XN-NF-80-56 (NP)

SUPPLEMENT 1

GENERIC MECHANICAL, THERMAL HYDRAULIC AND NEUTRONIC DESIGN FOR EXXON NUCLEAR TOPROD RELOAD FUEL ASSEMBLIES FOR PRESSURIZED WATER REACTORS - THERMAL MARGIN ANALYSIS

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THERMAL MARGIN ANALYSIS

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1.0 INTRODUCTION AND SUMMARY

ENC TOPROD fuel assemblies are an improved water-to-fuel ratio design for use in Westinghouse (2 loop) reactors in which fuel assemblies have a 14x14 array of rods. Assembly and rod pitch dimensions for these reactors are 7.803 inch and 0.556 inch, respectively. Previous ENC reload fuel for application in these reactors has fuel rods with outside diameters of 0.424 inch and 0.426 inch, depending upon the reload application. Westinghouse fuel in these reactors typically has a fuel rod diameter of 0.422 inch. The sixteen guide tubes in 14x14 assemblies have a diameter of about 0.540 inch. The single instrument tube located near the middle of the assembly typically has the same outside diameter as the fuel rods.

To achieve improved water-to-fuel ratio, the outside diameter of fuel rods in the TOPROD design has been reduced by about 2% to 0.417 inch. This yields about a 3% increase in flow area. Since the fuel pellet diameter is also reduced by about 2% in TOPROD fuel, the improvement in water-to-fuel ratio relative to ENC standard reload fuel is about 7%.

From a thermal hydraulic standpoint, the essential difference of TOPROD fuel is the 2% smaller rod size and 3% larger flow area. Spacer grids of TOPROD and ENC standard fuel are virtually identical, with the only difference being slightly larger dimples in the TOPROD spacers to properly contact the slightly smaller rods. Upper and lower tie plates are likewise essentially the same between the two designs.

Because TOPROD fuel differs only slightly from previous ENC fuel (2% in fuel rod diameter, 3% in flow area), the thermal hydraulic impacts of TOPROD fuel are small.

In the sample case of Prairie Island, the MDNBR for the limiting two pump coastdown transient has been calculated to be 1.85 for a full core of TOPROD fuel. This case is bounding for a mixed core of TOPROD and previous ENC fuel. The 1.85 value is 40% in excess of the minimum allowable MDNBR of 1.3. Because of the lower MDNBR, licensing and safety analyses are performed when TOPROD fuel is inserted into a reactor core either to (a) establish new thermal margins for the TOPROD fueled core; or (b) establish that conservatisms in existing thermal margin analyses are bounding of the slight reductions in DNBR performance of TOPROD fuel relative to standard fuel, and are bounding of potential reductions in DNBR performance of other fuel designs which are coresident with TOPROD fuel.

2.0 THERMAL MARGIN CRITERIA

The thermal margin performance requirement for ENC reload fuel design including TOPROD is as follows:

> The minimum departure for nucleate boiling ratio (MDNBR) will be $\geq$1.3 at overpower, using the W-3 correlation with corrections for non-uniform axial heating and cold wall effects.

4.0 SAMPLE THERMAL MARGIN RESULTS (PRAIRIE ISLAND)

The most limiting operational transient for Prairie Island is the "two pump coastdown" event. For this transient the MDNBR was calculated to be 1.85 for a full core of TOPROD fuel. Table 4.1 provides reference conditions and results of the analysis. The calculations were performed at 102% of rated power (i.e. at 1683 MWt) and assume a total power peaking factor, F_Q, of 2.32. This total peaking is 5% higher than the ECCS allowable total peaking of 2.21 for Prairie Island.

Table 4.2 presents calculations and sensitivity study results for core flow and thermal margins when TOPROD is mixed core loaded with previous ENC fuel. Also presented are thermal margins for previous ENC fuel alone. The MDNBR results for TOPROD fuel in the mixed core case are based on the sensitivity study result that MDNBR changes about 1.0% for each 1.0% change in flow. The MDNBR results for previous ENC fuel include the same MDNBR-to-flow sensitivity.

The reduced MDNBR performance of TOPROD relative to previous ENC 14x14 fuel is a direct result of its 2% reduced surface area and 3% higher flow area. This increased flow area leads to a 3% reduction in mass velocity and corresponding reduction in critical heat flux for TOPROD relative to previous ENC fuel for the same assembly flow rate.

Table 4.1 Island TOPROD Thermal Margin Analysis

Reactor Conditions		Nominal
Rated Core Power (MWt)		1650 (100%)
Total reactor flow rate (Mlb/hr)		68.2
Active core flow rate (Mlb/hr)		65.1
Core Coolant inlet temperature (^{o}F)		530.5
Core pressure (psia)		2250.0
Power Distribution		
Overall peaking (F_Q)	2.32	
Radial x local	1.55	
Axial	1.45	
Engineering factor	1.03	
Initial DNBR	2.24	
Transient Results (2-pump coastdown)		
MDNBR	1.85	
Time of MDNBR	3.35 seconds	
Pressure at time of MDNBR	2314 psia	
Peak Pressure	2550 psia	
Limiting Rod Average Heat Flux at time of MDNBR	306,660 $BTU/hr/ft^2$	

Table 4.2 Flow and MDNBR Results for Different Core Loadings

	All ENC Standard (.426)	Cycle 9 Mixed 1/3 ENC-Standard 2/3 TOPROD — ENC Limiting	Cycle 9 Mixed 1/3 ENC-Standard 2/3 TOPROD — TOPROD Limiting	All TOPROD (.417)
Limiting Assembly Flow Factor				
Core Average Mass Velocity $lbm/hr/ft^2$	2.456×10^6	2.401×10^6	2.401×10^6	2.375×10^6
Limiting Assembly Mass Velocity $lbm/hr/ft^2$				
Limiting Assembly Flow lbm/hr				
Initial DNBR	2.33	2.256	2.276	2.24
Transient MDNBR (2 pump coast-down)	1.92	1.86	1.88	1.85
% Changes in DNBR	+4.0%	+0.7%	+1.6%	-

5.0 REFERENCES

(1) J.D. Kahn, XN-74-5, Rev. 1, "Description of the Exxon Nuclear Plant Transient Simulation Model for Pressurized Water Reactors (PTSPWR)", May 1975.

(2) L.S. Tong "Boiling Crisis and Critical Heat Flux", AEC Critical Series, TID-25887, 1972.

(3) K.P. Galbraith, T.W. Patten, J.L. Jaech and M. McMallen, XN-75-48, "Definition and Justification of Exxon Nuclear Company DNB Correlation for PWR's", October 1975.

(4) K.P. Galbraith and T.W. Patten "XCOBRA-IIIC: A Computer Code to Determine the Distribution of Coolant During Steady State and Transient Core Operation," XN-75-21, April 197[illegible].

APPENDICES

A.2 SAMPLE CORE FLOW CALCULATION RESULTS

Table A.1 provides sample core flow distribution results for Prairie Island. Two cases are presented. The first is for previous ENC reload when it was first placed in a core of Westinghouse fuel. The second is for the second core loading of TOPROD, with a third core of the previous ENC fuel remaining. Table A.2 provides the breakdown of effects which contribute to the 0.984 flow factor for the second case. Figure A.1 provides the core loading and power distribution for this second (TOPROD) case.

Table A.1 Prairie Island Core Flow Distribution Results

Table A.2 Mass Velocity Flow Factor Breakdown in ENC-Standard/ENC-TOPROD Evaluation

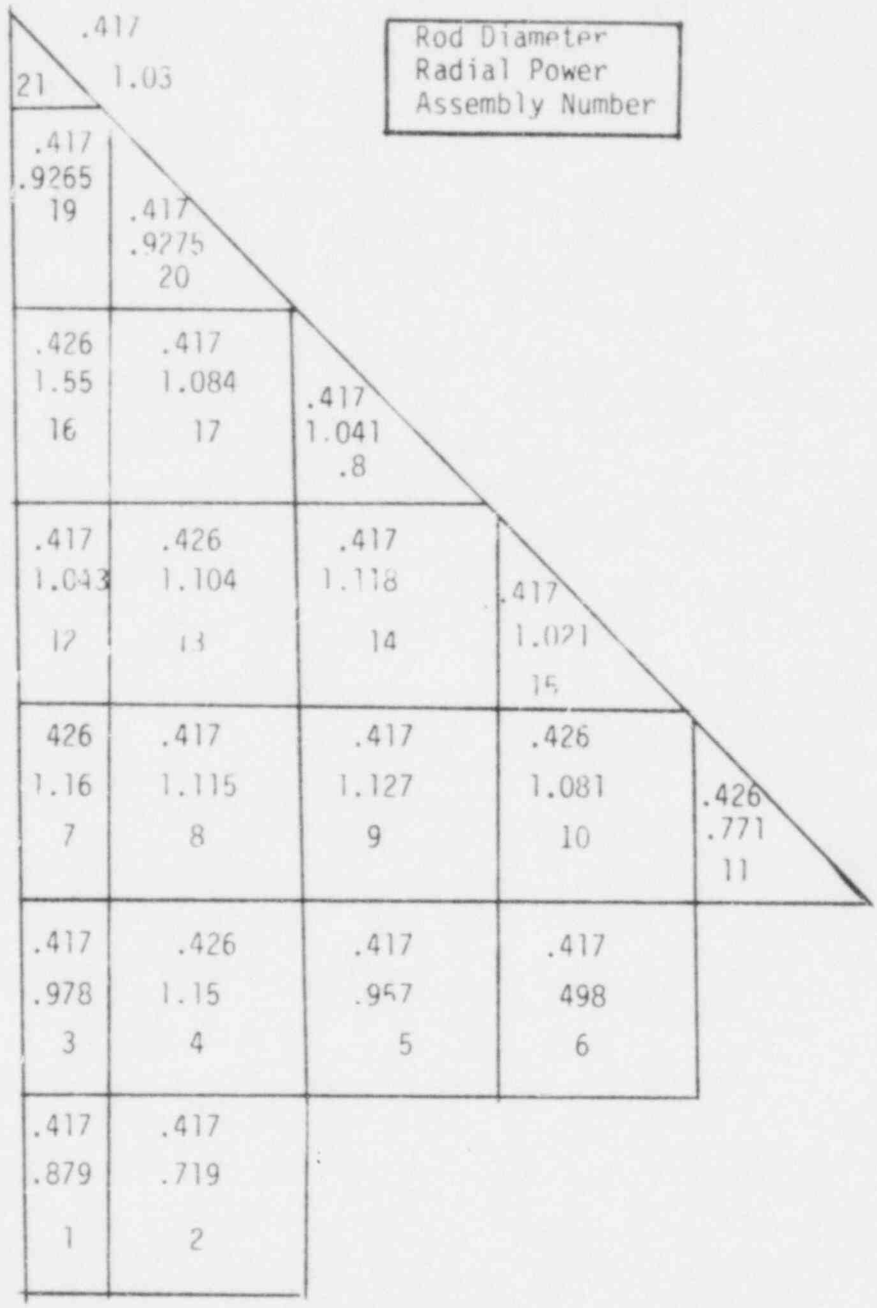

Figure A.1 Channel Layout Used Comparing TOPROD with ENC Standard

A.3 PRESSURE GRADIENT IN CORE FLOW CALCULATIONS

Question

How does the axial pressure vary between representative adjacent TOPROD and Standard Bundles?

Response

In comparing pressures axially for the core configuration illustrated in Figure A.1, the axial pressure drop of Bundle 16, peaked at 1.55 was compared with the axial pressure drop of Bundle 17, peaked at 1.084. Bundle 16 represents ENC standard fuel while Bundle 17 represents TOPROD fuel. The respective pressure drops are shown in Figure A.2. Table A.3 shows the pressures from which these were plotted. The TOPROD fuel has a pressure drop of while the standard has a pressure drop of

Table A.3 Pressure Drop

Figure A.2 Pressure Drop at 112% Overpower

A.4 SPACER EFFECT ON CORE FLOW

(COMPARISON OF MIXED CORE WITH AND WITHOUT SPACERS)

Question

Why did the flow factor decrease when the spacer resistance was removed?

Response

The relative resistance in the rodded region goes up. For the case of including spacers and bare rod friction, the ratio of the static pressure loss coefficients in the rodded region was = 1.033. With the spacers removed, this becomes = 1.0516. The only way the pressure drop can be maintained is for additional flow to be diverted from the resistive region to the less resistive region.

A.5 CROSSFLOW RESISTANCE CONSERVATISM

Question

How is the cross flow resistance value established for the thermal-hydraulic analysis?

Response

The lower the cross flow resistance, the greater the cross flow. For analysis of a bundle diverting flow, a low resistance is the most conservative approximation that can be made. ENC uses a value of 1.5 for its resistance coefficient for core wide calculations. This was established based on sensitivity studies which showed essentially little or no effect on flow factors due to the cross flow resistance. Results shown in subsection A.3 further emphasize that ENC's cross flow resistance is conservatively low since there is negligible radial pressure gradient in ENC results.

A.6 AXIAL MASS VELOCITY DISTRIBUTION

Question

Provide a figure showing the axial mass velocity distribution for Bundles 16 and 17 in Figure A.1

Response

Figure A.3 shows axial flow factors based on an inlet mass velocity of 2.399 mlb/hr-ft^2 for Bundles 16 and 17. The low flow factor for Bundle B (16) at X/L=0.7 is due to the occurrence of subcooled boiling at 112% overpower in an assembly with 1.55 radial peaking. Recovery in flow factor above X/L=0.7 is due primarily to the disappearance of the subcooled voids. Note that MDNBR in the hot assembly calculations occurs ahead of the subcooled boiling region at X/L=0.6.

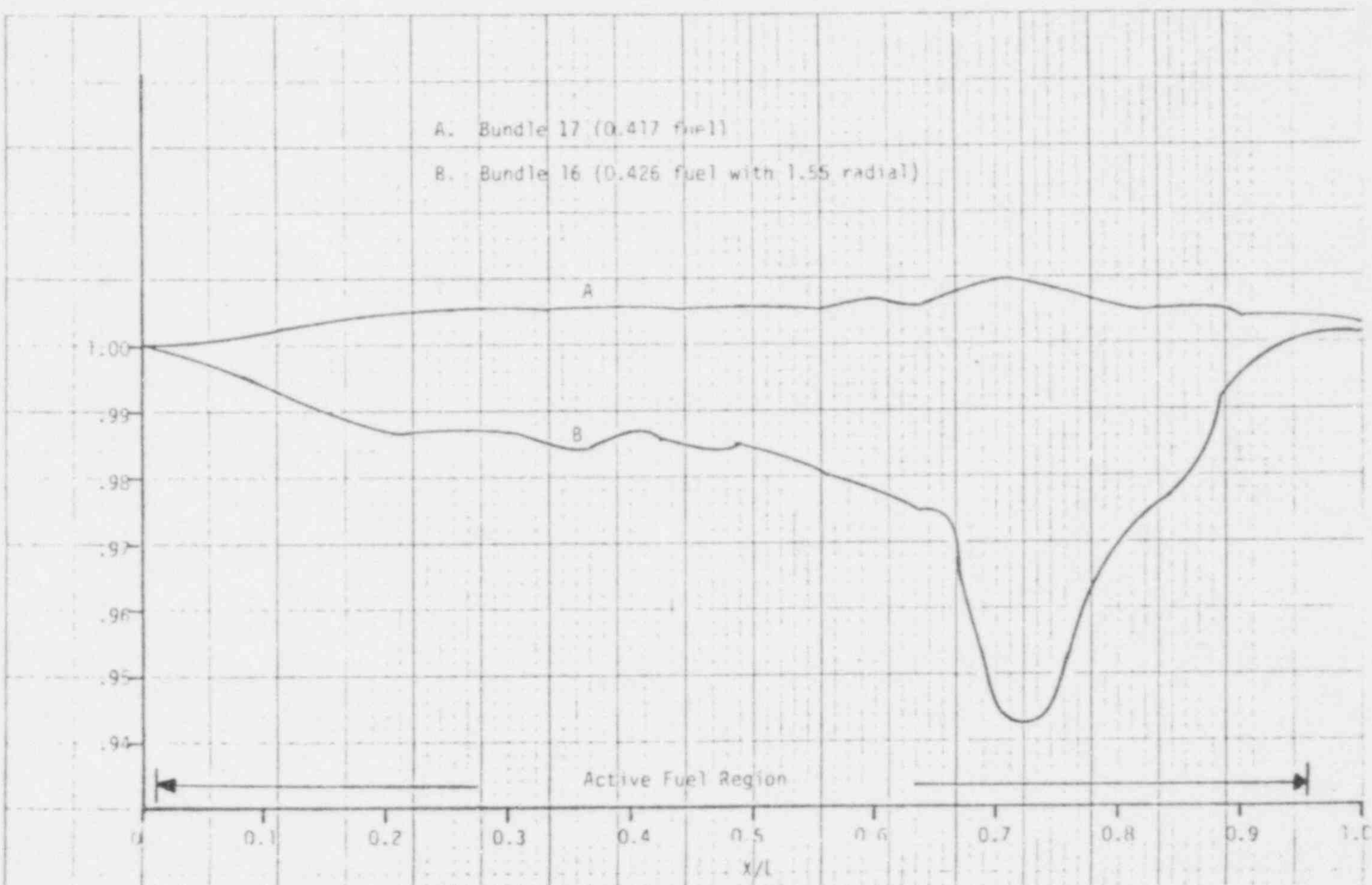

Figure A.3 Relative Axial Mass Velocity vs. Normalized Length

A.7 CROSSFLOW RESISTANCE SENSITIVITY STUDY

Question

Provide the results of the sensitivity study on crossflow resistance.

Response

Using the core flow model previously sent, the table below illustrates the flow factor sensitivity to crossflow resistance.

	Flow Factor	
K	Bundle 16	Bundle 17

A.8 EFFECT OF MASS FLOW ACROSS ASSEMBLY-TO-ASSEMBLY BOUNDARY

Question

Axially varying crossflow along the assembly-to-assembly boundary is not directly modeled in the hot assembly MDNBR calculations for TOPROD. Rather, this crossflow is accounted for by using an axial average hot assembly flow factor to define the hot assembly mass velocity. This mass velocity remains the same at all elevations in the hot assembly MDNBR calculations. The axial average hot assembly flow factor is obtained from the core flow calculation in which crossflow between assemblies is modeled. Justify the use of an axial average mass velocity flow factor versus a more obviously conservative approach such as a minimum flow factor, a channel exit flow factor, or a flow factor at the elevation at which MDNBR occurs.

Response

For conditions of interest, the sensitivity of MDNBR to local mass velocity and the sensitivity of MDNBR to local quality (or enthalpy) is small. The use of an axial average flow factor represents a compromise between having a mass velocity which produces the correct enthalpy at the MDNBR elevation, and the mass velocity actually occuring at the MDNBR elevation. This is illustrated as follows for the core flow calculation of Figures A.1 and A.3. The full length axial average flow factor for this distribution is as reported previously. The limiting assembly hot channel calculations show that MDNBR is calculated to occur at X/L=0.6, or about 15 inches ahead of the region in which boiling occurs, and at which point the flow factor is a minimum. At the MDNBR elevation, the flow factor is versus the full length axial average value. The axial average flow factor from the bottom of the assembly to the MDNBR elevation is and a flow factor of about this value would be required to achieve the correct enthalpy at the MDNBR elevation. Thus, use of the flow factor is about 0.41% conservative with respect to enthalpy, and about 0.63% nonconservative with respect to local mass velocity. The sensitivity of MDNBR to local enthalpy and local mass velocity are both about change in MDNBR per 1.0% change in local enthalpy or mass velocity. Thus the net discrepancy is about =0.1%. It is seen that the net effect of using the flow factor introduces compensating errors that just about identically cancel each other. Consideration of these same factors for the full core TOPROD core flow and MDNBR analyses indicates a net discrepancy also of about 0.1% in MDNBR for this case. This is also in agreement with the conclusion above that the errors are compensating.

A.9 ADDITIONAL COMMENT ON CROSSFLOW EFFECT

In subsection A.8, the effect of axially varying mass velocities on MDNBR calculations was addressed. The axially varying mass velocities are due to crossflow. The crossflow is such that typically the limiting assembly has reduced mass velocities in its mid-section relative to surrounding assemblies. The potential discrepancies in using an axial average mass velocity versus the mass velocity at the MDNBR elevation were identified as being very small (on the order of 0.1%). A second effect of flow across the assembly-to-assembly boundaries was not considered in the ENC response. This effect is the turbulent diffusion of lower enthalpy fluid into the limiting assembly from surrounding lower power assemblies. A comparison has been made of the enthalpy rise in the limiting assembly in the TOPROD core flow calculations versus the enthalpy rise in the TOPROD MDNBR calculation. This comparison indicates the planar average MDNBR plane enthalpy rise in the MDNBR calculation (without turbulent diffusion) which is about   higher than in the core flow calculation (with turbulent diffusion). This yields a corresponding conservatism in the MDNBR calculations in which all communication (crossflow and turbulent diffusion) across the assembly-to-assembly boundaries is neglected, of at least   The actual conservatism is expected to be   or more since:

(1) the turbulent mixing model used by ENC in the core flow calculation predicts much less mixing than is actually expected to occur; and

(2) since the detailed subchannel-to-subchannel enthalpy gradient between assemblies and hence the enthalpy in the MDNBR limiting subchannel is not reflected in the coarse mesh core flow calculations.

Thus, when turbulent diffusion is considered, the net effect of considering communication across the assembly-to-assembly boundaries in the MDNBR calculations versus the ENC approach using an axial average flow factor is a net conservatism estimated to be at least in MDNBR.

A.10 ADDITIONAL COMMENT ON PRAIRIE ISLAND - TOPROD CALCULATIONS

(a) Results provided in Table 4.2 indicate that the Full Core TOPROD case is most limiting with respect to MDNBR of the four cases considered. Crossflows for this case are relatively small (MDNBR plant flow factor $\geq$ 0.99).

(b) Subsection A.9 leads to the conclusion that ENC's use of an axial average flow factor in the MDNBR calculation versus a more rigorous approach of modeling axially varying crossflow and turbulent diffusion between the limiting and surrounding assemblies is conservative by at least in MDNBR.

(c) Even if turbulent diffusion were neglected, item (a) above remains true, and the potential change in MDNBR for the full core TOPROD case would be negligible .1%) and would be well within the bounds of actual calculational conservatism applied in the ENC analysis.

(d) The calculational conservatism (not discussed to date) is the use of an arbitrary 5% flow penalty in establishing the initial MDNBR of 2.24 in the TOPROD plant transient analysis.

A.11 EFFECT OF CROSSFLOW RESISTANCE ON AXIAL MASS VELOCITY DISTRIBUTION

Question

How does the axial variation in mass velocity change as crossflow resistance is increased?

Response

A sensitivity study employing crossflow resistances from zero to 25 showed little or no effect on the bundle average flow factors. The inspection of detailed output confirmed this effect was similar at all axial nodes.

A.12 EXPLANATION OF AXIAL MASS VELOCITY DISTRIBUTION

Question

Physically explain why axial mass velocity recovers after dropping to a minimum value at an axial location of X/L=0.7.

Response

Subcooled voids are predicted to occur within the limiting assembly which cause the density of the fluid to decrease when compared with other assemblies. To allow for expansion of the hot bundle fluid, the nodal axial mass velocity decreases. Because the axial heat flux then decreases on the rod, the heating is insufficient to maintain generation of subcooled voids. The influx of lower enthalpy fluid from adjacent lower powered bundles enhances subcooled void collapse. The density of the hot channel rises because of the subcooled void collapse. Surrounding channels have not generated subcooled voids. The hot assembly fluid contracts as subcooled voids collapse while adjacent cold assemblies expand. A comparison of axial flow is shown for three cases of interest in Figure A.4. Curve A represents the case of modeling with upper tie plate loss coefficients and subcooled voids. Curve B represents the model without subcooled voids. Curve C represents the model without subcooled voids and without the upper tie plate loss coefficient.

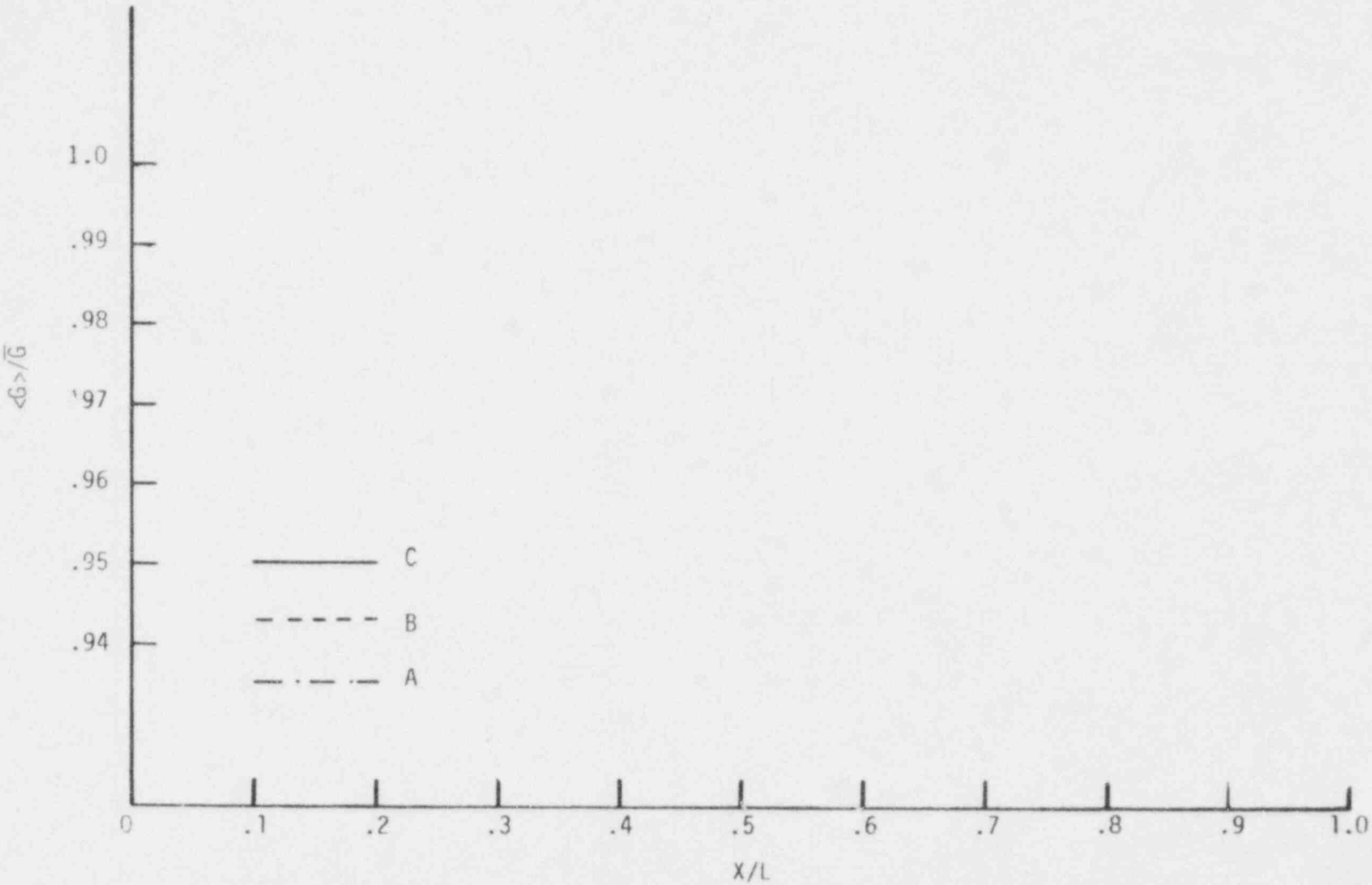

Figure A.4 Sensitivity of Model Assumptions to Axial Flow

A.13 EFFECT OF FUEL ROD BOW ON THERMAL MARGIN

The calculation of the DNBR reduction as a result of rod bow assuming a linear penalty function considers both DNB tests with rods bowed to closure and the degree of bowing as follows:

$$MDNBR_B = MDNBR_{NB} (1 - \delta_B)$$

and,

$$\delta_B = \frac{\Delta C}{C_o} \; 95/95 \; \delta_{bow}$$

where

$MDNBR_{NB}$ = MDNBR for nonbowed fuel

$MDNBR_B$ = MDNBR for bowed fuel

δ_B = fractional reduction in MDNBR due to bowing

$\frac{\Delta C}{C_o}$ 95/95 = anticipated fractional gap closure as a function of exposure

δ_{bow} = MDNBR reduction associated with bow to contact.

The calculation of DNB rod bow to contact penalty is based on DNB tests with rod bow as referred to in the NRC's Interim Safety Evaluation Report on Effects of Fuel Rod Bowing on Thermal Margin Calculations for

Light Water Reactors. Exxon Nuclear Company's detailed methodology for calculating fuel rod bowing and its MDNBR effect with a linear penalty function is given in XN-75-32, Supplement 1 (Computational Procedure for Evaluation Fuel Rod Bowing, June 1979).

The maximum anticipated fractional gap closure is based on rod bow measurements of ENC fuel similar to the Prairie Island design and currently being used in operating reactors. The above reference presents the results of rod bow measurements taken on ENC PWR reload fuel. The data base obtained from the above measurements include approximately 11,000 independent measurements of rod-to-rod spacings for interior as well as peripheral rod bows. After two cycles of operation, the results indicate rod bow which is a small fraction of that required for bow-to-contact. Application of this data to the ENC TOPROD design is in accordance with the aforementioned SER and includes a 1.2 multiplier to account for cold-to-hot variations in measured rod spacings, and a 1.5 multiplier to account for batch-to-batch variation. The maximum anticipated fractional gap closure through the fuel lifetime for TOPROD fuel is:

$$\frac{\Delta C}{C_o} \quad 95/95 = 0.485$$

This corresponds to a peak assembly burnup of 42,500 MWD/MTM. Since the fractional gap closure for TOPROD fuel is less than 50%, rod bow is not expected to have any significant impact on thermal margin. The effect of rod bow assuming a conservative linear penalty function follows.

Table A.4 provides a comparison of key results and rod bow penalties from the analysis of the "two pump coastdown" event with a full core of TOPROD fuel. The rod bow penalty is based on the linear penalty function. The heat flux and pressure parameters in Table A.4 correspond to the values calculated at the time of MDNBR. For conservatism, 60 psia has been added to the pressure prior to calculating the rod bow penalties shown in Table A.4. The bowed and unbowed MDNBR values for this transient are close to previously reported results for ENC fuel at Prairie Island. The bowed and unbowed MDNBR results are well above the allowable 1.3 value. Thus, no reduction in allowable reactor peaking is required as a result of a change in MDNBR due to rod bow.

Table A.4 Two Pump Coastdown Plant Transient and Thermal Margin Results for TOPROD Fuel at Prairie Island

Rod Heat Flux at time of MDNBR ($BTU/hr\text{-}ft^2$)	306,660
Pressure (psia)	2,314
$MDNBR_{NB}$	1.85
$(\Delta C/C_o)_{95/95}$	.485
δ_{bow}	.283
δ_B	.137
$MDNBR_B$	1.60

A.14 EFFECT OF AXIAL POWER DISTRIBUTION ON CORE FLOW

The effect of axial power distribution on core flow has been investigated by a sensitivity study for the full-core TOPROD core flow distribution case. Calculations were made for three axial power distributions using a relatively coarse axial nodalization The three axial power distributions were:

		Axial Peaking Factor	Fraction of Power in Top of Core
Case 1.	Chopped cosine	1.454	0.50
Case 2.	Up-skew	1.454	0.56
Case 3.	Down-skew	1.454	0.44

The limiting assembly axial mass velocity distributions for the three cases are shown in Figure A.5. For the chopped cosine and upskew cases, the MDNBR elevation is upstream of the drop-off in mass velocity when subcooled voids are calculated at X/L=0.7. For X/L<0.7, the mass velocities of all three cases are very similar and it is concluded that the use of the axial average mass velocity for the chopped cosine case in the TOPROD MDNBR calculation is appropriate. As noted in Subsection A.8, the full-length axial average mass velocity is slightly higher than the mass velocity at the MDNBR elevation, but is less than the axial a.erage mass velocity up to the MDNBR elevation. This leads to compensating errors in the MDNBR calculation such that the discrepancy in MDNBR is only about 0.1%.

Figure A.5 Normalized Flow vs Normalized Axial - Axial Sensitivity

Question:

Supply a plot of assembly flows for each axial power distribution.

Response:

Figures A.6, A.7, A.8 provide these distributions.

Question:

Supply the value and location of MDNBR for each axial power distribution.

Response:

The table below shows the relative MDNBR to that of the chopped cosine, and the nondimensional location of MDNBR.

Distribution	Relative Axial Location of MDNBR	Relative MDNBR Ratio
Chopped Cosine		
Downskew		
Upskew		

Figure A.6 Assembly Flows for 1.55 Radial Assembly and Adjacent Assembly Using Downskew Axial Profile

Figure A.7 Assembly Flows for 1.55 Radial Assembly and Adjacent Assembly Using Chopped Cosine Axial Profile

Figure A.8 Assembly Flows for 1.55 Radial Assembly and Adjacent Assembly Using Upskew Axial Profile

A.15 TRANSVERSE MOMENTUM PARAMETER, S/L SENSITIVITY

Question

Provide results of sensitivity to the transverse momentum parameter S/L

Response:

A sensitivity study was performed for resistances to crossflow from 0 to 25 and S/L from .01 to .5. This presents the axial flow profiles for the hot assembly for S/L of 0.01, 0.05, 0.1, 0.25 and 0.50 on Figures A.9, A.10, A.11, A.12 and A.13. For S/L $\geq$0.25, the results are essentially the same for each resistance and each S/L. As S/L tends towards 0.0, the crossflow tends towards zero and flow factor tends to 1.0. The table below summarizes axial average flow factor versus the parameter S/L.

S/L	Axial Average Flow Factor
.01	
.05	
.10	
.25	
.50	

Figure A.9 Assembly Flow for S/L = .01

Figure A.10 Assembly Flow for S/L = 0.05

Figure A.11 Assembly Flow for S/L = 0.1

Figure A.12 Assembly Flow for S/L = 0.25

Figure A.13 Assembly Flow for S/L = 0.50

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