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ZrH Reactor Lattice Spacing (Heat Transfer Considerations)

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ABSTRACT Temperature calculations for a 295 element ZrH reactor at fuel element spacings from 0.010" to 0.065" showed a very small dependence of reactor temperature on element spacing. It was found that one variation in coolant channel area (2 zones) was sufficient to satisfactorily shape the radial flow profile for the core.

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I. Introduction

A lattice spacing trade study was required to determine the optimum spacing for the 295 element ZrH reference reactor. The element to element spacings are to be maintained by fins on each fuel element. Large spacings result in higher NaK film heat transfer coefficients than tight spacings. This results in lower fuel temperatures and less temperature ripple circumferentially around the elements. The larger spacings also allow higher fins on the fuel elements which, in turn, promote more channel to channel mixing. The mixing tends to smooth out hot and cold channel effects. The larger spacings are limited by nuclear requirements (excess reactivity and reflector control) of the reactor. It is also desired to keep the Reynolds numbers of the individual channel flows above the laminar and critical flow regimes. However, for constant fuel element diameter and the same total coolant flow the Reynolds number is insensitive to element spacing. Pressure drop was not a critical item in the study since the ΔP for the core configurations considered was only 1/4 to 1 1/4 psi.

The following basic rules were set for the trade study configurations.

Reactor power	600 kw
Outlet temperature	1200°F
Inlet temperature	1065°F
Number of elements	295
Nominal assembly clearance	0.002"
Cladding material	Incoloy 800
Cladding ID	0.550"
Minimum clad thickness	0.015"
Gas gap width	0.0055"
Fin pitch	5.5 inches/turn
Core edge	No heat loss

The desired radial temperature profile has equal maximum fuel temperatures for all elements. Temperature control was performed by shaping the coolant flow profile, which was achieved by varying the flow channel areas. For this study the channel area variations in each configuration were made by increasing the fuel cladding thickness. An alternate method would be to maintain the cladding thickness at 0.015" and increase both the fuel slug and cladding diameter. From a thermal hydraulic viewpoint the results would be the same for either method if the radial power profile remained constant. The actual radial power profile for variable fuel slug diameter is flatter than the one for variable cladding and it peaks up at the zone boundaries where the fuel diameter increases.

Calculations were performed with the GEOM 2[(1)] program which treats a 1/12 (30°) repeating section of a hexagonal core. Axial and radial power profiles(2) for the calculations are shown in Figures 1 and 2. It was assumed that the tube fins were 50% efficient(3) in producing cross flow between adjacent coolant channels. Fin efficiency is defined as the ratio of actual coolant cross flow to the cross flow calculated assuming all coolant located between adjacent fin wraps crosses into the neighbor channel at the points where the fins cross over.

Since it is not practical to tailor each flow channel individually to achieve the desired flow profile the core was divided into zones with the individual flow channel areas equal to one another within each zone. An example of a four zone core is shown in Figure 3.

II. Results and Discussion

A. Nominal Spacing

The basic runs for the trade study investigation are listed in Table 1. The table shows the assembly clearance between fins, the lattice pitch, the spacing between fuel elements, and the number of element zones which were used to approximate the desired flow shape. The last column of the table lists the outer fuel ring for each zone. Fuel and coolant temperatures for the 0.630" and 0.610" lattice pitch cases are shown in Figures 4 and 5. Peak fuel temperatures for all the Table 1 runs are shown in Table 2. Peak fuel temperatures are plotted as a function of average spacing and number of zones in Figure 6. The constant spacing cases (1 zone) were not plotted because of the high peak fuel temperatures which result with no flow shaping. From Table 2 we find the highest peak fuel temperature for case 7 (1 zone) is 63°F hotter than for the four zone case 1. The one zone case would become of interest if the power profile were flattened by nuclear means such as a varied uranium loading, for which a uniform flow profile would suffice.

From Figure 6 we see that peak fuel temperature is not a strong function of element spacing. The main cause of the spacing dependence is the variation in NaK film coefficient, which increases as the fuel spacing increases. Since the NaK film is only a small part of the total heat transfer resistance a change in the film coefficient has only a small effect. Even the number of zones by which the ideal flow area is approximated does not have a large effect on the maximum peak fuel temperature in the core. Figure 6 shows a 15°F temperature drop in going from 2 to 4 zones for the core.

The data in Table 2 includes the maximum NaK temperature difference across an individual fuel element at the zone boundaries. The maximum differences occur at the reactor outlet. With reference to Table 1 we see from the Table 2 results that the cross element ΔT's are an inverse function of element spacing. This effect results from the direct relationship of mixing with fin height, with the larger fins being used to obtain the larger spacings. Table 3 shows fuel temperature and cross element ΔT data for the same cases as in Table 2 but with the assumption of no inter-channel coolant mixing. Comparison of the values in the two tables shows that mixing has little effect on peak fuel temperatures, but is quite effective in reducing the coolant temperature ΔT's around an element. Many of the cross element ΔT's increased 50 to 100% from the nominal mixing to the no mixing case.

B. Clustered Elements

Additional calculations were performed to determine the hot channel effect of a three element cluster under different spacing conditions. Three adjacent fuel elements were assumed to move together until their fins touched. The fuel rods were assumed to remain centered (or randomly positioned) within the cladding tubes. The amount of movement thus depended upon assembly clearance, or fin to fin spacing originally allowed. The result is then one small channel common to the three clustered elements and twelve enlarged channels around the cluster. Figure 7 shows the increase in cross element ΔT as a function of the initial element spacing and assembly clearnace. Comparison of the mixing and no mixing curves in Figure 7 show the beneficial effects of inter-channel mixing.

C. Asymmetrical Fuel Slugs

The effect of asymmetry of fuel slugs inside the cladding was also investigated. Fuel slugs in three adjacent elements were moved off-center to the side of their common coolant channel. For no mixing assumed, the cross element ΔT at the outlet for the three affected elements increased 60^{o}F over the symmetrical case. For nominal mixing this ΔT increase is only 9^{o}F. Again, the importance of inter-channel mixing is evident. With the three elements clustered in addition to the asymmetry condition, the cross element ΔT increase is 11^{o}F instead of 9^{o}F.

D. Tradeoffs

Based upon the above results, Figure 4 and Figure 6, the two (2) zone configuration is most appropriate for the reference reactor core. The 15^{o}F penalty in fuel temperature for the 2 zone over the 4 zone core is not significant when balanced against the advantages in manufacture, quality assurance, and assembly of a core with two types of fuel elements instead of four types.

For element spacings greater than 0.010" as considered here the only significant spacing effect is the hot channel ΔT caused by element clustering. With the small assembly clearances (≤.004") presently being considered, and with inter-channel mixing, the cross element ΔT is small, less than 10°F estimated from Figure 7. Actually, we would hesitate to use spacings less than 0.020" where each fin is only 0.008" to 0.010" high depending upon the assembly clearance. Fins smaller than this probably will not provide enough mixing to sufficiently reduce hot channel and cross element ΔT's. Above this minimum there is little advantage gained in thermal hydraulic characteristics by going to the larger spacings (other than the required spacing increases to obtain the proper zoned areas). Nuclear characteristics improve as the reactor becomes more compact, which makes the smallest allowable spacing most desirable. Typical spacings in a 2 zone core would be 0.020" for the outside zone and 0.040" for the inside zone.

Recent work has indicated the requirement for minimum cladding tube thickness of 0.025" and an initial radial gap width of 0.006" for the fuel elements. Figures 8 and 9 show peak fuel and coolant outlet temperatures for two cases with these changes included. Figure 8 shows the reference 2 zone core case with 0.02" and 0.04" spacing. Figure 9 shows a case where the peak fuel temperature was decreased 7°F by lowering the spacing in the outer core zone to 0.014". Not only is the 0.014" spacing below the minimum desirable but the cross element ΔT's at the zone boundary are quite large (~20°F). The gradient in coolant outlet temperature can be seen in Figure 9. The configuration of Figure 8 is thus the better of the two and is representative of the design currently being formulated. The peak to average of the radial power profile was reduced to 1.32 for these last two calculations. This is in line with the flattening effect observed when the variable channel areas are obtained by varying the fuel slug diameters instead of the cladding thickness.

III. Conclusions

The ideal flow profile can be satisfactorily approximated by a two (2) zone core with flow channel areas constant within each zone. For the small assembly clearances, ≤0.004", presently being considered the magnitude of the average fuel element spacing has very little effect upon peak fuel temperature and coolant temperature gradients even when considering cluster effects. These conclusions rely on the presence of considerable inter-channel mixing between the finned fuel elements. The prediction of this mixing effect is highly uncertain and the above conclusions will require re-evaluation after the results of the experimental mixing tests are known.

IV. References

1. TI-696-24-063, "Core Sector Thermal-Hydraulic Code GEOM2", E. Moody, March 26, 1970

2. TI-696-24-072, "Nuclear Performance Characteristics of the ZrH Reactor", K. Rooney and L. Swenson, May 21, 1970

3. Work of E. Moody, personal communication

FIGURE 1.
Axial Power Profile.

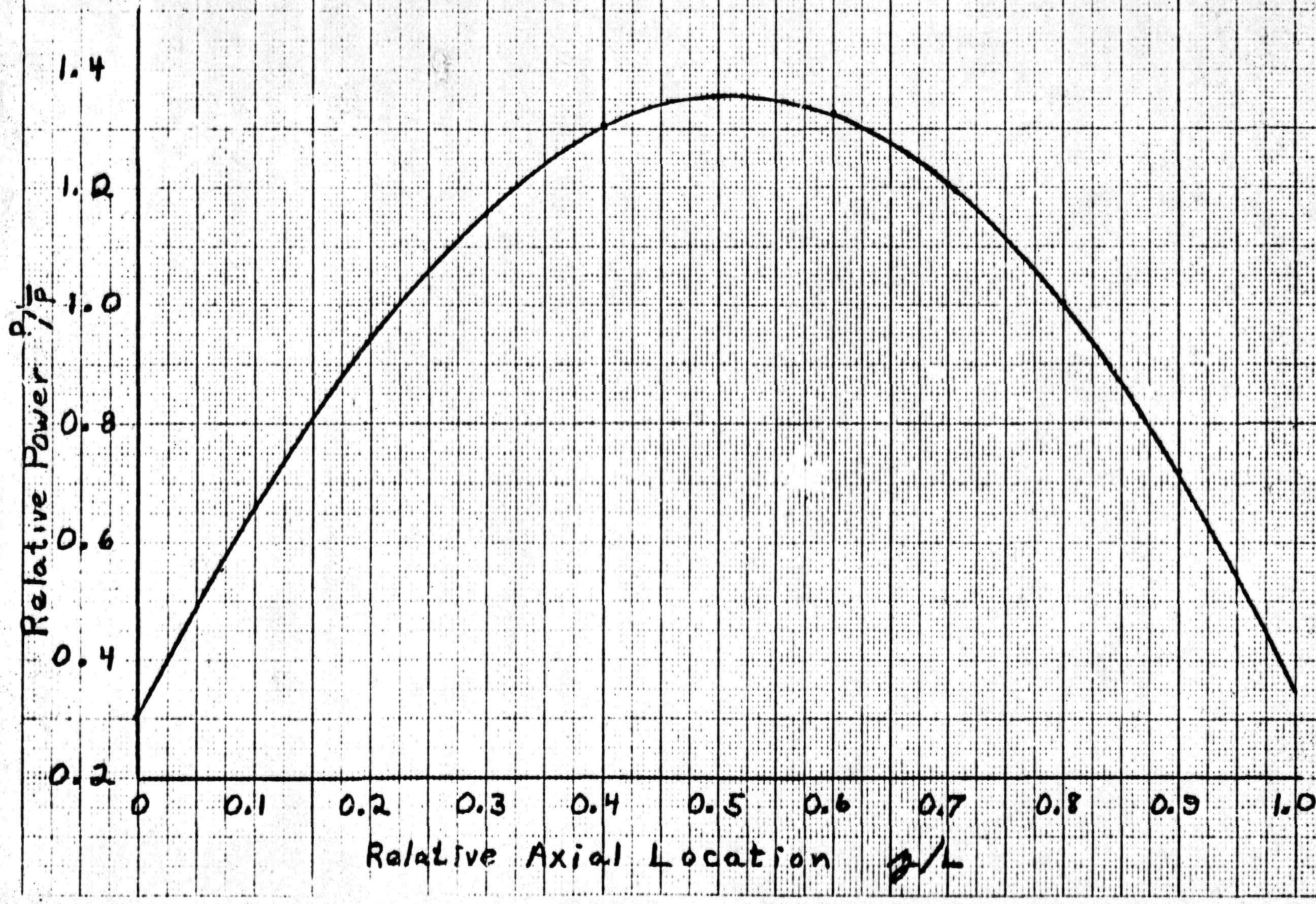

FIGURE 2.
Radial Power Profile

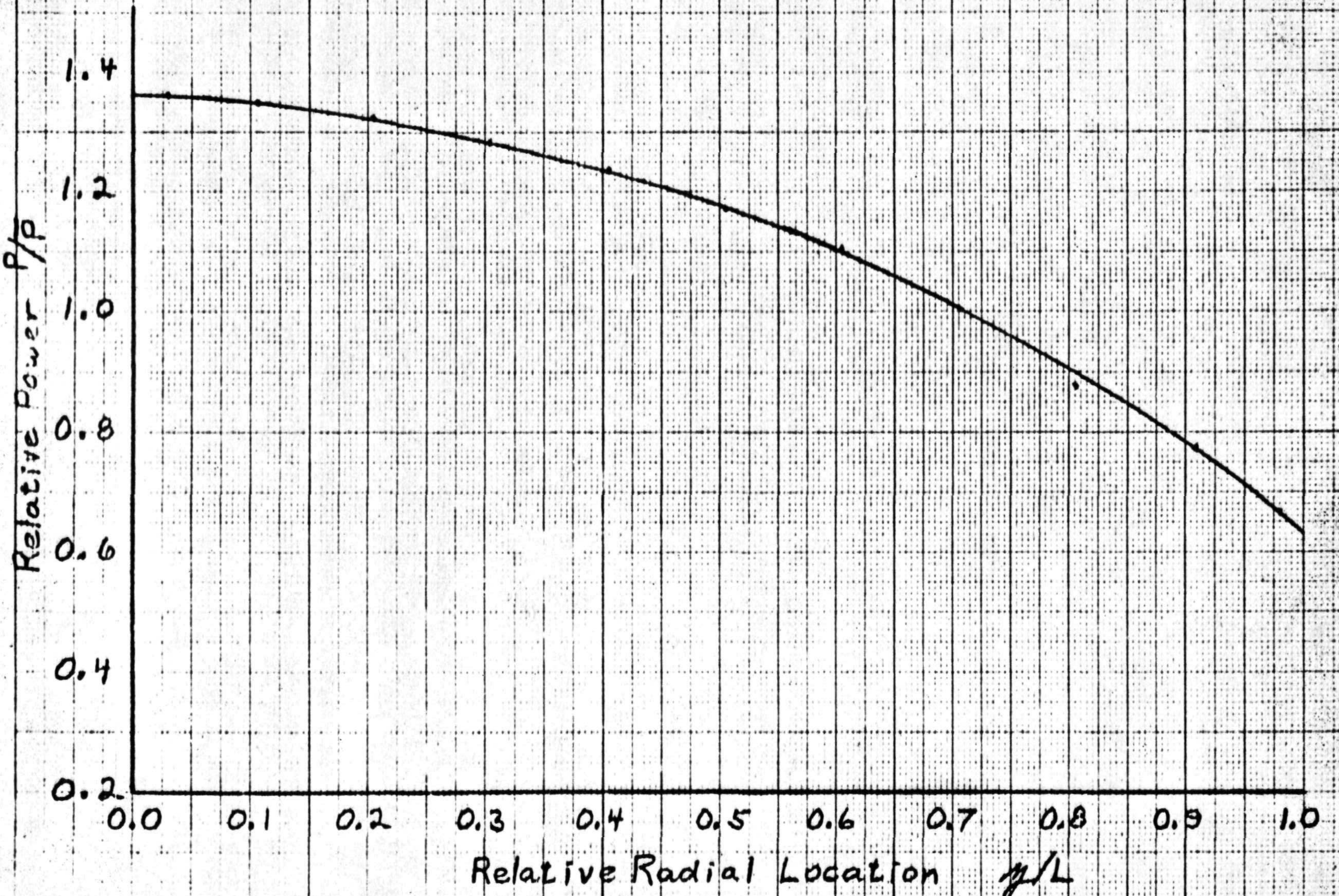

FIGURE 3. Example of Four Zone Approximation to Desired Flow Channel Area Distribution

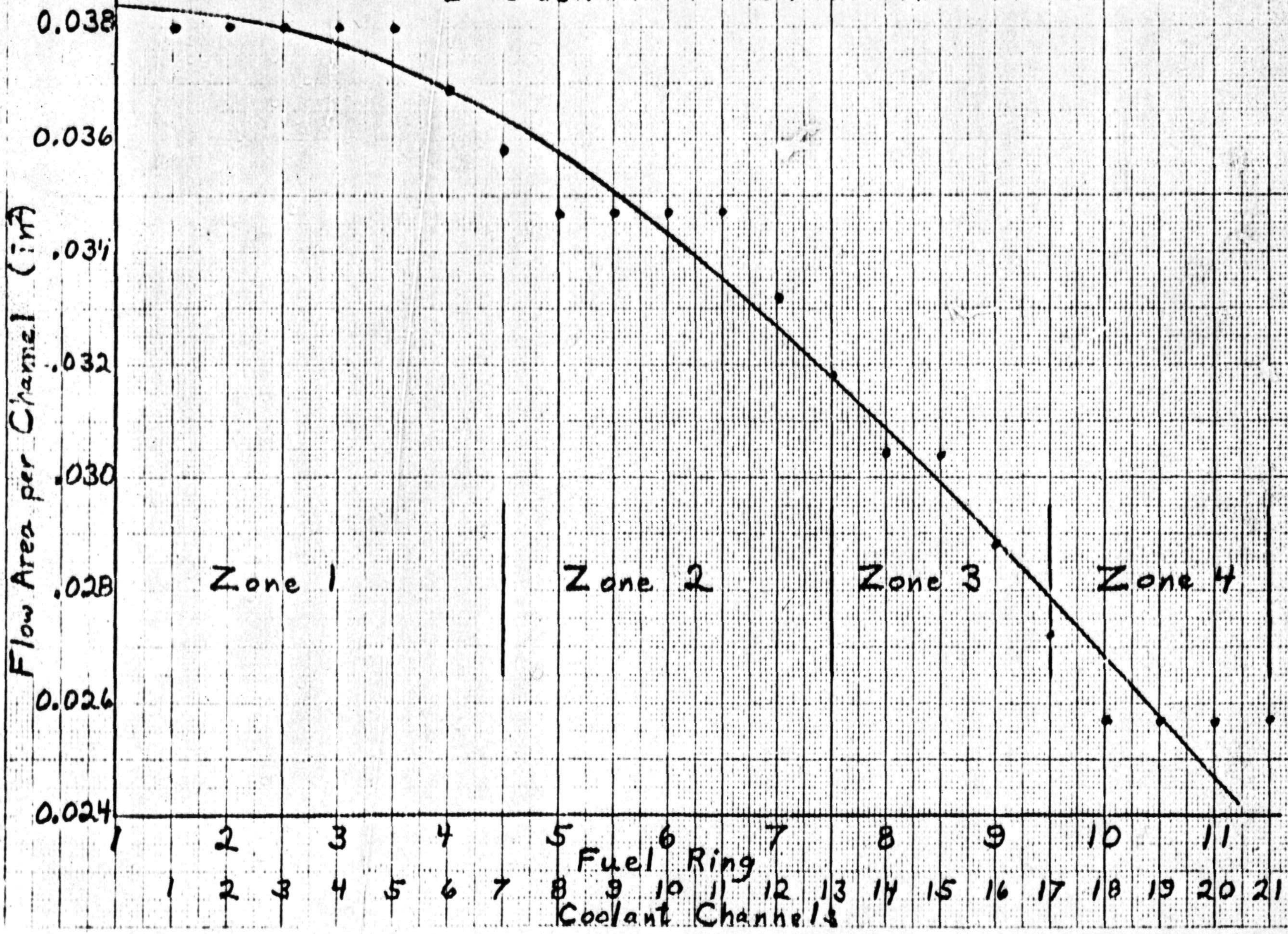

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TABLE I.

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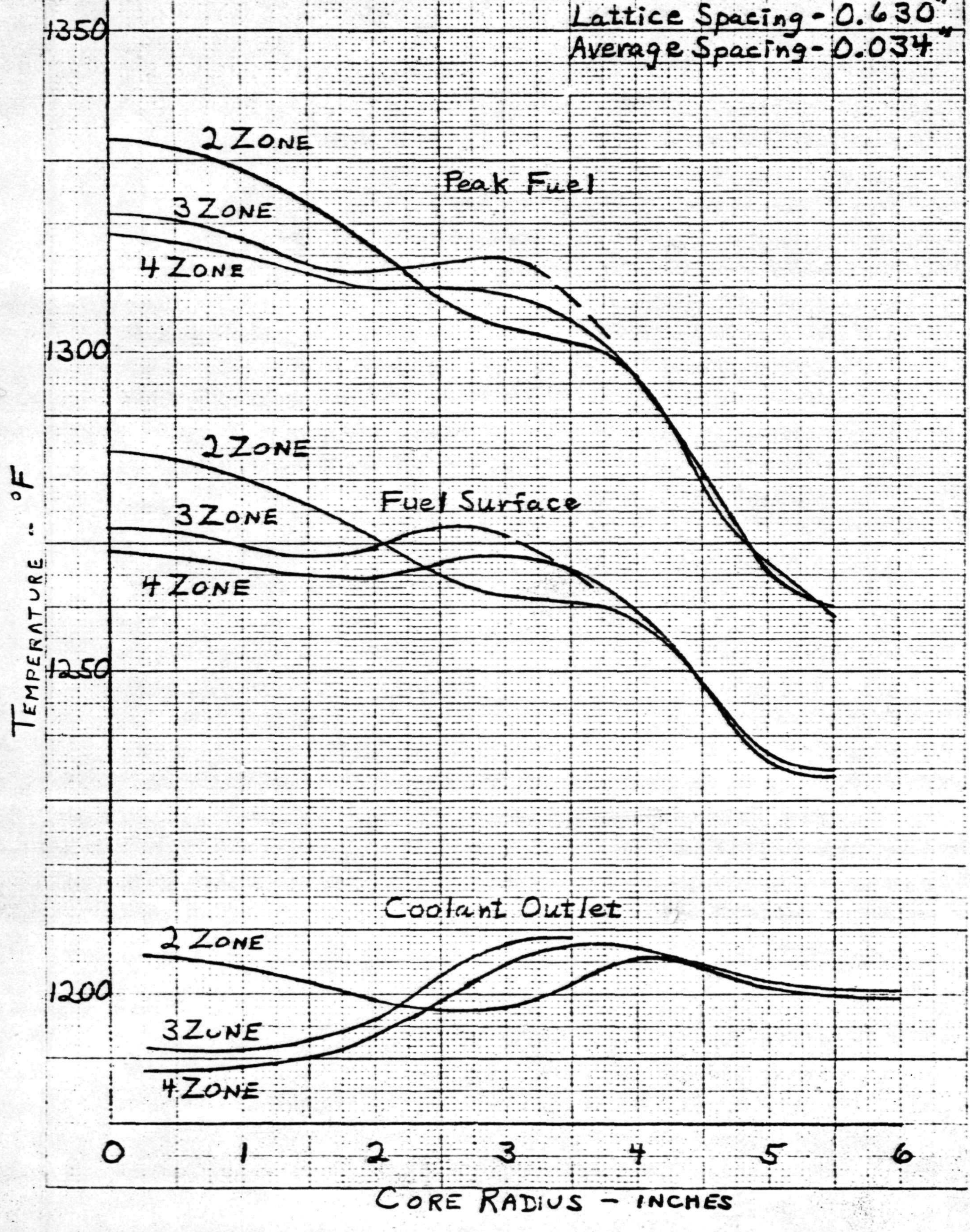
LATTICE SPACING STUDY
CASE CONFIGURATIONS

RUN No.	Assembly Clearance	No. Zones	Lattice Pitch	Minim. Spacing	Maxim. Spacing	Avg. Spacing	Zone Bound.
1	0.002"	4	0.630	0.023"	0.046"	0.035"	4, 6, 8, 11
2	0.004"	4	0.630	0.023"	0.046"	0.035"	4, 6, 8, 11
9	0.002"	4	0.620	0.017"	0.037"	0.027"	4, 6, 8, 11
10	0.002"	4	0.640	0.029"	0.056"	0.043"	4, 6, 8, 11
11	0.002"	4	0.650	0.036"	0.065"	0.050"	4, 6, 8, 11
12	0.002"	4	0.650	0.040"	0.065"	0.052"	4, 6, 8, 11
13	0.002"	4	0.610	0.010"	0.027"	0.019"	4, 6, 8, 11
7	0.002"	1	0.582	0.002"	0.002"	0.002"	11
18	0.004"	1	0.584	0.004"	0.004"	0.004"	11
20	0.002"	2	0.630	0.023"	0.039"	0.033"	7, 11
22	0.002"	2	0.610	0.010"	0.022"	0.017"	7, 11
27	0.002"	3	0.630	0.023"	0.044"	0.034"	5, 8, 11
29	0.002"	3	0.610	0.010"	0.026"	0.018"	5, 8, 11
31	0.002"	3	0.650	0.040"	0.062"	0.051"	5, 8, 11

FIGURE 4.
Temperature Profile For 600 kW, 1200°F Reactor



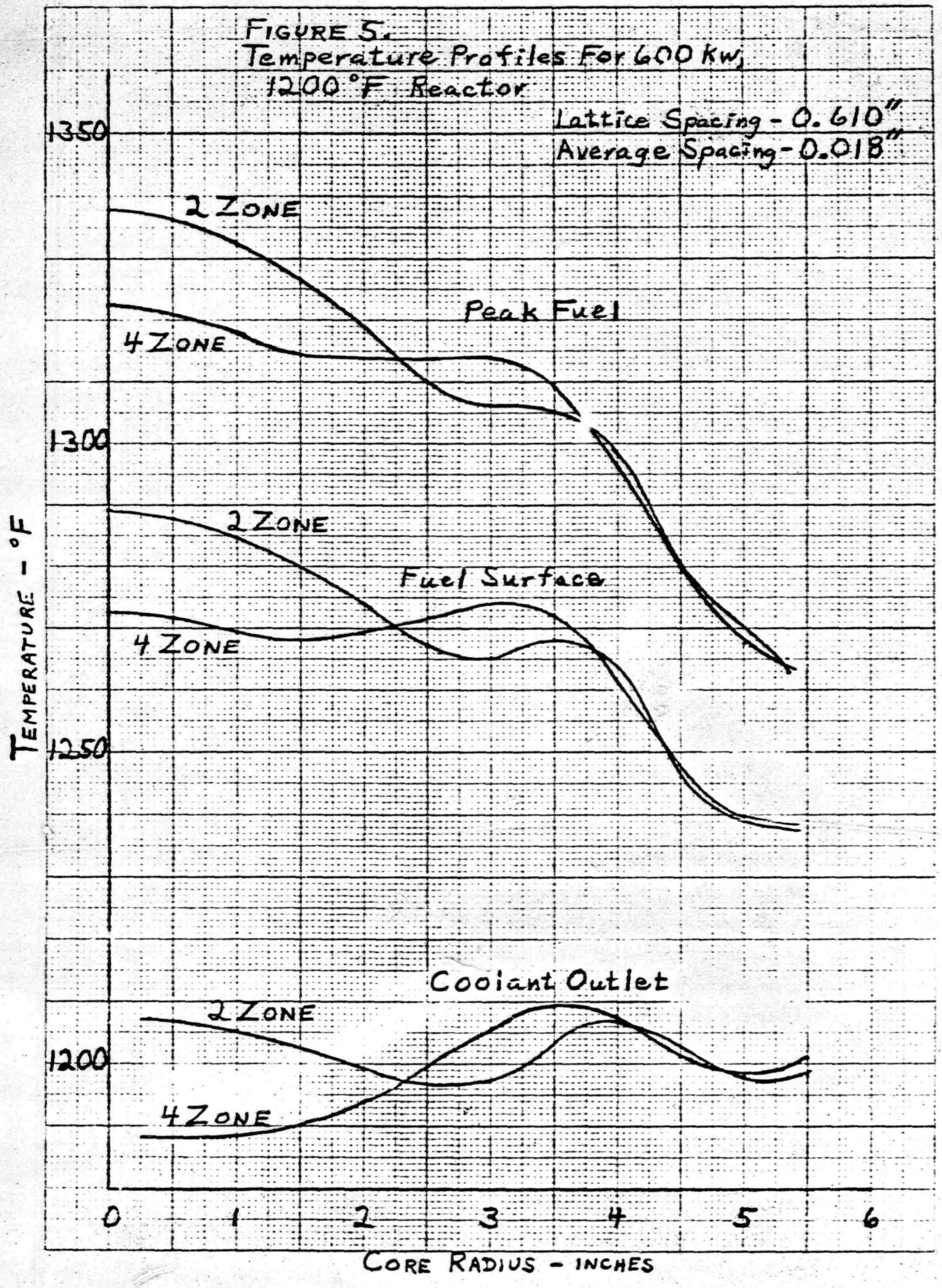


FIGURE 5.
Temperature Profiles For 600 kw, 1200°F Reactor

Lattice Spacing - 0.610"
Average Spacing - 0.018"

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CHECKED BY		REPORT NO. TI-759-240-007
DATE 9/8/70	TABLE 2.	MODEL NO.

Peak Centerline Fuel Temperatures and Cross Element ΔT's at Zone Boundaries For Nominal Inter-channel Mixing Assumed

	Peak Fuel Temps. °F				Cross Element ΔT at Zone Boundary °F			
RUN No.	Zone 1 Max Min	Zone 2 Max Min	Zone 3 Max Min	Zone 4 Max Min	Zone 1	Zone 2	Zone 3	Zone 4
1	1319	1312	1310	1286	4.8	7.7	4.9	6.9
	1310	1305	1281	1255				
2	1319	1311	1310	1286	5.0	8.0	5.2	7.3
	1310	1305	1281	1255				
9	1320	1313	1312	1288	5.0	8.2	5.5	7.7
	1311	1307	1283	1257				
10	1318	1312	1310	1286	5.1	7.8	4.9	6.1
	1310	1306	1281	1255				
11	1318	1314	1310	1286	5.2	7.9	4.8	5.4
	1311	1306	1281	1254				
12	1320	1317	1312	1283	5.1	7.2	5.8	9.7
	1314	1309	1281	1248				
13	1322	1316	1316	1291	5.1	8.8	6.4	9.2
	1313	1310	1285	1260				
7	1382							
	1251							
18	1378							
	1248							
20	1333	1301			6.6	2.0		
	1294	1254						
22	1338	1307			9.1	3.0		
	1298	1258						
27	1322	1316	1283		9.6	6.2	6.1	
	1313	1278	1254					
29	1326	1322	1288		11.5	7.6	7.4	
	1317	1280	1258					
31	1323	1319	1280		9.1	8.7	9.3	
	1315	1277	1247					

FIGURE 6
PEAK FUEL TEMPERATURE FOR 600 kw REACTOR

T_{OUT} 1200 °F
ΔT 135 °F
Radial Gap 0.0055"

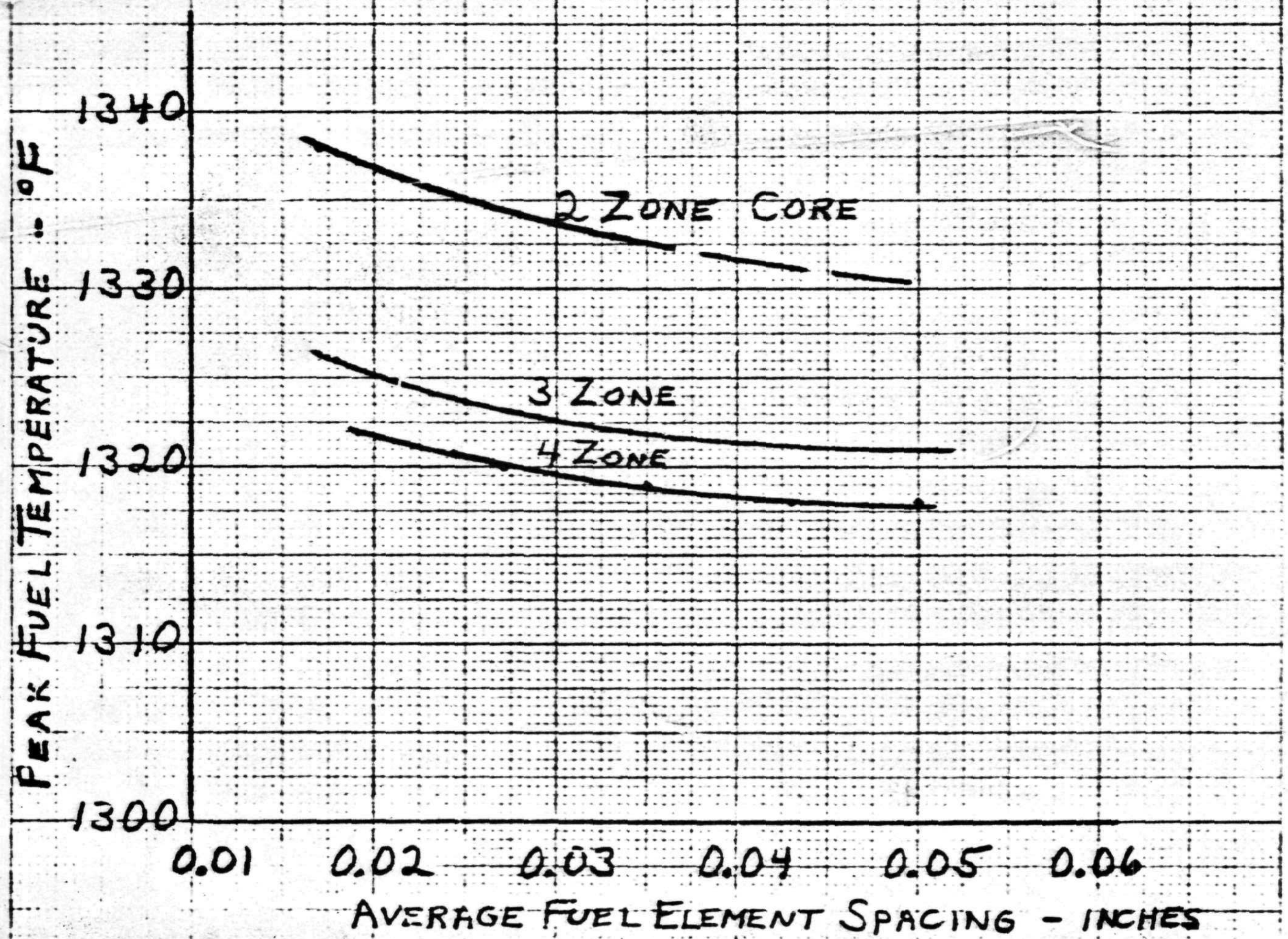

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TABLE 3.

Peak Centerline Fuel Temperatures and Cross Element ΔT's at Zone Boundaries For No Inter-channel Mixing

Run No.	Peak Fuel Temps. °F Zone 1 Max Min	 Zone 2 Max Min	 Zone 3 Max Min	 Zone 4 Max Min	Cross Element ΔT at Zone Boundary Zone 1	 Zone 2	 Zone 3	 Zone 4
1	1319	1311	1312	1287	4.2	11.4	11.3	17.5
	1307	1304	1279	1253				
2	1319	1311	1312	1287	4.2	11.4	11.3	17.5
	1307	1304	1279	1253				
9	1320	1312	1313	1288	4.2	11.2	11.2	15.9
	1308	1305	1281	1255				
10	1318	1311	1311	1286	4.5	11.7	11.2	18.7
	1306	1303	1279	1253				
11	1317	1313	1312	1286	4.6	11.8	11.3	19.3
	1307	1304	1279	1252				
12	1320	1316	1315	1283	4.8	12.2	16.4	20.8
	1310	1307	1280	1245				
13	1322	1314	1316	1291	4.1	11.1	11.1	13.4
	1310	1308	1284	1258				
7	1381							
	1250							
18	1377							
	1247							
20	1334	1304			19.5	2.4		
	1292	1252						
22								
27	1322	1319	1283		21.4	11.2	20.8	
	1310	1274	1252					
29	1325	1323	1287		20.7	11.2	16.5	
	1314	1278	1256					
31	1325	1322	1279		23.3	16.1	16.4	
	1312	1274	1243					

FIGURE 7.
Hot Channel ΔT as a Function of Assembly Tolerance (fuel centered in cladding)

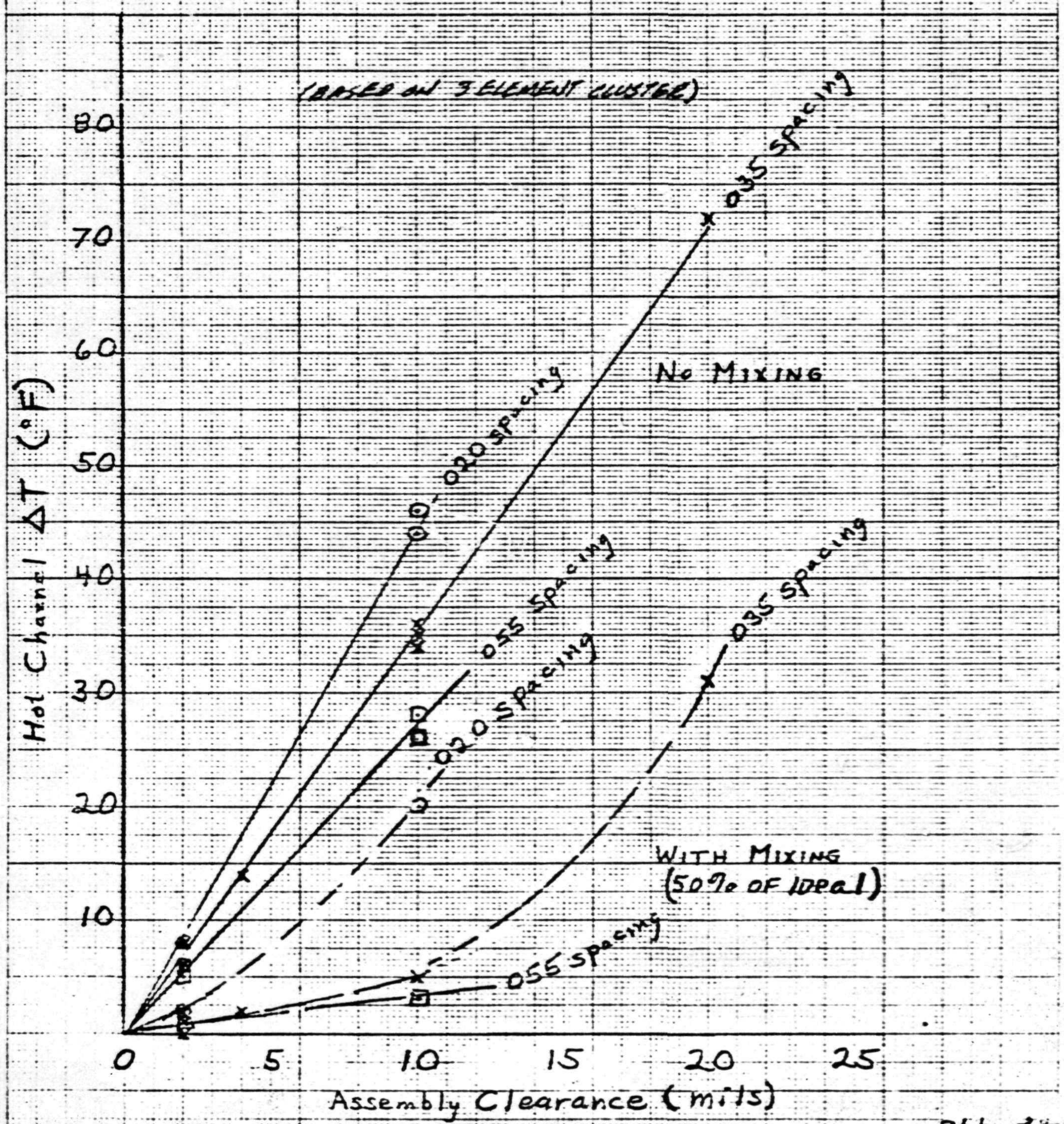

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FIGURE 8.
Peak Fuel and Coolant Outlet Temperatures
For a 2 Zone Core

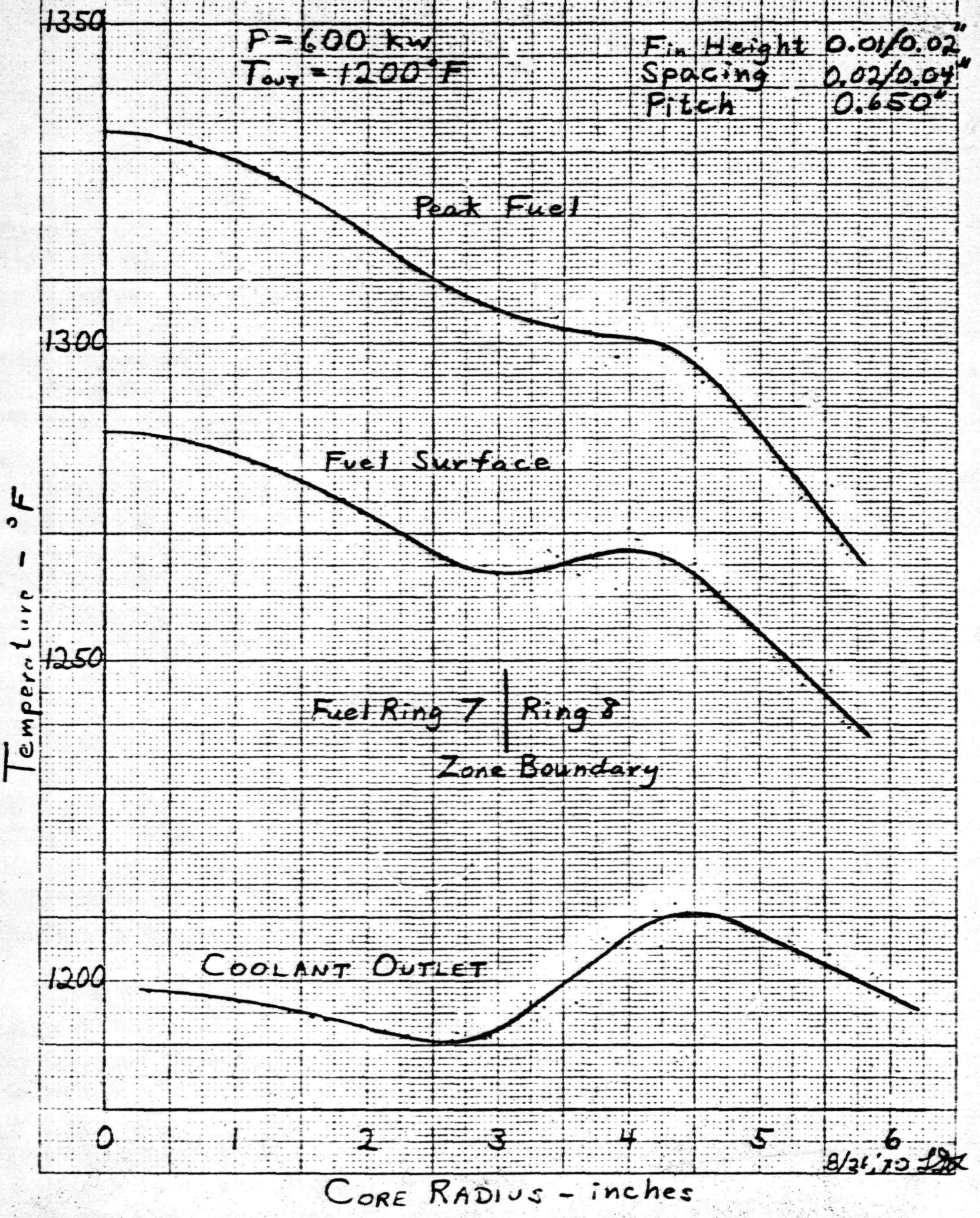

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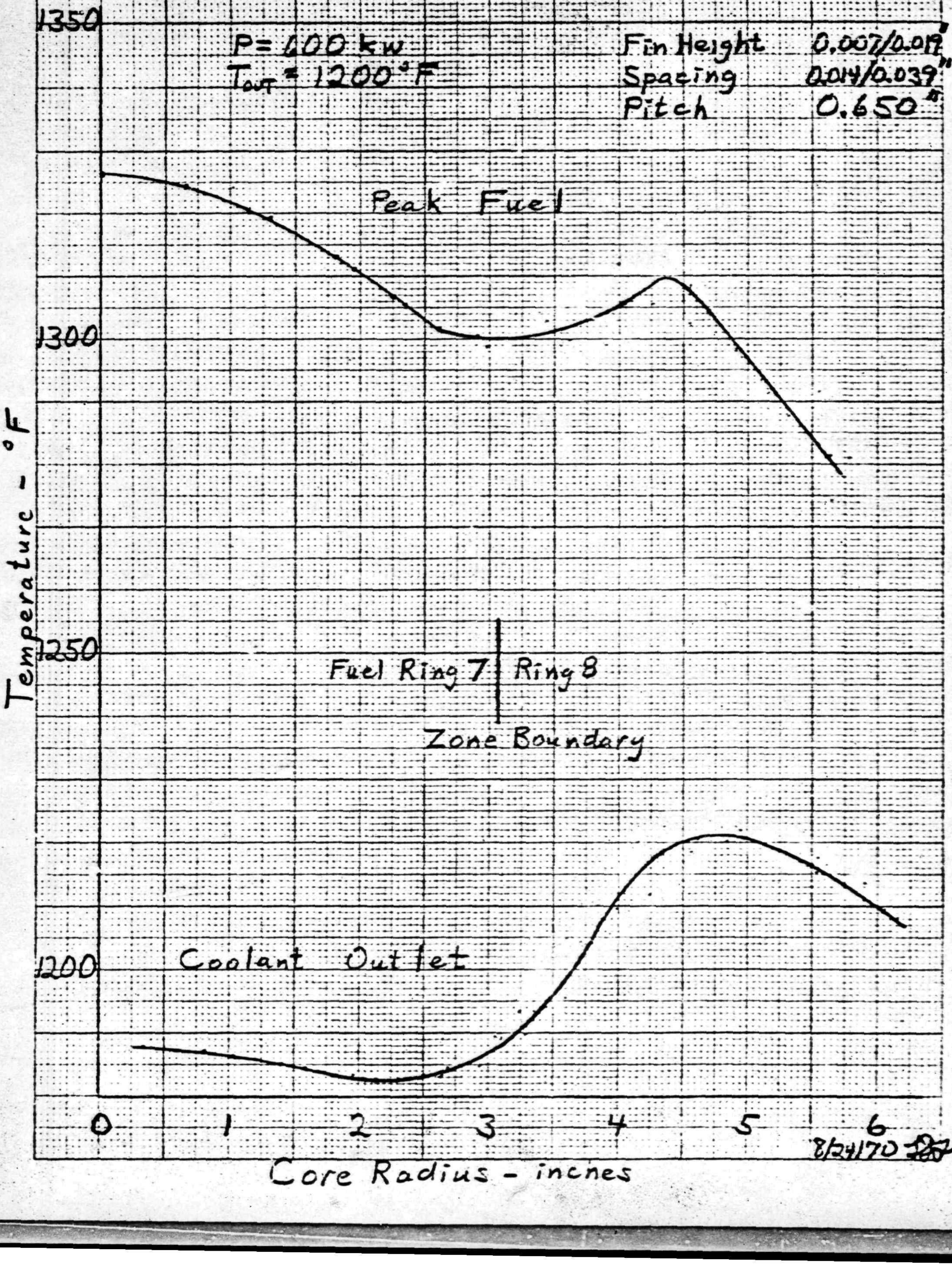
FIGURE 9.
PEAK FUEL AND COOLANT OUTLET TEMPERATURES FOR A 2 ZONE CORE



P = 600 kw
T_{OUT} = 1200 °F

Fin Height 0.007/0.019"
Spacing 0.014/0.039"
Pitch 0.650"

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