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NaK Film Coefficients and 6 θ Temperature Ripple for the ZrH Reference Reactor.

AUTHOR

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ABSTRACT

The TAP computer program was used to model a 180° segment of a fuel cell of the reference reactor. Thermal analyses of nominal conditions were made to determine 6 θ temperature ripples and NaK film heat-transfer coefficients. Effects of cladding thickness and coolant mixing are treated.

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NaK Film Coefficients and 6θ Temperature Ripple for the ZrH Reference Reactor

SUMMARY

Temperature profiles have been calculated for a 180°F segment of a fuel cell for nominal conditions in the ZrH reference reactor. Typical results of cladding temperature ripple are shown in Figure 4. Effects of coolant interchannel mixing are shown in Figure 6. The temperature and heat flux profiles were used to determine the average NaK film heat transfer coefficient for each condition. Table 1 shows the results for the configurations calculated.

Correlations of the cladding thickness effect and the coolant mixing effect are given in the results section. A correlation for the magnitude of the 6θ temperature ripple in the cladding is also given.

INTRODUCTION

Because of the relatively close packing of fuel elements in the ZrH (SNAP) reactors, both the fuel cladding and the coolant have a circumferential temperature ripple. This ripple peaks at the points of close approach between elements and minimizes midway between the peaks. The temperature ripple causes a complementary ripple in the circumferential heat flux at the cladding surface with peaks and valleys interchanged from those of the temperature ripple. A detailed determination of the temperature profiles in the cladding and coolant is necessary under these conditions to properly determine the effective NaK film coefficient of heat transfer and to evaluate the thermal stresses and bowing tendencies in the fuel elements. Currently used reactor codes either assume symmetry in the circumferential coordinate (TEMPRØ2[1]) or split each cladding tube into six average segments circumferentially, one for each coolant channel around an element (GEØM[10]).

Detailed circumferential profiles were calculated by Magee[2] for the S8DR reactor. Magee used an analytical solution of the heat transfer equation for the fuel slug and matched it at the fuel surface to a nodal model of the rest of the fuel cell; the fuel/cladding gas gap, cladding, and coolant. Magee looked at fuel packings with pitch to diameter (P/D ratio) of 1.00, 1.018, and 1.036, which were of particular interest for S8DR. Cladding thicknesses of 0.010 in. and 0.020 in. were investigated. A 30° symmetrical segment of a fuel element was used for the nodal calculation. Slug flow was assumed in the coolant channels.

Marchese[3][4] performed a parameter study of a closely packed bundle of elements with P/D = 1.00. His calculations included variations in the relative thermal conductivities of fuel, cladding, and coolant. Cladding thickness and gas gap effects were also investigated. Marchese's calculations assumed a fully-developed turbulent-velocity profile in the coolant instead of slug flow. Again, a 30° symmetrical section was used for the calculation. The entire problem was solved numerically using a nodal model.

By interpolation and extrapolation of previous work, Marchese estimated the circumferential ripple magnitude as a function of P/D and clad thickness.[5] This information was to be used in the initial design calculations of the ZrH reference reactor.

The present work was performed to determine specifically the temperature ripple and average NaK film coefficient for the geometry presently under consideration for the reference reactor. In addition, the effect of inter-channel mixing and off-center fuel slugs was to be determined. In order to better accomplish these last two objectives, a nodal model, similar to Marchese's, was expanded to include a 180° segment of a fuel cell.

CALCULATION MODEL

Radial and circumferential temperature distributions (steady state) for each configuration studied were determined numerically with the TAP computer program.[6] The model consists of a 180° segment of a horizontal slice through a fuel cell. The segment includes one-half of the fuel element slice, plus one-third of each of the three coolant channels associated with that side of the element (See Figure 1). The nodal model contains 427 mesh points: 61 in the fuel slug, 30 on the fuel surface, 60 in the cladding, 120 on the cladding surface (60 inside and 60 outside), and 156 in the coolant channels. A portion of the nodal model is shown in Figure 11.

The reactor core configuration presently under consideration has fuel elements of two different cladding outside diameters, 0.640 in. and 0.655 in. For the selected lattice pitch of 0.670 in. the P/D ratios of interest are 1.0469 and 1.0229. Calculations have been performed for both configurations. Reference dimensions for the two fuel configurations are given below.

	Configuration 1 (inch)	Configuration 2 (inch)
Element diameter	0.640	0.655
Lattice pitch	0.670	0.670
P/D	1.0469	1.0229
Element spacing	0.030	0.015
Cladding thickness	0.032	0.032
Barrier thickness	0.002	0.002
Gas gap width	0.006	0.006
Fuel slug diameter	0.560	0.575

Material thermal conductivity values used were:

	$k\ (\frac{Btu}{hr ft\ ^{o}F})$
U-ZrH (fuel slug)	12.
H_2 (gas gap)	0.22 to 0.26 (varies)
Barrier	1.
Incoloy 800 (cladding)	13.
NaK (coolant)	15.

The effect of the H_2 barrier material inside the cladding was included in the cladding nodes.

A constant heat generation rate in the fuel slug was assumed. Thus, each fuel node has a heat generation proportional to its volume (or area in this two-dimensional model). The heat sinks in the coolant nodes are proportional to the node area times the coolant velocity in that node. Fully-developed turbulent-velocity profiles were assumed. Values for the profiles were obtained from the work of Eifler and Nijsing.[7] Bare rods (no fins) were assumed when determining the velocity profiles. Velocity profiles used for the two P/D ratios studied are shown in Figures 2 and 3.

Interchannel mixing was modeled by having an azimuthal flow through the inside ring of coolant nodes around the element. The inside ring of nodes has a radial thickness of 0.0075 in. for the 0.015 in. spacing case, and 0.015 in. for the 0.030 in. spacing case. This model was chosen because of its applicability to the right-left-neutral fin model[8] presently being considered for the reactor core. In this model the fins on adjacent elements always re-enforce each other in mixing fluid from one channel to the next. In the model, the amount of azimuthal mixing flow assigned was one-fourth of the total full-flow mixing which a channel exchanges with its three neighbors.

The calculational model is subject to the following assumptions.

1) Boundaries of the model are lines of symmetry.
2) Eddy thermal conductivity in the coolant can be neglected (a reasonable assumption for NaK at Reynold's numbers below 20,000).
3) All heat flow is in the plane of the model (axial conduction can be neglected).
4) Only radial conduction (no azimuthal) exists across the gas gap.
5) Heat sinks in the coolant nodes are proportional to cross-sectional area times the coolant velocity for each node. This assumes an equal temperature rise in all coolant nodes.

RESULTS

Results from the calculations are shown in Table 1. All work done to date has been for two P/D ratios and two power densities. The higher power density, 2.37 kw/ft per element, is the power at the core center for the test core. The reference reactor has a center peak about 12% greater. The lower power, 1.98 kw/ft, is the power at the zone boundary where the lower P/D ratio is applicable. A few calculations were made for cladding thicknesses of 0.010 in. and 0.050 in. to evaluate the cladding thickness effect. Mixing was treated as a parameter with rates of 10, 20 and 30%/inch for both geometries studied. For comparison, the maximum mixing observed in the hydraulic test[9] was 35%/inch for fins with a 4-in. pitch. Presently envisioned fins have a 5-1/2 in. pitch and would have a lower mixing factor.

Table 1 lists the circumferential temperature ripple on the cladding OD, the average NaK film coefficient, and the equivalent Nusselt number for each case. Some runs were made assuming slug flow of the coolant and some assuming a fully developed turbulent velocity profile. The results differ by about 10% to 20% between the two assumptions with the turbulent velocity profile giving the more conservative results. Actual coolant velocity profiles with the finned rods would be slightly different from either of the two calculated. Data on the actual profile shape would be a desirable input to further calculations.

Cladding temperature ripples for different conditions are shown in Figures 4, 5, and 6. The curves in each figure are normalized to the same peak fuel temperature. Figure 4, for a 2.37 kw/ft power density, was normalized 27°F higher than Figures 5 and 6, which are for power densities of 1.98 kw/ft. Figure 4 shows the effect of P/D ratio (or spacing) on the temperature ripple. Figure 5 shows the effect of mixing. Figure 6 also shows the effect of mixing, but with a turbulent velocity profile assumed for the coolant instead of slug flow. Notice that the temperature peaks and valleys are swept slightly downstream in the mixing direction.

The thermal effect of a fin on the fuel cladding is shown in Figure 7. The fin considered was 0.015 in. high by 0.017 in. wide. (The current design is 0.080-in. wide.) The effect on the temperature ripple was a perturbation of only 1°F. Note that this result includes only the thermal effect of replacing the NaK coolant heat sink with cladding metal. It does not include the results of any hydraulic effect of the fin.

The results from Table 1 were correlated by equations for use in the GEØM thermal hydraulic computer program,[10] which treats a symmetrical segment of the whole core. The average NaK film heat transfer coefficient, $\bar{h}$, determined here for no mixing, turbulent velocity profile, and 0.010 in. clad thickness, is in agreement with values presently being used. Specific values are available in Figure 13, Reference 11, which is a graph of average Nusselt number $\left(\frac{\bar{h}\, d_e}{k}\right)$ as a function of P/D ratio. For cladding thicknesses other than 0.010 in. the following correlation is applicable:

$$\frac{\bar{h}_x}{\bar{h}_{010}} = 1 + \left(\frac{0.0229}{P/D-1}\right)^{0.8} \left(0.4394 - \frac{0.4423}{(X/.010)}\right)$$

where x = clad thickness in inches.

The effect of mixing can be accounted for by the equation:

$$\frac{\bar{h}_{mixing}}{\bar{h}_x} = 0.9935 + 0.02875 \times M - 0.2393 \times M(P/D - 1)$$

where M = mixing cross flow (%/inch).

Results of these two equations, along with the Table 1 calculations for the turbulent velocity profile assumption are shown in Figures 8 and 9.

Figure 10 shows the corrections for determination of 6θ temperature ripple by GEØM. The GEØM program uses the approximation that the minimum clad temperature at any axial location is approximately equal to the average coolant temperature in the adjacent coolant channel. These calculations show that for film coefficients below about 7,000 Btu/hr-ft^2 °F, the minimum cladding temperature falls a few degrees below the average NaK temperature. Deviations from the equal temperature assumption are shown in Figure 10 as a function of the average NaK film coefficient, $\bar{h}$, for the cladding segment under consideration. The ΔT correction follows the equation:

$$T_{correction} = \left(\frac{x}{.032}\right)^{-0.4} (PF) \left[3.764 - 0.0005125 \times \bar{h}\right]$$

where x = clad thickness in inches

PF = power density, kw/ft

$\bar{h}$ = average NaK film coefficient, Btu/hrft^2 °F.

CONCLUSIONS AND RECOMMENDATIONS

The calculational results reported in this document give the detailed fuel cell temperature profiles and average NaK film coefficients for the nominal conditions in the reference ZrH reactor. These are used as input for calculations of over-all core thermal performance by codes such as GEØM and for thermal stress determination in the cladding. Comparison of the calculational model to results of the coming finned heat transfer test(12) will provide further confirmation of this work.

Investigation of off nominal conditions, such as off-center fuel slugs and special effects at the core edge, is required and is presently under way. More detailed work on the thermal effect of the fin is also desirable.

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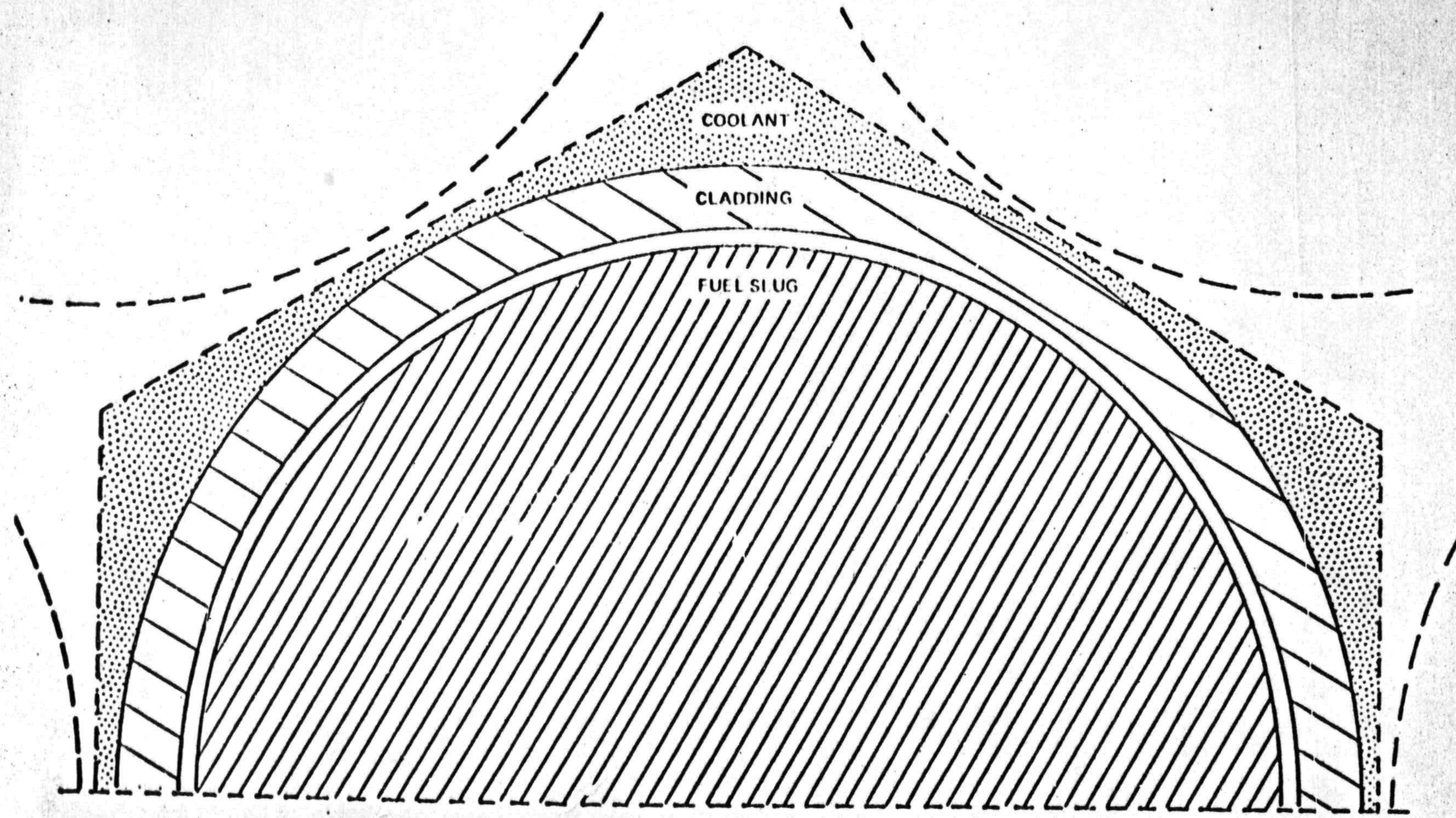

Figure 1. Geometry of 180° Fuel Segment Included in Heat Transfer Model

Figure 2. Tricusp Velocity Profiles For P/D = 1.047.

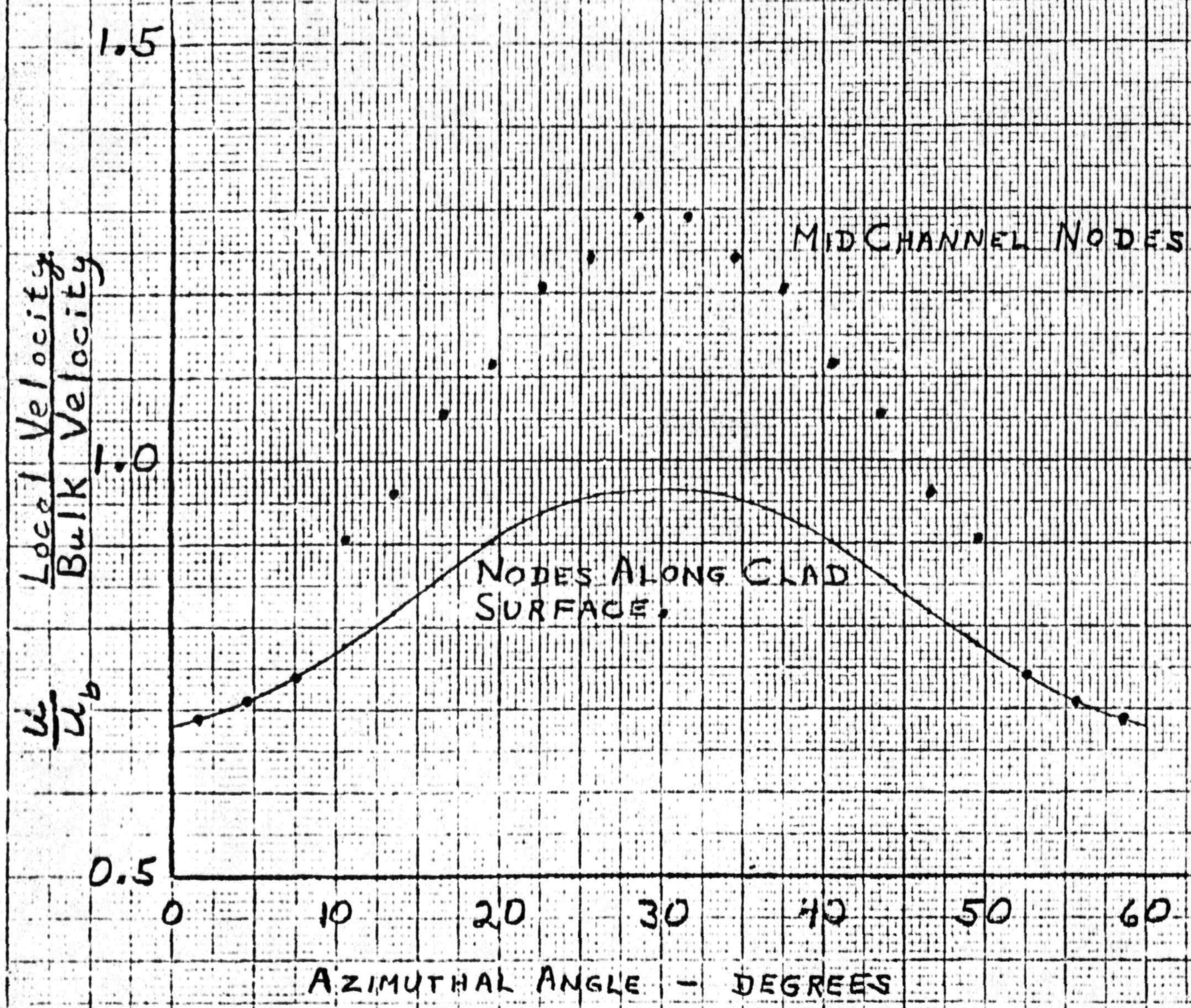

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Figure 3. Tricusp Velocity Profiles For P/D = 1.023.

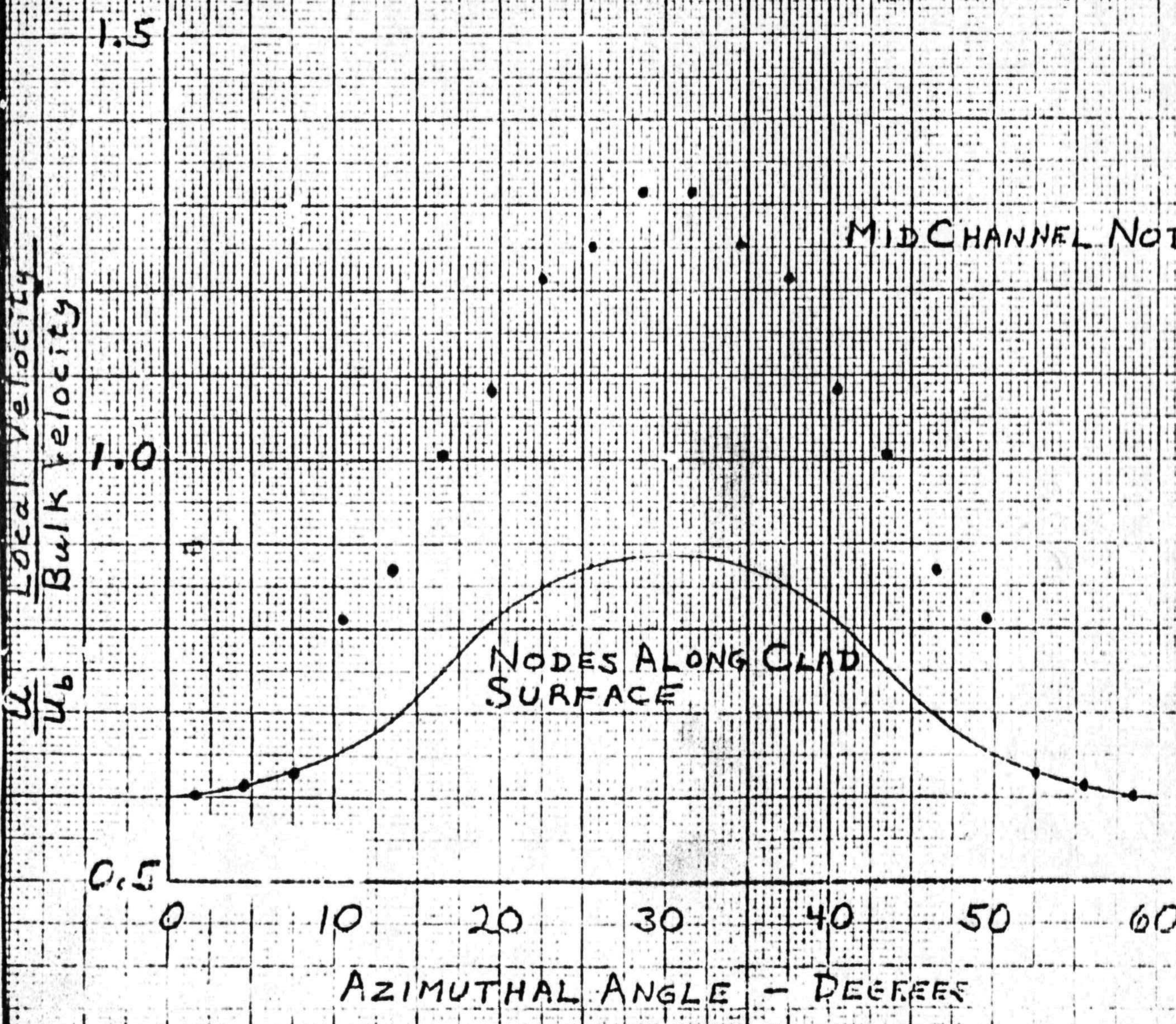

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Table 1.

NaK Film Coefficient, $\bar{h}$, and 6θ Ripple on Cladding; Derived From Calculations With 180° TAP Model

P/D	Q kw/ft	t_{clad} mils	MIXING %/IN.	T_{clad} (°F) above Avg. Coolant Max	Avg	Min	Clad Ripple °F	NaK Film $\bar{h}$	Nu
		Coolant Slug Flow							
1.0229	1.98	10	0	31.06	11.64	-5.83	36.9	3384	1.89
"	1.98	32	0	21.57	9.14	-2.84	24.4	4310	2.41
"	1.98	32	10	18.07	7.77	-2.13	20.2	5064	2.83
"	1.98	32	20	14.18	6.35	-1.11	15.3	6347	3.55
"	2.37	32	0	25.97	10.99	-3.41	29.4	4292	2.40
"	2.37	32	10	21.92	9.42	-2.72	24.6	5090	2.85
"	2.37	32	20	17.23	7.68	-1.48	18.7	6270	3.51
"	2.37	32	30	13.74	6.60	-0.50	14.2	7250	4.06
1.0469	2.37	10	0	22.51	8.99	-3.51	26.0	5363	3.98
"	2.37	32	0	17.32	7.89	-1.35	18.7	6133	4.55
"	2.37	32	10	13.93	6.77	-0.37	14.3	7214	5.35
"	2.37	32	20	10.90	5.85	+0.84	10.1	8360	6.20
"	2.37	32	30	9.20	5.40	+1.65	7.6	8963	6.65
		Turbulent Velocity Profile							
1.0229	1.98	10	0	38.32	14.34	-8.04	46.4	2747	1.54
"	1.98	50	0	23.77	10.44	-3.22	27.0	3773	2.11
"	1.98	32	0	26.56	11.20	-4.19	30.7	3517	1.97
"	1.98	32	10	22.02	9.45	-3.23	25.3	4211	2.36
"	1.98	32	20	17.38	7.65	-1.92	19.3	5225	2.92
"	1.98	32	30	14.20	6.58	-0.93	15.1	6089	3.41
1.0469	2.37	10	0	28.61	10.95	-5.94	34.6	4419	3.28
"	2.37	50	0	19.95	9.04	-1.97	21.9	5325	3.95
"	2.37	32	0	21.66	9.43	-2.77	24.4	5119	3.79
"	2.37	32	10	17.15	7.95	-1.33	18.5	6140	4.55
"	2.37	32	20	13.28	6.76	+0.23	13.1	7247	5.37
"	2.37	32	30	11.12	6.17	+1.29	9.8	7923	5.87

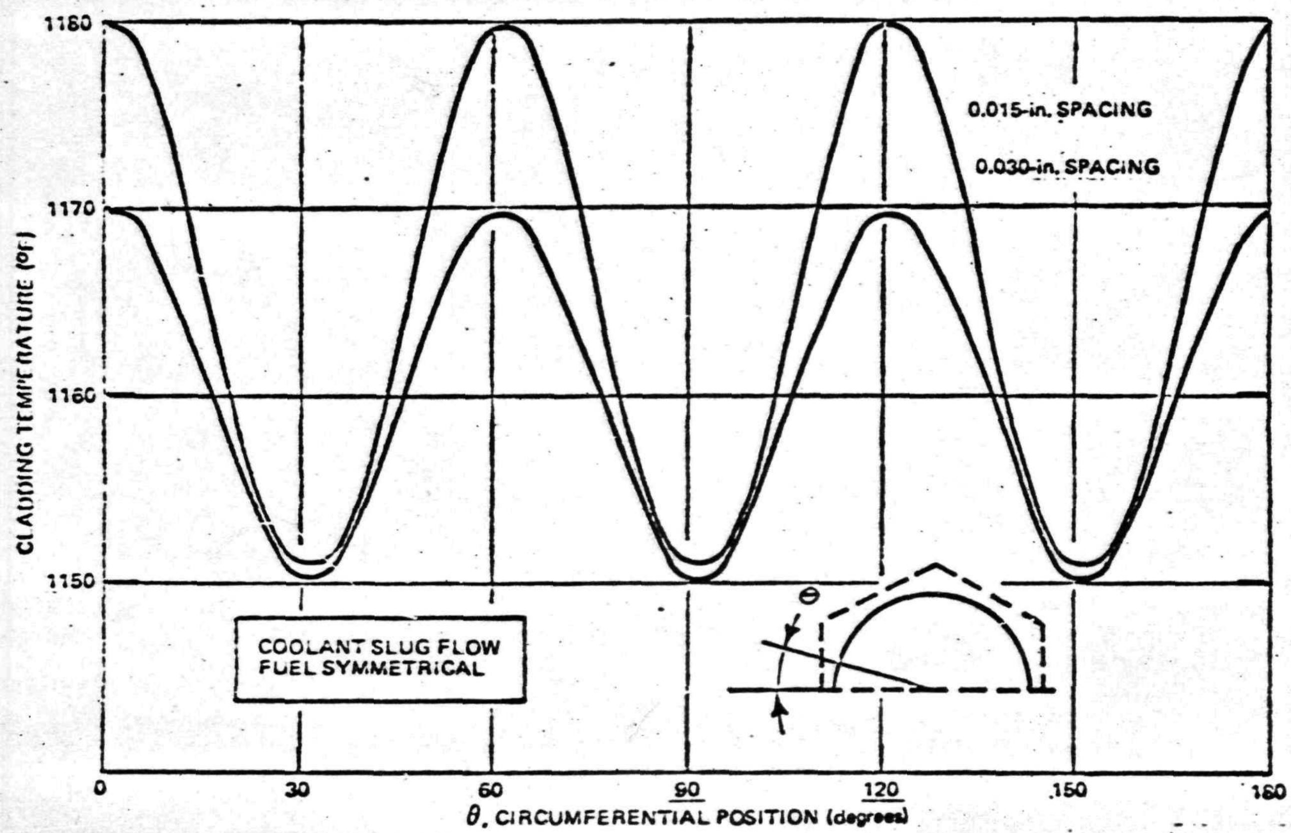

Figure 4 - Test Core Temperature Ripple on Cladding OD, Heat Flux: 2.37 kw/ft (Core Center)

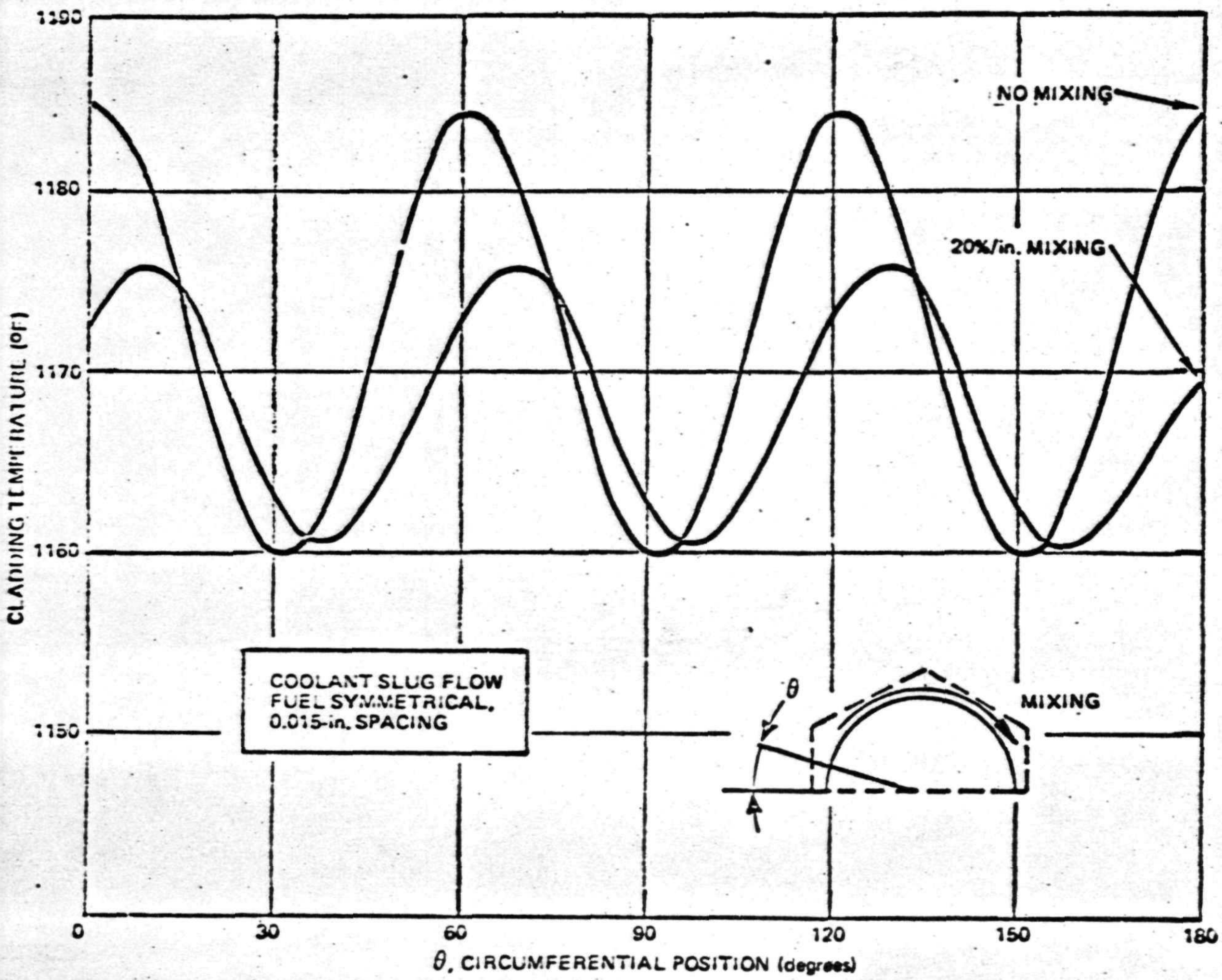

Figure 5 - Test Core Temperature Ripple on Cladding OD,
Heat Flux: 1.98 kw/ft (Zone Boundary)

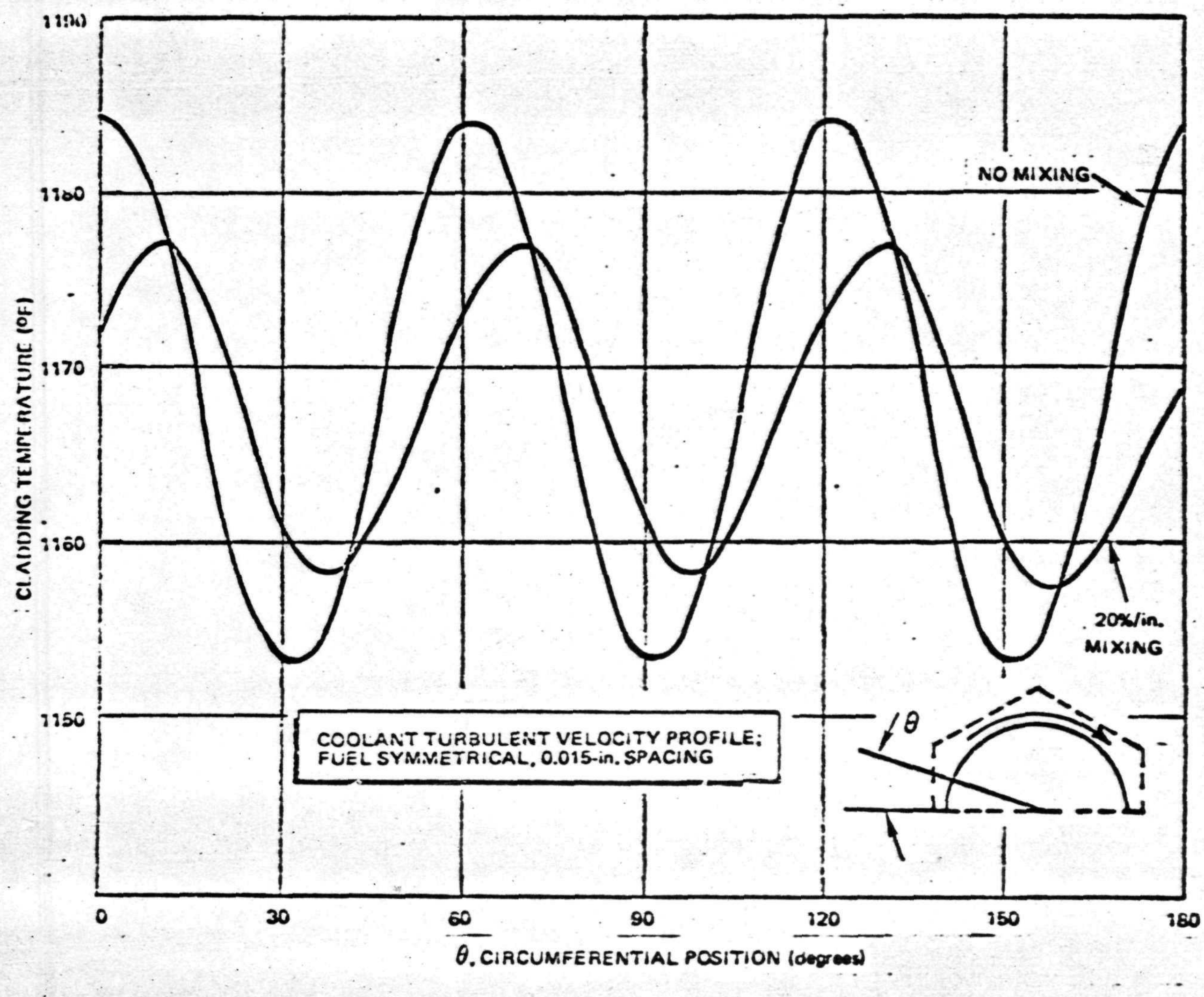

Figure 6 - Test Core Temperature Ripple on Cladding OD, Heat Flux: 1.98 kw/ft (Zone Boundary)

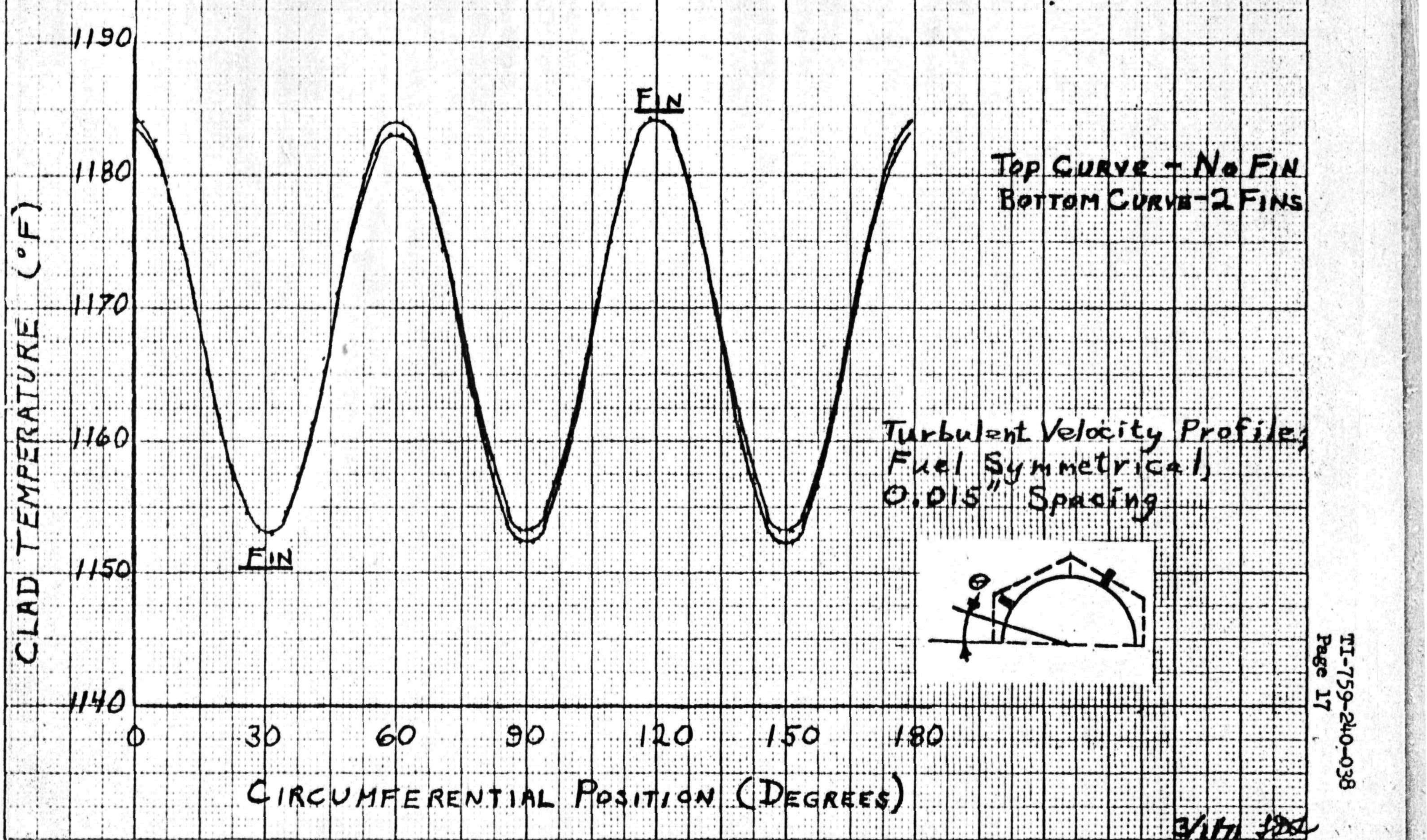

Figure 7. Effect of Fin on Temperature Ripple, Heat Flux: 1.98 kw/ft (Zone Boundary)

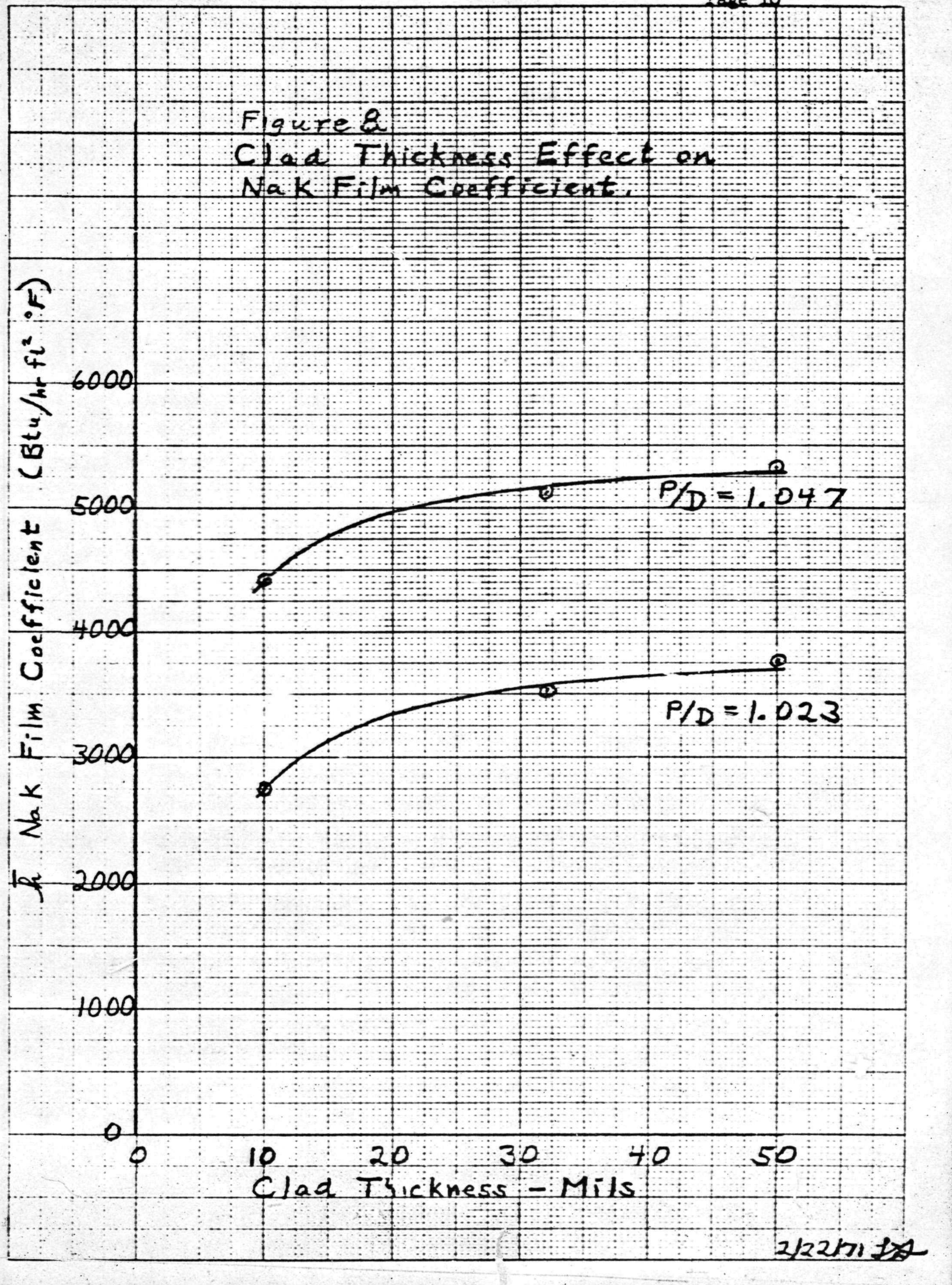

Figure 8
Clad Thickness Effect on NaK Film Coefficient.

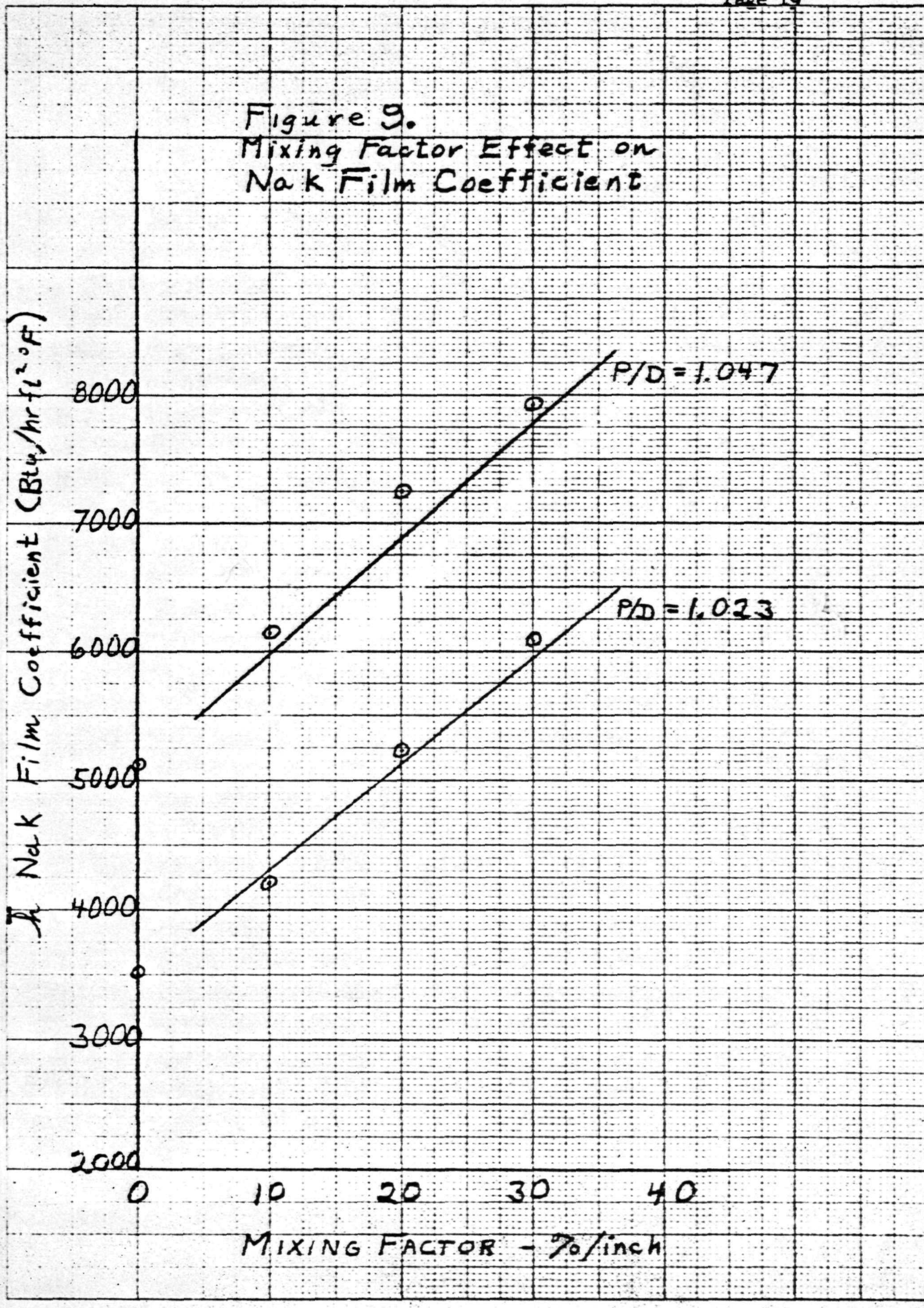
Figure 9.
Mixing Factor Effect on
NaK Film Coefficient
h NaK Film Coefficient (Btu/hr ft² °F)
8000
7000
6000
5000
4000
3000
2000
0
10
20
30
40
P/D = 1.047
P/D = 1.023
MIXING FACTOR - %/inch

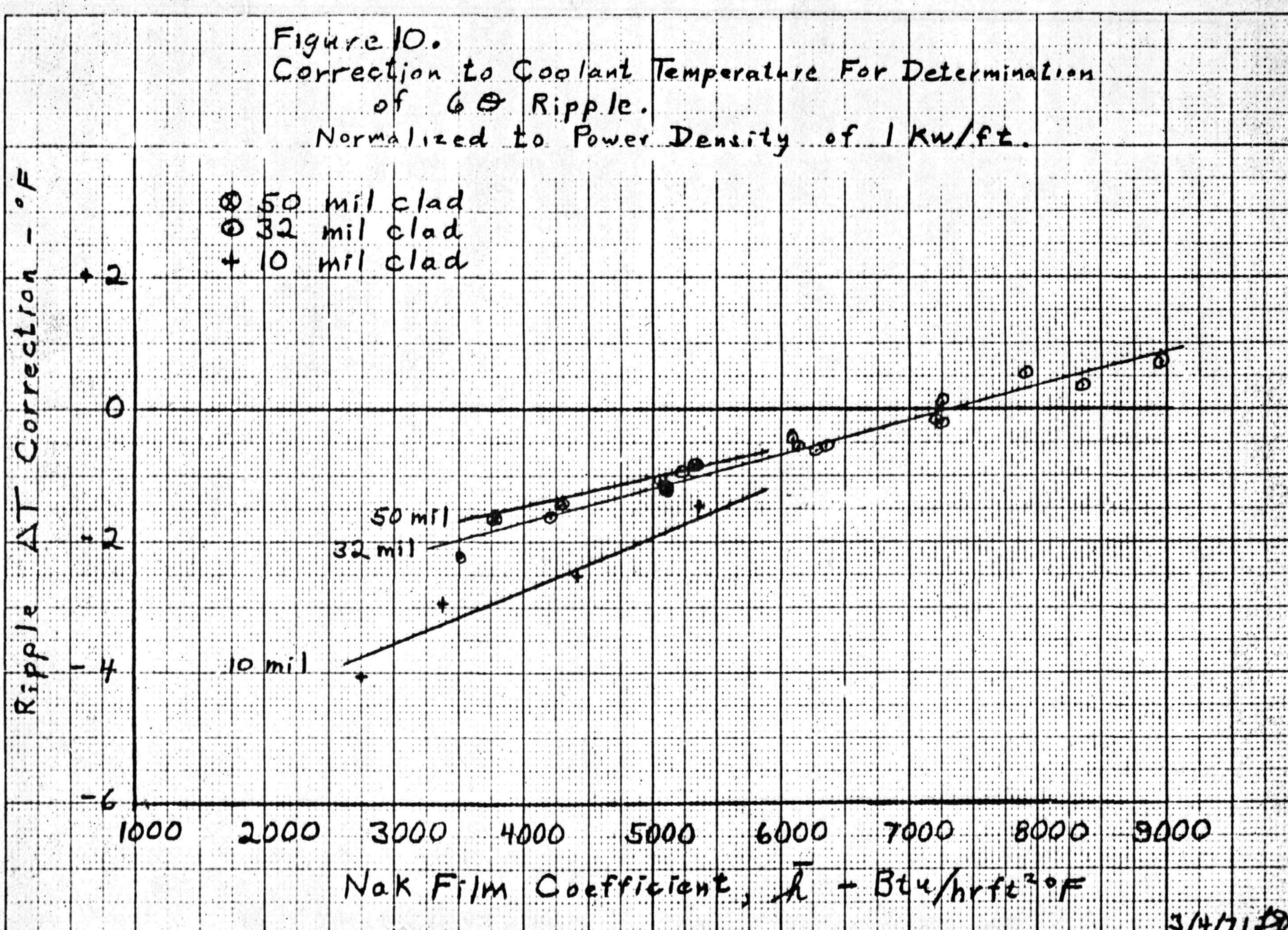
Figure 10.
Correction to Coolant Temperature For Determination of 6 Θ Ripple.
Normalized to Power Density of 1 Kw/ft.
⊗ 50 mil clad
⊖ 32 mil clad
+ 10 mil clad
50 mil
32 mil
10 mil
Ripple ΔT Correction - °F
2
0
-2
-4
-6
1000
2000
3000
4000
5000
6000
7000
8000
9000
NaK Film Coefficient, h̄ - Btu/hrft²°F
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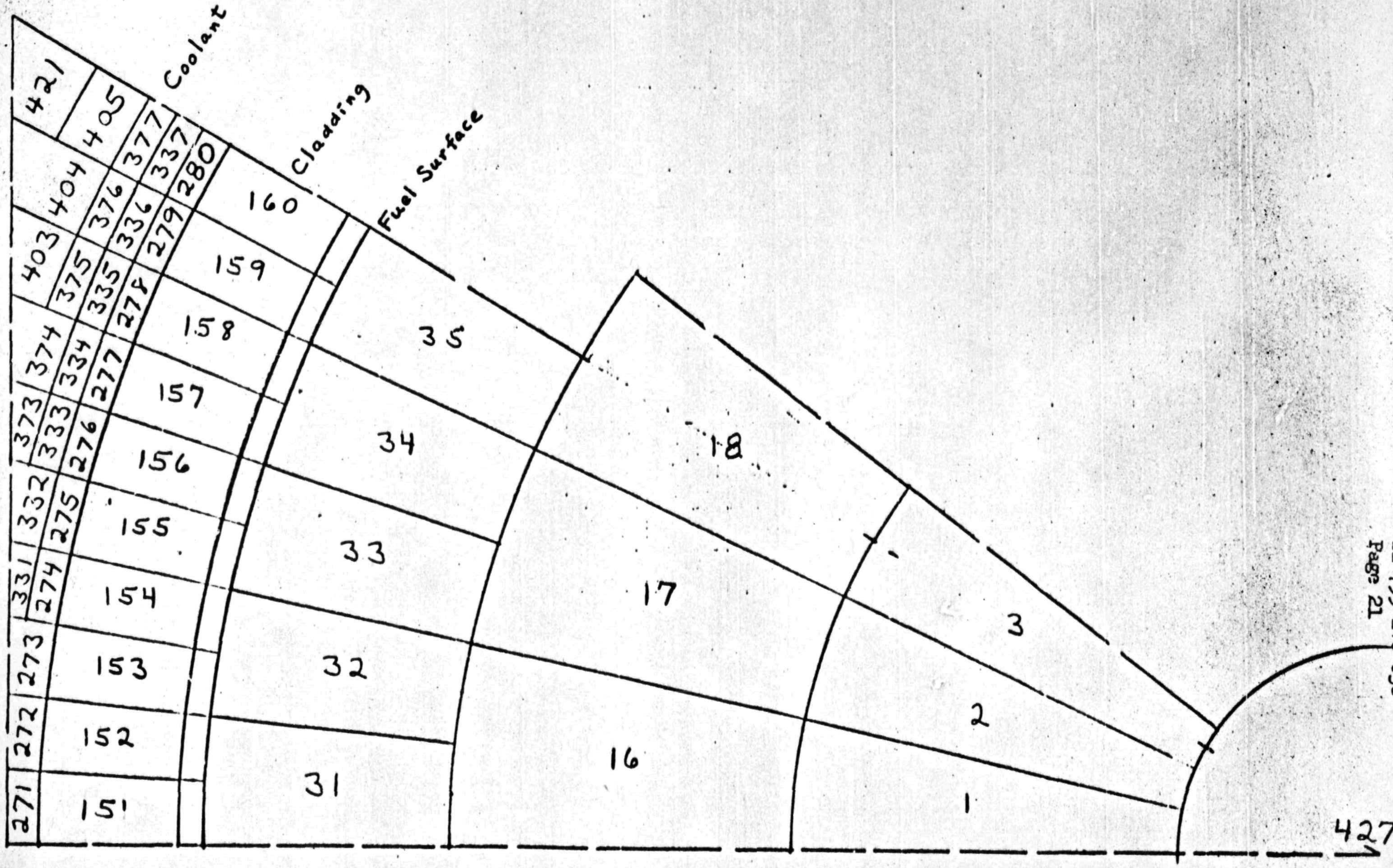

Figure 11. Portion of Nodal Model For 180° Segment.