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1. INTRODUCTION

This report documents a technical evaluation of the channel thermohydraulic stability methodology proposed by Westinghouse Nuclear Energy Systems in refs. 1 and 2 for analysis of their boiling water reactor (BWR) fuel. This methodology is based on calculations using the MAZDA-NF code, which is capable of modeling cross-flow between ventilated subchannels of the W-QUAD+ fuel type. Core-wide thermohydraulic stability has not been addressed yet by Westinghouse, and it should be the subject of a different review once the appropriate methodology is established.

Overall, and as a result of this review, we have found Westinghouse's channel stability methodology to be physically sound and appropriate. The design of the W-QUAD+ fuel seems to yield higher channel stability margins than conventional designs due to an increase of approximately 50% in the inlet orifice friction coefficient. In addition, the water-cross design allegedly reduces the density reactivity coefficient by approximately 25%, which implies even higher core-wide stability margins.

The main conclusions and recommendations of the present review can be summarized as:

(1) Westinghouse's calculation methodology presented in refs. 1 and 2 is acceptable for channel thermohydraulic stability estimation.
(2) The uncertainties associated with Westinghouse's channel stability calculations are estimated to be approximately 25%. Consequently, an acceptance threshold value of 0.75 is recommended for calculated channel decay ratios.
(3) Westinghouse has not suggested any course of action in case the threshold in point (2) is violated in a particular reactor. This issue should be addressed either on a generic basis ("SIL 380" type of technical specification) or in individual plant cases.
(4) A core-wide stability methodology has not yet been established by Westinghouse. This methodology must be reviewed separately.

The organization of this report is as follows: First, a summary of Westinghouse's stability methodology is presented in Sect. 2. Section 3 contains our technical evaluation of the current methodology, including benchmark comparisons, audit calculations using ORNL's code LAPUR, and a study of the main sources of error in the current methodology. The conclusions and recommendations arising from this review are presented in Sect. 4.

2. WESTINGHOUSE'S CHANNEL STABILITY METHODOLOGY

The channel thermohydraulic stability methodology proposed by Westinghouse Energy Systems is based on the MAZDA-NF code as described in refs. 1 and 2. The main characteristics of the MAZDA-NF code are:

(1) MAZDA-NF performs single-assembly calculations which take into account the coupled (i.e., ventilated) subchannels of the W-QUAD+ fuel.

(2) MAZDA-NF solves a set of linearized nodal equations in the frequency domain to obtain the channel transfer functions.

(3) The channel stability is evaluated from the above transfer functions and can be reported in terms of an asymptotic decay ratio.

(4) MAZDA-NF models the following dynamic processes that relate to channel thermohydraulic stability:
   - (a) heater wall dynamics, that is, fuel and cladding transfer functions;
   - (b) channel thermohydraulics based on energy, mass, and momentum conservation laws;
   - (c) boiling height dynamics, allowing for the study of the effect of inlet coolant subcooling, although subcooled boiling is not considered;
   - (d) subchannel interactions through ventilation holes, allowing for transverse momentum transfer;
   - (e) localized and distributed pressure drops due to spacers, inlet orifice, etc.

(5) For the purpose of benchmarking against channel stability tests, the MAZDA-NF code has, in addition, provisions for modeling the following dynamic processes:
   - (a) a simple neutronic feedback is included for comparison with other stability calculations.
   - (b) The recirculation loop dynamics, which include the riser section, downcomer, pumps, piping, etc., can be modeled to benchmark MAZDA-NF calculations against loop stability tests.

3. TECHNICAL EVALUATION

3.1 BENCHMARKS

Westinghouse has benchmarked the MAZDA-NF code against a variety of channel stability tests as well as analytical solutions. The analytical solutions are useful to test the validity of MAZDA's numerical implementation of the thermohydraulic model in terms of nodal equations. On the other hand, the benchmark calculations against channel stability tests yield information about Westinghouse's capability of modeling a real-life system for which all conditions are not exactly known.

The results of Westinghouse's analytic benchmarks show that the numerical implementation in the MAZDA-NF code is appropriate, in the sense that it is able to reproduce analytical results for simple configurations.

The results of stability test benchmarks show, in general, good agreement between calculations and measurements except for cases with low inlet subcooling. Referring to Tables 3.6a, 3.6b, and 3.8 of ref. 1, one observes that, as long as the inlet subcooling is greater than 35 Btu/lb_m, there is fairly good agreement between calculated instability-threshold powers and the measured values (with a generally conservative error of about 16%). However, with low subcooling values, the error can be as large as 35% (i.e., the calculated threshold power is 65% of the measured one). This behavior is consistent for all the tests benchmarked in ref. 1, and can be observed in Fig. 1.

Figure 1 presents the calculation relative error (i.e., the ratio between calculated and measured threshold powers) as a function of inlet subcooling. A clear dependency can be observed between the calculation error and the subcooling, but at the high subcoolings typical of BWRs (approximately 40 Btu/lb_m), MAZDA's calculation shows a smaller dispersion error of approximately 16%.

Figure 2 presents the calculation relative error as a function of threshold power for instability. Figure 2a corresponds to the points with inlet subcooling greater than 35 Btu/lb_m, while Fig. 2b contains points with lower subcooling. From a comparison of these two figures, a systematic (bias) error can be observed as a function of the subcooling (i.e., the points in Figs. 2a and 2b lie in different ranges); however, this error is not heavily dependent on the threshold power, as can be observed in Fig. 2. For completeness, Figs. 3 through 5 present, for low and high subcooling cases, the dependence of the calculated relative error on inlet orifice pressure drop, operating pressure, and coolant flow. We observe in these figures a trend similar to the threshold power (Fig. 2), in the sense that there is not an obvious relationship between MAZDA's error and any of these variables once the subcooling dependence has been removed.

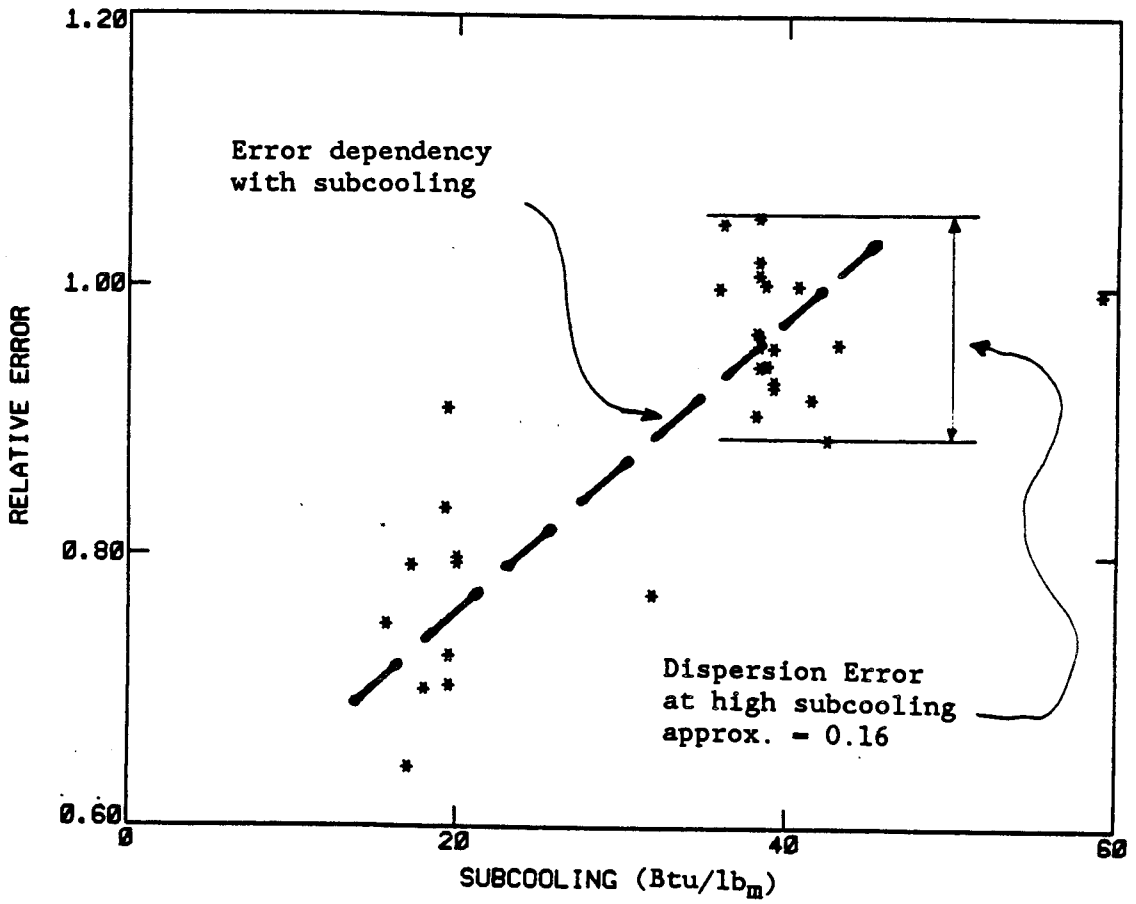


Fig. 1.

We can conclude from the above observations that the MAZDA-NF code is able to model appropriately the dynamic behavior of BWR channels for relatively wide ranges of all the above parameters except inlet subcooling. A typical inlet subcooling value in commercial BWRs operating at low flow conditions (when instabilities are likely) is 40 Btu/lb$_m$. In this range of subcooling, MAZDA-NF exhibits good behavior and predicts threshold powers fairly accurately (within 16%). Nevertheless, the error at low subcooling represents a modeling problem that should be taken into account when assigning a threshold value for acceptance of MAZDA-NF calculations.

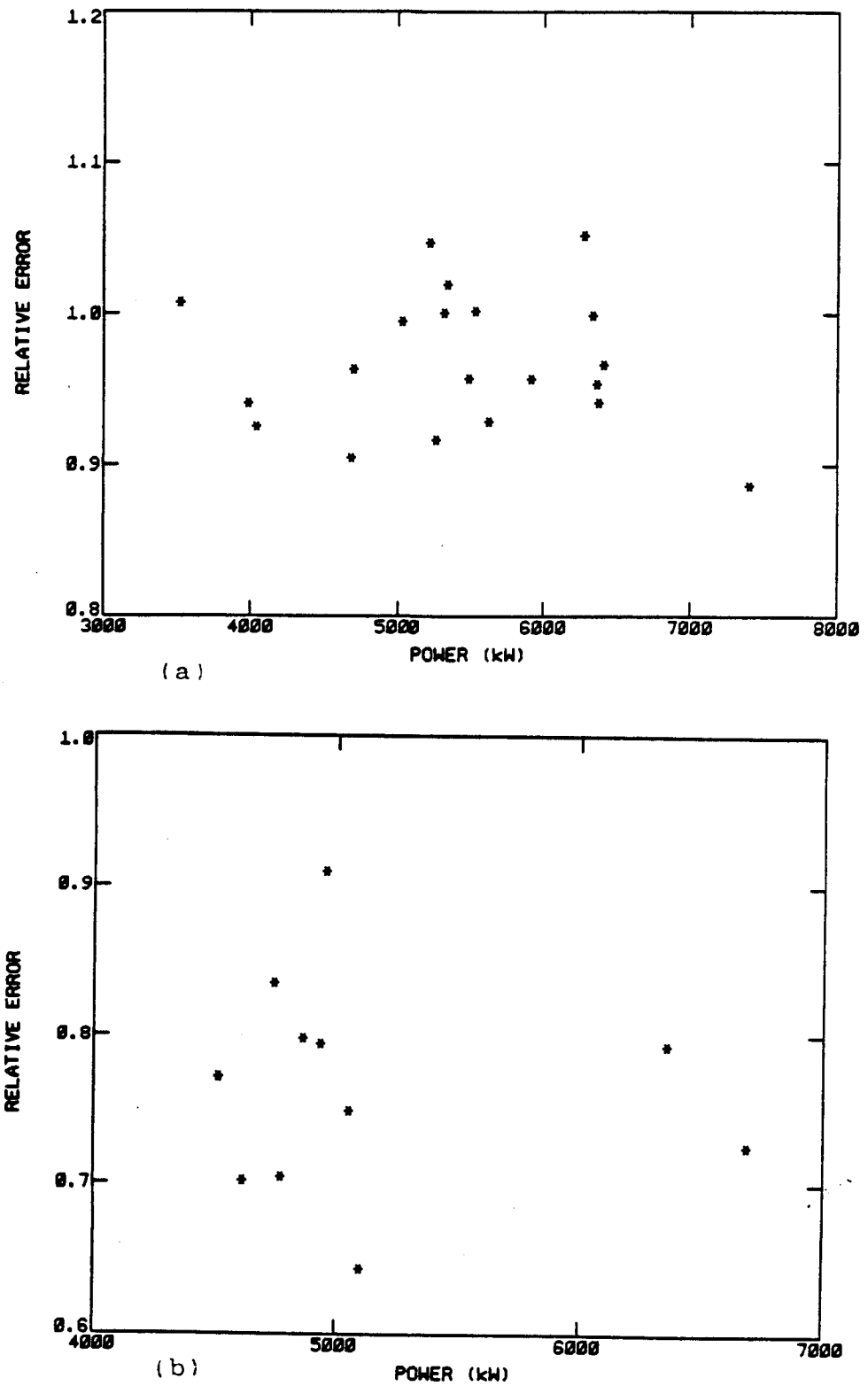


Fig. 2. Relative error (i.e., ratio of calculated to measured threshold power for instability) in MAZDA-NF calculations as a function of threshold power for instability: (a) subcooling greater than 35 Btu/lb_m, (b) subcooling less than 35 Btu/lb_m.

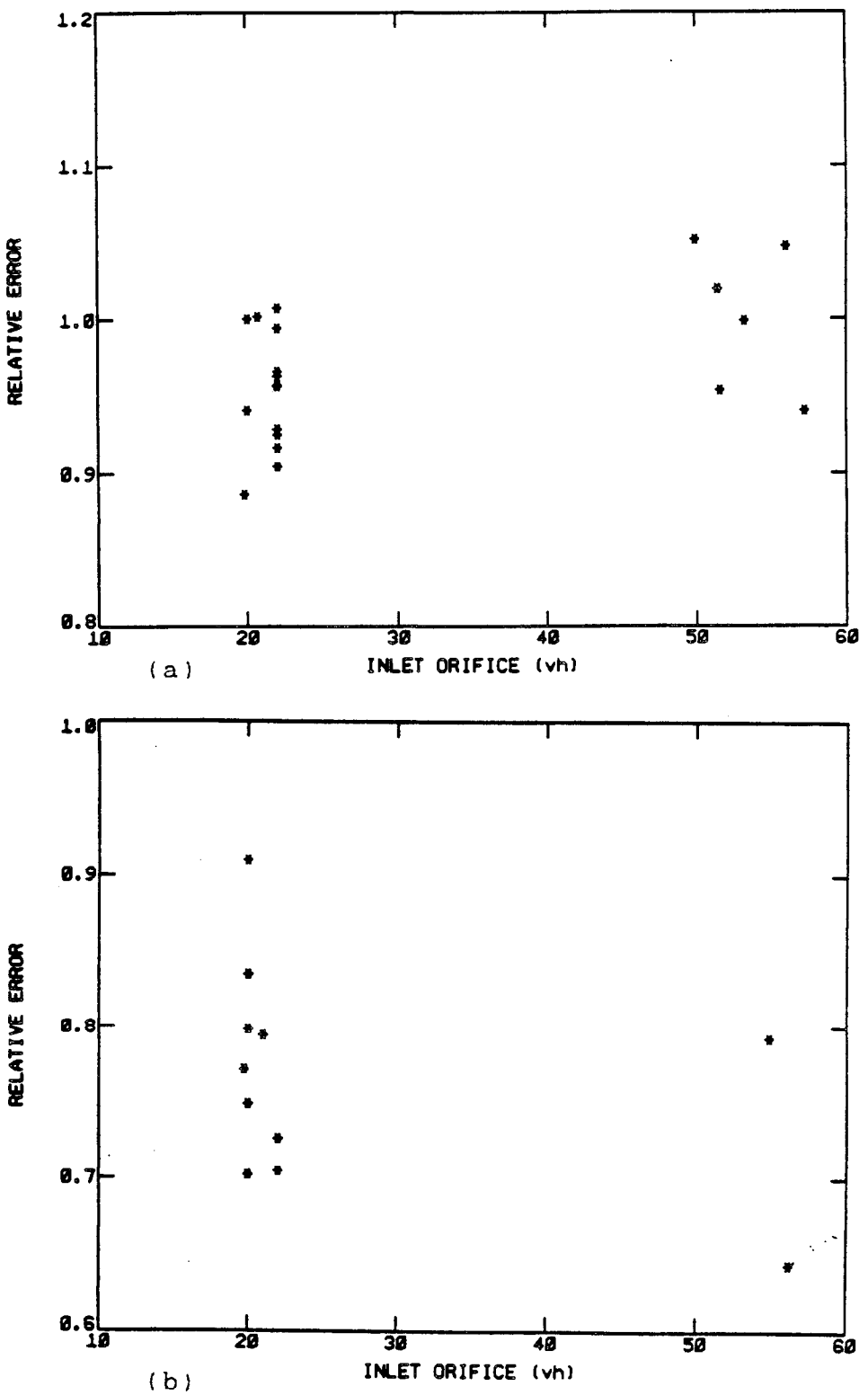


Fig. 3. Relative error (i.e., ratio of calculated to measured threshold power for instability) in MAZDA-NF calculations as a function of inlet orifice friction coefficient in velocity heads (vh): (a) subcooling greater than 35 Btu/lb_m, (b) subcooling less than 35 Btu/lb_m.

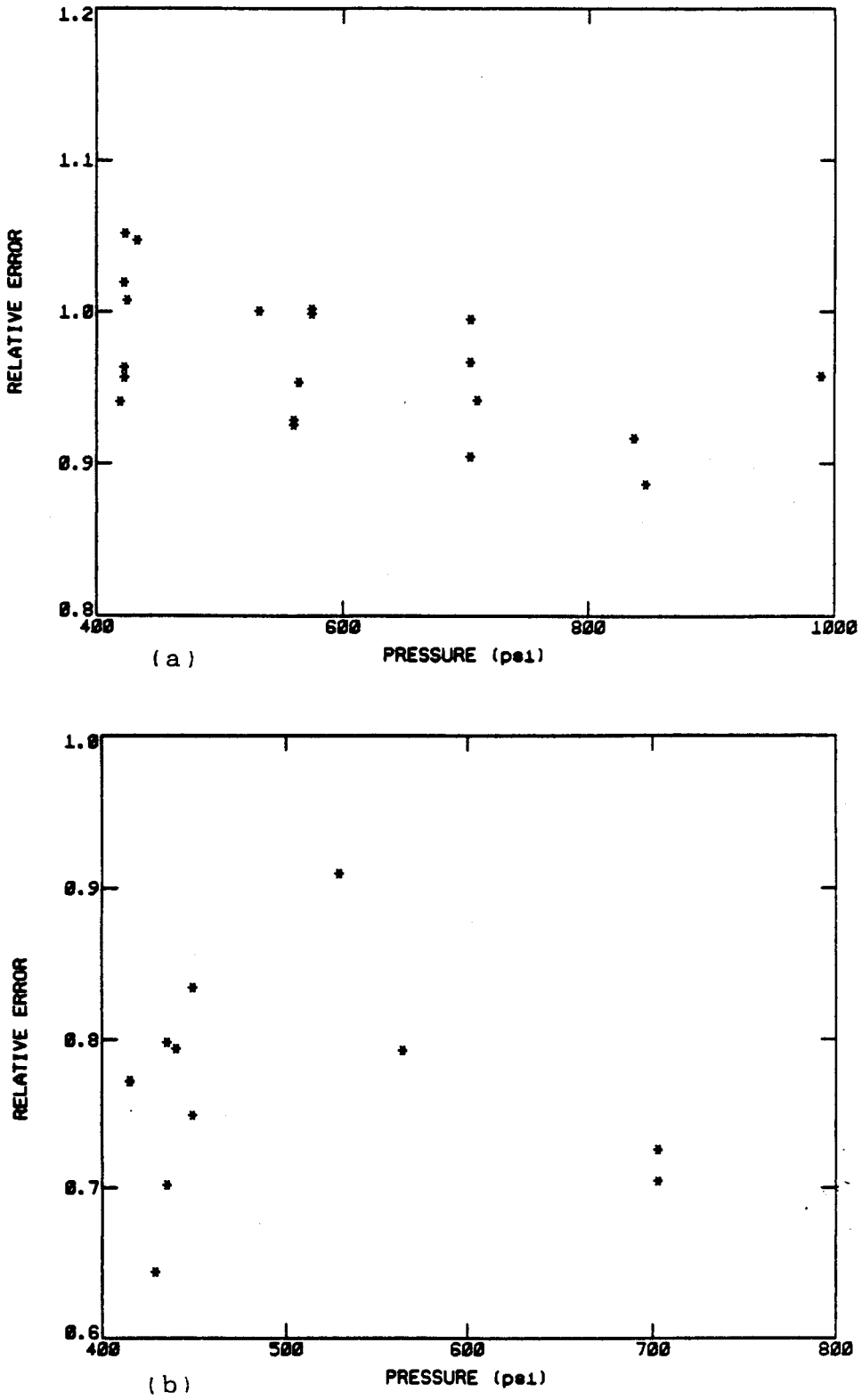
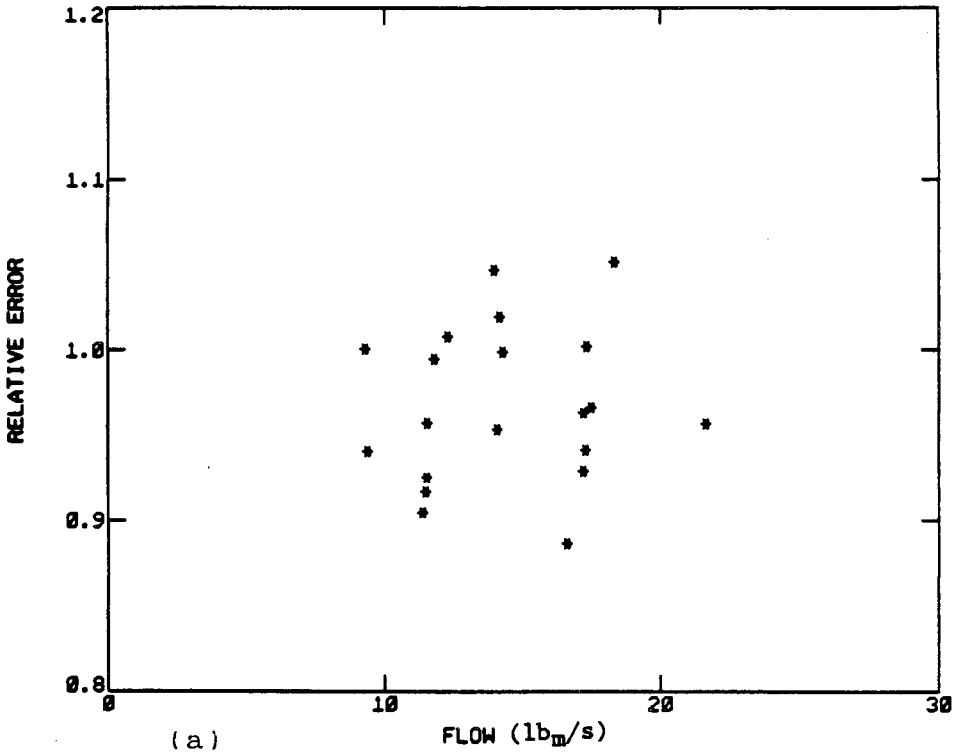


Fig. 4. Relative error (i.e., ratio of calculated to measured threshold power for instability) in MAZDA-NF calculations as a function of operating pressure: (a) subcooling greater than 35 Btu/lb_m, (b) subcooling less than 35 Btu/lb_m.



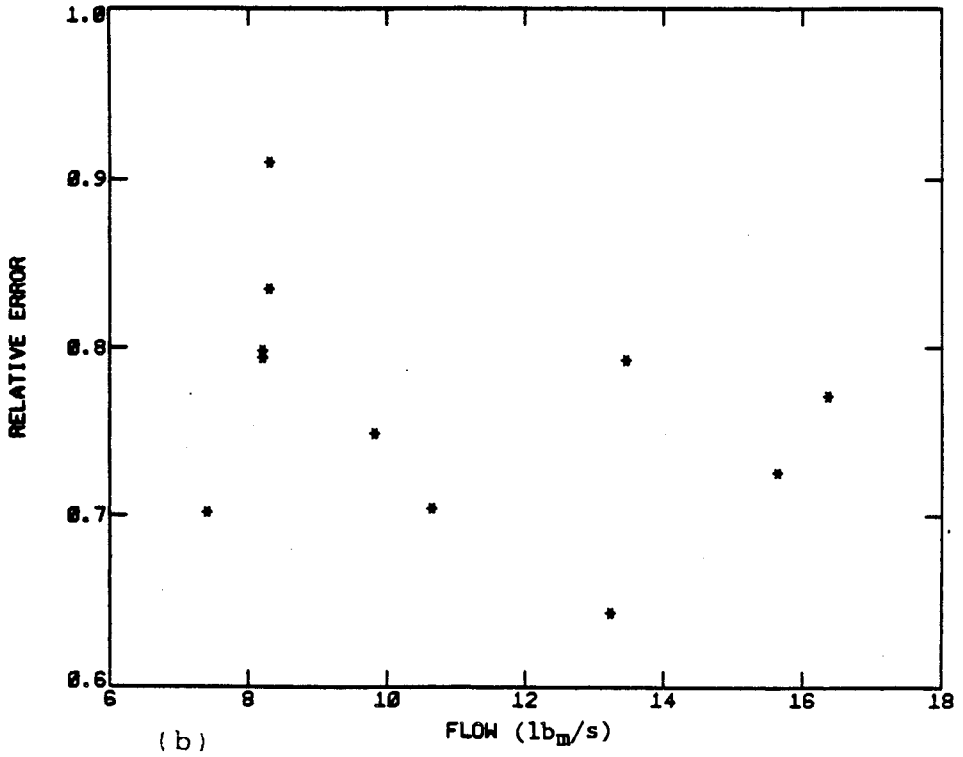


Fig. 5. Relative error (i.e., ratio of calculated to measured threshold power for instability) in MAZDA-NF calculations as a function of inlet flow: (a) subcooling greater than 35 Btu/lb_m, (b) subcooling less than 35 Btu/lb_m.

3.2 COMPARISON OF W-QUAD+ VERSUS OPEN LATTICE FUELS

Westinghouse presents in ref. 1 a comparison between its W-QUAD+ and conventional 8 x 8 open lattice fuel designs. The main differences can be summarized as follows:

(1) The W-QUAD+ design has a reduced channel pressure drop due to the design of the fuel spacers (not counting the inlet orifice). According to ref. 1, the spacer local friction coefficient in W-QUAD+ fuel is 50% smaller than in conventional open lattice designs. As shown in Sect. 3.3, this effect results in a negative contribution to the W-QUAD+ stability characteristics.

(2) Because of the reduced spacer friction, the W-QUAD+ design increases the single-phase friction at the entrance orifice to yield similar total pressure drop across the channel. According to ref. 1, the orifice local friction coefficient is 250% larger in W-QUAD+ than in open lattice designs. This increased inlet friction represents a significant improvement in channel stability characteristics that, as shown in Sect. 3.3, accounts for the major part of the enhanced stability characteristics of the W-QUAD+ fuel.

(3) The W-QUAD+ fuel design tends to yield smaller density reactivity coefficients due to the increased moderation in the water cross section between subchannels. This reduction represents an advantage for core-wide stability characteristics, but it does not affect channel stability. This advantage is void fraction and burnup dependent, and it may not be significant at end-of-cycle conditions with very high void fractions.

(4) W-QUAD+ fuel pins have smaller diameters than conventional 8 x 8 assemblies (5% smaller). This difference represents a negative contribution to their stability characteristics.

Overall, the W-QUAD+ BWR fuel design compares well with conventional 8 x 8 fuels in terms of stability performance. Under some conditions, the stability improvement can be as large as 50%. Most of this improvement is due to the redistribution between two-phase and single-phase frictions.

3.3 LAPUR AUDIT CALCULATIONS

A series of LAPUR audit calculations has been carried out to confirm Westinghouse's claims in ref. 1 about the effect on channel stability of the different design differences between W-QUAD+ fuel type and conventional open lattice designs. Table 1 contains a summary of the conditions modeled for these LAPUR audit calculations.

Table 1. LAPUR audit calculations[a]

Type of Fuel	Type of Inlet Orifice	Type of Spacers	Channel Decay Ratio
Conventional	Conventional	Conventional	0.79
W-QUAD+	W-QUAD+	W-QUAD+	0.51
W-QUAD+	Conventional	W-QUAD+	0.84
W-QUAD+	Conventional	Conventional	0.82
W-QUAD+	W-QUAD+	Conventional	0.47
W-QUAD+	W-QUAD+	Mixed[b]	0.61

[a]Single-channel calculation with 2-MW power and 0.3 Mlb/h/ft^2 mass flux. Inlet orifice friction coefficient for conventional type is 8.6 vh, while for W-QUAD+ type it is 19.5. Conventional type fuel has 7 spacers with 1.02 vh friction coefficient. W-QUAD+ type fuel has 6 spacers with 0.78 vh friction coefficient.

[b]Bottom 3 spacers W-QUAD+ type, top 3 spacers conventional type.

The first conclusion reached from these audit calculations is that indeed, as Westinghouse claims, the W-QUAD+ design yields lower decay ratios than conventional designs, when the parameters in Table 1 are used. (Note that these parameters have been extracted from ref. 1.) For the particular conditions considered in Table 1, the W-QUAD+ stability improvement is 35% (i.e., 0.51 versus 0.79) over the conventional 8 x 8 design.

The second interesting result is that the main improvement of the W-QUAD+ fuel seems to come from the increased inlet friction, rather than from the decreased spacer friction. Indeed, the W-QUAD+ spacer friction seems to have a destabilizing effect when compared to conventional type spacers. This could be explained by the fact that increased spacer friction in the bottom core stabilizes the channel.* That is, increased spacer friction has two competing effects due to its pressure drop increase in single- and two-phase flows. In this particular case, the increased single-phase drop dominates the destabilizing effect of the two-phase flow friction, yielding the higher stability performance exhibited by the W-QUAD+ fuel. This

*It is a well established fact that increased friction in the two-phase flow part of the channel destabilizes it, while single-phase (liquid) friction has a stabilizing effect. This effect is due to the fact that friction in two-phase flow produces a pressure drop with a phase delay that might lead to instabilities.

conclusion is supported by the last case in Table 1, which corresponds to a configuration with low friction (W-QUAD+ type) bottom spacers and high friction (Conventional type) top spacers. As expected, this configuration has a destabilizing effect.

3.5 DISCUSSION OF RESULTS

The results of the present review indicate that, overall, Westinghouse's mathematical treatment of the governing dynamic equations, as implemented in the MAZDA-NF code, is physically sound and appropriate for channel thermohydraulic stability estimations. However, we have found in the MAZDA-NF an apparent failure to model channels with low inlet subcooling values, which yields conservative errors as large as 35%. At high subcooling values (more representative of actual plant conditions), the dispersion error associated with MAZDA-NF calculations is approximately 15%.

A main source of error in stability calculations resides in determining the worst possible operating condition during a fuel cycle for performing the calculations. The error associated with this uncertainty is usually of the order of 10 to 20%. After review of Westinghouse's stability methodology for determining these operating conditions, we find this uncertainty appropriate for their calculations.

Based on the above study of errors, we estimate MAZDA-NF's uncertainty of calculated channel decay ratios to be of the order of 25%.

4. CONCLUSIONS AND RECOMMENDATIONS

The present review of Westinghouse's channel thermohydraulic stability calculations for BWR fuel, as implemented in the MAZDA-NF code, has found the overall methodology to be appropriate to estimate the thermohydraulic stability of new W-QUAD+ fuel designs as well as conventional open lattice fuels. The present review has also confirmed that the W-QUAD+ water-cross design should have improved stability characteristics when compared with conventional fuel designs. (For the particular cases considered in this review, this improvement is of the order of 35%.) Finally, the uncertainty associated with MAZDA-NF calculations has been estimated to be of the order of 25%.

As a consequence of the current review, we present the following set of recommendations regarding Westinghouse's channel thermohydraulic stability methodology as implemented in the MAZDA-NF code:

(1) A threshold value of 0.75 should be set for MAZDA-NF channel stability calculations. If this threshold value is exceeded, the channel should be considered to be unstable.
(2) Westinghouse must set a course of action in case the threshold in point (1) is violated. This issue can be addressed on a generic basis ("SIL 380" type of technical specification) or on an individual plant basis.
(3) Westinghouse has not yet established a core-wide stability methodology. This methodology must be the subject of a separate review.

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2. "Supplement 1 to WCAP-11146, A Response to NRC Questions on Westinghouse Topical Report, WCAP-11146 (Proprietary)," Letter Report NS-NRC-87-3267, September 1987.

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