion region calculations, which assumed a more mild radial power peaking factor. Nevertheless, the operator was allowed to have that extreme distribution without violating any thermal limits.

Figure A.5 shows a comparison of the equilibrium-cycle exclusion region for the Perry reactor (a BWR/6) and the exclusion region that results if the actual axial and power shapes from the recent BWR/5 event are used. As it can be observed, the standard BWR/6 exclusion region from NEDO-31960 is not as conservative as the actual region. Therefore, we have recommended that the BWROG must establish a criteria to limit the actual radial and axial peaking factors during startup operations to those values considered for the analyses of the exclusion region. This criteria must be based on parameters or information readily available to the operator in the control room.

Table A.1. LAPUR-FABLE/BYPSS benchmark/audit calculations

| Reactor type | Power (%) | Flow (%) | Corewide decay ratio | | Hot-channel decay ratio | |
|---|---|---|---|---|---|---|
| | | | FABLE | LAPUR | FABLE | LAPUR |
| BWR/3 | 42 | 30 | 0.77 | 0.68 | 0.34 | 0.28 |
| | 52 | 45 | 0.46 | 0.47 | 0.19 | 0.17 |
| | 71 | 45 | 0.65 | 0.64 | 0.35 | 0.38 |
| | 84 | 60 | 0.45 | 0.41 | 0.21 | 0.28 |
| BWR/5 | 42 | 30 | 0.65 | 0.73 | 0.50 | 0.50 |
| | 52 | 45 | 0.39 | 0.37 | 0.34 | 0.32 |
| | 71 | 45 | 0.56 | 0.50 | 0.55 | 0.62 |
| | 84 | 60 | 0.30 | 0.32 | 0.31 | 0.39 |

Table A.2. Typical LAPUR5X input deck for a BWR/3

```
LAPUR5X :: BWROG-1 BWR3 71/45
 1
988.8, 502.3, 1782.9, 44.01E6, 0.101, 0.035, 0.80, 1.0
 2
7, 24, 0, 1, 0, 0, 0, 1, 0
 3
5, 25, 25, 25, 25, 25
 4
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 30.48
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 30.48
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 30.48
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 30.48
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
     15.875, 15.875, 15.875, 30.48
 5
     0.27, 0.86, 1.02, 1.06, 1.08, 1.09, 1.10,
     1.11, 1.14, 1.15, 1.16, 1.16, 1.17, 1.17,
     1.17, 1.16, 1.15, 1.14, 1.11, 1.06, 0.98,
     0.85, 0.58, 0.27, 0.00
     0.92, 1.64, 2.00, 1.88, 1.70, 1.53, 1.37,
     1.25, 1.15, 1.07, 1.00, 0.95, 0.90, 0.86,
     0.81, 0.78, 0.74, 0.70, 0.66, 0.60, 0.53,
     0.44, 0.33, 0.19, 0.00
     0.20, 1.20, 1.40, 1.60, 1.51, 1.40, 1.30,
     1.22, 1.15, 1.09, 1.04, 1.00, 0.97, 0.94,
     0.90, 0.87, 0.84, 0.81, 0.78, 0.73, 0.67,
     0.59, 0.48, 0.33, 0.00
     0.20, 1.00, 1.10, 1.30, 1.29, 1.24, 1.19,
     1.14, 1.11, 1.08, 1.05, 1.03, 1.00, 0.99,
     0.96, 0.95, 0.93, 0.91, 0.89, 0.85, 0.81,
     0.75, 0.67, 0.54, 0.00
     0.03, 0.13, 0.12, 0.13, 0.32, 0.55, 0.77
     0.96, 1.15, 1.29, 1.41, 1.49, 1.57, 1.63
     1.70, 1.72, 1.74, 1.75, 1.72, 1.67, 1.54
     1.29, 0.69, 0.02, 0.00
 7
7,  1,   1,   1,   1,   1,   1,   1
 9
7, 127.2, 127.0,  98.6, 129.3,  97.4, 127.3,  25.0
 10
7,  36.8,  36.8,  36.8,  36.8,  36.8,  36.8, 229.0
 11
7, -0.280, -0.280, -0.280, -0.280, -0.280, -0.280, -0.280
 13
7,  0.,   0.,   0.,   0.,   0.,   0.,   0.
 14
7,  81,   87,   73,  106,   91,  202,   84
 15
7,  60,   60,   60,   62,   60,   62,   62
 16
7,  1,    1,    1,    2,    1,    2,    2
 17
     2, 411.48, 411.48
 18
     2, 231.24, 238.96
 19
     2, 97.97, 101.15
 20
     2, 97.97, 101.15
 21
     2,  1.33,  1.34
 22
     2,  0.1,   0.1
 23
```

```
    2,  0.1,  0.1
24
    2,  1.3,  1.3
25
    2, 0.125, 0.125
26
7,  1,   1,   1,   2,   1,   2,   2
27
    2, 10.44, 10.33
28
    2, 1.0439, 1.0414
29
    2, 0.5581, 0.5581
30
    2, 0.0373, 0.0373
31
    2, 0.0813, 0.0813
32
    2, 0.2675, 0.2347
33
    2, 0.0114, 0.0114
34
7,  1,   1,   1,   1,   1,   1,   1
35
    1,   1
36
       411.48
37
         1.40
53
 1.E-3, 1.E-3, 1.E-3, 2.E-5, 1.E-3, 1.E-9, 1.E-2, 5.E-8
54
    1, 12
 0
```

Table A.3. Typical LAPUR5W input deck for a BWR/3

```
LAPUR5W :: BWROG-1 BWR3 71/45
 1
  7, 1, 1
 2
    81,   87,   73,  106,   91,  202,   84
 3
    411.48
 4
```

```
      0.2, -0.3                                                                  0
5
 1   6
6
               1
7
   6, 0.185E-3, 1.226E-3, 1.096E-3, 2.210E-3, 0.647E-3, 0.236E-3
8
   6,   0.0124,   0.0305,   0.1110,   0.3010,   1.1300,   3.0000
9
               1
10
     1      0.0
11
               1
12
     1    4.E-5
17
       -2.5E-03
18
     1        7
19
              1,     1,     1,     1,     1,     1,     1
20
            1.2,    1.0,    0.8,    0.6,    0.4,    0.2,    0.0
21
         -5.64,   5.66,   14.06, 18.84,  20.51,  20.98,  21.44
22
   12,  0.20, 0.30, 0.40, 0.43, 0.46, 0.50, 0.53
      0.56, 0.60, 0.63, 0.66, 0.70
23
 0   1   1   1   1   1   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0
24
 1   1   1   1   1   1   1   1   1
28
    1.
29
     5      0.0     -0.5     -1.0     -1.5     -2.0
30
     0
```

Table A.4. Typical LAPUR5X input deck for a BWR/5

```
LAPUR5X :: BWROG-1 BWR5 71/45
  1
988.8, 505.7, 2359., 48.7E6, 0.095, 0.035, 0.80, 1.0
  2
7, 24, 0, 1, 0, 0, 0, 1, 0
  3
5, 25, 25, 25, 25, 25
  4
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 30.48
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 30.48
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 30.48
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 30.48
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 15.875, 15.875, 15.875, 15.875
        15.875, 15.875, 15.875, 30.48
  5
        0.319 , 0.9116, 1.1074, 1.1675, 1.1771, 1.1688, 1.1563
        1.1448, 1.1338, 1.1236, 1.1168, 1.1144, 1.115 , 1.1168
        1.1176, 1.1162, 1.1104, 1.0959, 1.0671, 1.0159, 0.9304
        0.7936, 0.6085, 0.2713, 0.0
        0.9200, 1.6400, 2.0000, 1.8800, 1.7000, 1.5300, 1.3700
        1.2500, 1.1500, 1.0700, 1.0000, 0.9500, 0.9000, 0.8600
        0.8100, 0.7800, 0.7400, 0.7000, 0.6600, 0.6000, 0.5300
        0.4400, 0.3300, 0.1900, 0.00
        0.6243, 1.4709, 1.6902, 1.6185, 1.5084, 1.4012, 1.2969
        1.2163, 1.1473, 1.0909, 1.0404, 1.0037, 0.9664, 0.9361
        0.8977, 0.8743, 0.8427, 0.8105, 0.7778, 0.7276, 0.6671
        0.5856, 0.4788, 0.3253, 0.0
        0.6279, 1.2755, 1.3809, 1.3471, 1.2940, 1.2406, 1.1870
        1.1442, 1.1067, 1.0752, 1.0465, 1.0253, 1.0033, 0.9852
        0.9619, 0.9475, 0.9278, 0.9074, 0.8863, 0.8531, 0.8118
        0.7536, 0.6716, 0.5385, 0.0
        0.1017, 0.6170, 0.7994, 0.9319, 1.0072, 1.0526, 1.0894
        1.1146, 1.1341, 1.145 , 1.1640, 1.1795, 1.1998, 1.2183
        1.2395, 1.2494, 1.2567, 1.2508, 1.2230, 1.1694, 1.0680
        0.8977, 0.6653, 0.2213, 0.0
  7
7,    2,    3,    4,    5,    5,    5,    5
  9
7, 121.11, 121.60, 121.72, 122.39, 121.26, 121.96,  32.94
  10
7,  27.7,  27.7,  27.7,  27.7,  27.7,  27.7,  193.0
  11
7, -0.280, -0.280, -0.280, -0.280, -0.280, -0.280, -0.280
  13
7,   0.,   0.,   0.,   0.,   0.,   0.,   0.
  14
7,   83,   87,  100,  110,  122,  170,   92
  15
7,   62,   62,   62,   62,   62,   62,   62
  16
7,    1,    1,    1,    1,    1,    1,    1
  17
      1   411.48
  18
      1   238.96
  19
      1   101.15
  20
      1   101.15
  21
      1     1.34
  22
      1     0.1
  23
```

```
     1     0.1
24
     1     1.3
25
     1   0.125
26
7,   1,    1,    1,    1,    1,    1,    1
27
     1   10.33
28
     1  1.0414
29
     1  0.5581
30
     1  0.0373
31
     1  0.0813
32
     1  0.2256
33
     1  0.0114
34
7,   1,    1,    1,    1,    1,    1,    1
35
     1     1
36
       411.48
37
         1.40
53
 1.E-3   1.E-3   1.E-3   2.E-5   1.E-3   1.E-9   1.E-2   5.E-8
54
     1    25
56
 11  12  13   0
 0
```

Table A.5. Typical LAPUR5W input deck for a BWR/5

```
LAPUR5W :: BWROG-1 BWR5 71/45
 1
  7, 1, 1
2
     83,   87,   100,   110,   122,   170,   92
3
```

```
      411.48
4
      0.2, -0.3
5
 1   6
6
              1
7
  6, 0.185E-3, 1.226E-3, 1.096E-3, 2.210E-3, 0.647E-3, 0.236E-3
8
  6,   0.0124,   0.0305,   0.1110,   0.3010,   1.1300,   3.0000
9
              1
10
     1       0.0
11
              1
12
     1     4.E-5
17
       -2.5E-03
18
     1          7
19
             1,       1,       1,       1,       1,       1,       1
20
           1.2,     1.0,     0.8,     0.6,     0.4,     0.2,     0.0
21
         -6.05,   3.63,   11.81, 17.19,   19.84,  20.78,  21.70
22
  12,  0.20, 0.30, 0.40, 0.43, 0.46, 0.50, 0.53
       0.56, 0.60, 0.63, 0.66, 0.70
23
 0   1   1   1   1   1   0   0   0   0   0   0   0   0
 0   0   0   0   0   0   0   0
24
 1   1   1   1   1   1   1   1   1
28
    1.
29
     5       0.0      -0.5      -1.0      -1.5      -2.0

30
    0
0
```

Table A.6. LAPUR calculations for a typical BWR/3
(DR = decay ratio, NF = natural frequency of oscillation)

| Flow (Mlb/h) | Power (MW) | Corewide* | | Out-of-phase | | Hot-channel | | Corewide** | |
|---|---|---|---|---|---|---|---|---|---|
| | | DR | NF (Hz) | DR | NF (Hz) | DR | NF (Hz) | DR | NF (Hz) |
| 10 | 800 | | | 0.93 | 0.31 | 0.80 | 0.27 | 1.13 | 0.31 |
| 20 | 800 | 0.82 | 0.26 | 0.36 | 0.34 | 0.32 | 0.29 | 0.64 | 0.34 |
| 20 | 1000 | | | 0.65 | 0.38 | 0.48 | 0.34 | 0.85 | 0.38 |
| 20 | 1200 | | | 0.95 | 0.41 | 0.67 | 0.37 | 1.07 | 0.41 |
| 29.4 | 1060 | 0.68 | 0.32 | 0.28 | 0.41 | 0.28 | 0.36 | 0.50 | 0.42 |
| 29.4 | 1200 | 0.79 | 0.34 | | | | | | |
| 29.4 | 1500 | | | 0.79 | 0.50 | 0.55 | 0.45 | 0.86 | 0.50 |
| 44 | 1306 | 0.47 | 0.37 | 0.14 | 0.48 | 0.17 | 0.42 | 0.29 | 0.48 |
| 44 | 1783 | 0.64 | 0.44 | 0.45 | 0.59 | 0.38 | 0.54 | 0.51 | 0.58 |
| 44 | 2000 | 0.69 | 0.43 | 0.66 | 0.62 | 0.49 | 0.57 | 0.64 | 0.61 |
| 44 | 2500 | 0.85 | 0.51 | 1.05 | 0.67 | 0.84 | 0.62 | 0.98 | 0.66 |
| 50 | 2500 | | | 0.82 | 0.70 | 0.59 | 0.65 | 0.73 | 0.70 |
| 50 | 2600 | | | 0.85 | 0.70 | 0.66 | 0.66 | 0.80 | 0.70 |
| 50 | 3000 | 0.79 | 0.57 | | | | | | |
| 58.7 | 2109 | 0.41 | 0.50 | 0.22 | 0.68 | 0.28 | 0.66 | 0.27 | 0.66 |
| 58.7 | 3000 | | | 0.64 | 0.84 | 0.50 | 0.77 | 0.51 | 0.81 |
| 58.7 | 3200 | | | 0.82 | 0.85 | 0.59 | 0.79 | 0.62 | 0.84 |

* Using average axial power shape for all channels.
** Using graded power shapes of Fig. A.3.

Table A.7. LAPUR calculations for a typical BWR/5
(DR = decay ratio, NF = natural frequency of oscillation)

| Flow (Mlb/h) | Power (MW) | Corewide* | | Out-of-phase | | Hot-channel | | Corewide** | |
|---|---|---|---|---|---|---|---|---|---|
| | | DR | NF (Hz) | DR | NF (Hz) | DR | NF (Hz) | DR | NF (Hz) |
| 10 | 500 | 0.76 | 0.17 | 0.52 | 0.22 | 0.74 | 0.20 | 0.75 | 0.22 |
| 10 | 600 | 1.06 | 0.18 | 0.74 | 0.24 | | | 0.96 | 0.24 |
| 20 | 800 | 0.76 | 0.24 | 0.49 | 0.31 | 0.40 | 0.27 | 0.65 | 0.31 |
| 20 | 1000 | 0.96 | 0.27 | 0.84 | 0.35 | 0.63 | 0.31 | 0.93 | 0.34 |
| 32.5 | 1396 | 0.73 | 0.35 | 0.68 | 0.46 | 0.50 | 0.42 | 0.72 | 0.45 |
| 32.5 | 1500 | 0.78 | 0.36 | 0.83 | 0.47 | 0.57 | 0.43 | 0.82 | 0.46 |
| 32.5 | 1600 | 0.83 | 0.38 | | | | | | |
| 48.7 | 2200 | | | 0.72 | 0.63 | 0.53 | 0.59 | 0.57 | 0.61 |
| 48.7 | 2360 | 0.50 | 0.49 | 0.87 | 0.65 | 0.62 | 0.60 | 0.69 | 0.63 |
| 48.7 | 2500 | 0.55 | 0.50 | 0.99 | 0.66 | 0.70 | 0.62 | 0.80 | 0.64 |
| 48.7 | 3000 | 0.71 | 0.55 | | | | | | |
| 48.7 | 3500 | 0.94 | 0.60 | | | | | | |
| 55 | 2500 | | | 0.68 | 0.69 | 0.51 | 0.65 | 0.49 | 0.67 |
| 55 | 2700 | | | 0.84 | 0.71 | 0.61 | 0.67 | 0.62 | 0.69 |
| 55 | 3000 | 0.50 | 0.57 | 1.07 | 0.75 | 0.78 | 0.70 | 0.84 | 0.72 |
| 55 | 4000 | 0.82 | 0.66 | | | | | | |
| 65 | 2791 | 0.32 | 0.58 | 0.32 | 0.78 | 0.39 | 0.75 | 0.23 | 0.74 |

* Using average axial power shape for all channels.
** Using graded power shapes of Fig. A.3.

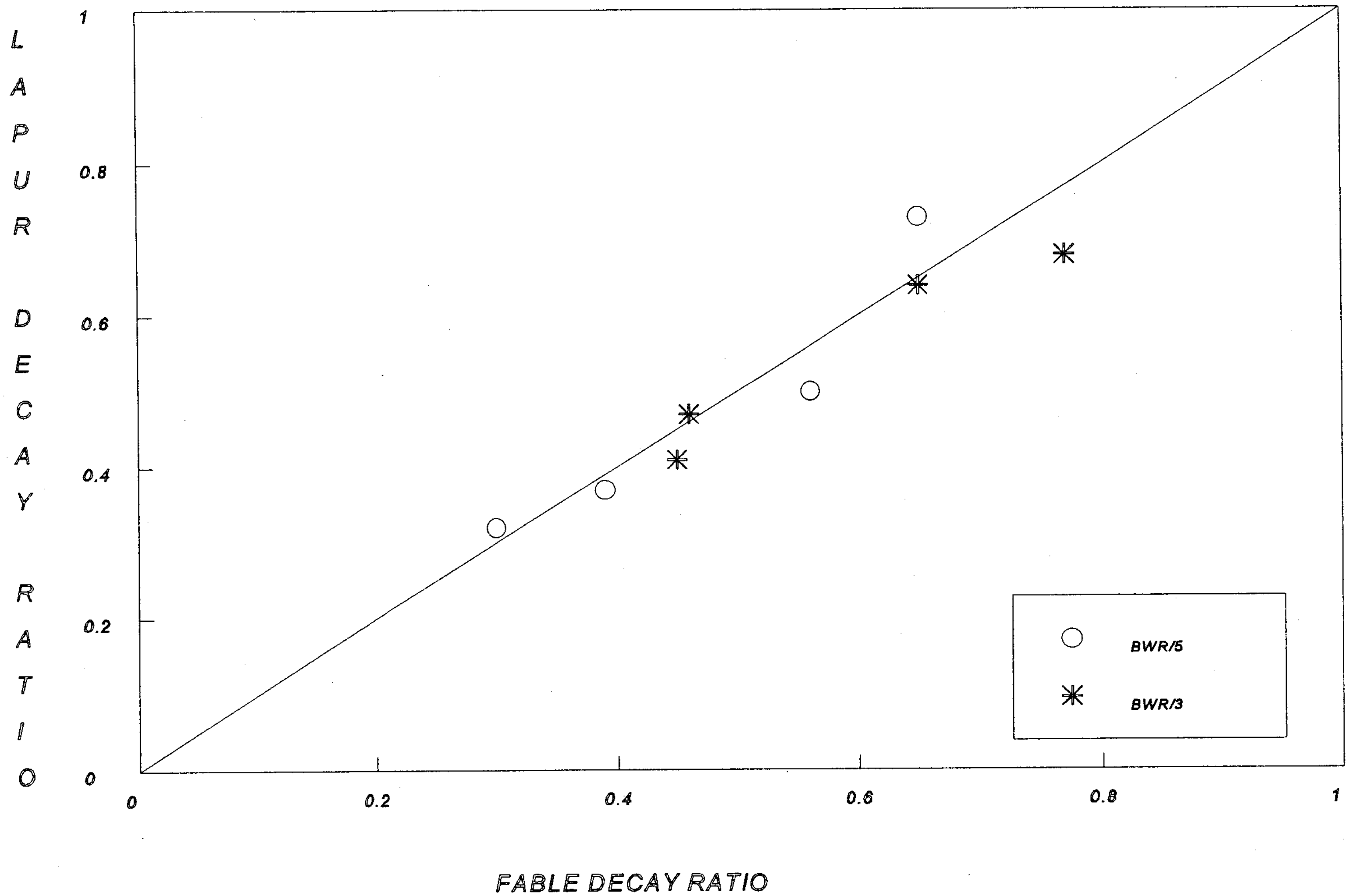


**Figure A.1**. Comparison between corewide decay ratios calculated by LAPUR and FABLE.

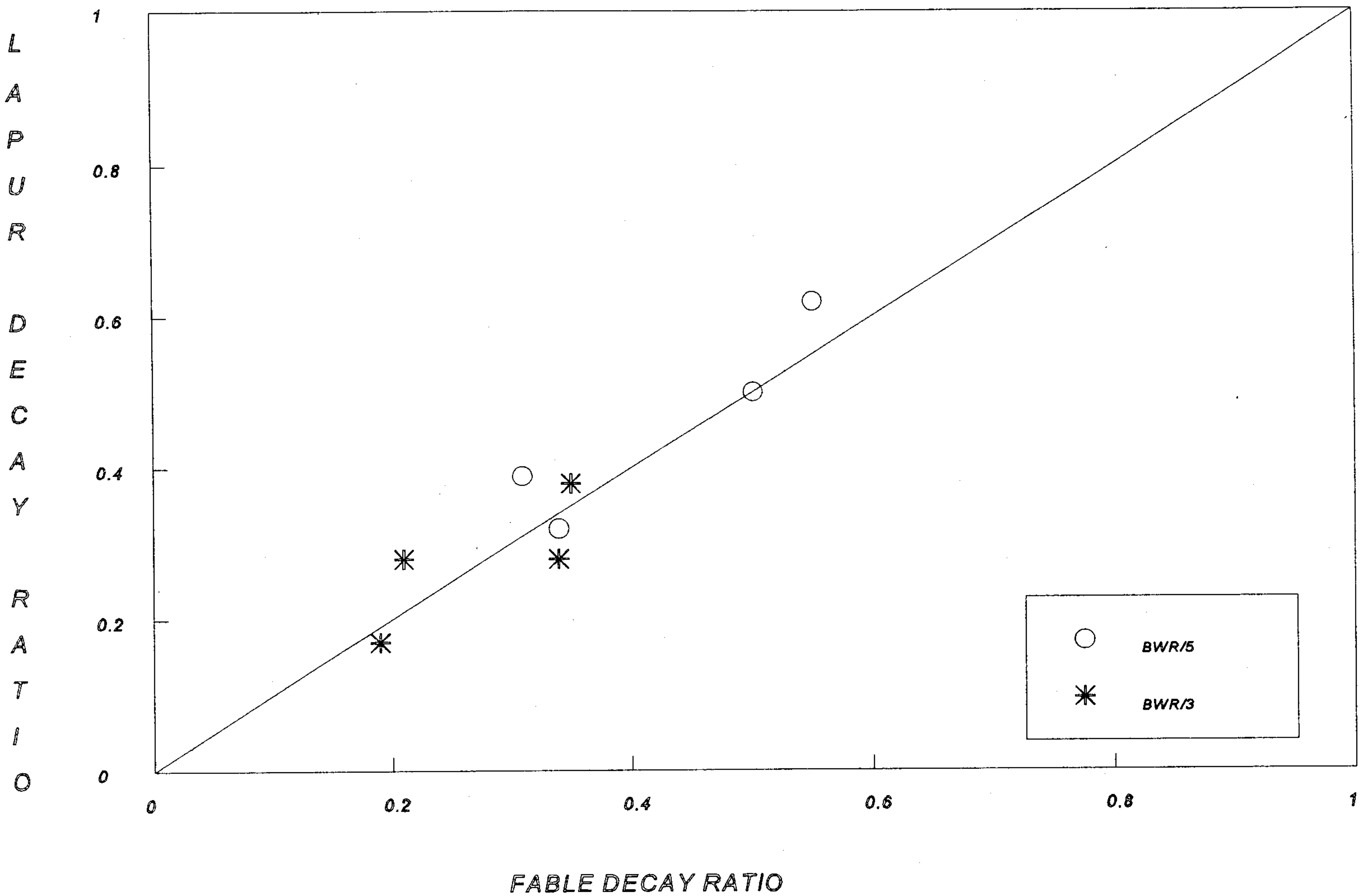


**Figure A.2**. Comparison between hot-channel decay ratios calculated by LAPUR and FABLE.

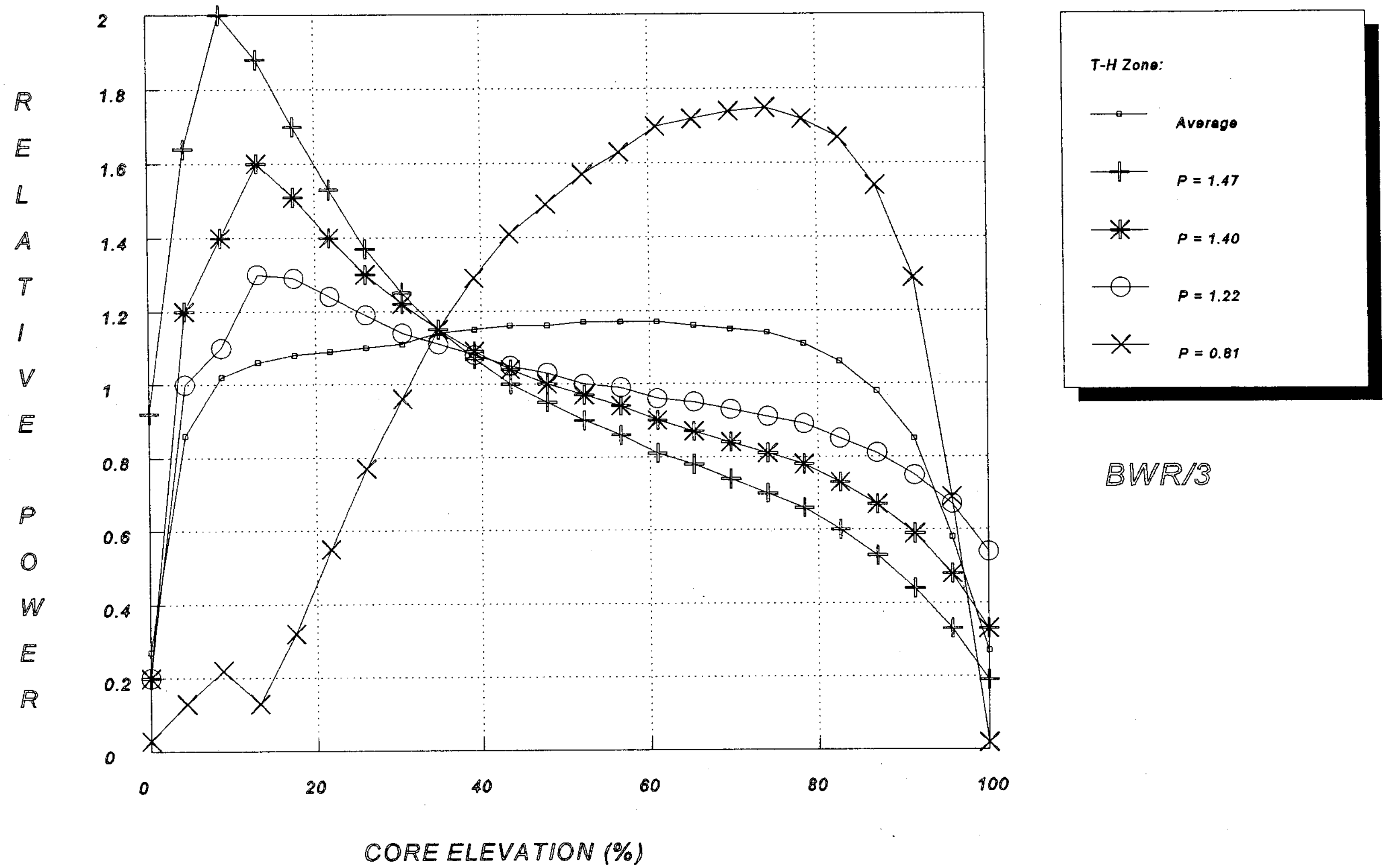


**Figure A.3**. Power shapes used for hot-channel and out-of-phase mode calculations in a typical BWR/3.

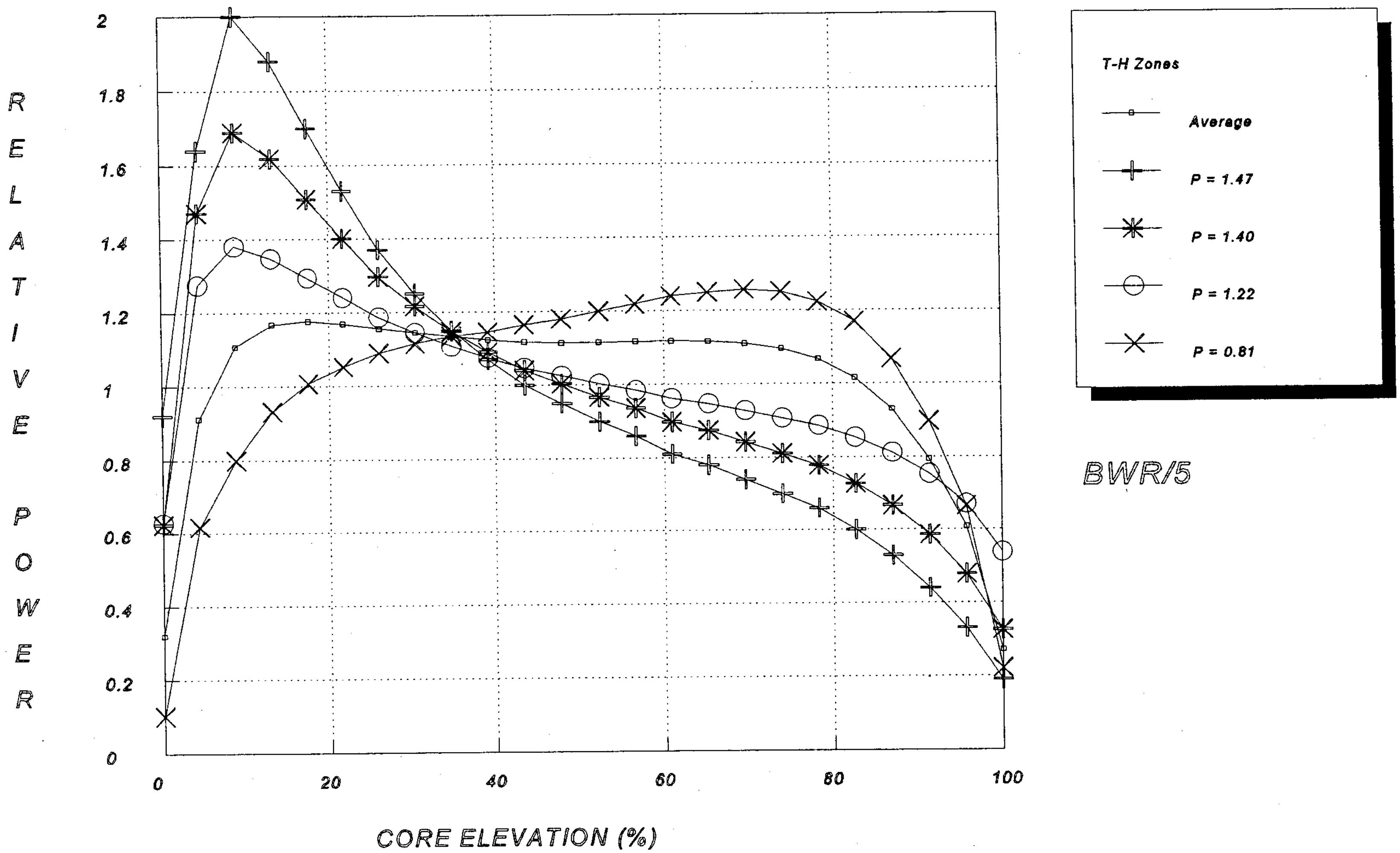


**Figure A.4**. Power shapes used for hot-channel and out-of-phase mode calculations in a typical BWR/5.

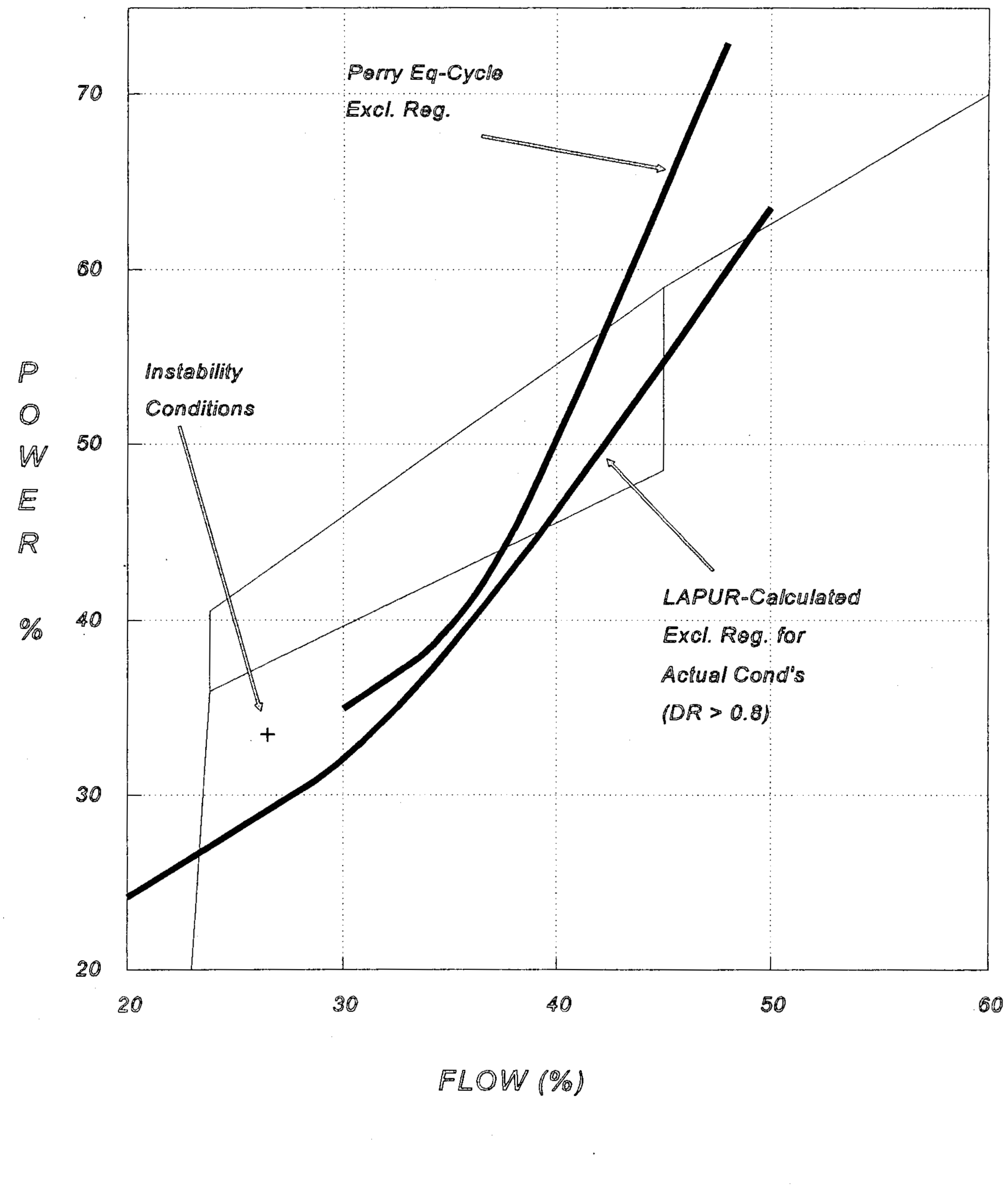


**Figure A.5.** Comparison between equilibrium-cycle exclusion region and the exclusion region for the specific operating conditions of a BWR/5 instability event.

## APPENDIX B
## Solution I-D REQUIREMENTS

This section defines a minimum set of items that will have to be provided to complete our review of Solution I-D. These items should be provided for the initial Solution I-D lead plant (Duane Arnold).

1. Describe how the exclusion region for administrative control actions will be calculated and defined.

2. Describe in detail the proposed administrative control actions if the reactor enters the exclusion region.

3. Describe any hardware or administrative control rod block functions that will be associated with the exclusion region. Specifically, describe how these functions are calculated and defined and what type of automated or operator action is required.

4. Describe in detail the information that the operator relies on to provide these administrative controls. In particular, describe how the information is presented to the operator and its "safety classification" (i.e, Class 1-E or not). Explain why this safety classification is adequate.

5. Describe what indications the operator would have in the control room if a power oscillation (either in-phase or out-of-phase) were to develop. Describe the operator actions required under these circumstances.

6. Provide analyses showing the area inside the exclusion region where the flow-biased scram does not provide protection for out-of-phase instabilities. These calculations determine the nonprotection line, which is defined as the line in the power-flow map below which the flow-biased scram does not provide automatic protection. Two lines must be defined:

   6.1 The nonprotection line at the 95% probability level with the initial CPR at technical specification limits.

   6.2 The nonprotection line at the 50% probability level with the expected initial CPR.

7. Provide reasonably bounding analyses showing that oscillations in the out-of-phase mode are highly unlikely in Solution I-D plants operating below the 50%-level nonprotection line. These calculations must be performed along the 50%-level nonprotection line and include at least the following cases:

   7.1 Calculations of core and hot-channel decay ratios using the standard BWROG procedures for exclusion region calculations (NEDO 31960). These calculations must show that the core decay ratio is significantly larger than the hot-channel decay ratio so that the predicted mode of oscillation for these conditions is in-phase. Provide documentation of the radial power distribution (in particular the hot-channel peaking factor) used in these calculations, and justify why the chosen peaking factors are conservative.

7.2 Calculations of core and hot-channel decay ratios using conservatively defined bottom-peaked power shapes that are more representative of startup conditions than the standard BWROG procedure. These calculations must include axial and radial power shapes representative of (1) normal startup and (2) operation with failed feedwater heaters. Document the actual power shapes used and justify their conservatism.

## LAPUR CALCULATIONS RELATED TO Solution I-D

A series of calculations have been performed with the LAPUR code to confirm the validity of the BWROG claim that small cores with tight inlet orifices are not likely to have out-of-phase instabilities. The results of our analyses show that indeed (as claimed by the BWROG) small cores and tight inlet orifices are beneficial for the out-of-phase mode. However, this benefit does not appear to be sufficient to completely discard the possibility of out-of-phase instabilities in these types of reactors; therefore, we have requested that the BWROG perform the calculations described in the preceding section. Table B.1 shows some of the results of these analyses.

### Effect of tight inlet orifice

For the calculations presented in Table B.1, we prepared a representative LAPUR input deck (shown in Table B.2) with a single thermohydraulic region and calculated the corewide and out-of-phase decay ratios as a function of the inlet restriction coefficient to simulate the differences between Solution I-D plants and others. In plants where solution I-D is applicable, the inlet restriction coefficient is of the order of 35 to 40 velocity heads, while other plants have values of the order of 25 to 30 velocity heads; for example, Duane Arnold (the proposed lead plant for Solution I-D) has an inlet orifice diameter of 2.09 inches, compared to 2.43 inches for LaSalle. We have to note that the conditions (especially the axial power shape) chosen for these analyses are not representative of normal operation, but they are achievable and not necessarily bounding; these conditions were chosen because they tend to excite the out-of-phase mode more than the corewide. Two main conclusions can be drawn from the results in Table B.1:

(1) The smaller inlet orifice by itself does not preclude the possibility of out-of-phase instabilities. For example, at 35 velocity heads, the out-of-phase mode is predicted to be unstable (decay ratio greater than 0.8) even at large eigenvalue separations of \$1.5.

(2) The smaller orifice by itself does not guarantee that the corewide mode will dominate and become unstable before the out-of-phase mode does. For example, at 35 velocity heads, the out-of-phase decay ratio is 0.90 at \$1.0 subcritical, while the corewide decay ratio is only 0.84.

In summary, even though smaller (tight) inlet orifices are beneficial and tend to stabilize the out-of-phase mode, increasing the orifice coefficient by about 10 velocity heads reduces the out-of-phase decay ratio by only 10% to 20% depending on the actual circumstances. Therefore, tight inlet orifice plants are less likely to have out-of-phase instabilities, but given that it only results in a 10% to 20% reduction, this effect by itself is not sufficient to preclude out-of-phase instabilities.

Effect of smaller cores

Smaller cores affect the stability of the out-of-phase mode by increasing the neutron leakage on the core periphery. Larger leakage rates tend to increase the eigenvalue separation between the fundamental and first azimuthal harmonic; the larger the separation, the more stable the out-of-phase mode (see Table B.1 for an example). Our evaluation analyses using the LAPUR code indicate that the net effect of reducing the core size in half is to reduce the out-of-phase decay ratio by 10% to 15%. This evaluation assumes constant loading patterns and fuel types; positive or negative changes of larger magnitude can be achieved by altering the loading patterns or fuel type. Therefore, we conclude that the net effect of the small core size by itself (although beneficial) is not sufficient to preclude out-of-phase instabilities in Solution I-D plants.

In first approximation (assuming a homogenous, cylindrical core), the eigenvalue separation of the first azimuthal mode, $\rho_s$, is given by

$$\rho_s = \frac{D \Delta B^2}{\nu \Sigma_f} \qquad \textbf{(B-1)}$$

where $\boldsymbol{D}$ is the diffusion coefficient, $\nu\Sigma_f$ is the fission cross section, and $\Delta B^2$ is the difference in geometric buckling between the fundamental and the first azimuthal modes.

The geometric buckling in a cylinder is approximately proportional to the inverse of the radius square and, therefore, is somehow inversely proportional to the number of bundles in the core. Consequently, if core A has half the number of bundles as core B, core A should have approximately twice the eigenvalue separation of core B. From Table B.1, we observe that doubling the eigenvalue separation results in a reduction of decay ratio of the order of 10% to 15%.

The eigenvalue separation, however, depends on many more parameters than just the core size. For instance, super low leakage loading patterns ($SL^3P$) have very low leakage and result in significantly lower eigenvalue separation than in a core the same size with a conventional loading pattern. Another parameter that affects the eigenvalue separation is the fission cross section [see Eq. (B-1)]; therefore, fuels with high enrichment (to allow for longer refueling cycles) should result in smaller eigenvalue separation that can negate the advantages of the small core.

In summary, the core size is an important parameter that affects the eigenvalue separation, but it is not the only one. It is, thus, hard to justify what the eigenvalue separation of a Solution I-D really is.

Operating experience

An additional argument against Solution I-D is the fact that Swedish reactors [for example, Ringahls-1 (see Reference 5)] have experienced out-of-phase instabilities. Swedish BWRs have very tight inlet orifices and have relatively small cores (for instance, Ringahls-1 has only 648 fuel bundles).

Table B.1. LAPUR-calculated decay ratios as a function of inlet orifice size

| | | Inlet restriction coefficient (velocity heads) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 25 vh | 30 vh | 35 vh | 40 vh | 45 vh | 50 vh |
| Average-channel decay ratio | | 0.62 | 0.57 | 0.52 | 0.48 | 0.44 | 0.41 |
| Corewide mode decay ratio | | 0.86 | 0.85 | 0.84 | 0.83 | 0.82 | 0.81 |
| Out-of-phase mode decay ratio, if eigenvalue separation is | $\rho$ = -\$0.5 | 1.08 | 1.02 | 0.96 | 0.92 | 0.87 | 0.83 |
| | $\rho$ = -\$1.0 | 1.06 | 0.97 | 0.90 | 0.83 | 0.77 | 0.71 |
| | $\rho$ = -\$1.5 | 1.01 | 0.90 | 0.81 | 0.73 | 0.66 | 0.61 |

Table B.2. LAPUR5X input for Solution I-D analyses

```
LAPUR5X Test case for BWORG Sol I-D
  1
977.0, 490.0, 1000.0, 20.E6, 0.0, 0.0, 0.63, 1.0
  2
1, 24, 0, 1, 0, 0, 0, 1, 0
  3
1, 25
  4
        15.24, 15.24, 15.24, 15.24, 15.24, 15.24, 15.24
        15.24, 15.24, 15.24, 15.24, 15.24, 15.24, 15.24
        15.24, 15.24, 15.24, 15.24, 15.24, 15.24, 15.24
        15.24, 15.24, 15.24, 45.53
  5
        0.95, 1.60, 1.80, 1.70, 1.55, 1.45, 1.30
        1.20, 1.15, 1.10, 1.00, 0.95, 0.92, 0.90
        0.86, 0.83, 0.80, 0.78, 0.72, 0.67, 0.62
        0.50, 0.40, 0.20, 0.00
  7
1,    1
  9
1,   764
 10
1,  30.0
 11
1, -0.280
 13
1,    0.
 14
1,   764
 15
1,    62
 16
1,    1
 17
        1   411.29
 18
        1   238.96
 19
        1   102.09
 20
        1   102.09
 21
        1     1.36
 22
        1     0.1
 23
        1     0.1
 24
        1     1.3
 25
        1   0.125
 26
1,      1
 27
        1   10.42
 28
        1   1.0400
 29
        1   0.5586
 30
        1   0.0373
 31
        1   0.0813
 32
        1   0.1356
 33
        1   0.0114
 34
1,      1
 35
        1      1
 36
            411.29
 37
              1.40
 53
 1.E-3   1.E-3   1.E-3   2.E-5   1.E-3   1.E-9   1.E-2   5.E-8
 54
```

```
   1     25
0
```

Table B.3. LAPUR5W input for Solution I-D analyses

```
LAPUR5W Test Case for BWROG Sol I-D
1
 1, 1, 1
2
     764
3
     411.29
4
     0.40, -1.5
5
 1  6
6
          1
7
     6  1.95E-4  1.10E-3  9.67E-4  2.09E-3  6.58E-4  1.34E-4
8
     6   0.0127   0.0317   0.0115   0.0331    1.40    3.87
9
          1
10
     1    0.0
11
          1
12
     1  3.29E-5
17
     -2.64 E-03
18
     1     7
19
          1     1     1     1     1     1     1
20
        1.2    1.0    0.8    0.6    0.4    0.2    0.0
21
       -2.662   8.006   18.751   23.450   26.545   27.381   27.805
22
7, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4
23
 0  1  1  1  1  1  0  0  0  0  0  0  0  0
 0  0  0  0  0  0  0  0
24
 1  1  1  1  1  1  1  1  1
28
    1.
29
3, -0.5, -1.0, -1.5
30
    0
 0
```

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