Babcock & Wilcox

Power Generation Group

P.O. Box 1260, Lynchburg, Va. 24505

Telephone: (804) 384-5111

December 13, 1978

Mr. D. B. Vassallo, Assistant Director
For Light Water Reactors
Division of Project Management
Office Of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Reference 1: Letter, D. B. Vassallo to J. H. Taylor, June 12, 1978 with enclosure "Calculation of the Effect of [illegible]el Rod Bowing on the Critical Heat Flux for Pressurized Water Reactors" as revised September 15, 1978.

Dear Mr. Vassallo:

Reference 1 requested that B&W provide a topical report which addresses the effects of fuel rod bow. B&W has reviewed this request and has determined that we will prepare the requested topical report. The submittal of this report has been scheduled for mid-1980 to permit the inclusion of additional data from Mk-B assemblies and the Mk-C demonstration assemblies. The tentative outline for this report conforms to the suggested outline in reference 1.

Until approval of the rod bow topical report, B&W intends to [illegible]e an interim method based on the procedure outlined in reference 1. [illegible] review and approval of this method on a schedule to support [illegible]3, Cycle 5 and/or Crystal River 3, Cycle 2 (2nd quarter 1979) [illegible]ted. These reloads will be the first to reference this [illegible] description of this method including the major inputs [illegible] calculation is provided in enclosure 1. Preliminary [illegible] with this approach and these input parameters has been [illegible] discussions with members of your staff. Appendix [illegible] provides a detailed description and data analysis [illegible] critical heat flux test recently completed by B&W, [illegible]es the value of K to be used in the penalty eval-

7812220146

Mr. D. B. Vassallo

To account for the rod bow penalty in licensing analyses, B&W will continue to analyze each cycle on a batch by batch basis. Utilizing the 1% DNB credit for the flow area reduction factor, the actual penalty to be applied to the DNB calculation at 33,000 MWD/MTU is 1.93% or a required DNBR of 1.34 instead of 1.30. The 1% DNB credit will offset the rod bow DNB penalty up to a burnup of approximately 21,300 MWD/MTU. Since no fuel assembly with a burnup in excess of approximately 21,300 MWD/MTU will produce sufficient power to become the limiting fuel assembly, no fuel rod bow DNB penalty will be required. B&W will continue to check each cycle to ensure the above assumptions remain valid.

If you have any additional question, please contact Mr. M. R. Stephens of my staff (Ext. 2772).

Very truly yours

J. H. Taylor
Manager, Licensing

JHT/fw

Enclosure: As stated

cc: B. K. Grimes - NRC
R. B. Borsum - B&W (Bethesda)

Determination of the Fuel Rod Bow DNB Penalty

Fuel Rod Bow Magnitude

The conservative rod bow projection (Equation 1) currently in use for licensing of 15 x 15 fuel will be used.

$$\sigma_b = 9 + .2 \sqrt{BU} \qquad (1)$$

σ_b = standard deviation of gap closure (mils)

BU = Burnup MWD/MTU

A comparison of Equation 1 with measured data previously reported in Reference 2, demonstrates that the conservatism of this bow projection is more than adequate to cover the uncertainties (batch to batch, cold to hot) suggested in Section 2 of Reference 1.

This is based on more than 25,000 measurements of which 3934 were in the span of maximum bow.

To conform to the format of Reference 1, Section 2, Equation 1 is put in the form of gap closure by:

$$\frac{\sigma_{\Delta c}}{c_o} = \frac{\sigma_b}{138} (100)$$ where 138 = nominal rod to rod gap (mils)

Therefore

$$\frac{\sigma_{\Delta c}}{c} = 6.52 + .145 \sqrt{BU} \text{ (\% closure)} \qquad (2)$$

$\frac{\sigma_{\Delta c}}{c}$ = Standard deviation of gap closure due to fuel rod bowing as adjusted for use in the procedure of Secti[illegible], Reference 1. It includes the 1.2 cold to hot factor of Section 2.2, Reference 1 and is worse than the true distribution in 95 out of 100 fuel batches (assumed equal to $1.2x\sigma_{95x95}$)

BU = Bundle Average Burnup (MWD/MTU)

Bowed Rod CHF Test

A bowed rod Critical Heat Flux (CHF) test has recently been completed by the Babcock & Wilcox Company. This test was performed using a Mark-C geometry rod bundle, and a detailed description and data analysis is presented in Appendix A. The principle result of this test was that there is no CHF rod bow penalty for rod-to-rod gap closures of 55% or less.

Although this result was obtained for Mark C geometry fuel, it is judged that the same statement can be made for Mark B geometry fuel. This judgement is based on comparisons of subchannel velocity profiles for the two geometries which show lower velocities (as a percentage of average velocity) in Mark C rod-to-rod gaps than in Mark B rod-to-rod gaps. This fact allows CHF to occur at lower heat fluxes in Mark C fuel and should make the Mark C geometry limiting with respect to bowed rod CHF performance.

The above conclusions are substantiated by tests of a bowed rod in their 14x14 rod bow geometry[3], which is very close to the Babcock & Wilcox Mark B rod bundle geometry. These tests demonstrated no CHF penalty for gap closures of 54% or less.

The Mk-C CHF test described above provides the value of K to be used in the penalty evaluation. The test to determine the function S and the values for σ_s and N_c have not been performed by B&W. B&W will use the function $\bar{S}$ given to B&W by the NRC on August 17, 1976, and the conservative values of σ_s and N_c given to B&W by the NRC on October 30, 1978.

Procedure for Calculating the Interim DNB Penalty

An example of the calculational technique that B&W intends to use is shown below. The following information will be used in the calculation.

Item	Value	Source
$\frac{\sigma_{\Delta c}}{c_o}$ (% closure)	$\frac{9 + .2\sqrt{BU}}{138}(100\%)$	Current Bow Projection Aproved by the NRC
$\frac{N_{\Delta c}}{c}$	3934	Letter K. E. Suhrke to D. F. Ross, September 10, 1976.
K	.55	B&W CHD Data Point (Appendix A)
$\overline{S}$	.9127(.35 + .0067)	Meeting with NRC 8/17/76
σ_s	.100	NRC Input (10/30/78)
N_c	10	NRC Input (10/30/78)
$\frac{M}{P}$ nb	1.00	B&W II Correlation
σ_{nb}	.127	B&W II Correlation
N_{nb}	207	B&W II Correlation

Given the above information the NRC procedure (Ref. 1) yields the following:

$$\frac{\sigma_{\Delta c}}{c} = 6.52 + .145\sqrt{BU}$$

At a burnup of 33,000 MWD/MTU,

$$\frac{\sigma_{\Delta c}}{c} = 32.85\%$$

$$\frac{K}{\sigma_{\Delta c/c}} = \frac{0.55}{0.3285} = 1.6743 \qquad \text{(Eq. No. in ref. 1)}$$

$$F(K/\sigma) = F(1.6743) = 0.0471 \qquad (4\text{-}11)$$

$$f(K/\sigma) = 1/\sqrt{2\pi}\; e^{-(K/\sigma)^2/2} = 0.09822 \qquad (4\text{-}10)$$

$$\sigma_u^2 = 2\left(\frac{1}{1-K}\right)^2 \sigma_{\Delta c/c_o}^2 \left\{\left[1 + \left(\frac{K}{\sigma_{\Delta c/c}}\right)^2\right] F\left(\frac{K}{\sigma_{\Delta c/c_o}}\right) - \left(\frac{K}{\sigma_{\Delta c/c}}\right) \times f\left(\frac{K}{\sigma_{\Delta c/c}}\right)\right\} - (\bar{U})^2 \qquad (4\text{-}8)$$

$$\bar{U} = 2\left(\frac{1}{1-K}\right)\sigma_{\Delta c/c_o}\left[f\left(\frac{K}{\sigma_{\Delta c/c_o}}\right) - \left(\frac{K}{\sigma_{\Delta c/c_o}}\right)F\left(\frac{K}{\sigma_{\Delta c/c_o}}\right)\right] \qquad (4\text{-}9)$$

$$\bar{U} = 2\left(\frac{1}{1-0.55}\right)0.3285[0.09822 - (1.6743)(0.0471)] = 0.028266$$

$$\sigma_u^2 = 2\left(\frac{1}{1-0.55}\right)^2 (0.3285)^2\{[1 + (1.6743)^2](0.0471) - (1.6743)(0.09822)\} - (0.028266)^2$$

$$\sigma_u = 0.12187$$

The variance in δ:

$$\sigma_\delta^2 = (\bar{S})^2\sigma_u^2 + (\bar{U})^2\sigma_s^2 + \sigma_u^2\sigma_s^2 \qquad (4\text{-}14)$$

$$\sigma_\delta^2 = (0.3256)^2(0.12187)^2 + (0.028266)^2(0.100)^2 + (0.12187)^2(0.100)^2$$

$$\sigma_\delta = 0.041606$$

$$\bar{\delta} = \bar{S}\cdot\bar{U} = (0.3256)(0.028266) = 0.009203 \qquad (4\text{-}15)$$

$$N_{\delta-1} = \frac{(\sigma_u^2 + \sigma_s^2)^2}{\dfrac{\sigma_u^4}{N_{\Delta c/c_o} - 1} + \dfrac{\sigma_s^4}{N_c - 1}} = \frac{[(0.12187)^2 + (0.100)^2]^2}{\dfrac{(0.12187)^4}{3934-1} + \dfrac{(0.100)^4}{10-1}} = 55 \qquad (4\text{-}16)$$

The variance of the random variable $DNBR_b$:

$$\sigma_b^2 = \sigma_{nb}^2[(\overline{1-\delta})^{-1}]^2 + [(M/p)_{nb}]^2\sigma_\delta^2 + \sigma_\delta^2\sigma_{nb}^2 \qquad (4\text{-}17)$$

$$\overline{(1 - \delta)^{-1}} = 1 + \bar{\delta} + (\bar{\delta})^2 + \sigma_\delta^2 \qquad (4\text{-}18)$$

$$\sigma_b^2 = (0.127)^2[1 + 0.009203 + (0.009203)^2 + (0.041606)^2]^2 + (1)^2(0.041606)^2 + (0.041606)^2(0.127)^2$$

$$\sigma_b = 0.13508$$

$$N_{b-1} = \frac{(\sigma_{nb}^2 + \sigma_\delta^2)^2}{\frac{(\sigma_{nb})^4}{N_{nb} - 1} + \frac{(\sigma_\delta)^4}{N_{\delta-1}}} = \frac{[(0.127)^2 + (0.041606)^2]^2}{\frac{(0.127)^4}{207 - 1} + \frac{(0.041606)^4}{55}} = 242 \qquad (4\text{-}20)$$

$K_{248}^{95\times95} = 1.819$ (Sandia Corporation Monograph, D. B. Owen)

$$DNBR_b^{95\times95} = \frac{1}{(M/p) - \bar{\delta} - K_b^{95\times95}\sigma_b} = \frac{1}{1 - 0.009203 - 1.819(0.13508)} \qquad (4\text{-}21)$$

$\therefore$ $DNBR_b = 1.3421.$

$$DNBR_{nb} = \frac{1}{1 - (1.835)(0.127)} = 1.3039$$

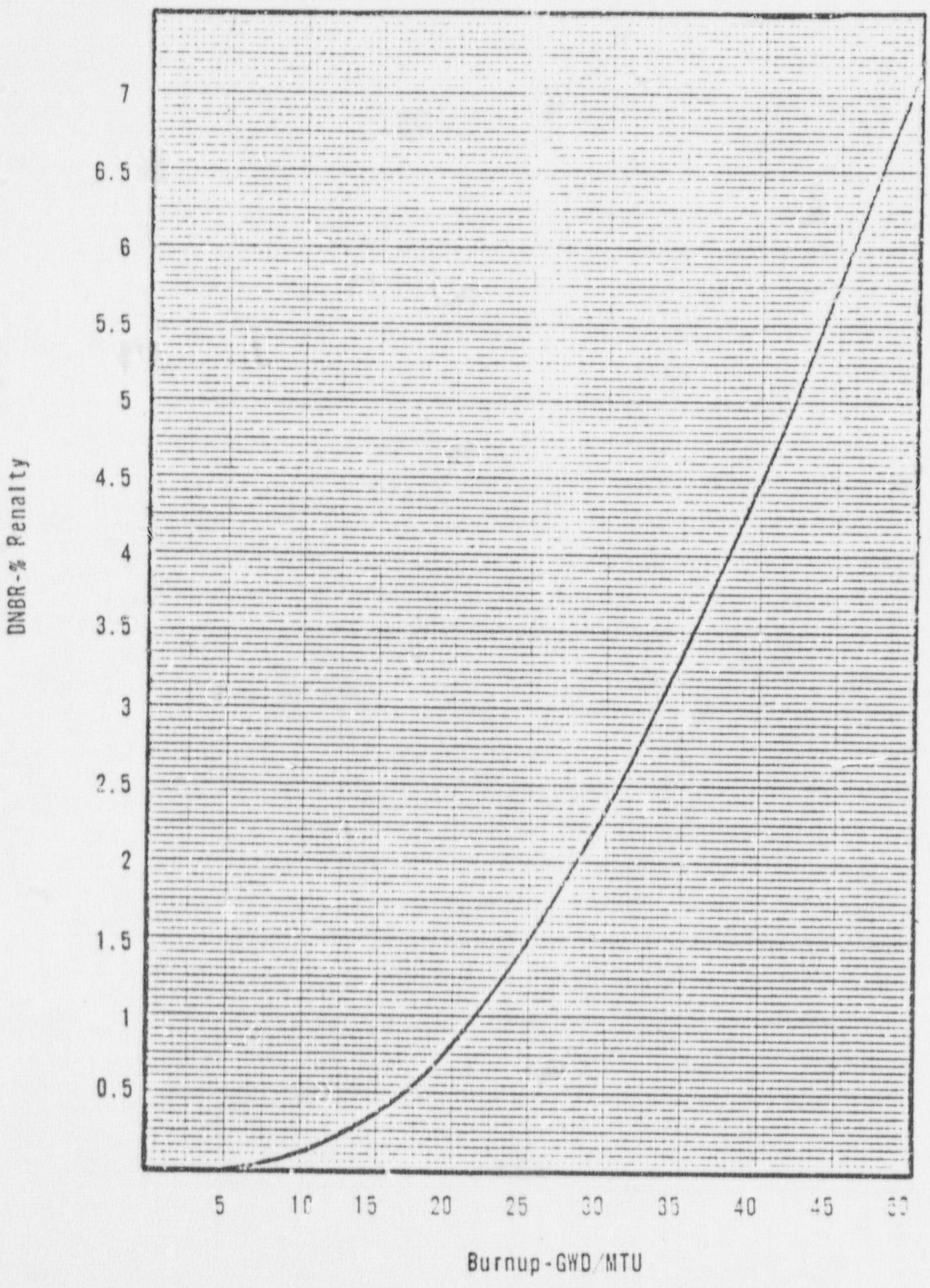
$$\% \text{ penalty} = \frac{1.3421 - 1.3039}{1.3039}(100\%) = 2.93\%$$

Figure 1 shows a plot of the calculated DNB penalty verses burnup. The calculated penalty shown on the graph does not consider the 1% DNB credit for the flow area reduction factor. All B&W DNB calculations are performed with a flow area reduction factor. Therefore, the actual penalty to be applied to the DNB calculation at 33,000 MWD/MTU is 1.93% or a required DNBR of 1.34 instead of 1.30.

To account for the rod bow penalty in licensing analyses B&W will continue to analyze each cycle on a batch by batch basis. The 1% DNB credit for the flow area reduction factor will offset the rod bow DNB penalty up to a burnup of approximately 21,300 MWD/MTU. Since no fuel assembly with a burnup in excess of 21,300 MWD/MTU will produce sufficient power to become the limiting fuel assembly, no fuel rod bow DNB penalty will be required. B&W will continue to check each cycle to ensure that the above assumptions remain valid.

DNB PENALTY VS BURNUP

Figure 1



References

(1) Letter, D. B. Vassallo to James H. Taylor, 6/12/78, enclosure "Calculation of the Effect of Fuel Rod Bowing on the Critical Heat Flux for Pressurized Water Reactor" as revised 9/15/78.

(2) Letter, K. E. Suhrke to D. F. Ross, 9/10/76, "Fuel Rod Bow Projection."

(3) Markowski, E.S., et al, "Effect of Rod Bowing on CHF in PWR Fuel Assemblies," ASME Paper 77-HT-91.

(4) Topical BAW-10000A, May 1976, "Correlation of Critical Heat Flux in a Bundle Cooled by Pressurized Water."

APPENDIX A TO ENCLOSURE 1

Analysis of Bowed and Unbowed CHF Test Data

BABCOCK & WILCOX

Power Generation Group
Nuclear Power Generation Division
P. O. Box 1260
Lynchburg, Virginia 24505

Analysis of Bowed and Unbowed CHF Test Data

CONTENTS

1. INTRODUCTION

As part of a continuing 17x17 geometry test program on the 7-MWe heat transfer facility at the Alliance Research Center (ARC), B&W has tested two 5x5 non-uniform guide tube bundles. The bundles (C9 and C10) were identical in geometry and heated design effects except that in the C10 bundle one of the hot rods was bowed into the guide tube channel to achieve approximately 55 percent closure in the rod-to-rod gaps.

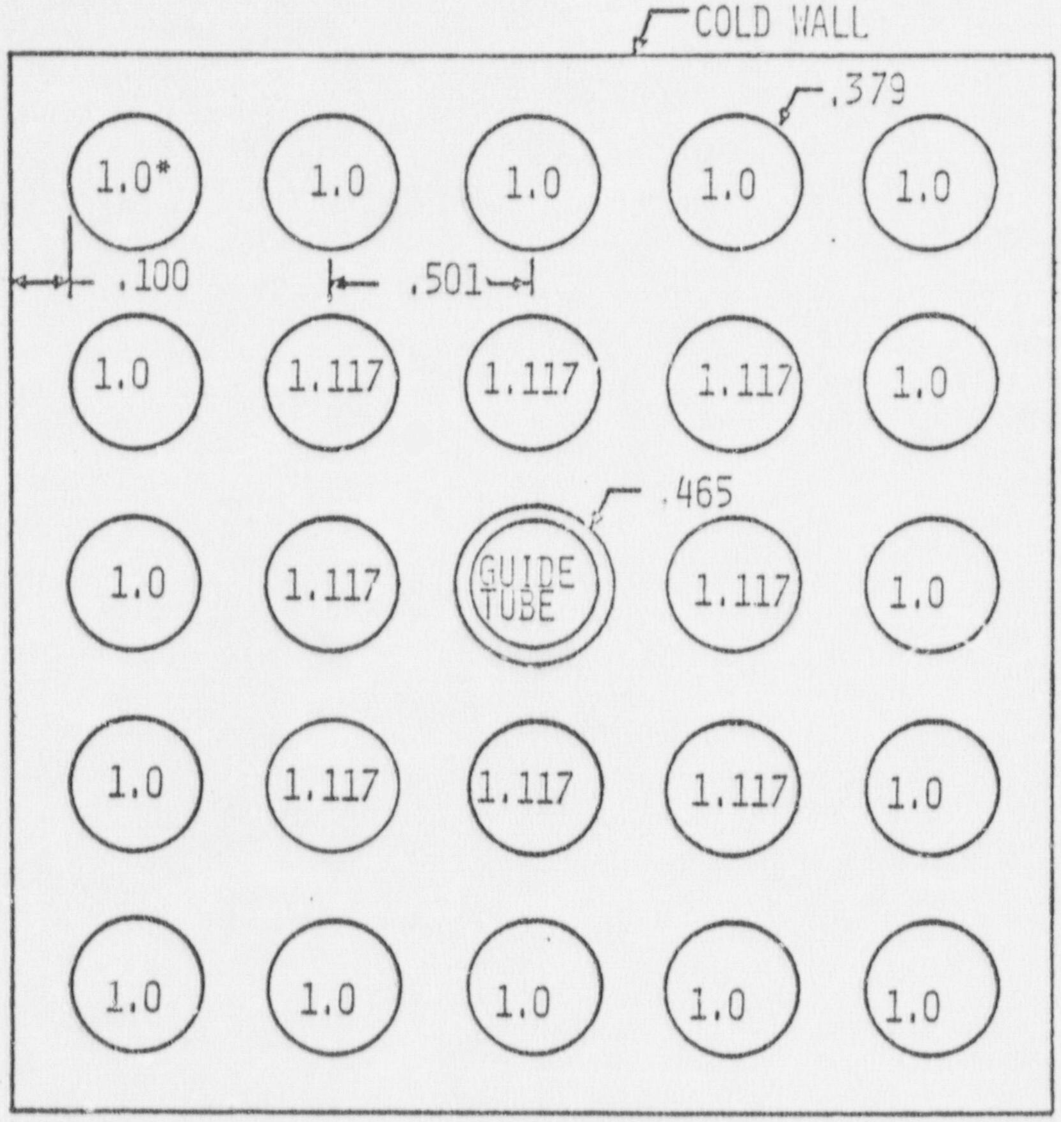
This pair of tests presents an excellent opportunity to determine the effects of a bowed rod on critical heat flux (CHF) under reactor operating conditions at a value of bow (closure) above that actually expected to occur. Analysis of the data from these tests is approached on both a subchannel and a bundle average basis. The analysis shows a negligible bow penalty on CHF under the tested conditions.

2. TEST DESCRIPTION

The ARC 7 MWe heat transfer facility is a sophisticated, computer controlled arrangement with the capability of testing full length (12 foot) CHF bundles under pressures of up to 2600 psia, flow of up to 4 million lbm/hr-ft^2, and inlet enthalpies approaching saturation.

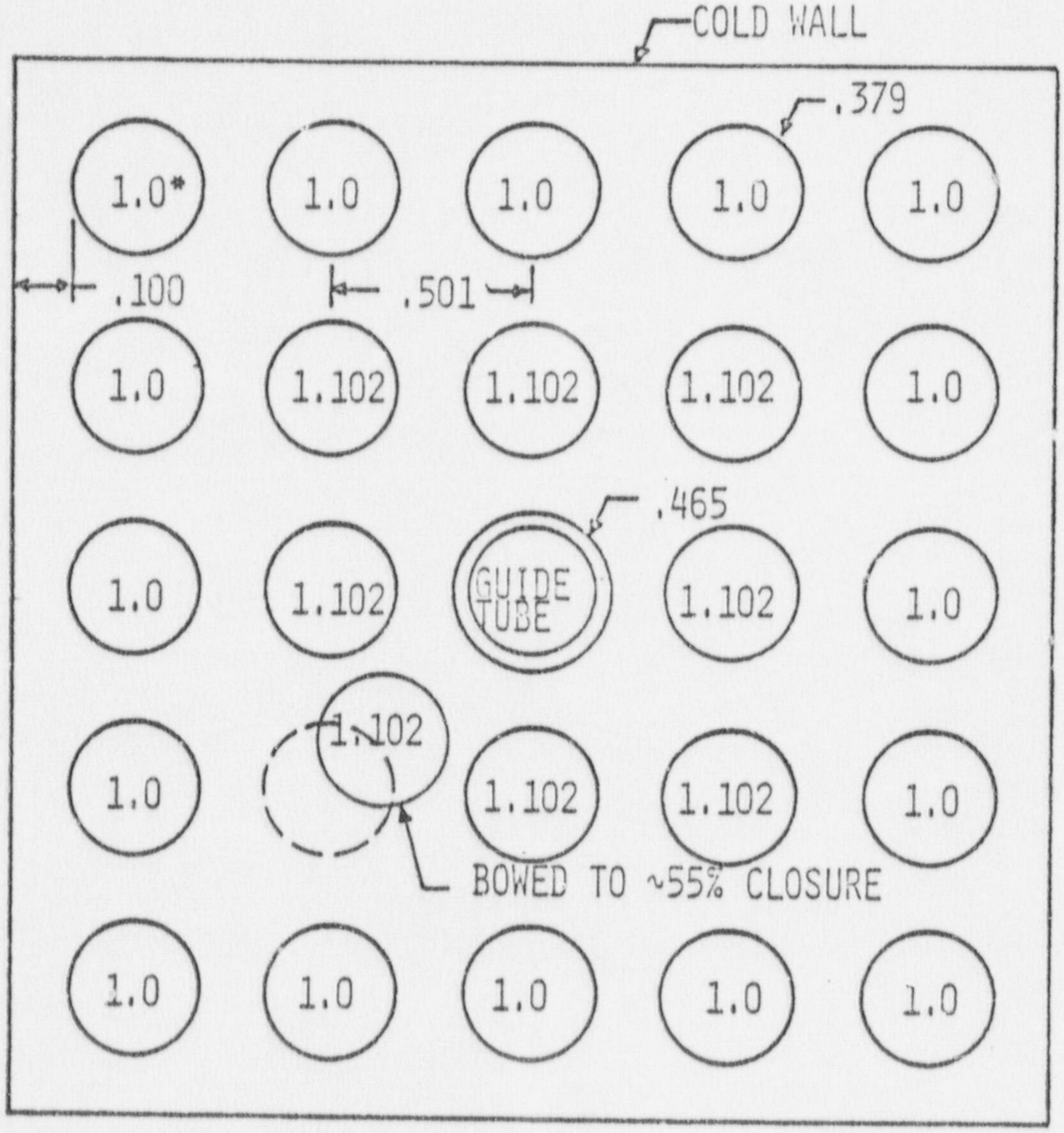
The two bundles (C9 and C10) were identical in design except for the C10 bowed rod. Figure 1 shows the C9 (unbowed) bundle cross section and dimensions, while Figure 2 shows the C10 (bowed) bundle. An axial representation of the bundles along with the tested axial heat distribution (a symmetric 1.67 peak-to-average flux shape) is shown in Figure 3. The on set of transition from nucleate to film boiling (the CHF point) was determined using acoustical thermocouples spaced each 4.5 inches axially over the last 6 feet of the bundle.

FIGURE 1: C9 (UNBOWED) TEST GEOMETRY



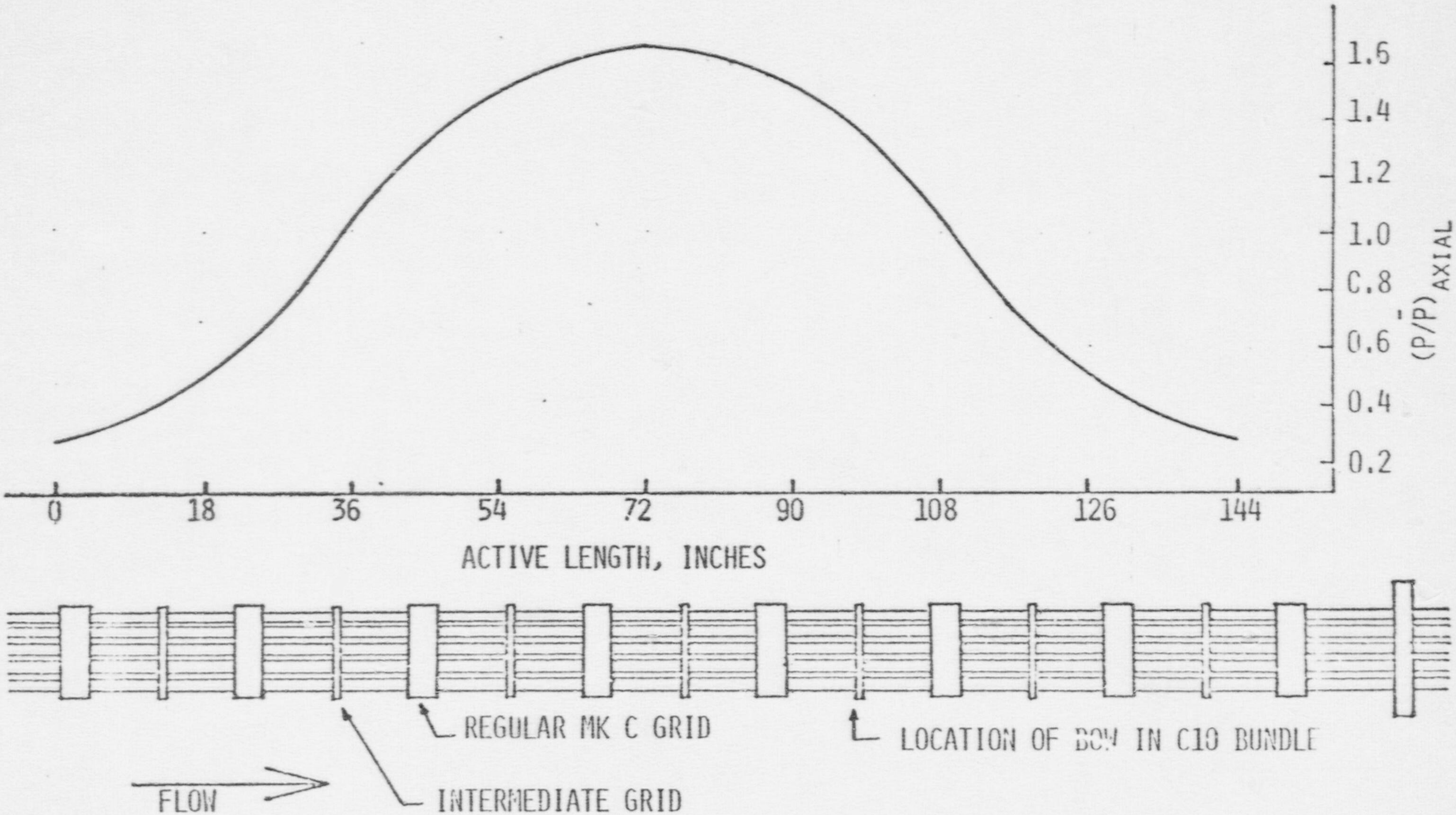
* ROD NUMBERS ARE RELATIVE HEAT FLUXES

FIGURE 2: C10 (BOWED) TEST GEOMETRY



* ROD NUMBERS ARE RELATIVE HEAT FLUXES

FIGURE 3: NON UNIFORM GUIDE TUBE BUNDLES



3. ANALYSIS

3.1. Subchannel Basis

CHF is traditionally correlated as a function of local (subchannel) geometry, mass velocity, pressure, and quality. A correlation of this form requires the use of a subchannel computer code to predict these local conditions within the bundle. For this analysis the LYNX2 computer code[1] was used in conjunction with an interim Mk-C CHF correlation (BXC). The results were then compared to each other in the form of measured to predicted critical heat fluxes. The results of this comparison are shown in Table 1 and Figure 4. It should be noted that the measured to predicted CHF ratios differ by 1.3 percent which is well within the observed repeatibility in CHF testing.

Table 1

Results of Subchannel Analysis

	Bundle	
	C9(Unbowed)	C10(Bowed)
M/P (Measured to predicted CHF ratio using BXC)	1.211	1.195
σ (standard deviation)	0.082	0.073
n (number of data points)	81	74

3.2. Bundle Average Basis

Since geometry, heat and flow conditions were nearly equal between bundles another comparison is pertinent. The observed average heat fluxes to CHF can be plotted versus inlet subcooling in parameters of mass velocity. These plots exhibit linear trends and thus any difference in bundle performance should be quite obvious. This was done for both bundles and the plots of the raw data are shown in Figures 5 and 6 for bundles C9 (unbowed) and C10 (bowed) respectively. A direct comparison of these two figures is possible

if the tested mass velocities are equal. This was not the case as the C9 mass velocities averaged approximately 4 percent greater than those of the C10 bundle. Consequently a one to one correction of power to flow (at each mass velocity) was made to both bundles to correct the observed CHF heat fluxes to correspond to exact mass velocities of 1.5 through 3.5 million lbm/hr-ft^2. A linear least squares regression was then performed on both sets of data in parameters of these mass velocities. The results are shown in Figure 7 as a comparison of the bundle average CHF conditions. The average difference obtained in the manner was 1.2 percent which is, again, within the observed repeatability in CHF testing.

3.3. Data Ranges

The ranges of the observed and calculated test parameters are shown in Table 2. Additionally, the observed CHF locations in the bundles are of interest. In both bundles, primary CHF always occurred on one of the hot rods. In C9, 80 percent occurred on corner hot rods and 20 percent on adjacent hot rods. In C10, 33 percent occurred on corner hot rods with 67% on adjacent hot rods. Also 75 percent of the C10 burnouts occurred on the bowed rod or one of the two closest to it.

The axial position of C9 and C10 burnouts was also quite similar. Burnout was first detected at either 101.5 or 106 inches on 79 percent of the C9 data and 76 percent of the C10 data. Only 5 percent of C10 burnouts occurred at the point of maximum bow (approximately 97 inches on the active length).

FIGURE 4
COMPARISON OF C9 AND C10 DATA
TO THE BXC CHF CORRELATION

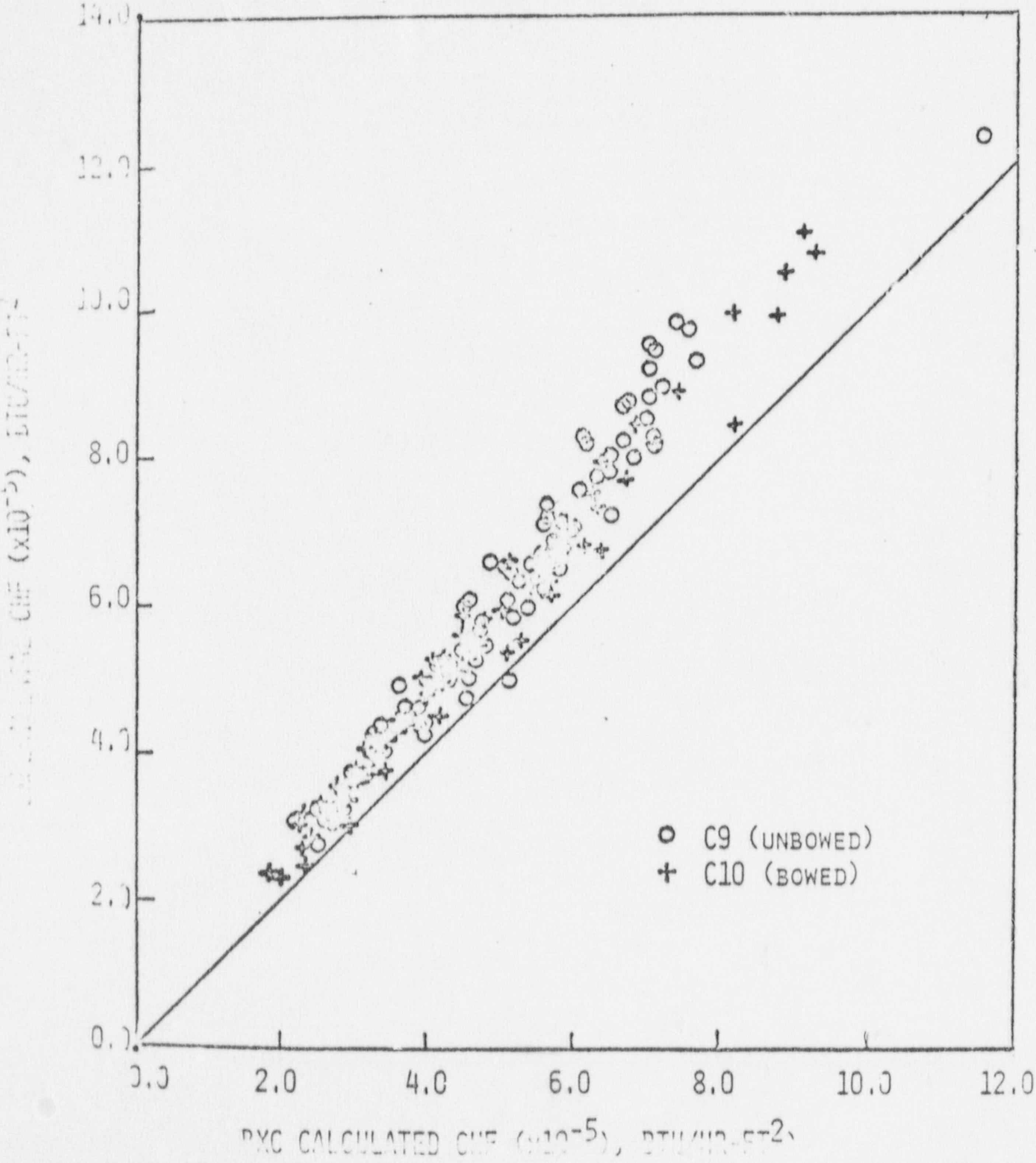
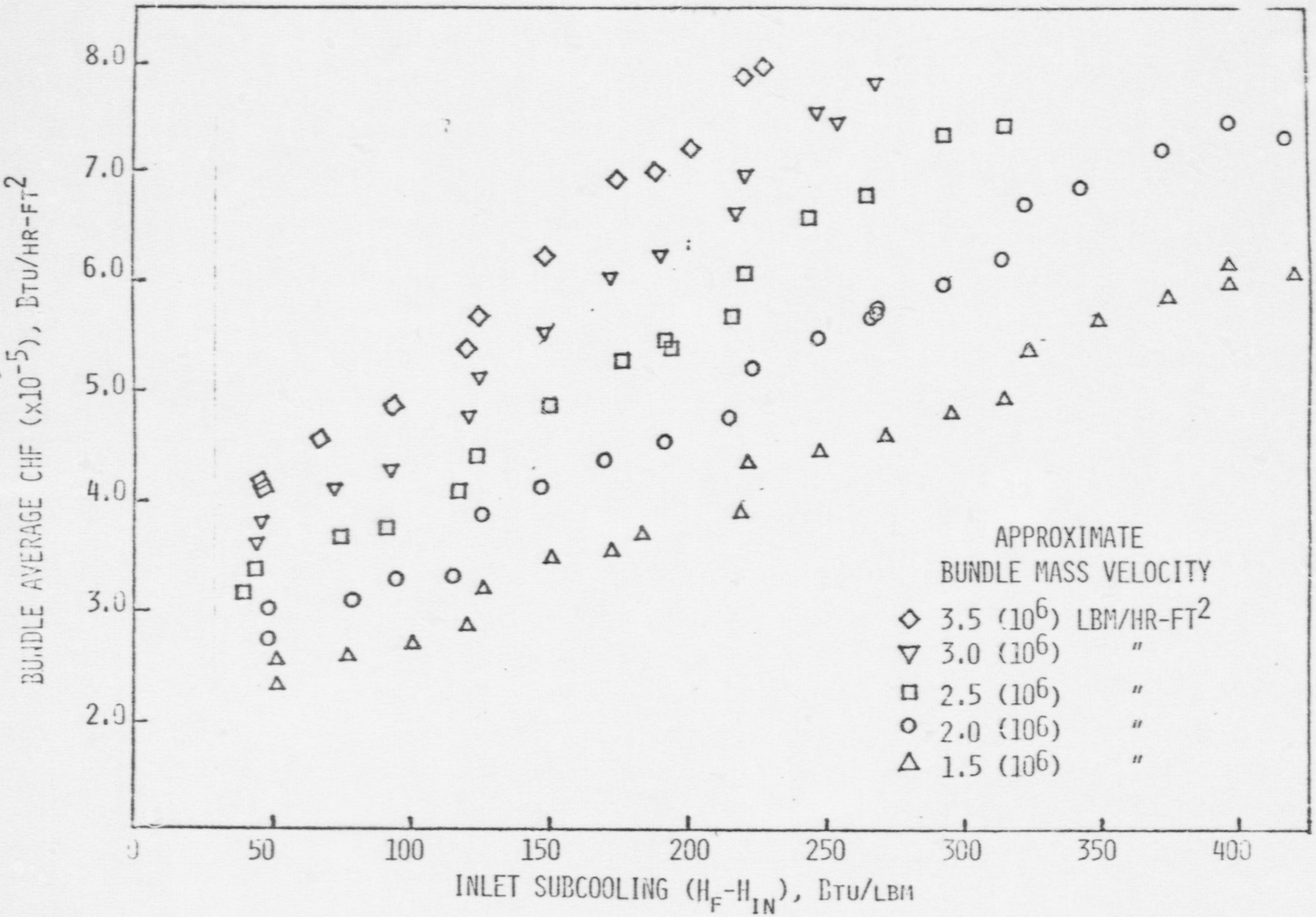
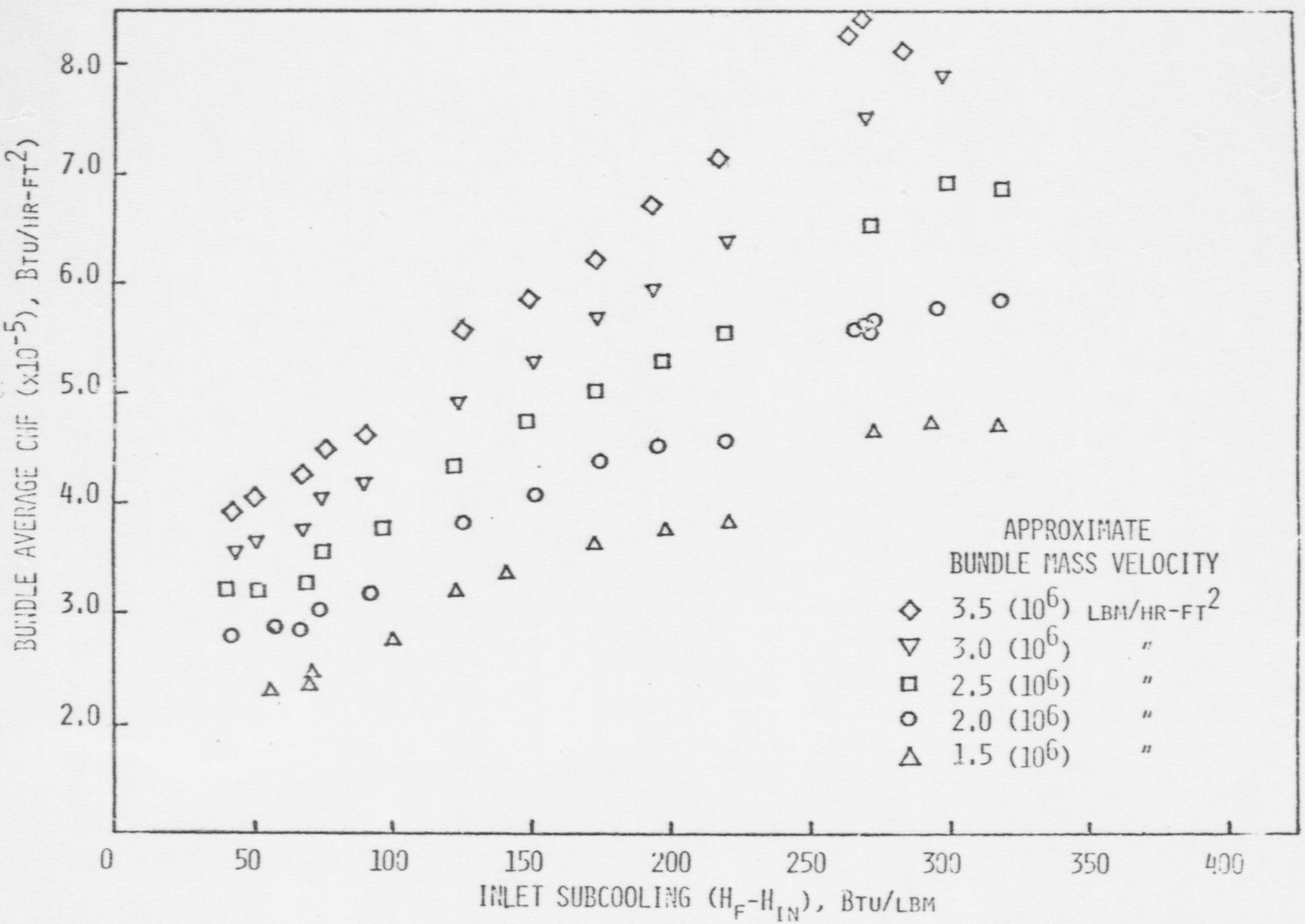


FIGURE 5: [illegible]



BUNDLE AVERAGE CHF (x10^-5), BTU/HR-FT^2
8.0
7.0
6.0
5.0
4.0
3.0
2.0
0
50
100
150
200
250
300
350
400
INLET SUBCOOLING (H_F-H_IN), BTU/LBM
APPROXIMATE
BUNDLE MASS VELOCITY
3.5 (10^6) LBM/HR-FT^2
3.0 (10^6) "
2.5 (10^6) "
2.0 (10^6) "
1.5 (10^6) "

FIGURE 6: C10 (BOWED) RAW BUNDLE DATA



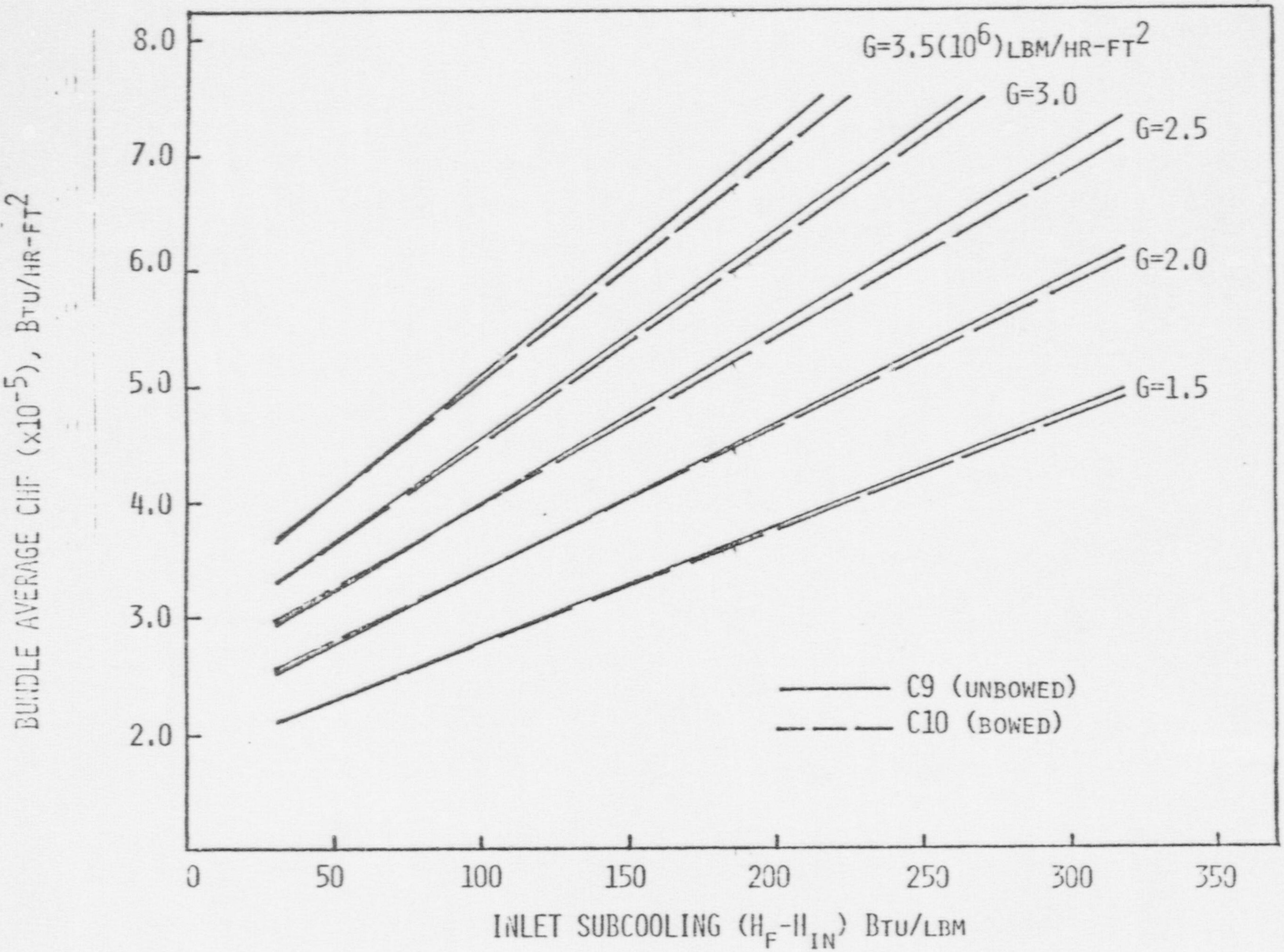


FIGURE 7: LEAST SQUARES FIT OF CORRECTED C9 AND C10 BUNDLE DATA

Table 2

Data Ranges

	Bundle	
	C9(Unbowed)	C10(Bowed)
Pressure, psia	1600-2400	1600-2400
Mass Velocity, $lbm/hr\text{-}ft^2 \times 10^6$	1.5-3.5	1.0-3.5
Inlet Enthalpy, Btu/lbm	300-600	400-650
Quality (at CHF)%	-45 to +21	-21 to +27
Inlet subcooling, Btu/lbm	40-420	41-320

4. CONCLUSIONS

The analysis of the data by two different methods shows CHF performance differences between bundles of approximately 1 percent. This is well within the range of observed CHF test repeatability for similar bundles. The conclusion drawn from this analysis is that under typical reactor operating conditions, and at rod bow configurations producing maximum closures of up to 55 percent of the nominal rod gaps, zero or negligible CHF degradation is observed.

5. REFERENCES

1. "LYNX2 - Subchannel Thermal-Hydraulic Analysis Program," BAW-10130, October 1976.