NEDO-24284-A
CLASS I
MARCH 1984

LICENSING TOPICAL REPORT

ASSESSMENT OF FUEL ROD BOWING IN GENERAL ELECTRIC BOILING WATER REACTORS

R. J. WILLIAMS

GENERAL ELECTRIC

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This document contains 89 pages which include forematter pages i through xxx, 1 through 24, and Appendices A and B.

NUCLEAR ENGINEERING DIVISION • GENERAL ELECTRIC COMPANY
SAN JOSE, CALIFORNIA 95125

GENERAL ELECTRIC

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

MAY 31 1983

Mr. J. F. Quirk, Manager
BWR Systems Licensing
Nuclear Safety & Licensing Operations
General Electric Company
175 Curtner Avenue
San Jose, California 95125

Dear Mr. Quirk:

Subject: Acceptance for Referencing of Licensing Topical Report NEDE-24284-P, NEDO-24284, Entitled "Assessment of Fuel Rod Bowing in General Electric Boiling Water Reactors"

We have completed our review of the subject topical report submitted December 23, 1980 by General Electric Company letter MFN-221-8. We find this report is acceptable for referencing in license applications for Boiling Water Reactors to the extent specified and under the limitations delineated in the report and the associated (NRC) evaluation which is enclosed. The evaluation defines the basis for acceptance of the report.

We do not intend to repeat our review of the matters described in the report and found acceptable when the report appears as a reference in license applications except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the report.

In accordance with established procedures (NUREG-0390), it is requested that GE publish accepted versions of this report, proprietary and non-proprietary, within three months of receipt of this letter. The accepted versions should incorporate this letter and the enclosed evaluation between the title page and the abstract. The accepted versions shall include an -A (designating accepted) following the report identification symbol.

Should our criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, GE and/or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Dino C. Scaletti for
Cecil O. Thomas, Chief
Standardization & Special
Projects Branch
Division of Licensing

Enclosure:
As stated

ENCLOSURE

SER ON GENERAL ELECTRIC FUEL ROD BOWING TOPICAL REPORT

Report Title:	Assessment of Fuel-Rod Bowing in General Electric Boiling Water Reactors
Report Numbers:	NEDE-24284-P NEDO-24284
Report Date:	August 1980

1. INTRODUCTION

Under contract to NRC, Brookhaven National Laboratory (BNL) reviewed the subject General Electric (GE) topical report on fuel rod bowing in GE boiling water reactors (BWRs). The BNL evaluation (Enclosure 1 to Reference 1) of GE's report is attached as Enclosure 1. The BNL evaluation provides a summary of GE's experience with fuel rod bowing. To date, GE's experience predominately consists of thermal-hydraulic testing with simulated sub-assemblies, the development of an analytical model for assessing the influence of fabrication and operational variables on fuel rod deflection, and surveillance performed on lead test assemblies (LTAs). GE has not reported any operational problems arising from fuel rod bowing since early bowing-induced, high-temperature oxidation failures (Ref. 2) of segmented fuel rods.

The BNL technical evaluation on the GE report concluded that the report did not establish with confidence the effects of fuel rod bowing in GE fuel because of insufficient quantitative rod-to-rod spacing data. After reviewing the BNL evaluation, GE provided additional rod bowing information, which was not contained in the topical report nor in the GE responses (Ref. 5) to BNL questions (Refs. 3 and 4).

We have subsequently reviewed that information and many of the references cited therein. This review, which augments the original BNL evaluation, follows.

2. THERMAL-HYDRAULICS

The GE thermal-hydraulic experiments and their applications in the analyses of critical power performance are summarized in the BNL evaluation, which is attached as Enclosure 1.

3. NEUTRONICS

The only neutronic effect of BWR fuel rod bowing is a potential for a small local peaking factor increase. There are no significant reactivity effects. For situations involving isotropic bowing, the small locally increased peaking factor in one rod would be accompanied by decreased peaking factors in other rods in the assembly and no net change in planar-average assembly power density would occur. Therefore, there would be no significant effect on LOCA temperature calculations, which are primarily dependent on the planar-average assembly power density in BWRs. The small increase in LHGR (linear heat generation rate) is not significant for other events since LHGR limits are not approached for other events, which are limited by MCPR (minimum critical power ratio).

4. GAP CLOSURE

As discussed in the BNL evaluation, GE has developed an analytical fuel rod deflection model. The model accounts for some of the established parameters that contribute to bowing, but no information was provided for its verification, thus the staff did not make a finding on the adequacy of the model.

The General Electric data base did not include rod-to-rod spacing measurements on standard production fuel, but contained measurements on 4 LTAs, which are characterized in Table 1. As seen in Table 1, one of these LTAs was irradiated in Quad Cities 1 and the other three were irradiated in Monticello. All 4 LTA fuel designs are stated to be typical of the standard 8x8 design. Gap spacing measurements were taken only on peripheral rods via periscope. The General Electric topical report states that peripheral rods have the greatest propensity for bowing, but it does not provide the basis for this conclusion.

Since interior rods can be thermal-hydraulically limiting, this aspect remains troubling insofar as the difference between interior and periheral rod bow magnitudes is unknown.

When performing inspections on the LTAs, about a dozen precharacterized rods were removed from each bundle for individual examinations, such as profilometry. Such inspection procedures provided valuable information on individual rod performance (e.g., cladding creep), but adversely affect the prototypicality of the collective rod behavior (i.e., gap spacing.). This is because about 75% of the precharacterized rods were in bundle peripheral locations so that their precise positioning directly affected about 50% of the total number of gap spacing measurements taken. Gap spacing measurements recorded after bundle reassembly (thus allowing for recalibration) might have provided some insight on the gap closure dependence on burnup.

Free-hanging rod bow measurements were taken on many of the precharacterized rods in the first inspection of the Quad Cities LTA surveillance program and occasionally in others (for instance, Peach Bottom 2 (Ref. 16)). Though indicative of the degree of rod straightness, this type of measurement is not useful in quantifying in-bundle gap spacing. However, it is noteworthy that the Quad Cities free-hanging bow measurements (Ref. 7) appear non-isotropic and exhibit a resultant bow vector which is directed away from what would have been the center of the Quad Cities cores. An identical situation is typically encountered in CANDU fuel designs, which have large flux gradients across bundles (Ref. 17). In general, non-randomness of the bowing will preclude the use of the analysis techniques that rely on the commonly employed, empirically structured, statistical methodologies.

In summary, we conclude that the GE measurements have not revealed bowing of a serious nature. In fact, as identified in Table I, the maximum closure measured was 55%. However, some of the reservations described above on the adequacy of the data base, that is: (1) the lack of interior rod spacing measurements, (2) the affect of LTA disassembly/assembly on subsequent spacing measurements, (3) possible bowing anisotropy, and (4) the lack of statistical interpretations, were motivation for us to seek additional evidence to support GE's conclusion.

Thus, we looked to 2 other sources of information to support GE's finding that significant fuel rod bowing will not occur in GE BWR fuel assemblies. These sources are (a) gap spacing measurements on Exxon BWR fuel (Ref. 18) and (b) PWR fuel vendors' gap closure models (Refs. 19, 20, 21, and 22). Assuming that the GE fuel propensity for rod bowing is equivalent to that of competitors' designs, both the Exxon data and the PWR fuel vendor models, which have all been heretofore approved (Ref. 23) for licensing applications, can be extrapolated to the BWR 8x8 fuel geometry. We caution that this assumption is basically unqualified, overlooks the metallurgical and fabrication uniqueness, and is employed here solely for the purpose of establishing geometrical comparisons.

The Exxon gap spacing data comes from nine 7x7 and five 8x8 BWR assemblies that were irradiated in Oyster Creek. These assemblies had varying exposures up to 25,200 MWd/MTU. In all, more than 10,000 gap spacings were taken on the 14 assemblies with a leaf-spring probe apparatus, which was used to measure both interior and exterior gaps. We used tabulated standard deviations of the gap spacings from only the worst spans (exhibiting the greatest bowing) of each assembly and corrected those values for the cold-to-hot effect, normalized to the GE 8x8 geometry, and converted to 95th percentiles (L/I, etc. according to the guidance in Ref. 24). A linear regression on the 95th percentile data indicated a reasonable fit with a 0.88 correlation coefficient (based on the number of percentile values, this corresponds to 1 chance in 50 of random occurrence (Ref. 25)). The extrapolation of this resulting curve does not predict gap enclosures of significance until beyond traditional BWR burnups. (General Electric has not identified a gap closure design limit (threshold) at which a CPR penalty would be warranted. Therefore, we have compared the closure rate to the proprietary design closure limit employed by Exxon and which the NRC staff has approved (Ref. 26)). Consequently, we conclude that the Exxon BWR gap spacing data support the GE contention.

Additional support for GE's conclusion was also obtained when the NRC staff normalized the 4 approved PWR fuel vendor gap closure models, which are each based on many thosands of probed-gap spacing measurements, to the GE BWR 8x8 design. In fact, the extrapolation of the resultant average closure curve (a proprietary curve) when compared to the Exxon gap closure limit indicated no concern until reaching burnups beyond traditional BWR exposures.

Therefore, on the basis of (a) the reported GE data base and GE's statement that "To date, no significant fuel rod bowing has been detected in GE BWR fuel assemblies" [sic, excluding segmented-rod designs] and (b) our own calculations using other vendors' proprietary information, we conclude that the GE report, when supplemented with the supporting information that was generated by the NRC staff, provides an adequate basis for concluding that no operational penalties on GE BWR fuel are warranted at this time and that GE's fuel rod bowing topical reports NEDO-24284 and NEDE-24284(P) are acceptable for reference. However, we were not able to reach a judgement on the GE analytical model for predicting the degree of bowing due to the lack of GE data with which to qualify the model.

5. CONCLUSION AND REGULATORY POSITION

We conclude that the GE report, when supplemented with the supporting information that was generated by the NRC staff, provides a basis for concluding that no operational penalties on GE BWR fuel are required and that the GE topical report as supplemented with the supporting information is acceptable for reference. In addition, if adverse rod bowing behavior (rod-to-rod gap closures greater than 50% of nominal) is observed in GE-supplied fuel in the future, NRC should be notified in order to ascertain the need for critical power ratio penalties.

6. REFERENCES

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2. "Current State of Knowledge of High Performance Zircaloy Clad UO_2 Fuel," GE report NEDO-10173, May 1970.

3. J. R. Miller (NRC) letter to G. G. Sherwood (GE) dated June 12, 1981.

4. J. R. Miller (NRC) letter to G. G. Sherwood (GE) dated November 2, 1981.

5. J. F. Quirk (GE) letter to J. R. Miller (NRC) dated April 6, 1982.

6. R. Delgado, Jr. and S. Y. Ogawa, "8x8 Fuel Surveillance Program Pre-Irradiation Characterization Quad Cities 1 Fuel Assembly," GE report NEDE-20871, April 1975.

7. D. O. Sheppard, et al., "8x8 Fuel Surveillance Program Quad Cities 1 Fuel Assembly GEH-24 First Interim Measurement of Precharacterized Fuel Assembly," GE report NEDM-21430, October 1976.

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16. D. O. Sheppard, "Boiling Water Reactor Fuel Rod Performance Evaluation Program Task C: First Cycle Interim Site Examination of the Lead Test Assembly Fuel and Channels at Peach Bottom 2," GE report NEDC-23719, October 1977.

17. D. A. Powers (NRC) memorandum for P. S. Check, "CRNL Trip Report, 11/15-16/77, December 2, 1977.

18. "Non-Destructive Examination of Exxon Nuclear Fuel at the Oyster Creek Reactor Spring 1977 (EPRI Contract RP895-1-4)," Exxon report XN-NF-77-49, November 1977.

19. "Fuel & Poison Rod Bowing," C-E report CENPD-225-P, Supplement 3-P, June 1979.

20. "Fuel Rod Bowing in Babcock & Wilcox Fuel Designs," B&W report BAW-10147-P, April 1981.

21. "Fuel Rod Bow Evaluation," Westinghouse report WCAP-8691, Revision 1, July 1979.

22. "Computational Procedure for Evaluating Fuel Rod Bowing," Exxon report XN-NF-75-32(NP), Supplement 1, July 1979.

23. L. S. Rubenstein (NRC) memorandum for T. M. Novak, "SERs for Westinghouse, Combustion Engineering, Babcock & Wilcox, and Exxon Fuel Rod Bowing Topical Reports," October 25, 1982.

24. O. D. Parr (NRC) letter to G. G. Sherwood (GE) dated September 21, 1978.

25. H. D. Young, "Statistical Treatment of Experimental Data," McGraw-Hill, New York (1962).

26. "Generic Mechanical Design for Exxon Jet Pump BWR Reload Fuel," ENC report XN-NF-81-21(P)(A), Revision 1, September 1982.

TABLE 1

LTAS ON WHICH PERPHERAL GAP SPACING MEASUREMENTS WERE TAKEN

Plant	LTA	Burnup (MWd/MTU)	Sides Measured	Spans Measured	Ref.
Quad Cities 1	GEH-24	0	2	8	6, 7, 8
		7500	2	8	7
		12700	2	8	8
Monticello	MTB099*	0	2	8	9
		3538	----- 1 datum**-----		10
		20500	2	8	11
		25900	----- 5 data ------		12
		33800	4	7	13, 14
		39628	----- 6 data ------		15
	MTB048	33800	4	7	14
	MTB071	33800	4	7	14

*Damaged during handling and subsequently reconstituted with 7 new spacers, new lower tie plate, and new capture rod at EOC3.

** At 55% closure, this is the most severe of all reported gap measurements taken on non-segmented GE fuel rod designs.

TECHNICAL EVALUATION OF THE GENERAL ELECTRIC FUEL ROD BOWING TOPICAL REPORT NEDE-24284-P

Prepared by

J.F. Carew

August 1982

Core Performance Group

Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

TOPICAL REPORT EVALUATION

REPORT IDENTIFICATION:	NEDE-24284-P [NEDO-24284 (Non-Proprietary)]
REPORT TITLE:	Assessment of Fuel-Rod Bowing in General Electric Boiling Water Reactors
REPORT DATE:	August, 1980 [August 1980]
ORIGINATING ORGANIZATION:	General Electric Company

1.0 Background

In 1973 Westinghouse reported fuel rod bowing observations in PWRs to the Atomic Energy Commission. This fuel rod bowing was a deviation in straightness of fuel rods believed to be caused by irradiation effects. The major concerns with this phenomenon were the potential effects on bundle power distribution and on the margin of fuel rods to departure from nucleate boiling (DNB).

Subsequent to the initial observations of fuel rod bowing in PWRs, the NRC met in November 1974 with General Electric to discuss fuel rod bowing in General Electric BWR fuel. It was thought that the BWR fuel is less susceptible to bowing because of the design differences between BWR and PWR fuel and the different operating characteristics.

Before Westinghouse first reported irradiation induced fuel rod bowing in PWRs, GE had carried out numerous thermal-hydraulics experiments during 1971 and 1972 (references 1 and 2) to assess the impact of rod bowing in BWRs on critical power performance. These initial tests were performed to determine the thermal-hydraulic effects on reduced channel clearances in 9 rod and 16 rod 7x7 fuel geometries. For these arrays, the performance of the corner rod of the assembly was thermal-hydraulically limiting. In 1974, an additional series of full-size 64-rod 8x8 tests (reference 3) were run since this was the new GE lattice design and could be limited by interior rod performance.

In response to an NRC request (reference 4), in August 1980, GE summarized their experience on fuel rod bowing and its impact on performance in the topical report, NEDE-24284-P.

2.0 Summary of Topical Report

The General Electric report on fuel rod bowing is summarized in the following.

2.1 Rod Bowing Data Base and Analysis

General Electric has visually inspected more than 1000 fuel bundles. General Electric estimates that several thousand rods in these bundles have been visually examined, typically at eight different locations along the rod with actual measurements performed and recorded on 3 occasions only when significant reductions in rod-to-rod spacing were observed. The fuel types examined included 7x7, 7x7R, 8x8R and 8x8RP assemblies with most of the bundles being inspected being of the 7x7 design. The burnups ranged to traditional discharge levels. The measurement techniques employed included the use of either a calibrated borescope or periscope recticles and the use of back lighting.

Since most of the rod-to-rod spacing data is qualitative (i.e., according to GE, general visual observations that no significant deviations in spacing occurred), GE concludes that there is insufficient data to determine the customary 95/95 one-sided upper tolerance for gap closure.

The GE topical report does not address the questions of:

1. Data corrections coming from biases introduced by the measurement technique.
2. Data adjustments and exclusions.
3. Normality checks.
4. Translation of gap closure to rod bow data.

2.2 Basic Correlations and Methods

2.2.1 Gap Closure

General Electric does not provide a correlation between measured bowing and burnup. The report states that an analytical model for fuel rod bowing has been developed and the influence of initial bowing, tubing eccentricity, thermal gradients and fast neutron flux gradients on creep bowing of axially loaded fuel rods has been investigated. However, no details on the analytical model or indication of benchmarking against measured data is presented.

General Electric used their analytical bowing model to predict fuel rod bowing for UO_2 rods and for gadolinia-loaded rods. General Electric has used the model to predict time-dependent rod deflections as a function of initial bow and eccentricity.

2.2.2 Thermal-hydraulic Effects

A series of 9-rod tests was carried out in the 2 MW heat-transfer loop at GE. These tests included an evaluation of the effects of:

1. Reduced corner rod clearances (60 and 30 mils from the channel wall).
2. Standard corner rod clearance (138 mils) with intermediate rod bowing (75 mils clearance at bowing).
3. Combined reduced clearance (60 mils) and rod bowing (30 mils at bowing).

The purpose of these tests was to conservatively appraise the effect of bowing and the reduction of corner rod clearances on the boiling transition. Sixteen-rod experiments were conducted in the ATLAS 17.2 MW heat-transfer loop. As in the 9-rod experiments, the effects of bowed corner rods and reduced corner clearances were evaluated. In addition to the number of rods, this series of experiments differed from the 9-rod tests in that GE considered the configuration of the 16-rod tests to be a more realistic simulation of possible reactor clearance conditions.

Experiments were also carried out for 8x8 bundles in the same 17.2 MW ATLAS facility. In these tests, a group of four rods were diagonally bowed until adjacent rod-to-rod spacings at the midpoint between two spans were 60 mils. In all tests, the critical bundle power was determined as a function of subcooling for different mass flows.

General Electric concludes that for typical BWR operating conditions, the experiments with realistic axial power profiles indicate a maximum critical power penalty of less than 4%. Since GE does not expect the large geometry distortion of the test hardware to occur in the reactor, this penalty value is considered an upper limit.

General Electric concludes that since the ATLAS tests have shown an uncertainty in the critical power prediction using the R-factor method to be small, a penalty of less than 4% with bowed rods demonstrates that the effects of rod bowing are included in the overall correlation uncertainties.

2.2.3 Neutronics Effects

Neutronics aspects of the effects of fuel rod bowing are not presented in the report.

3.0 Summary Of Technical Evaluation

The bowing of fuel rods results in a deviation of fuel rod straightness and a subsequent variation in the fuel rod-to-rod spacing. The major concerns with fuel rod bowing are (1) the reduction in fuel rod-to-rod spacing and resulting decrease in margin to boiling transition and (2) the increase in fuel rod-to-rod spacing and resulting increase in local power peaking. Also of concern are the potential effects of fuel rod fretting and corrosion which may arise as the fuel rod spacing is reduced to contact. The General Electric evaluation of the consequences of fuel rod bowing is described in the topical report, NEDE-24284-P, described in the previous section.

This topical report, the included references, associated NRC/General Electric correspondence and submittals were the principal subject of this review. During the review several areas were identified as having high relative importance and/or a substantial degree of uncertainty and the review was correspondingly focused on these areas. These included (1) the extent of the gap closure data base and (2) the measurement and determination of the critical power ratio (CPR) penalty as a function of rod displacement. The more important questions that were raised during the course of the review were transmitted formally to GE as round 1 and round 2 questions. The GE response to these questions (reference 5) was reviewed in detail and the following summarizes the major concerns with the response.

A critical element in the proposed General Electric fuel rod bowing methodology is the assumption that "no significant fuel rod bowing" takes place in BWR fuel assemblies. In response to question 4, it was stated that virtually all of the rod-to-rod spacing data is "qualitative (i.e., general observations that no significant deviations in spacing occurred)." This lack of quantitative rod bowing data is the result of fuel surveillance procedures which only require recording closures that result in rod-to-rod spacings of less than a specific GE proprietary value. While most of the rod-to-rod spacings may be close to nominal, the distribution of spacings greater than this proprietary value is essentially unknown. Without knowledge of this spacing distribution, we have been unable to make the required estimates of the effects of fuel rod bowing on either the critical power ratio or peak rod powers. In particular, the CPR penalties that have been determined by General Electric for the "extreme case" of rod-to-rod clearances of 0.060 inch may not be that extreme, especially in view of (1) the threshold at 50% closure and (2) the rapid increase in thermal margin penalty for rods close to contact in PWRs.

4.0 Technical Position

We conclude that the topical report lacks sufficient quantitative rod-to-rod spacing data to establish with confidence the effects of fuel rod bowing on BWR fuel performance.*

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*At the conclusion of our review, we were informed by NRC that a small number of General Electric rod-to-rod measurements had been made. We have not reviewed this data and cannot say how this data might have influenced our evaluation.

ACKNOWLEDGMENT

The author wishes to thank Drs. Dale A. Powers and Ralph O. Meyer of the Core Performance Branch of the NRC for guidance and several valuable discussions during the course of this review.

Thanks is also due Dr. Wolfgang P. Barthold for reviewing various sections of the topical report and for his contribution to the writing of the introductory section of this technical report.

References

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2. "Deficient Cooling - Eleventh Quarterly Progress Report," January 1 - March 31, 1972, E.E. Polomik et al., GE report GEAP-10221-11, April 1972.

3. "Critical Power Performance Characteristics of 64-rod (8x8) fuel bundles with Geometric Variations," GE report NEDE-13413, April 1975.

4. Letter, O.D. Parr (NRC) to G.G. Sherwood (GE), Subject: Fuel Rod Bowing Topical Report, September 21, 1978.

5. "Responses to NRC questions on GE letter 'Assessment of Fuel Rod Bowing in GE BWR'S (NEDE-24204-P), dated 8/20'," letter, J.F. Quirk (GE) to James R. Miller (NRC), April 6, 1982.

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TABLES

ILLUSTRATIONS

ABSTRACT

The purpose of this document is to report the results of an extensive effort performed by General Electric to evaluate the potential and consequences of General Electric boiling water reactor (BWR) fuel rod bowing.

General Electric's fuel surveillance program observations relative to rod bowing are described in this report together with the results of analytical evaluations of the probable extent of fuel rod bowing. Also presented are the results of an extensive thermal-hydraulic test program performed to assess the significance of rod bowing on fuel asembly thermal-hydraulic performance. Based on the presented information, General Electric concludes that fuel rod bowing does not constitute a viable failure mechanism or represent a significant safety concern for General Electric fuel in boiling water reactors.

1. SUMMARY

The potential and consequences of fuel rod bowing have been assessed by General Electric through: (1) the performance of an aggressive fuel surveillance program, (2) the development and application of a conservative fuel rod bowing analytical model, and (3) the performance of an extensive thermal-hydraulic experimental program. Results from the surveillance program, in which over 1000 bundles have been nondestructively examined over the last 10 years, indicate that excessive rod bowing does not occur in General Electric boiling water reactors (BWRs). The conservative fuel rod bowing analytical model confirms that excessive rod bowing is not expected for General Electric BWR fuel. The thermal-hydraulic test program has demonstrated that thermal margins are not substantially reduced for simulated bowed-rod clearances as low as 0.030 inch. Based on this information, General Electric concludes that fuel rod bowing does not constitute a viable failure mechanism or represent a significant safety concern for General Electric fuel in boiling water reactors.

2. INTRODUCTION

The bowing of fuel rods has been observed in the fuel bundles designed and manufactured by several pressurized water reactor (PWR) fuel manufacturers. The deviation in rod-to-rod spacing produced by this bowing may have a potentially significant effect on the margin of the fuel rods to departure from nucleate boiling (DNB), and thus rod bowing has been identified as a potential fuel integrity problem.

Subsequent to the initial observation of rod bowing, the Nuclear Regulatory Commission (NRC) requested an evaluation of fuel rod bowing effects from the PWR vendors. The NRC recognized at that time that the fundamental design differences and operating characteristics reduced the potential for fuel rod bowing in BWRs as compared to PWRs.[1]

At a meeting held in November 1974, General Electric discussed with the NRC the fuel rod bowing of General Electric BWR fuel. In the conclusions to that meeting, the NRC Staff concurred with General Electric that fuel rod bowing is not a significant safety concern for GE BWR fuel. General Electric subsequently provided the NRC with additional information concerning the effects of fuel rod bowing on BWR core performance and provided answers to NRC questions in that area.[2]

The purpose of this topical report is to document formally the information provided by General Electric in these submittals and responses and to describe in more detail General Electric's work in this area.

3. FUEL DESIGN

The basic GE BWR design concept consists of a stack of high-density (95% TD) solid right cylindrical UO_2 pellets enriched with U-235 and enclosed within a Zircaloy-2 cladding tube. The cladding tube is evacuated, backfilled with helium, and sealed by Zircaloy end plugs welded at each end. The Zircaloy cladding thickness is sized to be essentially free-standing under the $\sim$1000 psi BWR environment. Adequate free volume is provided within each fuel rod in the form of a pellet-to-cladding gap and a plenum region at the top of the fuel rod to accommodate thermal and irradiation expansion of the UO_2 and the internal pressures resulting from the helium fill gas, volatile impurities, and gaseous fission products released over the design life of the fuel. The fuel rods are spaced and supported in square arrays between upper and lower tie plates. This composite structure is termed a fuel bundle. The current 8x8 fuel bundle design contains 62 fueled rods and 2 water rods. The water rods provide improved neutron moderation in the interior of the bundle, and one of the water rods provides axial positioning for the seven Zircaloy spacers along the fuel assembly which provide rod-to-rod spacing between upper and lower tie plates. The spacers incorporate an active spring force to positively position the fuel rods laterally while providing for axial differential expansion. In addition, the spacers transmit fuel rod lateral loads to the open-ended Zircaloy channel enclosing the bundle. Eight of the peripheral fuel rods are threaded into the lower tie plate and are fastened to the upper tie plate to support the fuel bundle weight during fuel-handling operations. Inconel-X expansion springs on the upper-end-plug shank between the fuel rod and upper tie plate ensure positive engagement of the lower end plug in the lower tie plate. These springs, in conjunction with the spacer springs, allow independent axial expansion of the fuel rods, thus limiting the potential for rod bowing. The typical BWR fuel assembly design concept is illustrated in Figure 1.

The essential elements of this design concept which have precluded significant rod bowing in GE fuel bundles are:

1. free-standing cladding,

2. channels which provide lateral strength without the need for high spacer spring forces, and

3. a slip-fit connection between the fuel rod and upper tie plate which incorporates expansion springs on the upper-end-plug shank to provide positive fuel rod positioning in the lower tie plate while allowing for axial expansion of the fuel rods.

4. GENERAL ELECTRIC FUEL SURVEILLANCE PROGRAM

4.1 EARLY OPERATING EXPERIENCE AND SURVEILLANCE

The only observed failure of General Electric BWR fuel rods due to rod bowing occurred during the early operating experience with segmented fuel rods. These failures occurred in five segments (out of more than 7700 segments operated) due to high-temperature accelerated local oxidation which was attributed to bowing of the nonstress-relieved corner rods. These corner rods contacted the fuel channel and locally restricted the coolant flow. This early experience with segmented fuel designs is documented in NEDO-10173.[3]

With the change in the early 1960s to a nonsegmented, stress-relieved cladding and the current spacer design concept, which incorporates an active spring force to positively position the fuel rods while providing for axial differential expansion, there has been no evidence of appreciable rod bowing in GE production fuel. Fuel inspections, either visual inspections during normal refueling outages or more detailed nondestructive examinations as a part of General Electric's active fuel surveillance program, have not provided any indication of rod bowing as a viable failure or life-limiting mechanism.

4.2 CURRENT SURVEILLANCE PROGRAM

The General Electric fuel surveillance and development fuel programs (Lead Test Assemblies) are specifically intended to monitor fuel performance in operating reactors to identify and characterize unexpected phenomena, such as rod bowing, which could impact on fuel integrity and performance. Detailed visual examination of fuel-bundle exteriors and individual rods employing borescopes or periscopes are some of the inspection techniques used in this program Reference 2 indicated that in the 7 years leading up to 1977, approximately 200 fuel bundles (>4800 peripheral rods) had been visually inspected with no indication of significant rod bowing. Between 1977 and the present, GE has intensified its surveillance and inspection programs and has inspected in detail (nondestructively tested) an additional 800 bundles (a total of over 1000 bundles to January 1980) without any indication of significant rod bowing. Measurement techniques employed in these later inspections include the use of either calibrated borescope or periscope reticles and the use of backlighting. This improved approach allows an observation of the minimum spacing between adjacent rows of rods, thereby including internal as well as peripheral rods. The maximum decrease in rod-to-rod spacing employing this technique on an 8x8 surveillance bundle has been found to be within the measurement accuracy of the calibrated reticles * . The photograph in Figure 2 illustrates typical rod-to-rod spacing for an 8x8 fuel bundle at an exposure of ~15,000 MWd/MT.

4.3 REFUELING INSPECTIONS

During the course of a typical refueling outage, there are further opportunities to identify the existence of gross in-reactor rod bowing. At the time that a fuel assembly is discharged from the reactor to the spent fuel pool, the bundle is dechanneled and frequently given a routine visual inspection. The dechanneling operation itself could aid in identifying gross permanent rod distortion. If the peripheral rods in the assembly, which in general have the highest propensity for bowing, are grossly deflected toward the channel wall, resistance to channel removal may occur. This condition has not, however, been experienced to date with full-length fuel rods.

*General Electric Company Proprietary Information has been deleted.

In addition, peripheral bundle visual examinations are performed during refueling outages. While information from these examinations is qualitative in nature, any gross bowing (>70 mils) would be easily detectable. To date there has been no indication of such bowing.

5. ANALYTIC EVALUATION OF ROD BOWING

5.1 INTRODUCTION

An analytical model has been developed and analyses have been performed to assess the influence of initial bowing, tubing eccentricity, thermal gradients, and fast neutron flux gradients on the potential for in-reactor creep bowing of axially loaded fuel rods.

These analyses demonstrate that with all known rod bowing effects considered, no significant rod bowing is predicted for General Electric fuel designs.

5.2 ANALYSIS MODEL

The fuel rod was analyzed as a continuous beam with axial loading at the ends and at each spacer location Time and axial variations in temperature, thermal gradient across the rod diameter, fast neutron flux, and neutron flux gradient across the rod diameter were included in the analysis.

5.3 ROD BOWING ANALYSIS INPUT PARAMETERS

Table 1 contains the basic fuel rod parameters used in the row bowing analyses. Values shown in the table were considered uniform over the rod length and constant in time throughout the analyses. Design basis values of internal rod pressure, peak linear heat generation rate, and average cladding temperature were varied with exposure for fuel rods and without gadolinia. Three typical BWR axial power profiles were also considered in the analysis, corresponding to top-, center-, and bottom-peaked power shapes. Fast neutron flux was also varied axially.

The influence of control rod pattern changes was investigated parametrically by considering two types of operating conditions:

1. control rod fully withdrawn throughout fuel lifetime (worst case condition) or

2. six major control rod pattern changes each year (more realistic case).

A parametric analysis was performed using combinations of the above variables to assess the influence of fast neutron flux and thermal gradients on rod bowing.

In addition, a sensitivity study was performed to investigate the influence of initial rod bowing and eccentricity by varying independent variables individually from a base case. The independent variables included the above parametric variables, various initial bowing magnitudes, and manufacturing tubing eccentricities.

5.4 ANALYSIS RESULTS

Tables 2 through 4 summarize the results of the fuel rod bowing analysis giving deflection in mils at end-of-life conditions.*

Table 2 shows that the sensitivity to thermal gradient and fast neutron flux gradient is small . Tables 3 and 4 show parameter sensitivity studies based on manufacturing data for initial rod bowing and tubing eccentricity.

*

These tables show that, even with the conservative assumptions used in the analysis, the maximum bowing at end-of-life conditions is less than . This is small when compared to the initial nominal rod-to-rod clearance of

These analyses demonstrate that in-reactor fuel rod bowing resulting from temperature gradients, fast-neutron flux gradients, tubing eccentricities, and initial bowing is not significant in the GE fuel design. This analysis is consistent with field observations which verify that fuel rod bowing is not a viable failure or life-limiting mechanism in GE BWR fuel.

6. THERMAL HYDRAULIC TESTING AND POTENTIAL CONSEQUENCES OF ROD BOWING

Numerous thermal-hydraulic experiments have been performed to assess the impact of rod bowing. The results of this testing indicate that rod bowing of the magnitude expected in GE BWR fuel has no impact on critical power performance. The initial tests were performed to determine the thermal-hydraulic effects of reduced channel clearances in 9-rod (72-in. heated length) and 16-rod (144-in. heated length) 7x7 fuel geometries.[5-8] The tests were performed in the 2000-kW water heat transfer loop and the 17.2-MW ATLAS water loop with typical BWR grid spacers and non-uniform axial power profiles. In these tests rod-to-channel clearances as low as

indicated only slight differences in critical power performance, almost within the data uncertainty between nominal design and reduced-clearance assemblies. Full details of these results and a description of the tests can be found in Appendix A.

The above tests, which were performed before 1974, emphasized the performance of the corner rod of the assembly, as designs prior to the introduction of the 8x8 lattice were thermal-hydraulically limited at this location. Because the 8x8 fuel designs can be limited by interior rod performance, an additional series of full-size 64-rod 8x8 tests was run in the ATLAS loop to evaluate the effects of severe interior rod local geometry abnormalities.

Clearances between the most limiting rods in the bundle were reduced over a span between two spacers to . Critical power performance was unaffected in the reduced-clearance bundle at BWR operating conditions.

In addition to the reduced-clearance test, a separate test was performed in which the four critical rods in the bundle were mechanically bowed toward one another with resulting clearances between . The deformations were so severe that in order to hold the rods in position it was necessary to develop a process whereby the rods were first bowed into position and then heli-arc-welded together over a 3/32-in. diameter area. Critical power performance was unaffected in the bowed assembly at BWR operating conditions.

A survey of literature on rod bowing which pertains mainly to PWR bundle geometries and coolant conditions[9-17] confirmed that severe deviations from the nominal geometry would be required to produce any noticeable effect on critical power performance. It was concluded from the literature that DNB would not be significantly affected by rod spacing, even for rod-to-rod spacings as low as 0.015 inch.

General Electric therefore concludes, on the basis of the test data presented, that even for substantial local geometry variations there is a negligible effect on critical power performance.

7. IMPACT ON LOCA PERFORMANCE AND ABNORMAL OPERATING TRANSIENTS

Rod bowing has no effect on the MAPLHGR used by GE BWRs because in-reactor fuel rod bowing during normal operation has no effect on the blowdown heat transfer characteristics or the ECCS effectiveness during a LOCA. This has been substantiated by full-scale ECCS tests which were carried out with large amounts of rod bowing present. Results of these tests indicated that the bowed rods had no effect on the blowdown heat transfer characteristics or on the ECCS effectiveness.

It is conceivable that more substantial rod bowing can occur during the later stages of a LOCA when the ECCS is operating. These effects have been considered in detail[19] and found to have no effect on the calculated MAPLHGR.

It has been shown earlier (see Section 6) that the effect of rod bowing on critical power performance is negligible down to very small rod-to-rod clearances far in excess of that expected for GE BWR fuel rods. Therefore, rod bowing is not expected to have any significant impact on critical power during Abnormal Operating Transients (AOTs) in General Electric BWRs.

8. CONCLUSIONS

Through periodic surveillance on a total of over 1000 bundles during the past 10 years and extensive experimental and analytical programs, General Electric draws the following conclusions on fuel rod bowing:

1. An aggressive fuel surveillance program has shown that the proven GE fuel design successfully limits the propensity for fuel rod bowing. To date, no significant fuel rod bowing has been detected in GE BWR fuel assemblies.

2. Analytical evaluations confirm that the expected extent of thermal and fast neutron flux gradients, tubing eccentricities, and initial bowing will not result in significant fuel rod bowing in General Electric BWR fuel assemblies.

3. Extensive thermal-hydraulic testing indicates that local abnormalities in rod geometry resulting in reduced rod-to-rod spacing, such as rod bowing, have no significant detrimental effect on critical power performance down to clearances on the order of 30 mils.

Therefore, fuel rod bowing does not constitute a viable failure mechanism or represent a significant safety concern for General Electric fuel in boiling water reactors.

Table 1
ROD BOWING ANALYSIS-FUEL ROD PARAMETERS
(GE Company Proprietary)

Tubing Inside Diameter	
Cladding Thickness	
Rod Length	
Distance between Spacers	
Number of Spacers	
Tubing Material	
External (Core) Pressure	

Table 2

INFLUENCE OF THERMAL GRADIENT AND
FAST NEUTRON FLUX GRADIENT ON FUEL-ROD BOWING

(GE Company Proprietary)

Table 3

INFLUENCE OF INITIAL BOWING ON FUEL ROD BOWING

(for zero initial eccentricity)

(GE Company Proprietary)

Independent Variable	Final Deflection (mils)

a

Table 4

INFLUENCE OF TUBING ECCENTRICITY ON FUEL ROD BOWING

(for zero initial bow)

(GE Company Proprietary)

Independent Variable	Final Deflection (mils)

a

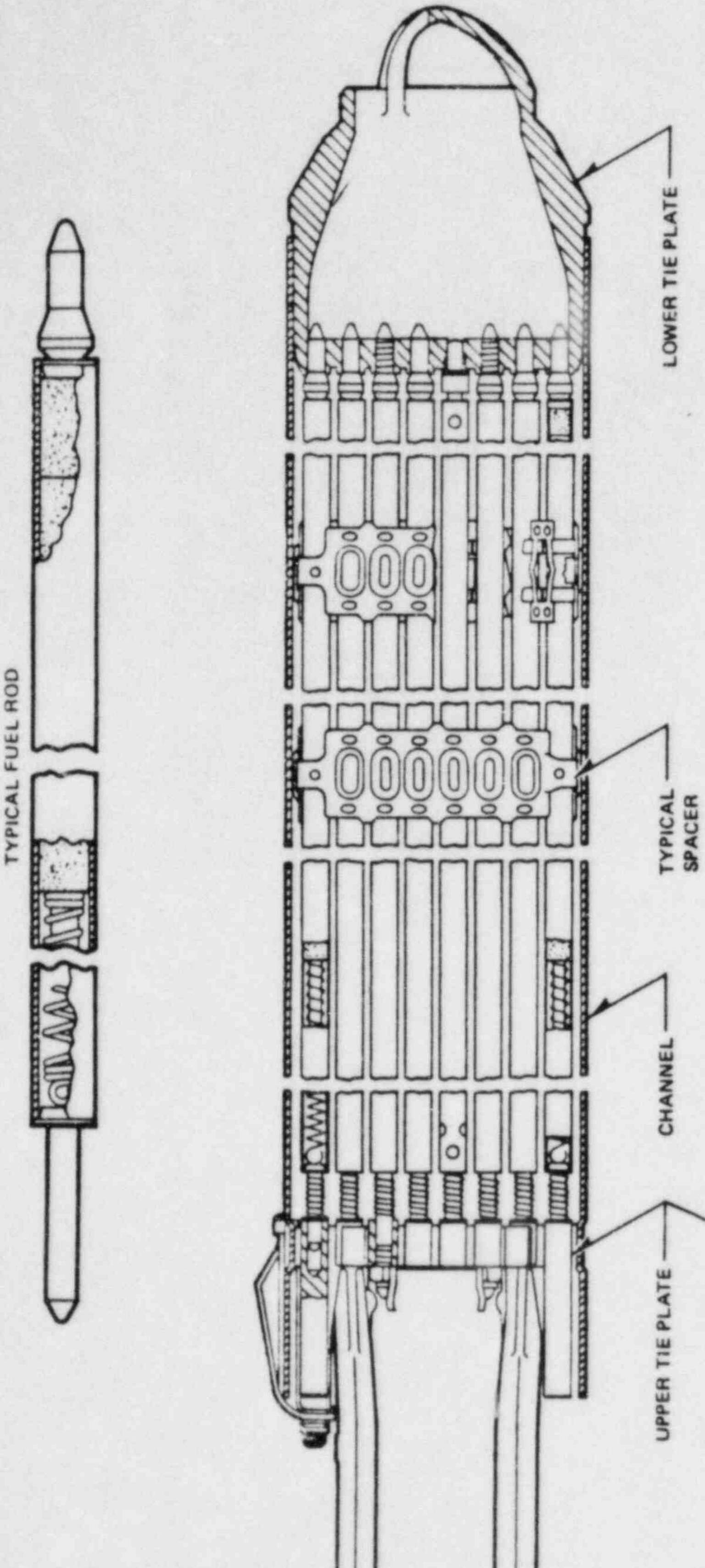

Figure 1. Fuel Assembly Cross Section

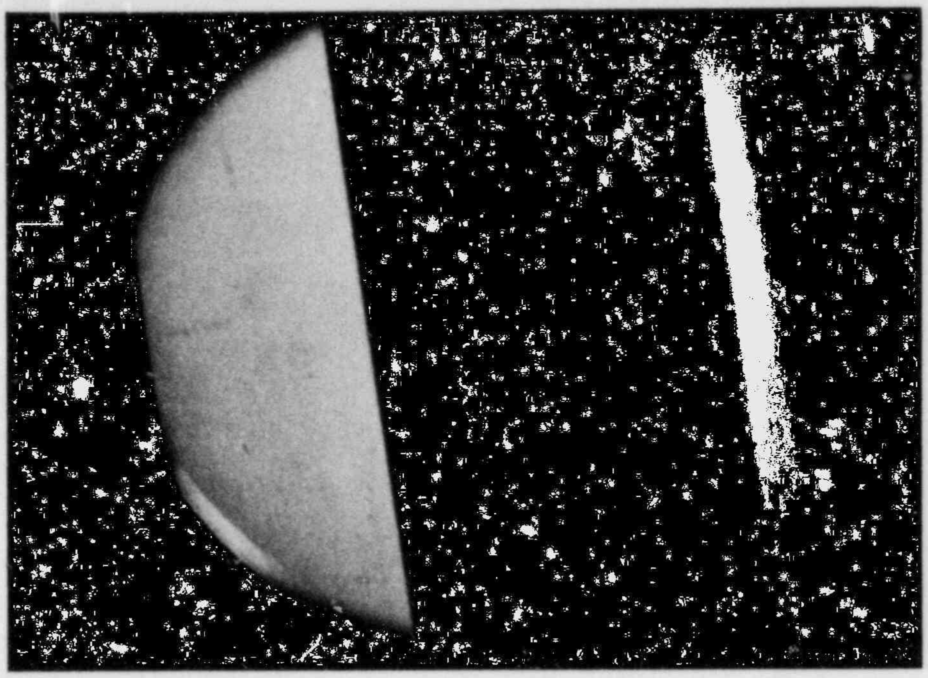

Figure 2. Typical Rod-to-Rod Spacing (Exposure ~15,000 MWd/MT)

Figure 3. (GE Company Proprietary)

INITIAL BOWING

Figure 4. (GE Company Proprietary)

9. REFERENCES

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4.

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18.

19. "General Electric Company Analytical Model for Loss-of-Coolant Accident Analysis in Accordance with 10CFR50, Appendix K," NEDO-20566, January 1976.

APPENDIX A

THE EFFECT OF REDUCED CLEARANCE AND ROD BOWING ON CRITICAL POWER

A.1 INTRODUCTION

Rod bowing in a reactor can result from several causes. Rod bowing is characterized as variable displacement of the fuel rod between the grid spacers (typically with maximum displacement midway between spacers). These spacers maintain radial dimensions in the bundles at discrete axial positions. The tests of the program described in this appendix evaluated various cases, with a corner rod bowed toward the corner of the flow channel and with interior rods bowed toward each other.

Reduced rod clearance is intended to characterize rod-to-wall and rod-to-rod dimensions that are below nominal and have no particular relationship to the axial positions of the grid spacers. Such reduced clearances can occur in a reactor from manufacturing tolerances or from deformation of bundle hardware during operation (e.g., bulging of flow channels). The tests of this program did not just simulate reduced rod clearance conditions that could actually occur in a reactor. Instead, extreme conditions of reduced rod clearance were tested. However, the test results from these extreme cases have considerable value for reactor design since they demonstrate the limited effect reduced rod clearance can have on the boiling transition phenomenon.

A.2 TEST EQUIPMENT

The program was conducted in three segments. The initial series utilized a 9-rod bundle with a 72-in. uniformly heated length. The second series utilized a 16-rod bundle with a full 144-in. heated length and representative axial-power profile.

The

test loops and bundle hardware are detailed in the following paragraphs.

A.2.1 Nine-Rod Experiments

These tests were conducted in the 2000 kW water heat transfer loop at General Electric Company, San Jose. A detailed description of the loop is contained in GEAP-10221-9.[A-1] Power was supplied by an induction regulator with a Hall-Effect watt transducer for measurement. Flow was redundantly measured with a turbine flowmeter and an orifice/pressure transducer system. Inlet subcooling was established from thermocouple measurements. System pressure was monitored with a Bourdon tube gauge.

Boiling transition was monitored with thermocouples embedded in the cladding surfaces of indirect heaters. Data were obtained by setting the test section pressure, flow, and inlet subcooling at steady values and slowly increasing power until one or more rod thermocouples indicated the onset of transition boiling.

For uniform axial heat-flux profile tests, initial boiling transitions were always observed at the end of the heated length. Subsequent data points were obtained by changing inlet conditions and repeating the power-increment process. This series included data at 800 and 1000 psia for mass fluxes of 0.25, 0.50, and 1.0 x 10^6 lb/h-ft^2.

Experiments included evaluation of the effects with (1) reduced corner rod clearances (0.060 and 0.030 inch from the wall), (2) standard corner rod clearances (0.138-in.) with intermediate rod bowing (0.075-in. clearance at bowing), and (3) combined reduced rod clearance (0.060-in.) and rod bowing (0.030-in. clearance at bowing).

The arrangement of rod spacing and sensing thermocouples for the symmetrical assembly is illustrated in Figure A-1(a). The axial locations of the grid spacers are indicated in Figure A-1(b).

The reduced corner clearances were obtained on the corner rod (Rod A) by making special inserts for the last 19 inches of the heated length. These inserts included material that raised the normal channel wall to produce the desired clearance. Details of the clearance between the rod and the corner inserts are shown in Figure A-2. The inserts were designed so the reduced clearance was obtained over a full quarter of the rod perimeter, and additional material was provided to form a smooth transition to the channel walls, as shown in Figure A-2(a). An axial profile of the assembly is shown in Figure A-2(b). For the 0.030-in. clearance case, two small buttons 0.030-in. high were brazed to the outside of the rod sheath to maintain a constant clearance in the corner annulus over the 18-in. approach length to the end of the heated length. For the 0.060-in. clearance case, only one button was used. The 0.030-in. clearance assembly had 1/8-in. outside diameter pins brazed onto the A, C, and G rods at 9-3/4 inches below the end of the heated length to provide radial support for Rod A. The latter and the corner pins were installed to prevent undue distortion in the 18-in.-long reduced-clearance corner channel. The unobstructed length-to-diameter ratios in the annulus were 79 and 133 for the 0.060- and 0.030-in. clearances, respectively. This provided sufficient length for development of flow before detection of boiling transition. There is virtually zero probability that two spacers could simultaneously deform to produce such small clearances in an actual BWR fuel bundle. However, the intent was to appraise conservatively the effects of parametric reductions of corner-rod clearances on the boiling transition. Since the abrupt geometry change with these inserts would tend to divert additional flow, the results are actually conservative even for these nominal clearance values.

Assemblies with corner rod (Rod A) bowing toward the channel were accomplished with diagonal support pins, as illustrated in Figure A-3. The pins were brazed onto the E and I rods at the 9-3/4-in. level below the end of the heated length. This resulted in a bowing with minimum clearance at the midpoint between the last spacer and the end of the heated length, as shown in Figure A-3(b). A streamlined pin was brazed onto Rod A, facing the corner to insure that the proper clearance was maintained during testing. Additional streamlined 1/8-in. outside diameter pins were brazed onto Rods A, C, and G to give Rod A lateral support and to prevent it from slipping off the diagonal pin. The combined rod bowing and reduced-clearance test was accomplished with a 0.060-in. insert in the corner (Rod A), with pins designed for a minimum rod-corner dimension of 0.030 inch. An elevation view of this assembly is schematically shown in Figure A-3(c).

A.2.2 16-Rod Experiments

These tests were conducted in the 17.2-MW water heat transfer loop, ATLAS, at General Electric Company, San Jose. A complete description of this loop is contained in GEAP-10221-11.[A-2] Power is supplied from a rectified (d-c) silicon controlled rectifier system and measured with special Hall-Effect watt transducers. Flow is measured redundantly with both turbine flowmeters and orifices. Test section inlet temperature is measured with a calibrated resistance temperature detector and checked by three thermocouples. System pressure is measured with a Bourdon tube gauge and a calibrated pressure transducer.

The 16-rod experiments used directly heated tubes with 144-in. heated length. Nonuniform tube-wall thickness was used to produce a truncated cosine axial power profile (peak/average of 1.387) typical of operating reactors. The boiling transition was monitored with thermocouples attached to the inner surfaces of the heater tubes. The electrically heated fuel rod simulators were supported by nine typical BWR grid spacers. The spacer locations and the radial and axial positions of the rod thermocouples are illustrated for the standard clearance reference bundle in Figure A-4.

Experiments in this 16-rod series included evaluation of the effects with a bowed corner rod and also with reduced corner clearance. The rod-bowing bundle details are illustrated in Figure A-5. The standard clearance reference bundle was modified with small, streamlined pins fitted and brazed to the rods to ensure a permanent bowing. Additional thermocouples were included in Rod 16 to monitor for possible boiling transition along the bowed length. In order to investigate the most limiting region, the rod bowing was placed in the segment where boiling transition first occurred with nominal clearances. Two small beads were brazed between the rod and the channel at the midpoint of the bowing to maintain the 0.060-in. rod-wall clearance during test operation.

The reduced corner clearance geometry is illustrated in Figure A-6. The reduced corner clearance was obtained by milling part of the bands off two sides of Spacers 2 and 3 and then shimming those two spacers toward the Rod 16 corner. The result is a 19-1/2-in. length along Rod 16 with a uniform reduced rod-to-wall clearance of 0.060 inch. This configuration simulates possible reactor clearance conditions somewhat more realistically than the nine-rod configuration but still represents a highly conservative case.

A.3 RESULTS

Appraisals of the geometry change effects can be accomplished by comparison with data obtained from the standard-clearance reference bundles for the test series (9-rod, 16-rod).

A.3.1 Nine-Rod Results

The performance comparisons are based upon linear fits to the symmetrical reference bundle data, as illustrated in Figures A-9 and A-10. Performances for the entire range of geometry configurations are summarized in Figure A-11 for 800 lb/in.^{2} results, and in Figure A-12 for the 1000 lb/in.^{2} results. Inspection of these figures indicates only modest effects on the boiling transition performance. The extreme cases of rod bowing and clearance reduction (i.e., with 0.030-in. dimensions) show penalties in critical power that increase with both mass flux and inlet subcooling. For inlet conditions typical of BWR operation (i.e., subcooling of 20 Btu/lb), the maximum penalty is approximately 9%. The less severe cases show only slight penalties that are nearly within the uncertainty of the data.

The trends of these data with mass flux suggest that the critical power penalties are partially caused by adverse flow diversion from the local restrictions, as flow distribution is more sensitive to local restrictions at higher mass fluxes. The increased penalties observed at higher subcooling may be the result of local vapor binding under bubbly flow conditions.

A.3.2 16-Rod Results

The 16-rod, symmetrical clearance, reference-bundle data are plotted in Figures A-13 and A-14 for 800 lb/in.^{2} and 1000 lb/in.^{2}, respectively. These nonuniform axial power profile data can again be well represented with linear fit lines. Composite plots of the results from all three assemblies are shown in Figures A-15 and A-16. In general, these more accurate reactor simulation data show less effect than the previous nine-rod experiments, particularly at high inlet subcooling. The 800-lb/in.^{2} results of Figure A-15 actually show a slight but consistent improvement with the 0.060-in. clearance for typical BWR inlet subcoolings. The maximum critical power penalty for either reduced clearance or rod bowing is less than 4%. The very small magnitudes of these penalties are particularly significant in view of the extreme geometry distortions studies. It is probable that immersion of the corner rod into the liquid film flowing on the fuel channel wall is partially responsible for the small sensitivity to reduced rod-to-channel dimensions.

A.4 CONCLUSIONS

The current work provides an extensive evaluation of the effects of rod bowing and reduced clearance for a BWR fuel bundle. For typical BWR operating conditions, experiments with realistic axial power profiles indicate maximum critical power penalties less than 4%. Since the geometry distortions of the test hardware are extreme cases which are not likely to occur in actual practice, this penalty value represents an upper limit for normal reactor design considerations.

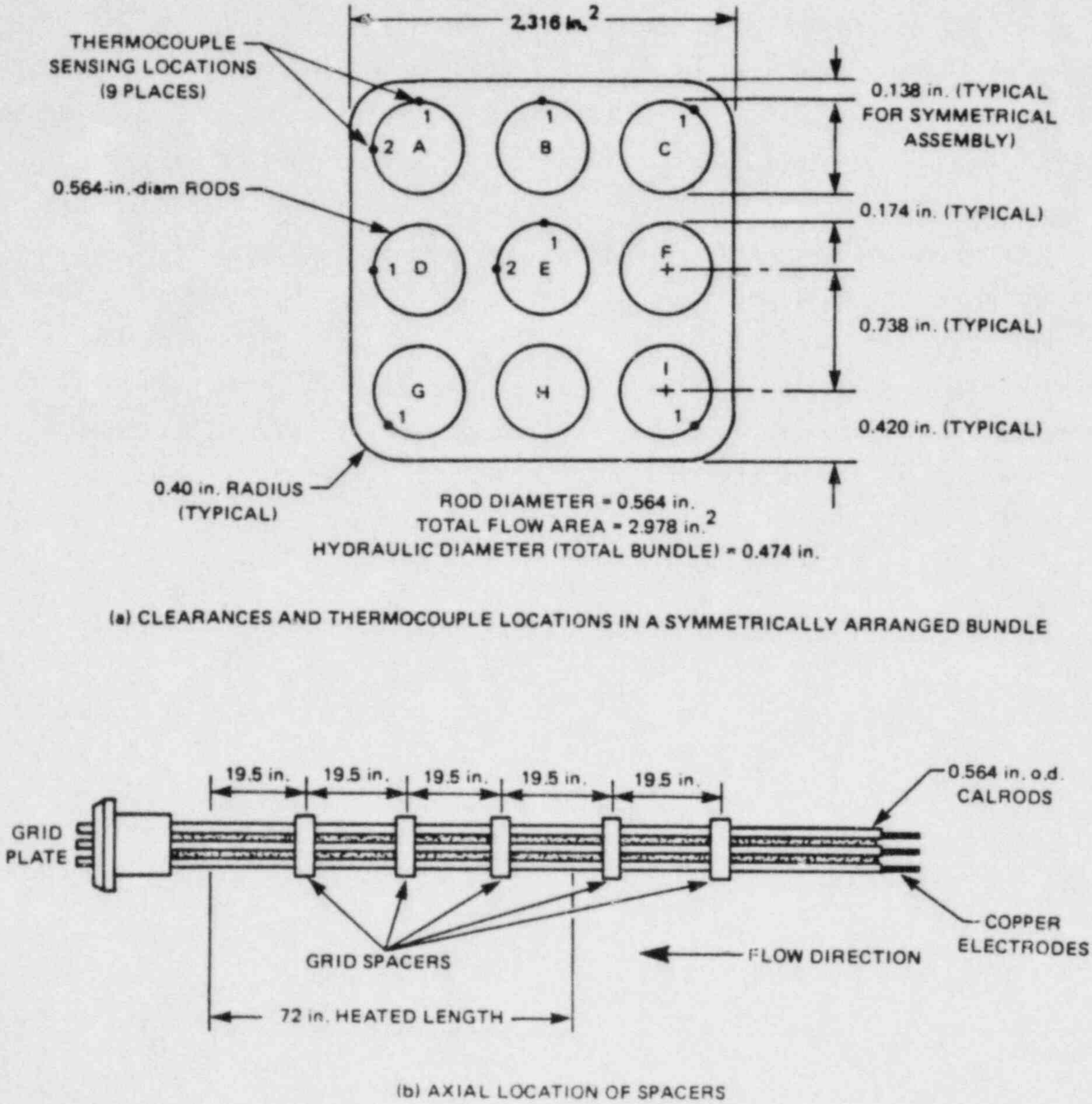


Figure A-1. Symmetrical Nine-Rod Test Section Showing Grid Spacer, Thermocouple, and Rod Locations

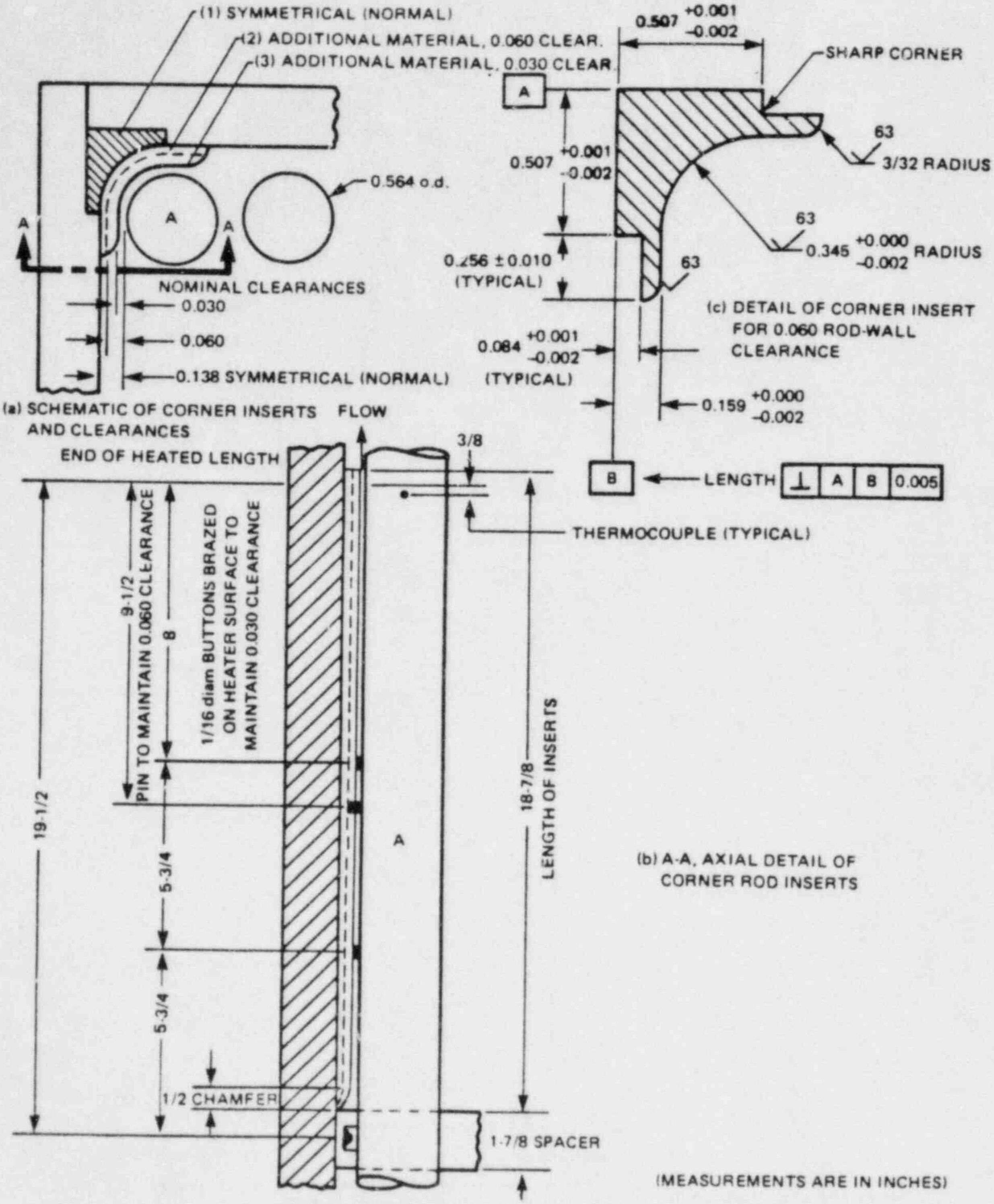


Figure A-2. Schematic and Detail of Corner Rod Clearances

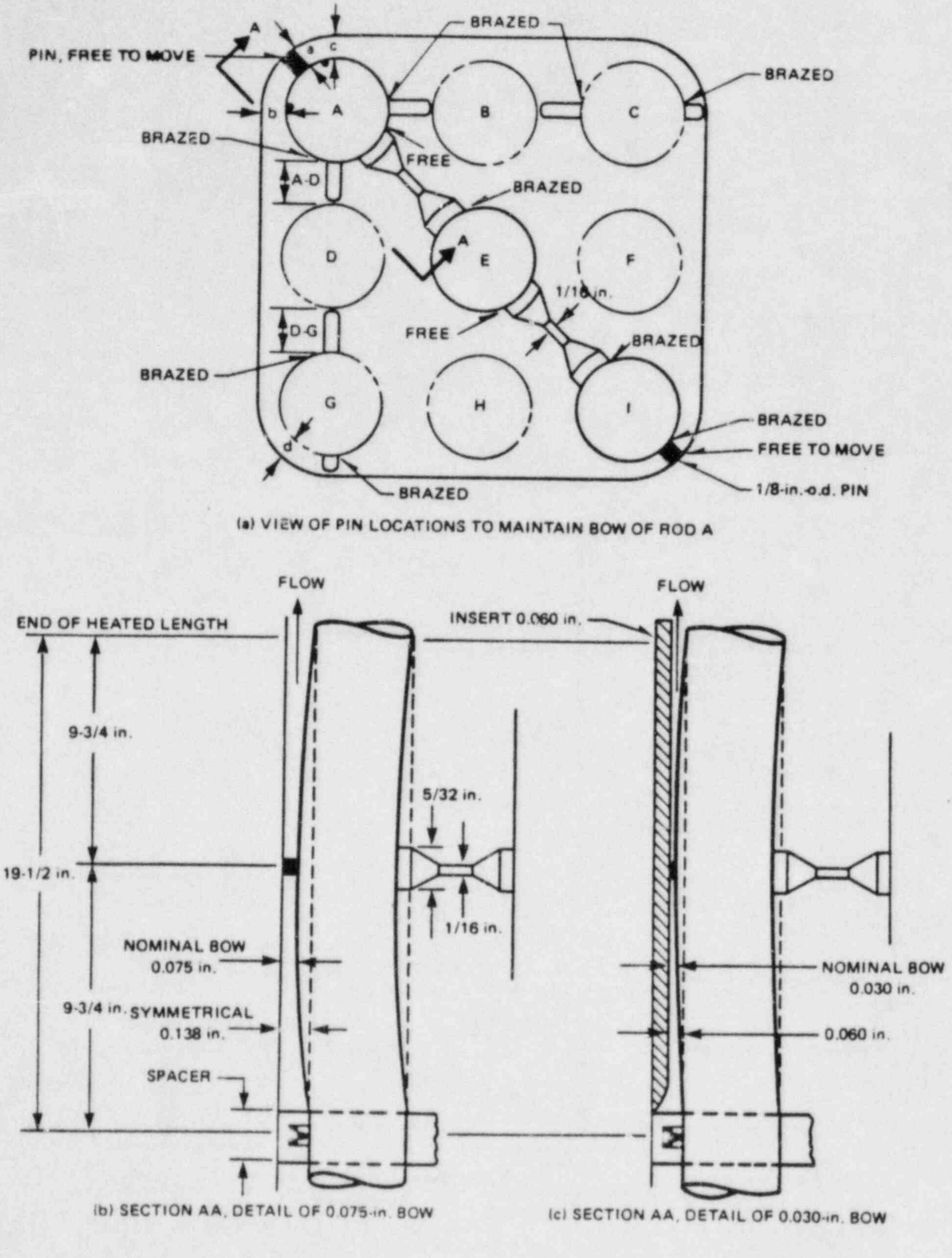
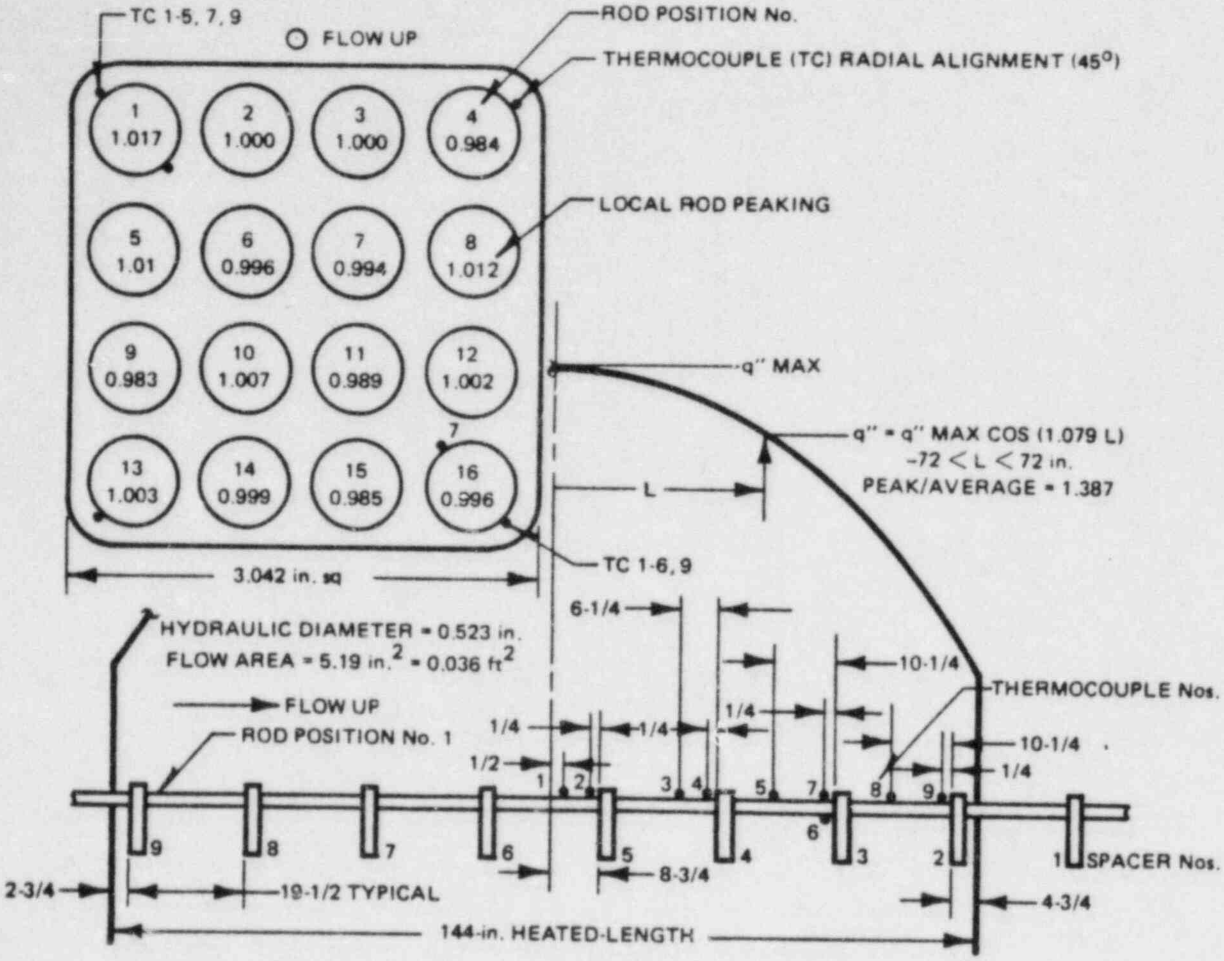
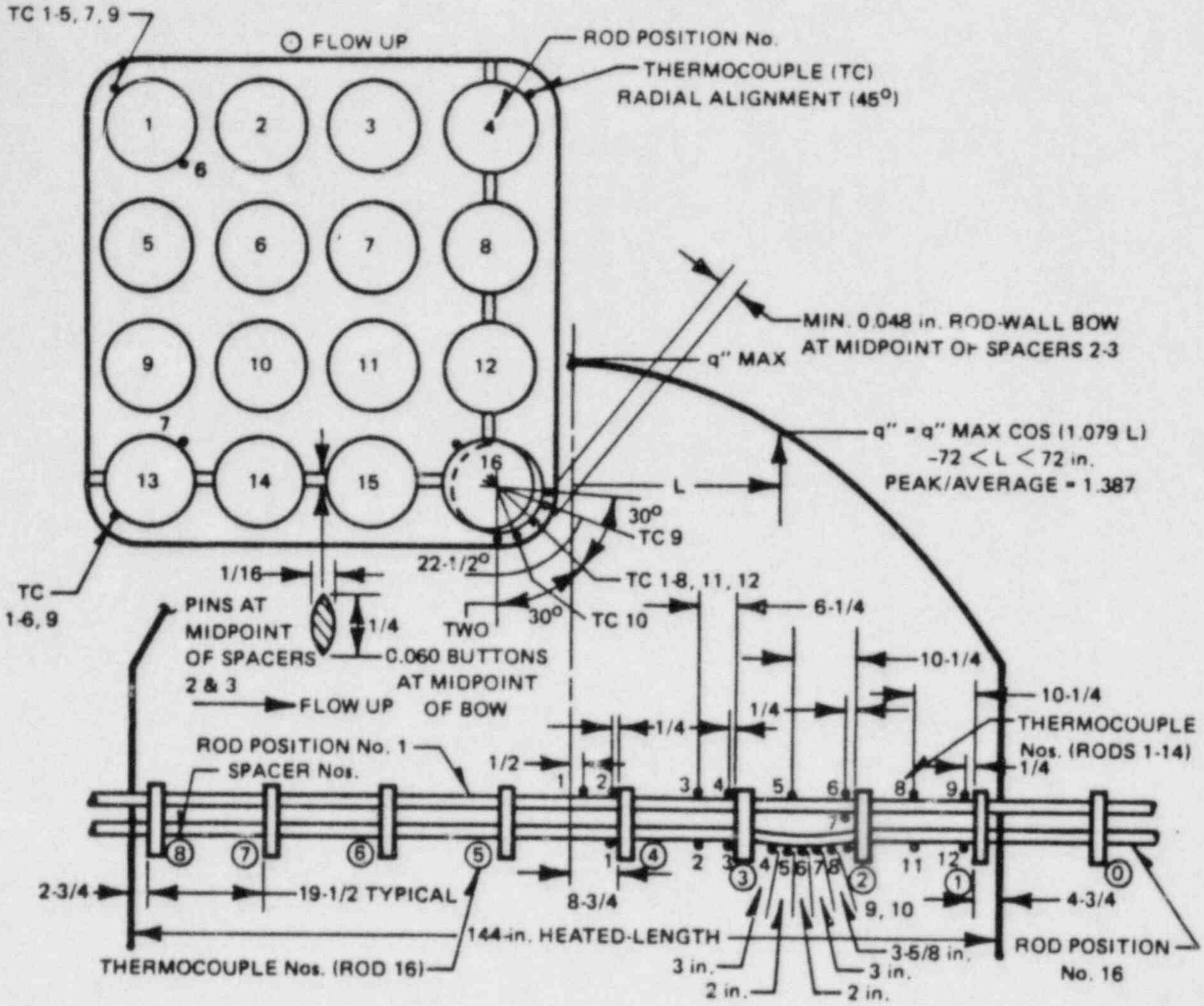


Figure A-3. Detail of Pins for Bowed Corner Rods



ROD POSITION No.	THERMOCOUPLE No. 1	2	3	4	5	6	7	8	9
1	•		•	•	•	•	•		•
3	•	•	•	•					
4					•	•		•	•
5	•	•	•	•					
6	•	•	•	•					
7					•	•		•	•
10	•	•	•	•					
11					•	•		•	•
12					•	•		•	•
13	•	•	•	•					
14					•			•	•
16	•		•	•	•	•	•		•

Figure A-4. Radial and Axial Locations of Thermocouples and Spacers (Uniform Radial Flux and Clearances)



ROD POSITION No.	THERMOCOUPLE No. 1	2	3	4	5	6	7	8	9
1	•		•	•	•	•	•		•
3	•	•	•	•					
4					•	•	•		•
5	•	•	•	•					
6	•		•	•					
7					•	•	•		•
10	•	•	•	•					
11					•	•		•	•
12					•	•		•	•
13	•		•	•	•	•	•		•
14					•	•	•		•
16	(BOWED)	12 THERMOCOUPLES ARRANGED AS ABOVE							

Figure A-5. Radial and Axial Locations of Thermocouples and Spacers (Uniform Radial Flux, Bowed Corner Rod)

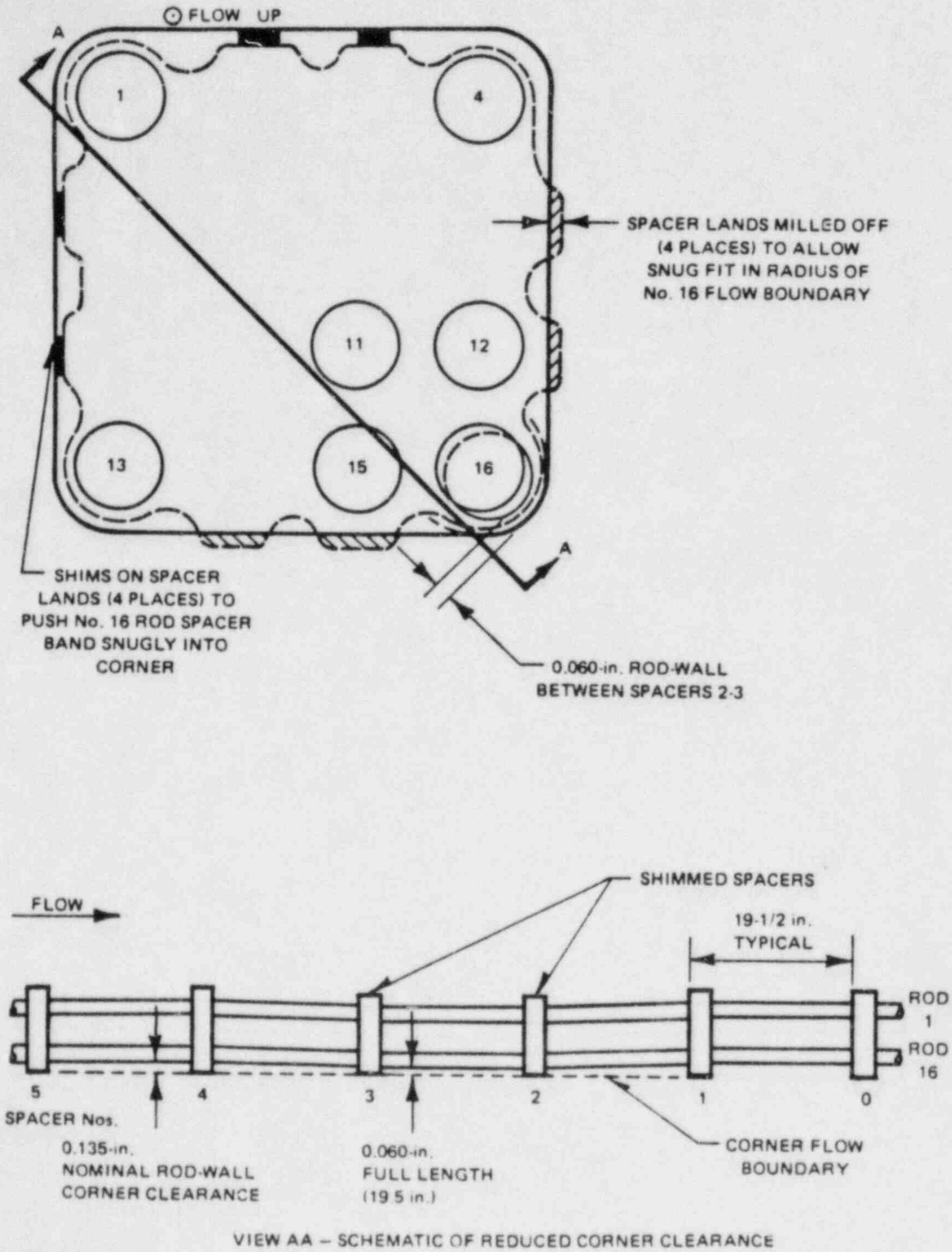


Figure A-6. Schematic of Reduced 0.060-in. Corner Clearance

Figure A-7. (GE Company Proprietary)

Figure A-8. (GE Company Proprietary)

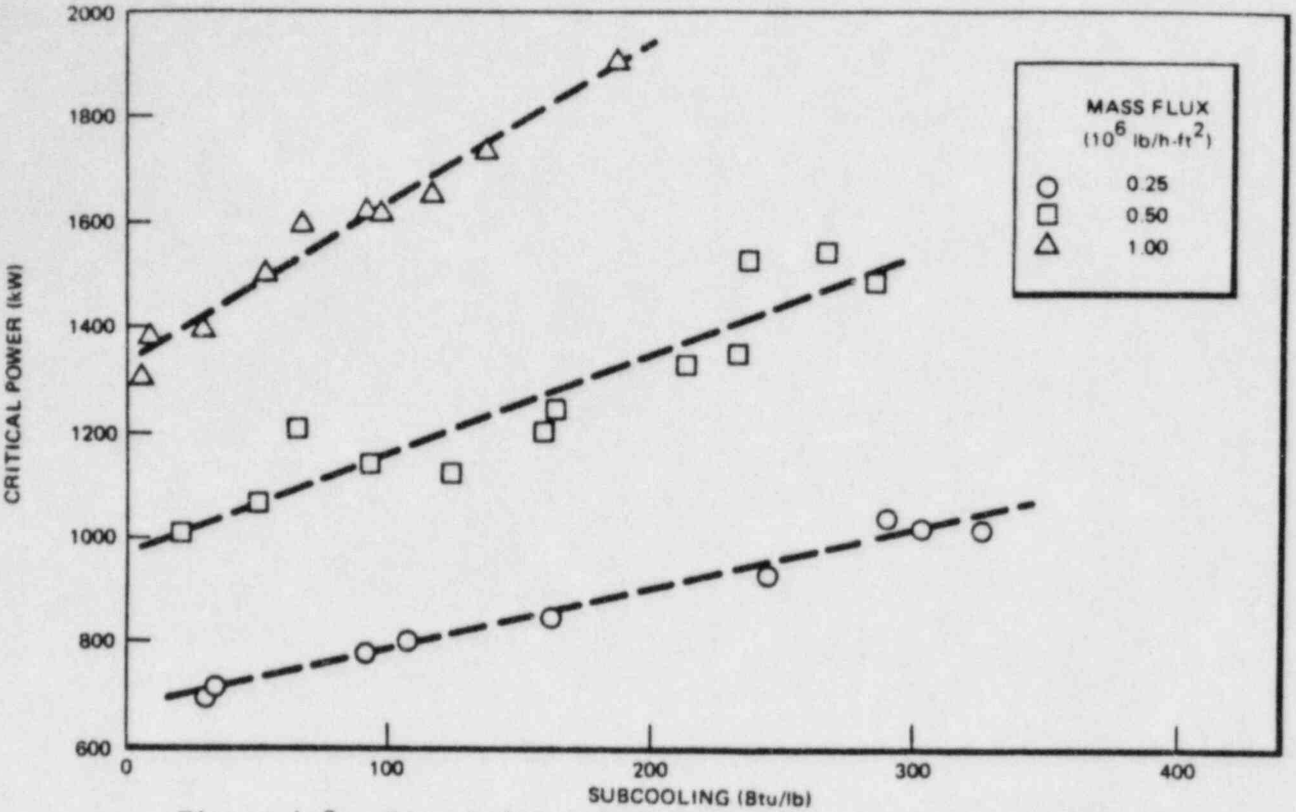


Figure A-9. Nine-Rod Critical Power in a Symmetric Radial Assembly - 800 lb/in^2

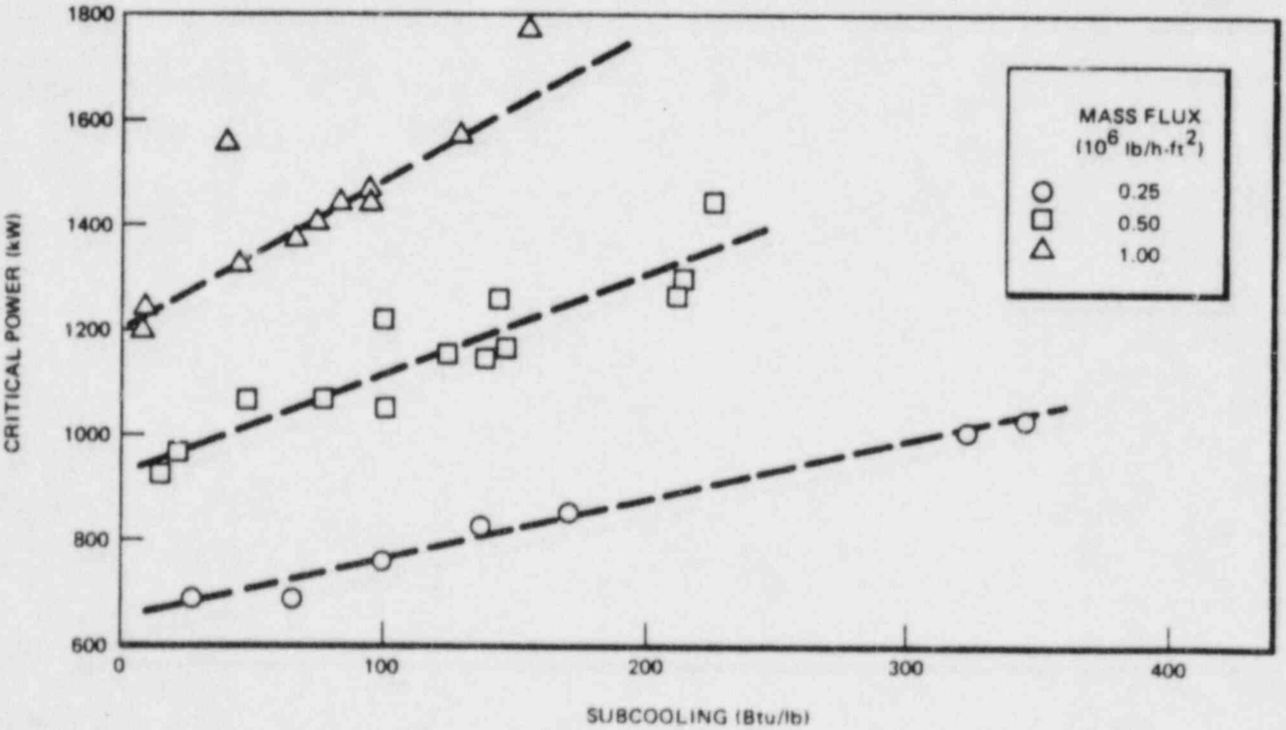


Figure A-10. Nine-Rod Critical Power in a Symmetric Radial Assembly - 1000 lb/in^2

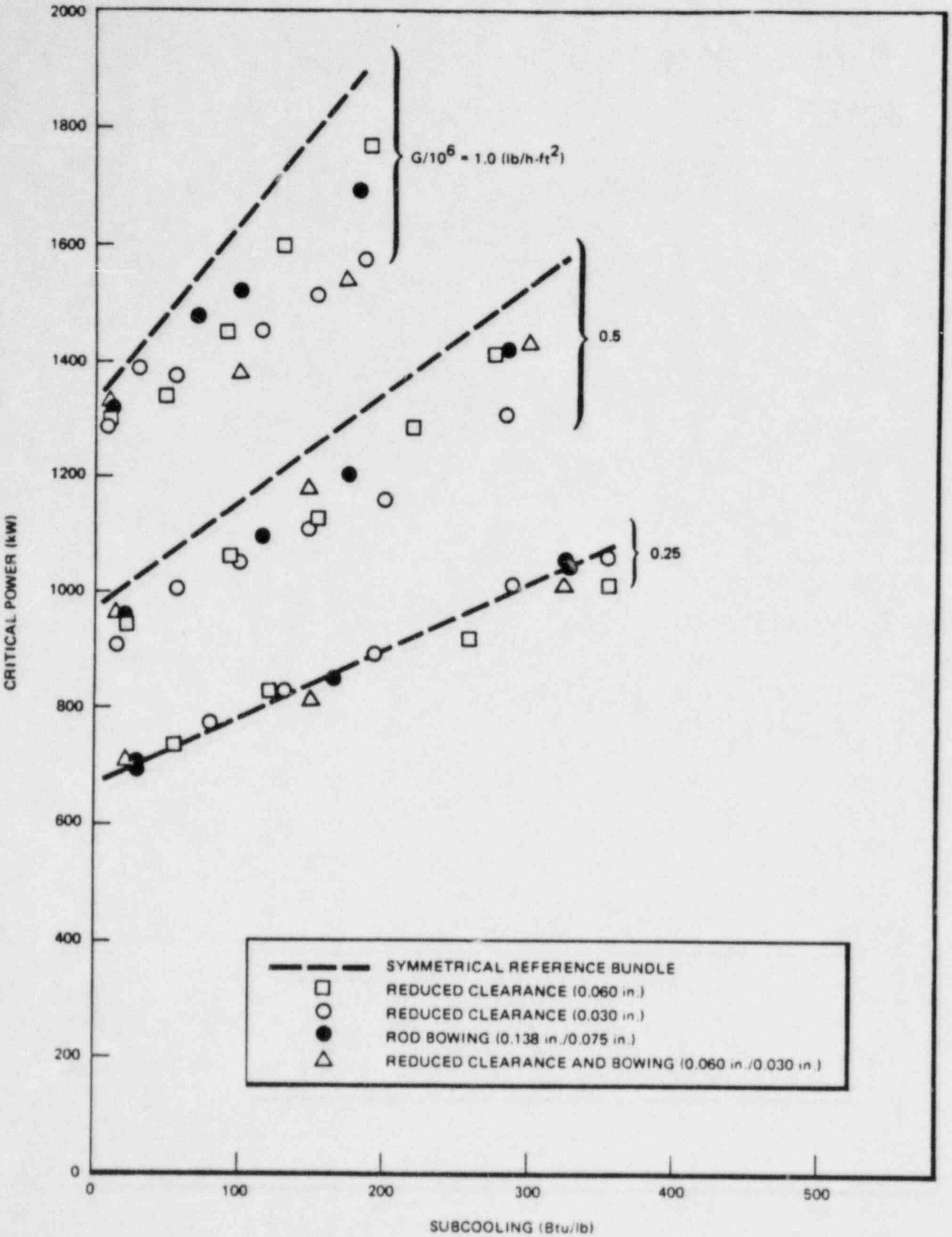


Figure A-11. Composite Critical Power Summary - Nine-Rod Uniform Axial Flux - 800 lb/in^2

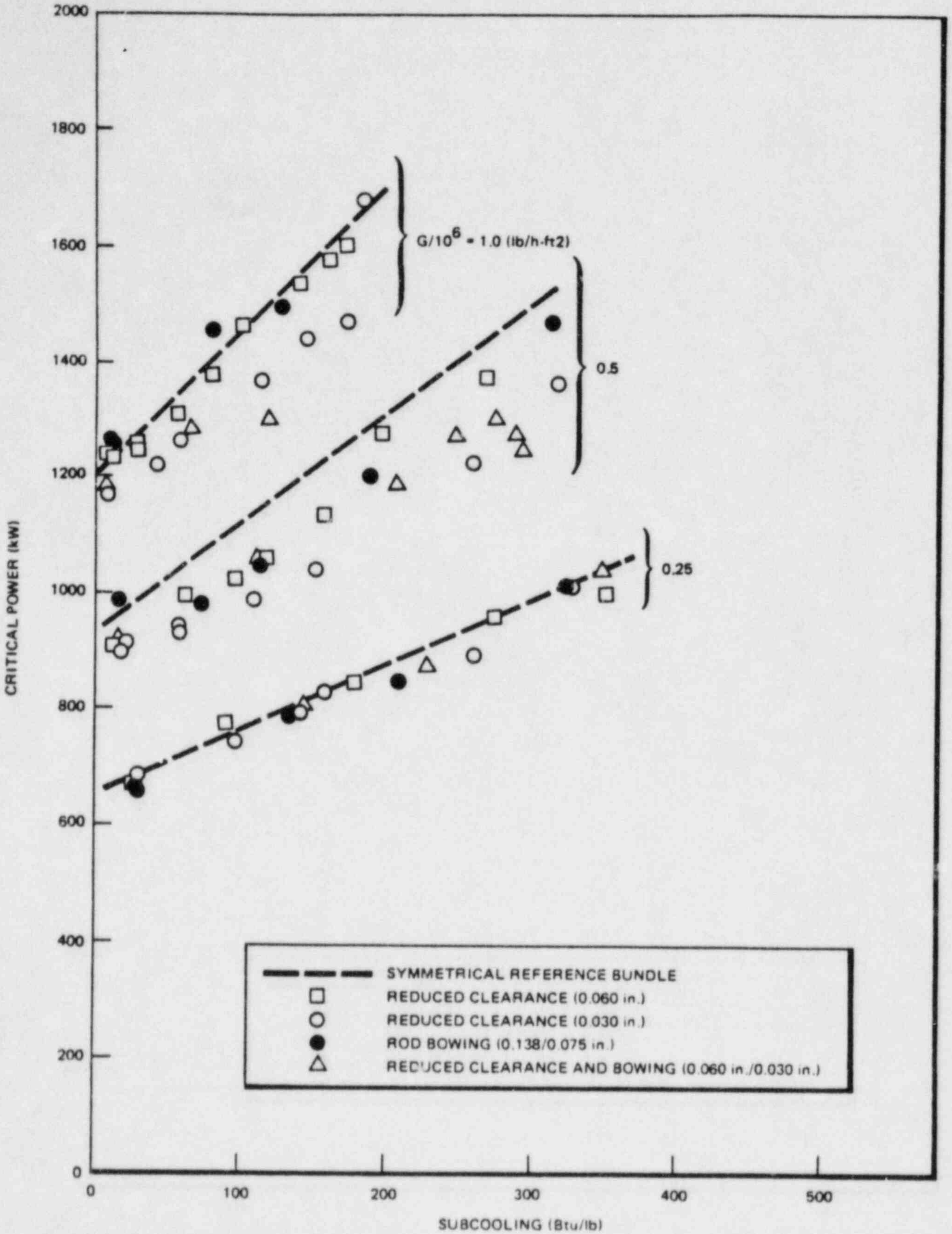


Figure A-12. Composite Critical Power Summary - Nine-Rod Uniform Axial Flux - 1000 lb/in^2

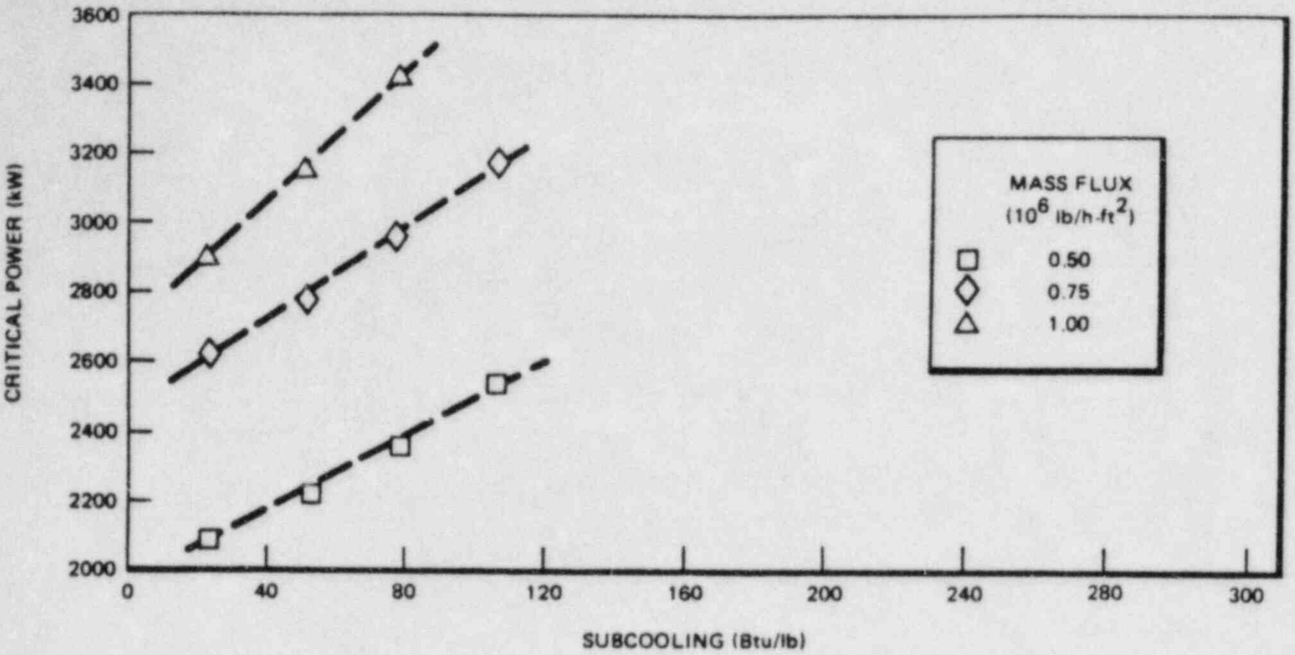


Figure A-13. 16-Rod Critical Power in a Symmetric Radial Assembly - 800 lb/in^2

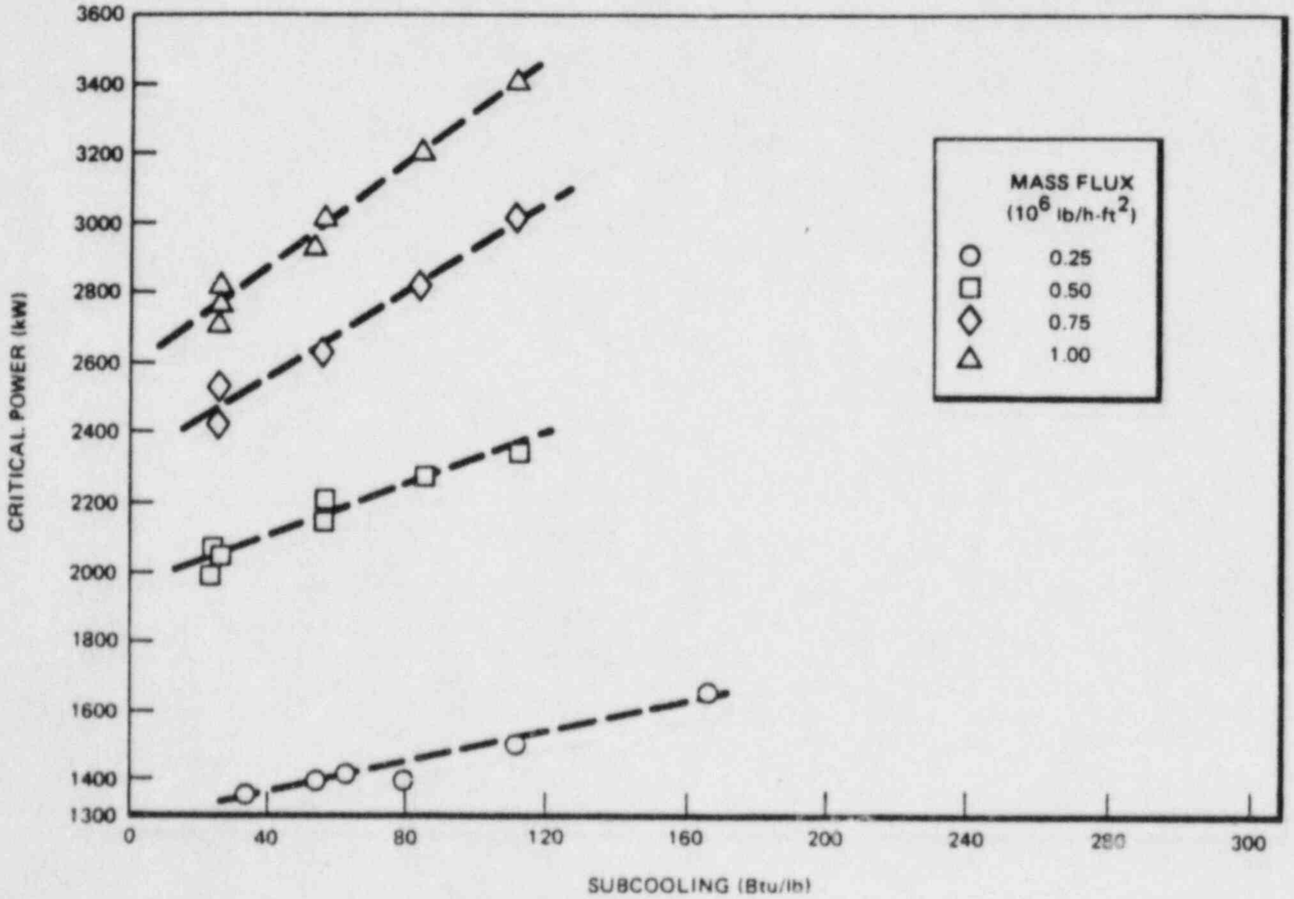


Figure A-14. 16-Rod Critical Power in a Symmetric Radial Assembly - 1000 lb/in^2

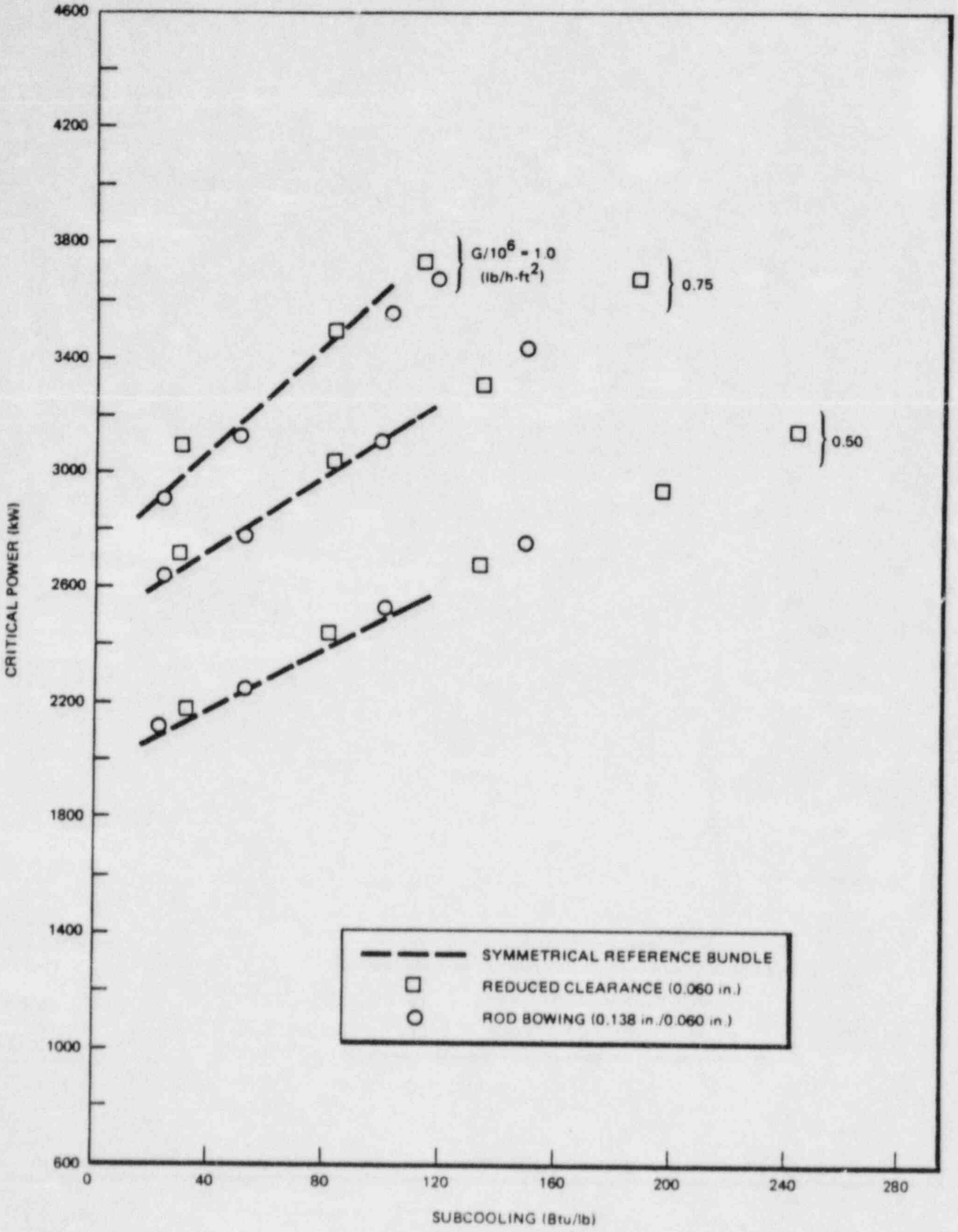


Figure A-15. Composite Critical Power Summary, 16-Rod Cosine Axial Flux - 800 lb/in^2

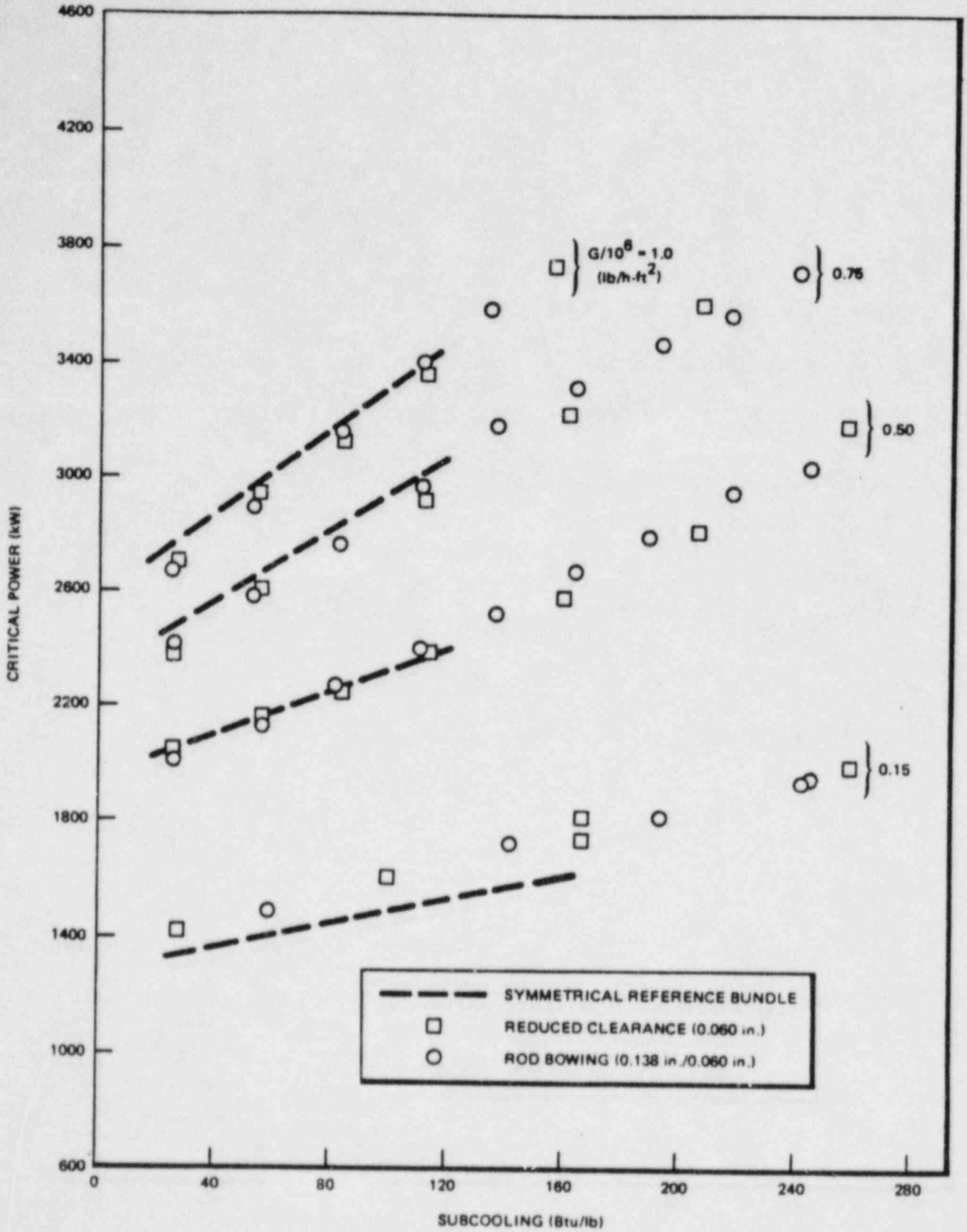


Figure A-16. Composite Critical Power Summary, 16-Rod Cosine Axial Flux - 1000 lb/in^2

A.5 REFERENCES

1. E. E. Polomik et al., "Deficient Cooling - Ninth Quarterly Progress Report," July 1 - September 30, 1971, GEAP-10221-9, October 1971.

2. E. E. Pol mik et al., "Deficient Cooling - Eleventh Quarterly Progress Report," January 1 - March 31, 1972, GEAP-10221-11, April 1972.

3.

APPENDIX B

RESPONSE TO NRC QUESTIONS

QUESTION 1:

During certain transients and accidents, large local flux and thermal gradients and stresses are expected. Can these or other mechanisms give rise to greater bowing and a larger decrease in gap closures than would be determined using the proposed gap closure correlations? If so, how are these bowing increases accounted for?

RESPONSE:

As discussed in NEDE-24284-P, a conservative rod bow analytical model has been developed and conservatively applied for the evaluation of GE BWR rod bow potential. In this analysis, the influence of fast neutron flux and thermal gradients across a fuel rod was investigated by perturbing the calculation with bounding gradients throughout fuel lifetime. As shown in Table 2 of NEDE-24284-P, the sensitivity of rod bow to these gradients is small relative to the small amount of maximum calculated bowing.

It is conceivable to postulate transients and accident conditions wherein the thermal and flux gradients are more severe than those examined in the report. However, the extensive GE BWR in-reactor experience base confirms the conclusions drawn from the bounding analytical evaluation that GE BWR fuel rod bowing is small and does not represent a viable failure mechanism. In the period since mid-1975, General Electric fuel has experienced approximately

Routine fuel inspections at these reactors indicate that these transients, which typify actual reactor operation, did not produce any significant rod bowing. Also, numerous BWR ramp type tests carried out to simulate overpower transients presented no evidence of significant rod bowing. Therefore, significant rod bowing is not expected under normal or abnormal operating transient conditions. Relative to the safety consequences of fuel

RESPONSE TO QUESTION 1: (Cont'd)

rod bowing, Section 7 of NEDE-24284-P discusses the effect of rod bowing on fuel performance during the loss-of-coolant accident. The conclusions from this section, which are based on full-scale ECCS tests of BWR fuel bundles, indicate that bowed rods have no effect on blowdown heat transfer characteristics, ECCS effectiveness, or the calculated MAPLHGR. Further, extensive thermal-hydraulic testing, described in the appendix to NEDE-24284-P, indicates that significant rod bowing has no significant detrimental effect on critical power performance.

In summary, therefore, the General Electric analytical model for rod bowing does not predict any significant rod bowing as a result of expected flux and thermal gradients. These predictions are substantiated by an extensive data base from both actual reactor operation and experimental tests. In the cases where very large local flux or thermal gradients may exist, for example, under departure from nucleate boiling or loss-of-coolant accident conditions, full-scale tests indicate that bowed rods do not impact fuel performance.

QUESTION 2:

How is the effect of the unobserved bowing accounted for in the GE power peaking analysis?

RESPONSE:

The effect of rod bowing on the effective local peaking in a bundle is not explicitly taken into account by the R-factor analysis method. Tests run in the ATLAS heat transfer facility, and described in GE Report NEDE-24284-P (Page A-7, Paragraph A-4), show that the change in measured critical power is less than 4% for tests representative of extreme rod bowing, far in excess of that observed in GE BWR fuel.

QUESTION Q-2:

What fraction of the total ( ) CPR prediction uncertainty is due to rod bowing? How much rod bowing was present in the measurement data used to determine the ( ) uncertainty and is this rod bowing typical in frequency and magnitude of EOL rod bowing?

The draft response to Question 2 does not indicate how the effect of rod bowing on local rod powers is accounted for in the determination of power peaking (e.g., LHGR, KW/FT, etc.). Describe in detail how this effect is included in the calculation and monitoring of BWR local power peaking.

RESPONSE:

The components of the CPR prediction uncertainty are identified and quantified in the Licensing Topical Report "General Electric BWR Thermal Analysis Basis (GETAB): Data, Correlation, and Design Application," (NEDO-10958, November 1973), which has been separately reviewed and approved by the NRC Staff.

Discussion of the accuracy of the local fuel rod power calculation is included in the Licensing Topical Report, "Lattice Physics Methods Verification," (NEDO-20939, June 1976), which has been separately reviewed and approved by the NRC Staff.

QUESTION 3:

Are there any segmented fuel rods presently in operation?

RESPONSE:

Yes, there are segmented test fuel rods presently in operation in the following reactors:

Plant		Number Bundles	Number of[a] Segmented Rods In a Bundle Initial	Current	No. of Segments Total	Documentation
Quad Cities 1	(STR)[b]	1	20	16	80	NEDE-20236
	(BLTA)[c]	4	2	2	32	NEDO-24147
Monticello	(STR)	1	32	24	128	NEDE-20179
Millstone 1	(STR)	1	30	25	120	NEDE-20592

[a]Four segments screwed together to form one full length

[b]Segmented Test Rod

[c]Barrier Lead Test Assembly

NEDE-20236-P Quad Cities 1 Segmented Test Rod Bundle, dated January 1974 (currently in third revision)

NEDO-24147 Quad Cities 1 Reload 4 Supplemental Licensing Information for Barrier Lead Test Assemblies, dated September 1978

NEDE-20179 Supplement to Monticello Second Reload Licensing Submittal, dated November 1973

NEDE-20592-P Millstone 1 Segmented Test Rod Bundle, dated August 1974 (currently in fifth revision)

RESPONSE TO QUESTION 3: (Cont'd)

None of the segmented rods are considered by GE to be production rods. Furthermore, these bundles have full length production fuel tie rods, thereby averting problems observed with early production fuel. In addition, none of the segmented rods are the peak power rods in their respective bundles.

QUESTION Q-3:

Are the differences in bundle and rod design sufficient to insure that these segmented rods will not undergo the bowing displacements of previous segmented rods? If not, indicate in detail how the effects of segmented rod bowing are included in the GE CPR and power peaking analysis for Quad Cities 1, Monticello, and Millstone 1. Is the CPR and power margin between the bundle peak rod and segmented rods sufficient to account for bowing effects?

RESPONSE:

The referenced segmented fuel rods that experienced significant bowing displacements were part of a very early fuel bundle design where the segmented rods were screwed together across plate-type spacers. The axial mechanical constraint provided by this configuration could not accommodate axial fuel rod growth, thereby resulting in the observed bowing. This early design concept was replaced in the early 1960s with the basic concept used today that includes through-rod spacers that can accommodate full length production fuel rods. The segmented rods used with this design concept consist of four individual segments screwed together end-to-end with appropriate upper and lower end plug extensions to become, in essence, a full-length fuel rod. All fuel rods in the assembly, including segmented rods, are then free to expand axially. Therefore, the mechanical constraint of the early design, responsible for the observed bowing, has been eliminated. All segmented rod bundles in Quad Cities 1, Monticello, and Millstone 1 are of this latter improved design concept. Site poolside work on the segmented rod bundles for selected removal/replacement activities has not identified any segment bowing problems.

QUESTION 4:

In the recent measurements of the 800 fuel bundles, what types of bundles were measured? What was the range of bundle exposures? How many and what type of rods were measured? How many rod-to-rod spacing measurements were made? Can it be concluded that the 95/95 one-sided upper tolerance limit on gap closures for the 8x8 bundles is equal to or less than 0.010 inches? What was the maximum decrease in rod-to-rod spacing measured for all bundles? What is the 95/95 one-sided upper tolerance limit on gap closures for all bundles?

RESPONSE:

A compilation of all BWR fuel bundles inspected by GE as of June 1981 is provided below:

RESPONSE TO QUESTION 4: (Cont'd)

a statistical analysis to determine the 95/95 one-sided upper tolerance cannot be properly performed.

QUESTION Q-4:

In support of the statement "no significant fuel rod bowing has been detected in GE BWR fuel assemblies," provide a summary of the results of all visual inspections and measurements of rod-rod gap closure. Specifically, provide the gap closure frequency distribution indicating the number of gap observations that fall within a given gap closure interval. If necessary, in intervals where observational data is limited, the data may be supplemented by assuming the underlying gap closure distribution is normal (unless inconsistent with the measurement data). This distribution of gap closure observations should be presented in tabular form and in sufficient detail to allow determination of the gap closures that bound 68 and 95 percent of the observed gap closures. Also indicate the number of observations that were made in each interval.

If based on either measurement data or specific fuel design, the gap closure is expected to be significantly larger for a particular plant, cycle, or fuel design, indicate the expected increase in the 68 and 95 percent upper tolerance limits.

RESPONSE:

The procedures used by GE personnel to make observations of the fuel bundles noted in the response to Question 4 do not lend themselves to the statistical analysis requested by this question. Field observations are made for a number of reasons, only one of which is for observation of the potential for rod bowing, and are generally qualitative in nature or coarsely quantitative. Therefore, data is not routinely collected in a form which would allow the generation of a meaningful frequency distribution.

QUESTION 5:

To what extent does the channel box distort and bow, and how does this affect the local power and CPR calculation?

RESPONSE:

Fuel channels can deform by bulging and/or bowing. Channel bulge is the outward displacement of the channel wall due to the pressure differential across the wall and is addressed in NEDE-21354.* Channel bow is the lateral displacement of the channel, and is generally caused by the differential growth of the opposite walls of the channel when in a neutron flux gradient.

During operation, the channel box is subject to a pressure difference which has its maximum value at the lower end of the channel and which decreases monotonically to zero at the top of the channel. Inspections of channels following a period of in-core service have shown that the deflections are greatest over the lower third of the channel length and diminish towards the ends of the channels. Tests were carried out in the GE ATLAS Test Facility to determine the effect of channel box distortion on the bundle critical power.

*NEDE-21354, BWR Fuel Channel Mechanical Design and Deflection," dated September 1976.

RESPONSE TO QUESTION 5: (Cont'd)

In light of these results, it was concluded that no significant critical power effect is to be expected for this geometry condition.

Figure 1. (GE Company Proprietary)

QUESTION Q-5:

In draft Response 5, it is stated that at EOL, a channel deformation of ( ) mils has been observed. What is the effect of this bow on the local rod powers, especially those on the bundle periphery adjacent to the water gap? What is the effect of this distortion on CPR as a result of the increase in local rod powers? With what frequency is this magnitude distortion expected to occur? What is the expected variation or standard deviation in water gap width due to distortion of this type? What is the effect of this type of distortion on the prediction and monitoring of CPR and local power peaking (KW/FT, LHGR, etc.), and how is it accounted for?

Channel bulge will have a similar effect on local rod powers. How is the effect of increased rod powers due to channel bulging accounted for in the prediction and monitoring of CPR and local power peaking (e.g., KW/FT, LHCR, etc.)?

RESPONSE:

The capability of the General Electric analytical models to accurately predict local fuel rod powers was a topic included in a separate licensing topical report. That licensing topical report, "Lattice Physics Methods Verification," (NEDO-20939, June 1979), which has been separately reviewed and approved by the NRC Staff, provides a detailed description of the approaches used, and the results of the assessment of the accuracy of the local fuel rod power calculation.

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