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LICENSING TOPICAL REPORT

ASSESSMENT OF FUEL ROD BOWING IN GENERAL ELECTRIC BOILING WATER REACTORS

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This document contains 40 pages which include forematter pages i through viii, 1 through 13, and Appendix A.

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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 assembly 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 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 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 ~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 positions seven Zircaloy spacers axially 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. Figure 1 illustrates the typical BWR fuel assembly design concept.

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 [illegible] 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.

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

Design basis values of internal rod pressure, peak linear heat generation rate, and average cladding temperature were varied with exposure for fuel rods with 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

The analyses demonstrated 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.[4-7] 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 nonuniform axial power profiles. In these tests rod-to-channel clearances as low as 0.030 inch indicated only slight differences in critical power performance, almost within the data uncertainty between nominal design and reduced-clearance assemblies. Full details of the 9- and 16- rod tests can be found in the Appendix.

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 substantially reduced over a span between two spacers. 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 each other. 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[8-16] 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 test data, 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 Maximum Average Planar Linear Heat Generation Rates (MAPLHGR) used by General Electric boiling water reactors because in-reactor fuel rod bowing during normal operation has no effect on the blowdown heat transfer characteristics or the Emergency Core Cooling System (ECCS) effectiveness during a Loss-of-Coolant Accident (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 an LOCA when the ECCS is operating. These effects have been considered in detail[17] 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.

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.

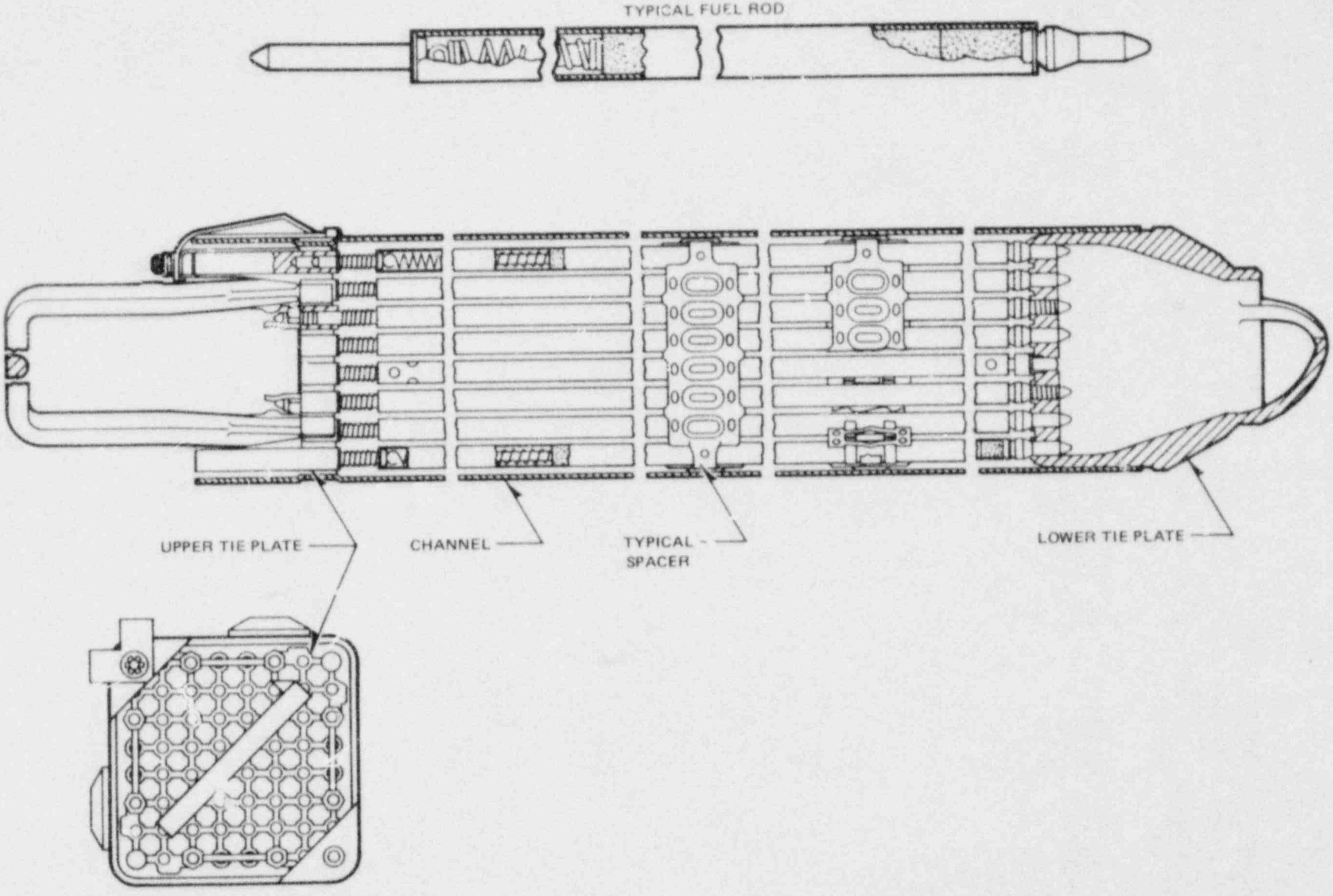


Figure 1. Fuel Assembly Cross Section

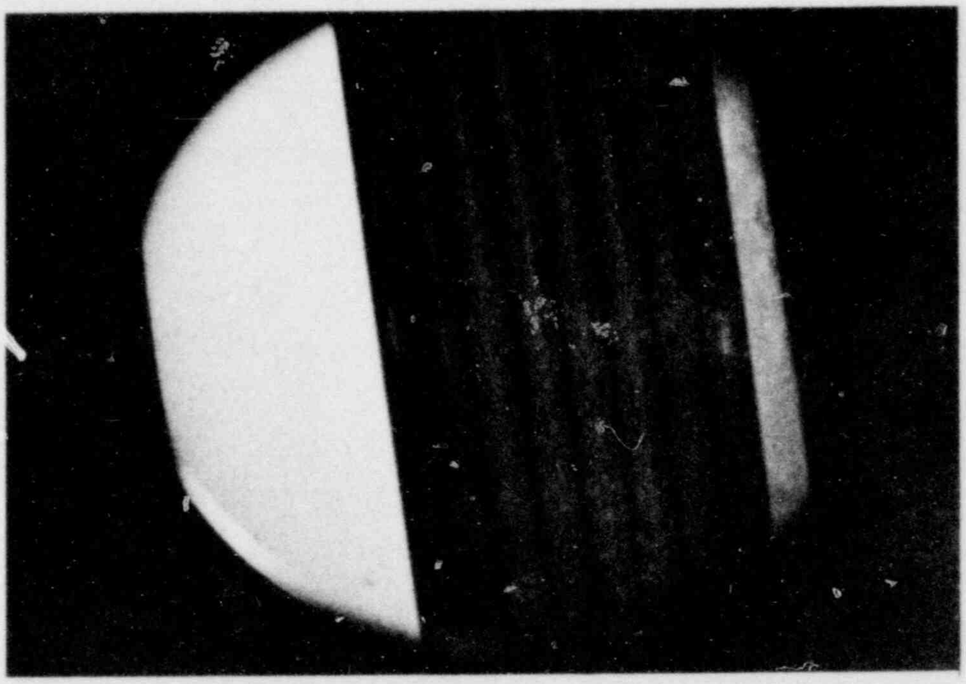


Figure 2. Typical Rod-to-Rod Spacing (Exposure ~15,000 MWd/MT)

9. REFERENCES

1. Letter, O. D. Parr to G. G. Sherwood, "Fuel Rod Bowing Topical Report," 9/21/78.

2. Letter, G. G. Sherwood to D. G. Eisenhut, "NRC Questions on Rod Bowing," 3/29/77.

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

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

5. E. E. Polomik et al., "Deficient Cooling - Tenth Quarterly Progress Report," October 1-December 31, 1971, GEAP-10221-10, April 1972.

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

7. E. E. Polomik et al., "Deficient Cooling - Twelfth Quarterly Progress Report," April 1-June 30, 1979, GEAP-10221-12, July 1972.

8. B. W. LeTourneau et al., "Critical Heat Flux and Pressure Drop Tests with Parallel Upflow of High Pressure Water in Bundles of Twenty 3/4-Inch Rods," Nuclear Science & Engineering, Vol. 54, 1974, pp. 214-232.

9. R. B. Nixon et al., "The Effect of Reduced Clearance and Rod Bow on Critical Power in Full-Scale Simulations of 8x8 BWR Fuel," ASME 75-HT-69.

10. D. H. Lee and R. B. Little, "Experimental Studies into the Effect of Rod Spacing on Burnout in a Simulated Rod Bundle," AEEW-R-178, 1962.

11. R. H. Towell, "Effect of Rod Spacing on Heat Transfer Burnout in Rod Bundles," DP-1013, 1965.

12. S. J. Green et al., "Critical Heat Flux Tests on a Coolant Channel Simulating a Closely Spaced Lattice of Rods," Two-Phase Flow and Heat Transfer in Rod Bundles, ASME, 1969.

13. "Fuel and Poison Rod Bowing," Combustion Engineering CENPD-225, October 1969.

14. "Computation Procedures for Evaluating Fuel Rod Bowing," EXXON Nuclear Co., XN-75-32(NP), July 1979.

15. "Fuel Rod Bow Evaluation," Westinghouse Electric Corp., WCAP-8692 Rev. 1.

16. R. T. Lahey et al., "The Effect of Reduced Clearance and Rod Bow on Critical Power in Simulated Nuclear Reactor Rod Bundles," Proceedings of the International Meeting on Reactor Heat Transfer, ANS, Karlsruhe, 1973, pp. 520-537.

17. "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 inch 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 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 17,200-kW 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 and 16-rod bundles).

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-7 and A-8. Performances for the entire range of geometry configurations are summarized in Figure A-9 for 800 lb/in.^{2} results, and in Figure A-10 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.

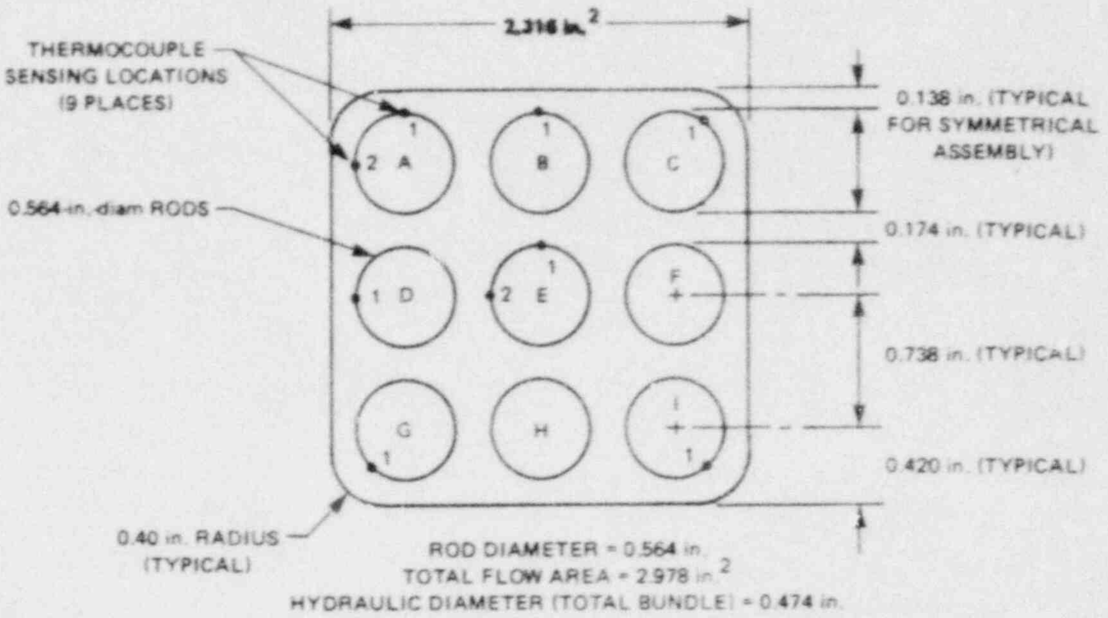
The trends of these data with mass flux suggest that the critical power penalties are partially caused by adverse flow diversion from the local restrictions, as flow distribution is more sensitive to local restrictions at higher mass fluxes. The increased penalties observed at higher subcooling may be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

A.3.2 16-Rod Results

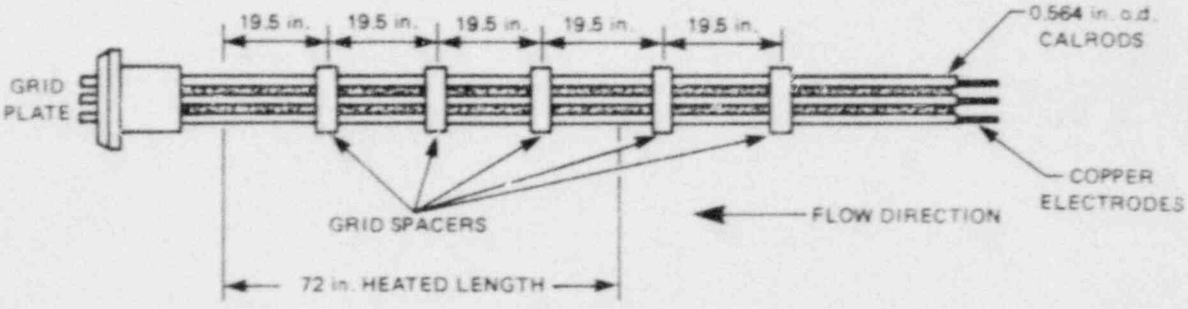
The 16-rod, symmetrical clearance, reference-bundle data are plotted in Figures A-11 and A-12 for 800 lb/in.^{2} and 1000 lb/in.^{2}, respectively. These nonuniform axial power profile data can again be well represented with linear fit lines. Composite plots of the results from all three assemblies are shown in Figures A-13 and A-14. 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-13 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.



(a) CLEARANCES AND THERMOCOUPLE LOCATIONS IN A SYMMETRICALLY ARRANGED BUNDLE



(b) AXIAL LOCATION OF SPACERS

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

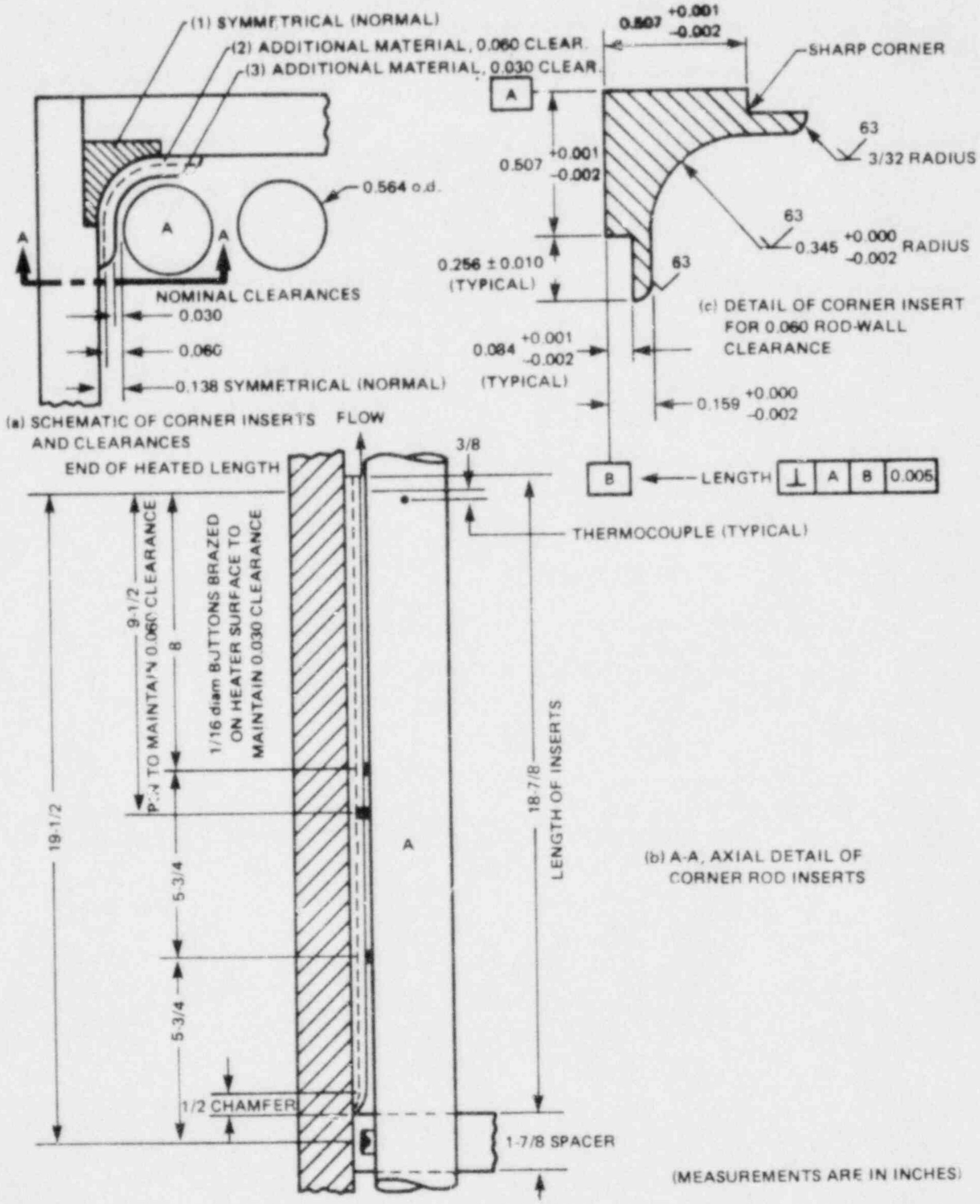
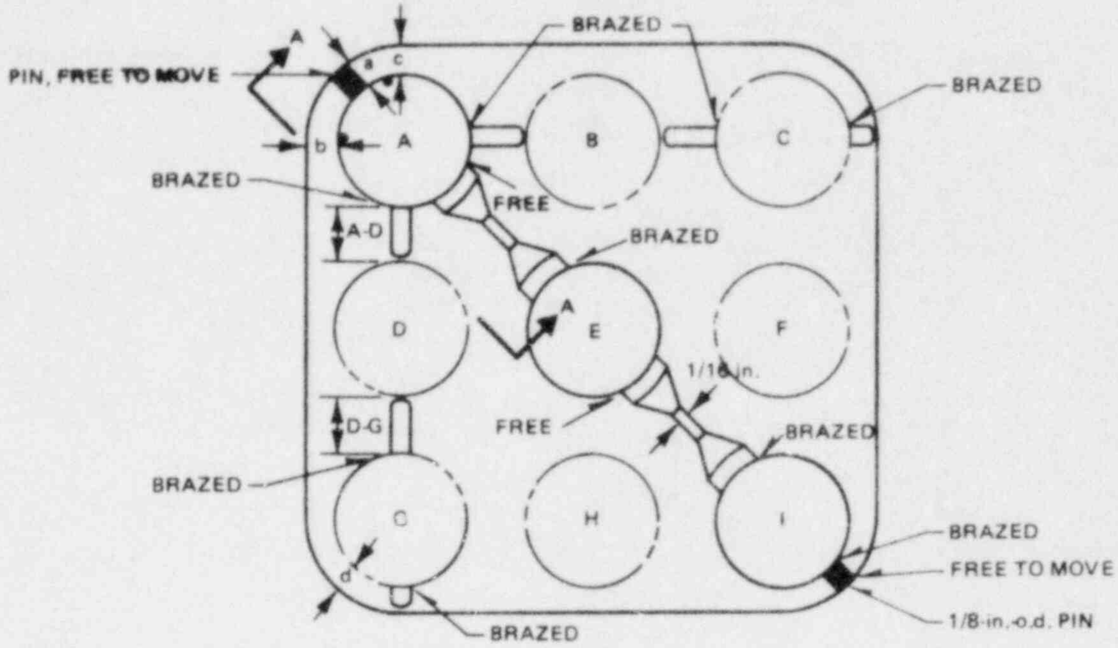
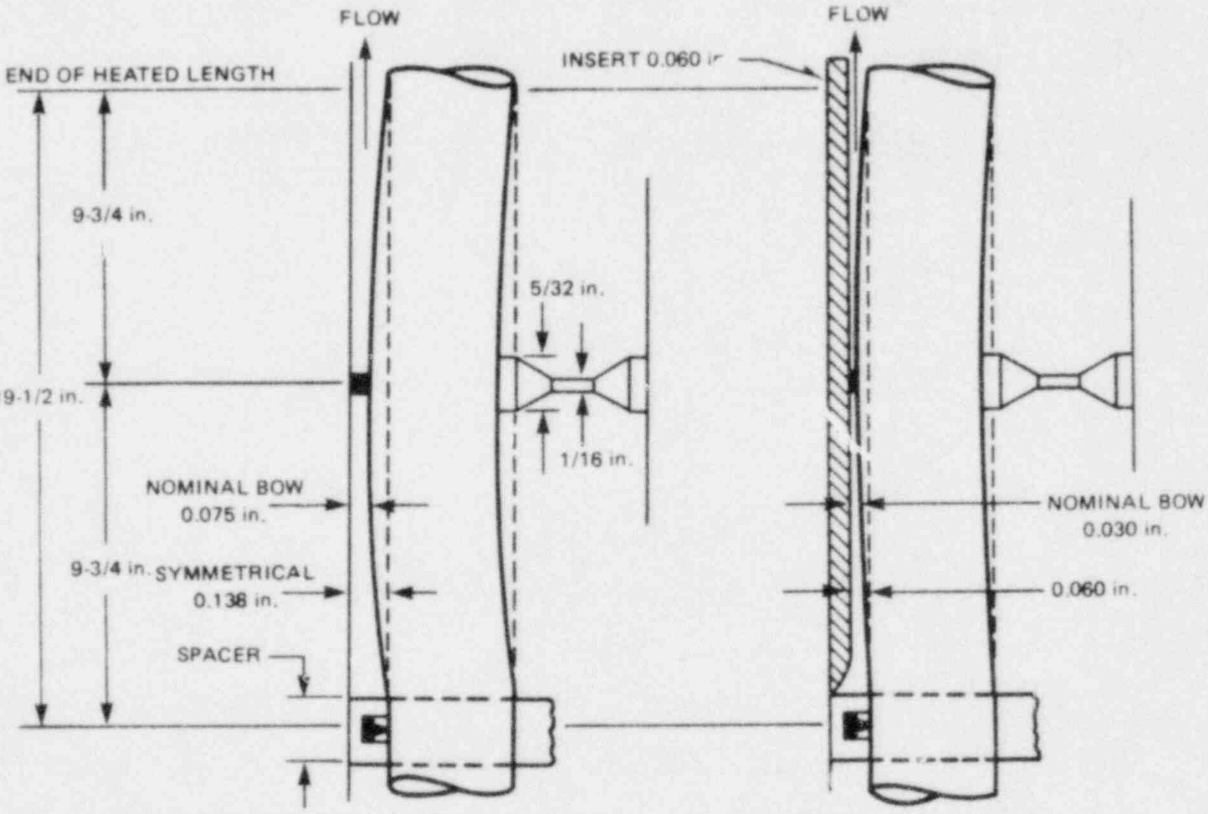


Figure A-2. Schematic and Detail of Corner Rod Clearances



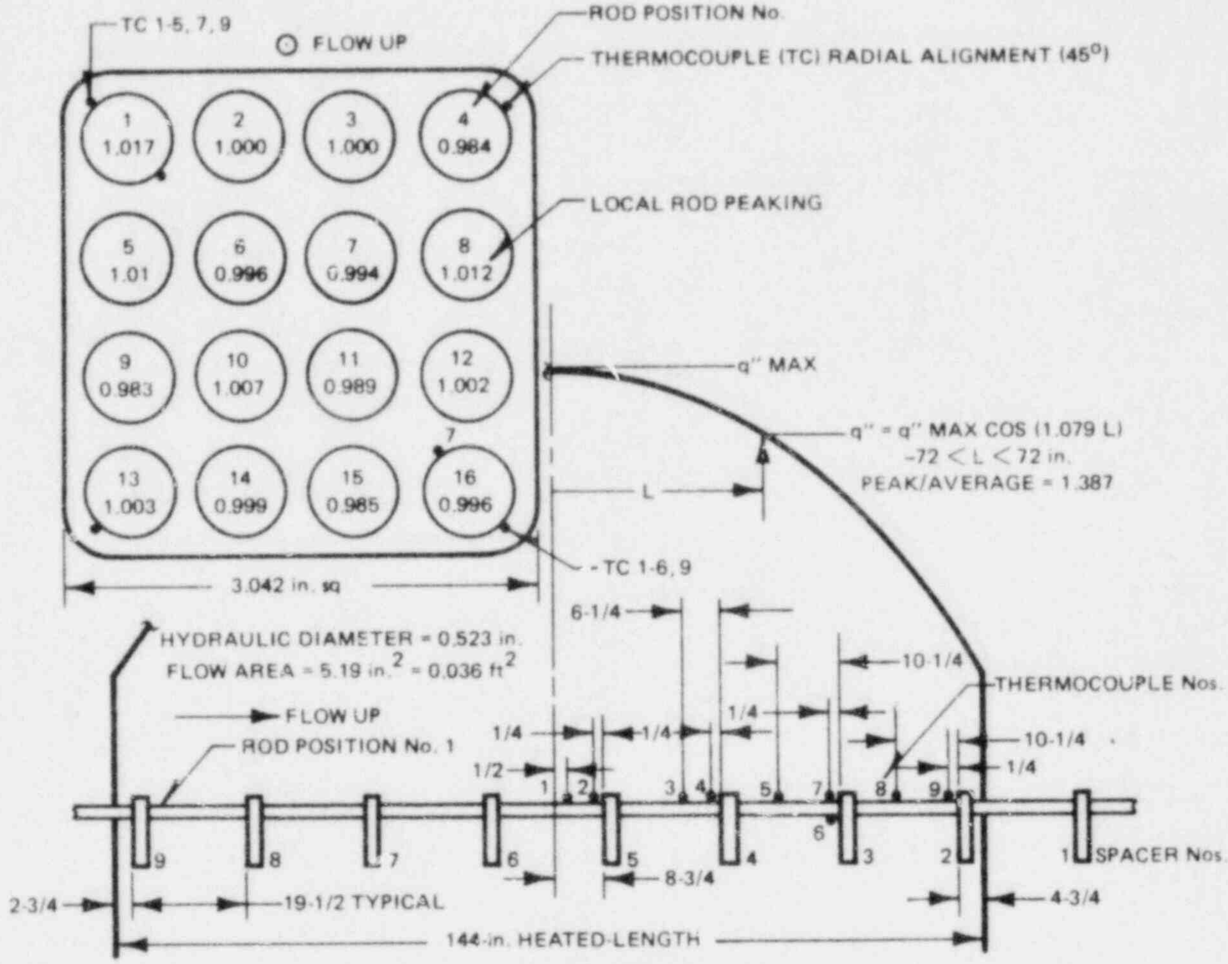
(a) VIEW OF PIN LOCATIONS TO MAINTAIN BOW OF ROD A



(b) SECTION AA, DETAIL OF 0.075-in. BOW

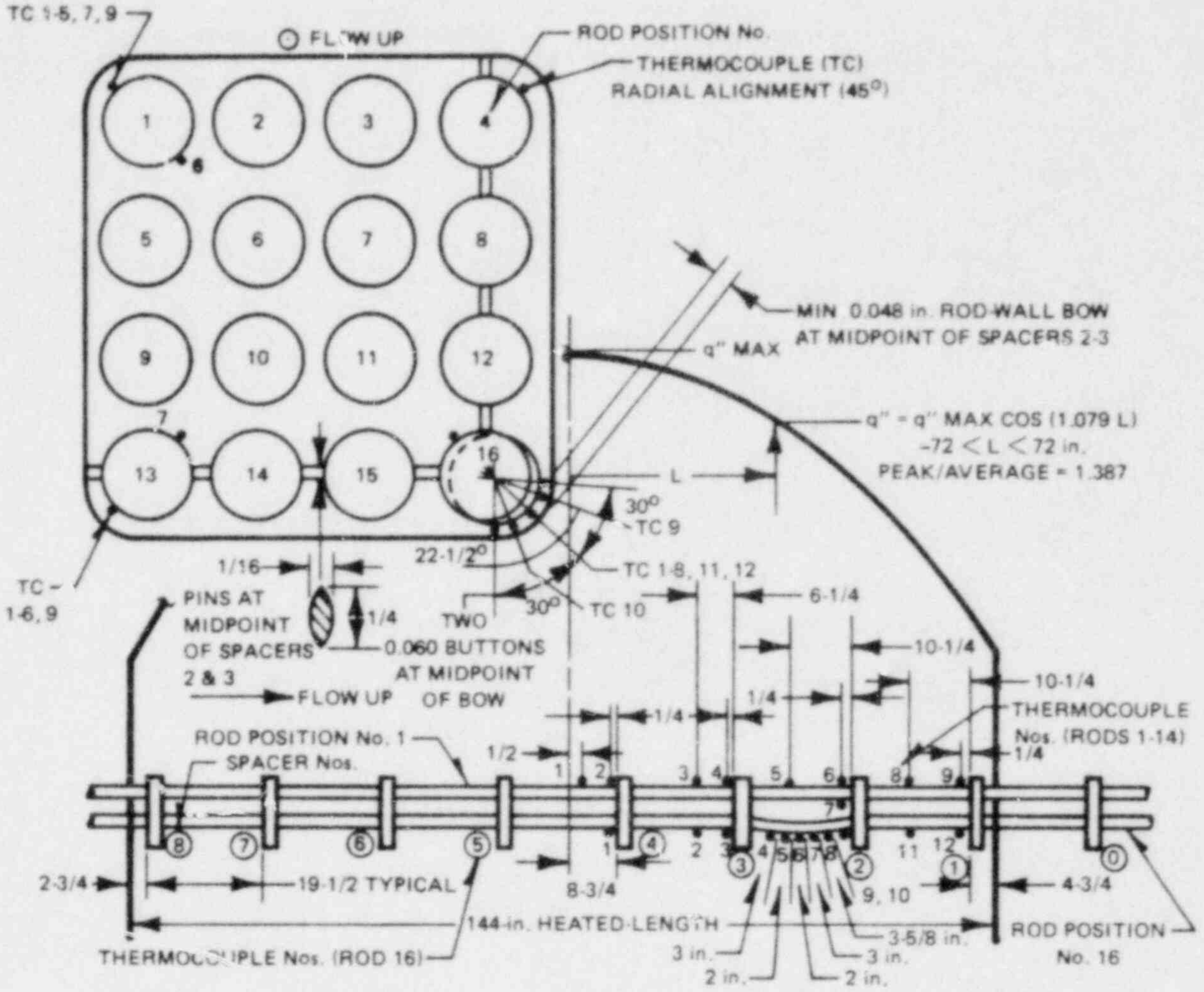
(c) SECTION AA, DETAIL OF 0.030-in. BOW

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



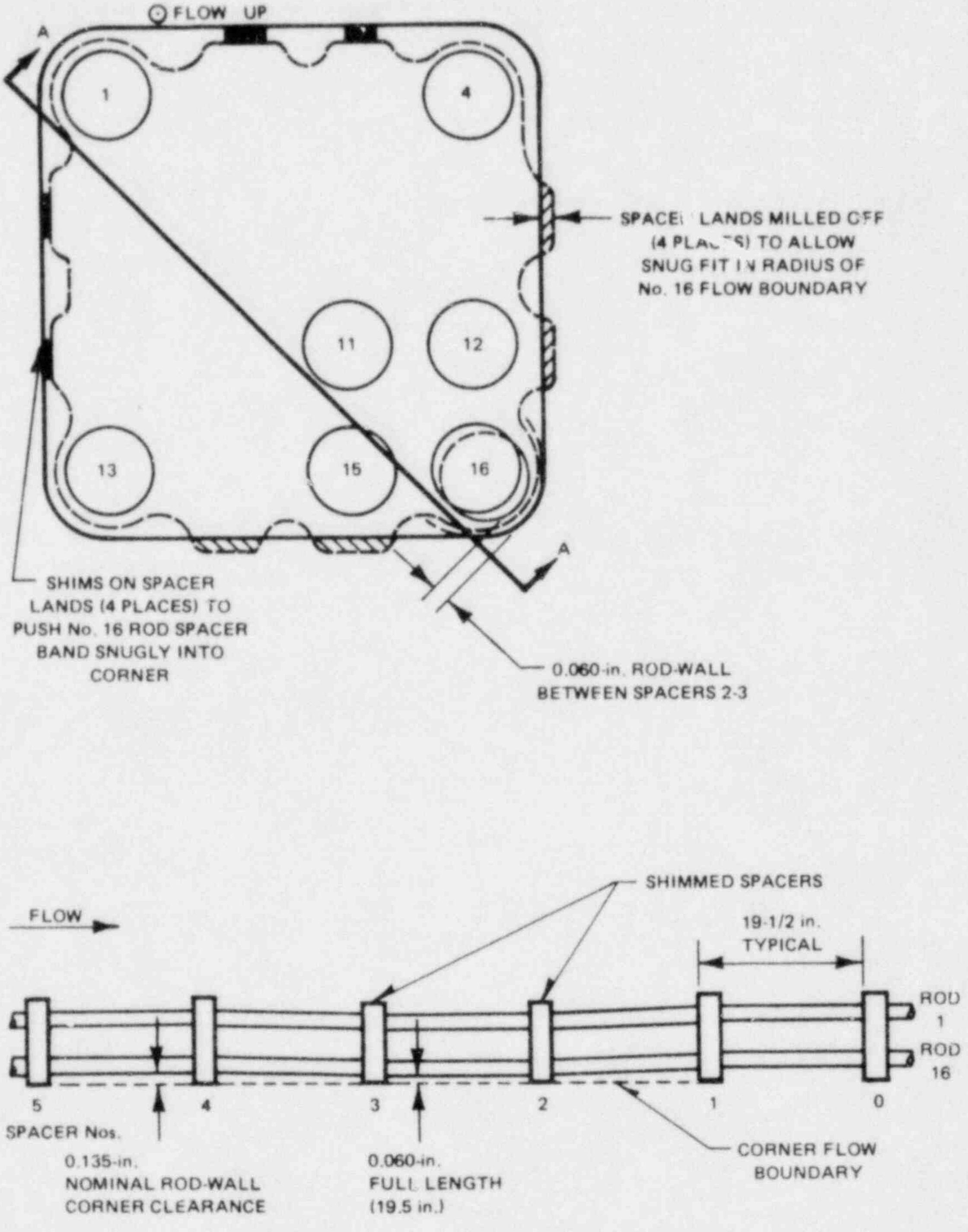
ROD POSITION No.	THERMOCOUPLE No.								
	1	2	3	4	5	6	7	8	9
1	•		•	•	•	•	•		•
3	•	•	•	•					
4					•	•		•	•
5	•	•	•	•					
6	•	•	•	•					
7					•	•		•	•
10	•	•	•	•					
11					•	•		•	•
12					•	•		•	•
13	•	•	•	•					
14					•			•	•
16	•		•	•	•	•	•		•

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)



VIEW AA – SCHEMATIC OF REDUCED CORNER CLEARANCE

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

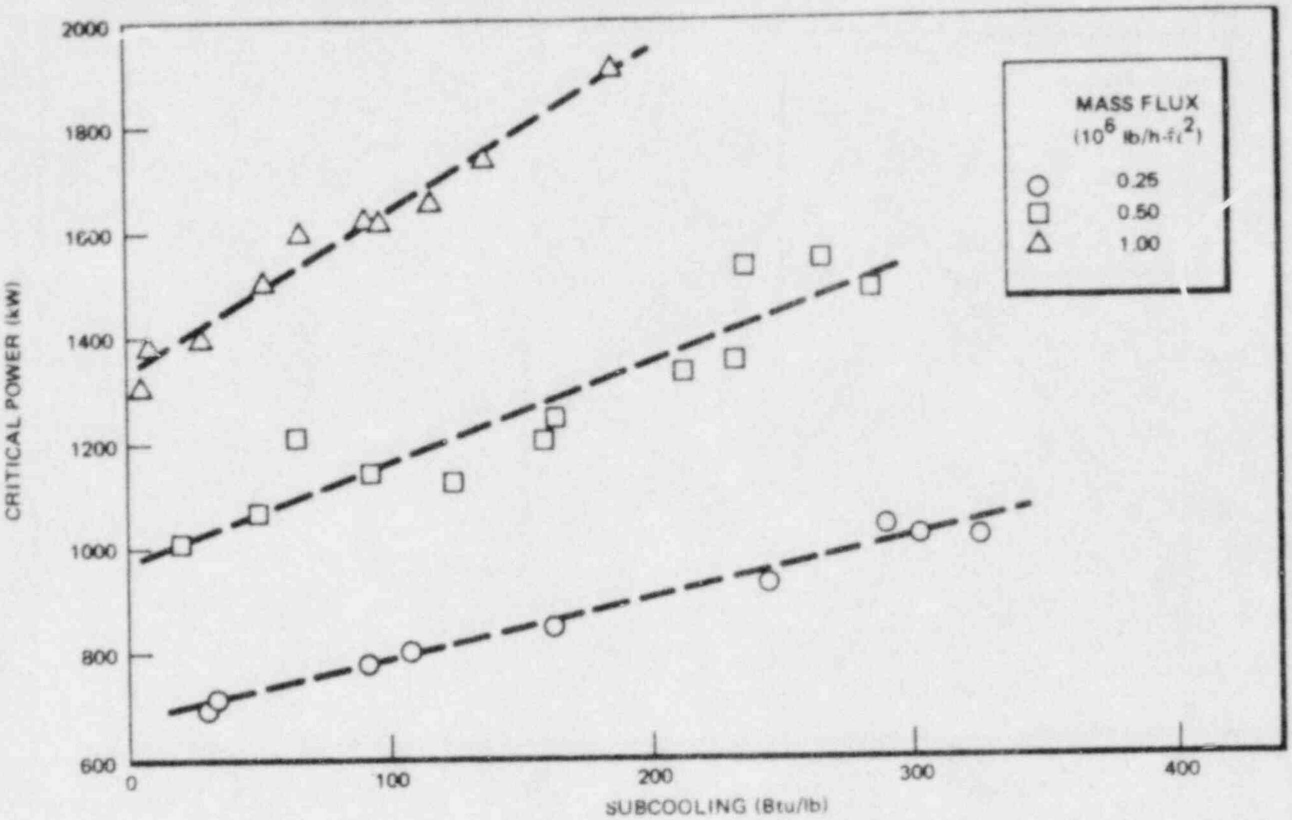


Figure A-7. Nine-Rod Critical Power in a Symmetric Radial Assembly - 800 lb/in.^{2}

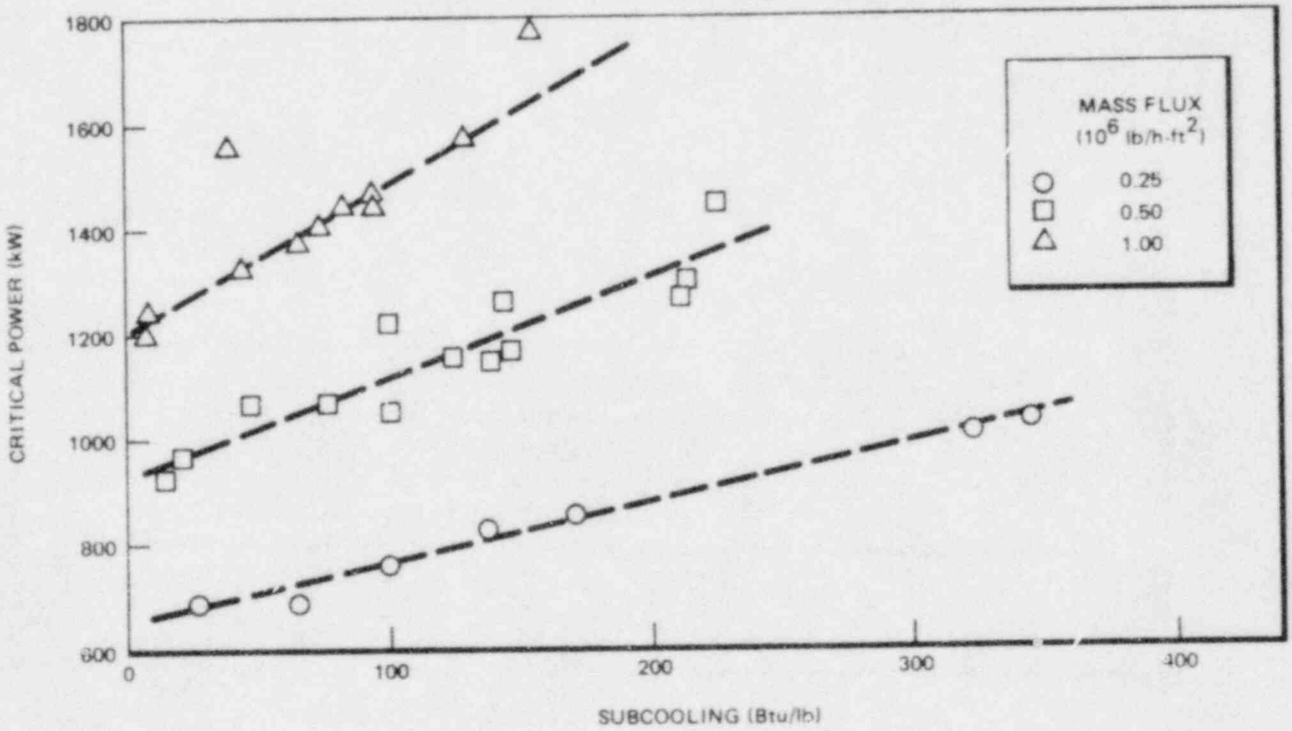


Figure A-8. Nine-Rod Critical Power in a Symmetric Radial Assembly - 1000 lb/in.^{2}

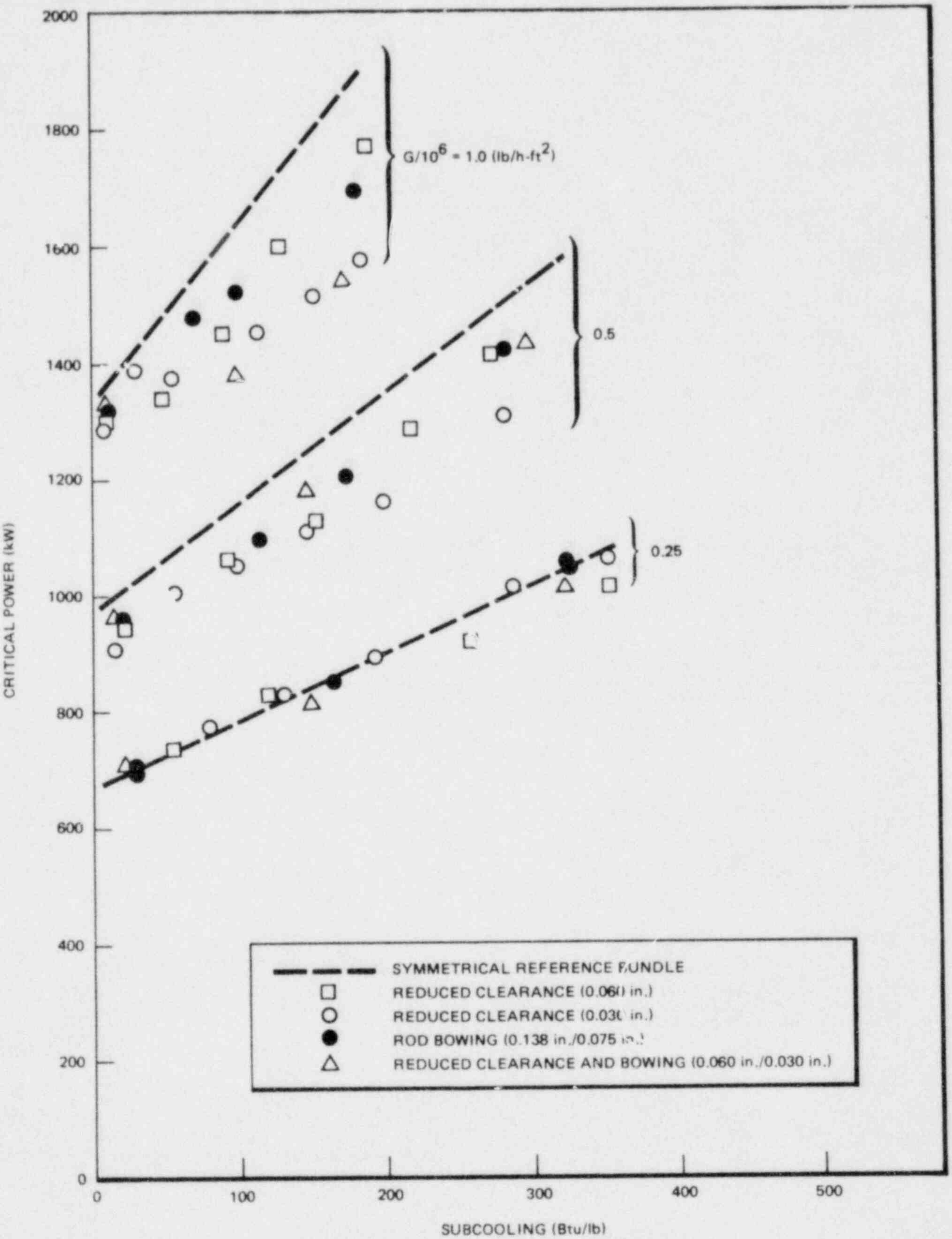


Figure A-9. Composite Critical Power Summary - Nine-Rod Uniform Axial Flux - 800 lb/in.^{2}

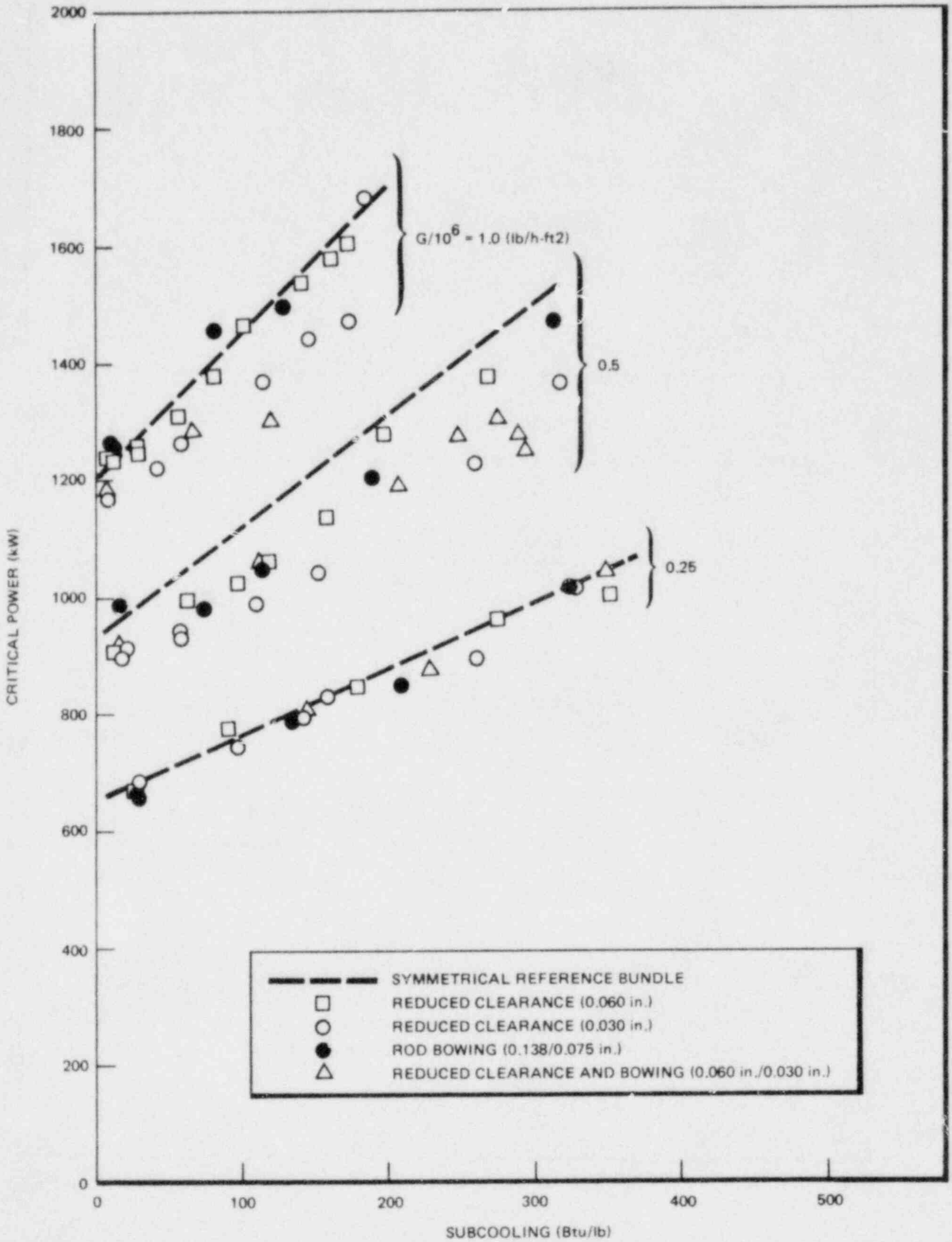


Figure A-10. Composite Critical Power Summary - Nine-Rod Uniform Axial Flux - 1000 lb/in.^{2}

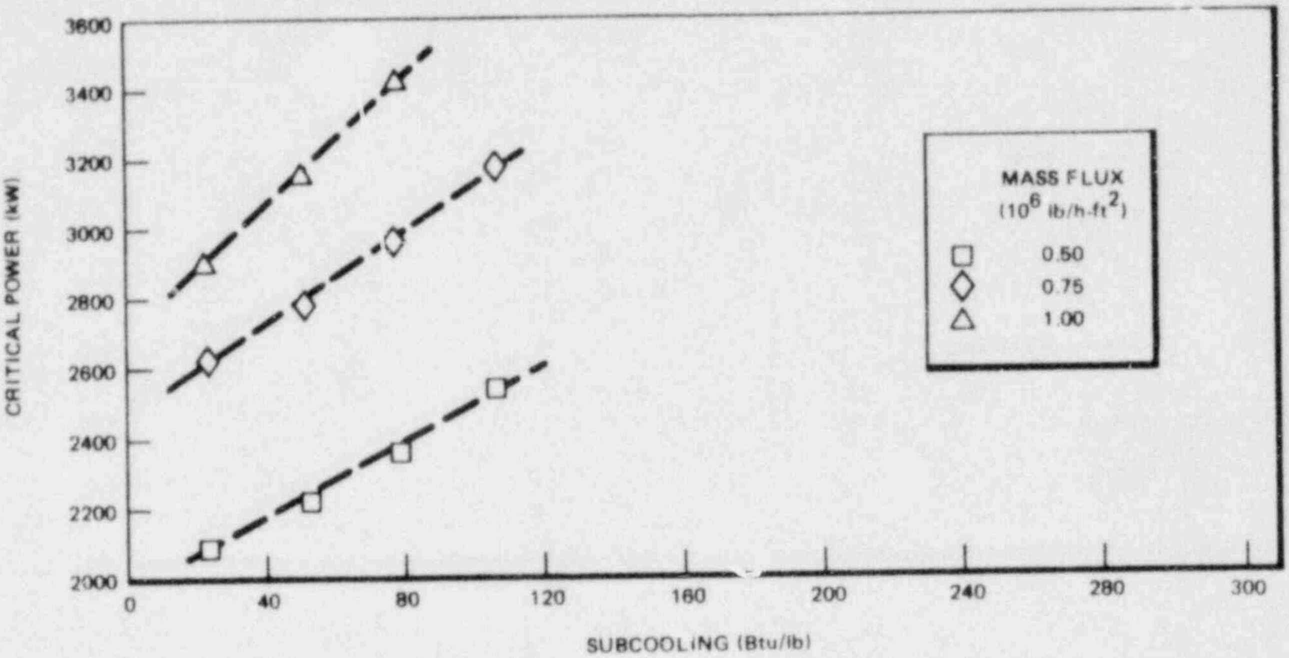


Figure A-11. 16-Rod Critical Power in a Symmetric Radial Assembly - 800 lb/in.^{2}

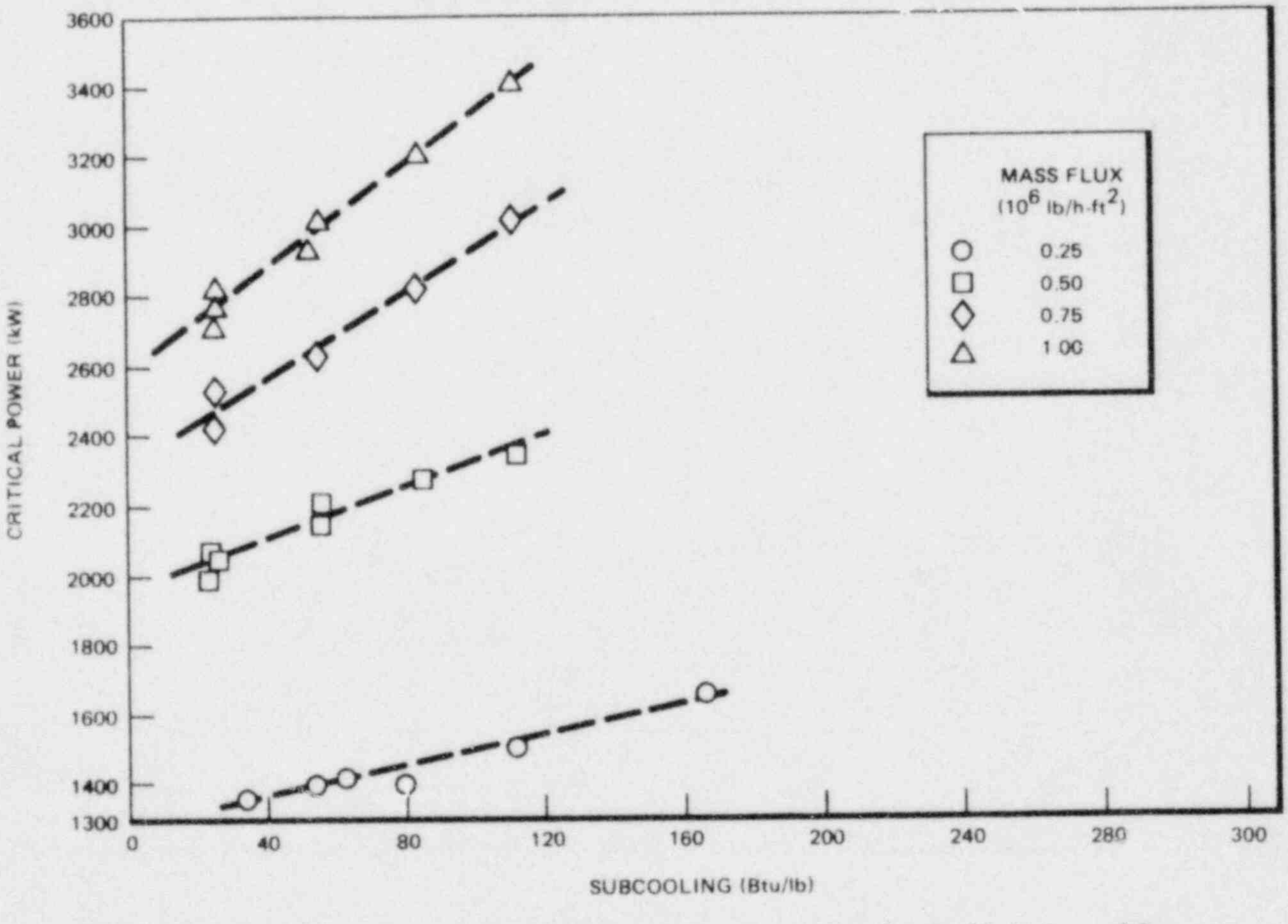


Figure A-12. 16-Rod Critical Power in a Symmetric Radial Assembly - 1000 lb/in.^{2}

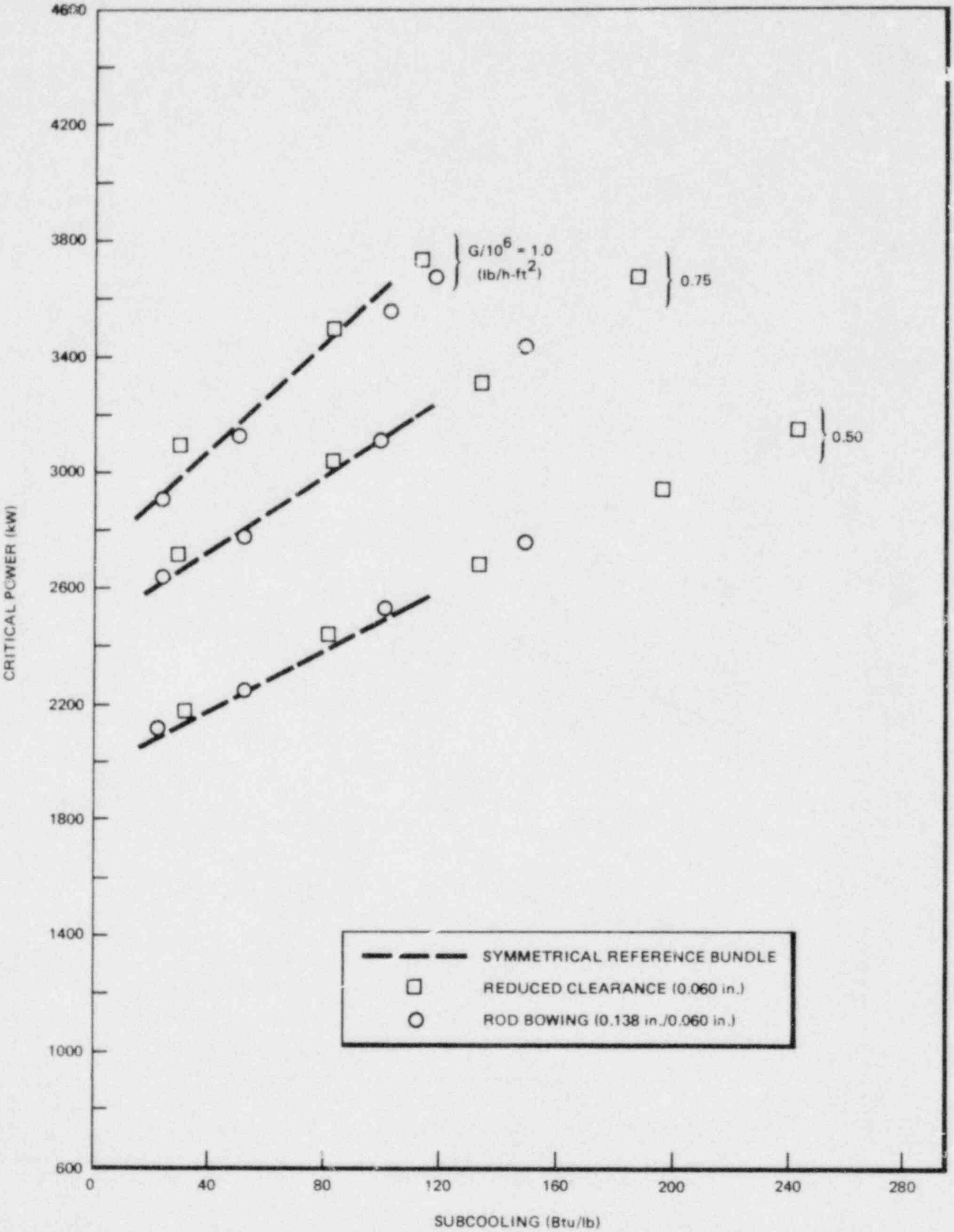


Figure A-13. Composite Critical Power Summary, 16-Rod Cosine Axial Flux - 800 lb/in.^{2}

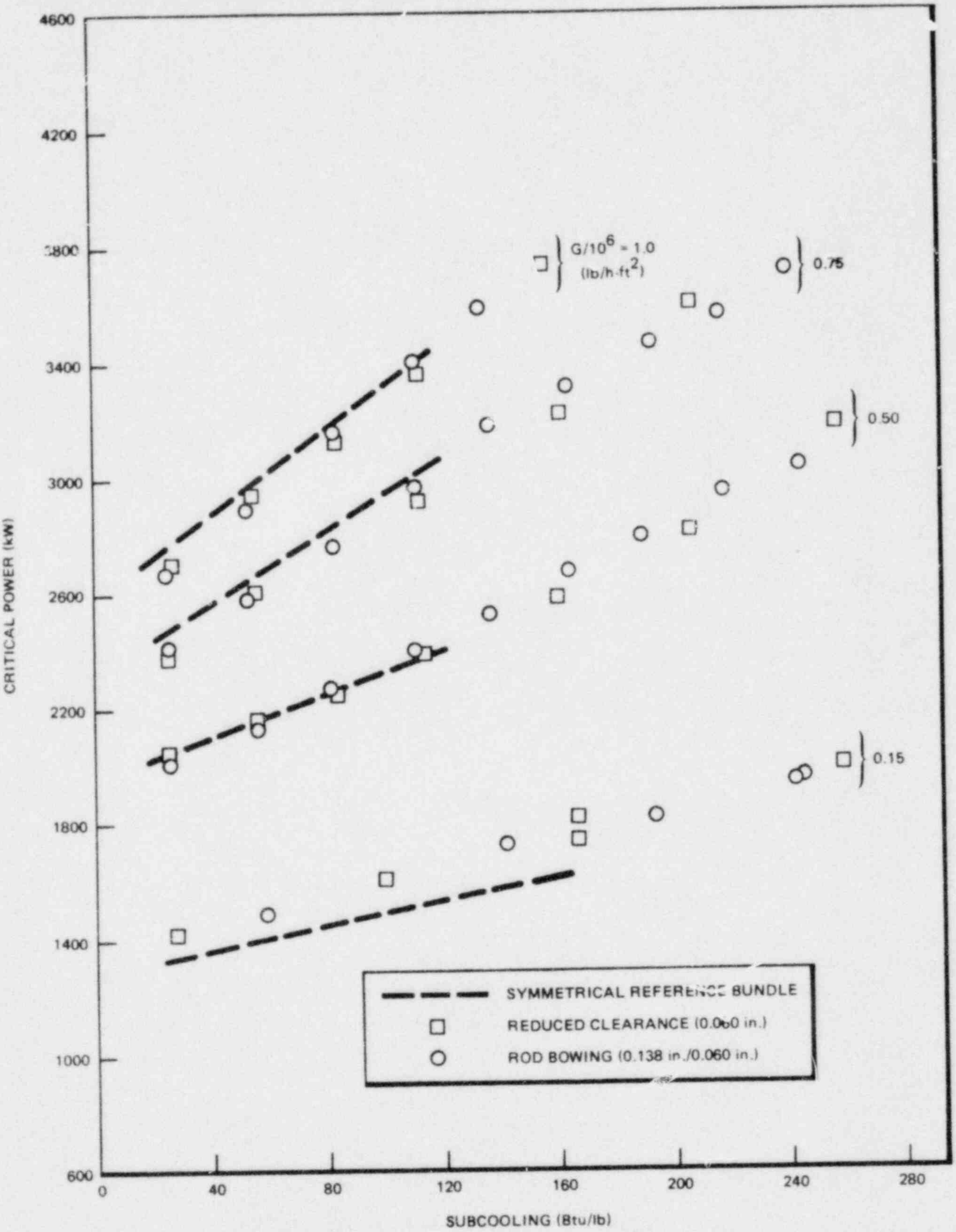


Figure A-14. Composite Critical Power Summary, 16-Rod Cosine Axial Flux - 1000 lb/in.^{2}

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

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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.

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