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PNPF RECOVERY CORE LOWER GRID PLATE TEMPERATURES

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R. Audette R. Glera M. Heisler W. Henoch J. Jacobson R. Jetter J. McEdwards H. Moore W. Morgan H. Rood J. Susnir (9) C. Willis L. Zimmer		STATEMENT OF PROBLEM Determine the maximum axial temperature gradient near the center of the lower grid plate generated by gamma heating and cooled by the flow of coolant through clearance annuli between holes in the grid plate and element lower end fittings of various configurations. Determine an acceptable clearance which results in minimum outlet thermocouple error.				
		ABSTRACT Alternate configurations of element lower end fittings are considered in the determination of clearances and leakage flows through holes in the lower grid plate. Gamma heating rates in the lower grid plate for a 41-element core operating at 30 Mw are calculated. Heat transfer coefficients are derived. Axial temperature profiles at an adiabatic locus in the hottest region of the plate are determined for each configuration. For an end fitting of 4.353 in. diameter two limiting cases are considered. With zero clearance (a plugged hole) the maximum differential temperature is found to be 51F, producing a deflection of the lower grid plate conservatively calculated not to exceed 25 mils and no outlet thermocouple error due to mixing. With a diametral clearance of 0.020 in., resulting from maximum tolerances, the temperature gradient is found to be 15F, producing a plate deflection of approximately 7 mils and an outlet thermocouple error due to coolant mixing of about 1F at 100% element flow. It is concluded that this configuration is acceptable from thermal and hydraulic considerations and that no thermocouple shroud will be required to reduce mixing errors.				

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1. CONFIGURATIONS ANALYZED

The PNPF lower grid plate⁽¹⁾ is carbon steel 64.5 inches in diameter and 6 inches thick. Holes for the 85 element positions have an entering 5/8 in. x 45° chamfer terminating in a 4.378 in. bore for 1/4 in. The bore is then enlarged to 4.478 in. for the remainder of the hole. This enlargement, not shown in Reference (1), is illustrated in Figure 1.

The primary objective in conducting this study was to determine, from hydraulic and thermal considerations, an acceptable clearance between the holes in the grid plate and the fuel element lower end fittings. Three element configurations were considered. The first, with an end fitting nominal diameter of 4.358 in. (cold), would provide, at the minimum bore in the hot condition, a diametral clearance of about 0.010 in. with minimum tolerances and about 0.020 in. with maximum tolerances. The second configuration⁽²⁾ has a nominal diameter of 4.312 in., providing a diametral clearance of 0.066 in. The third configuration, that of the lower plug⁽³⁾ of the Core I elements, has four axial recessed areas or flutes cast in the plug. Only nominal dimensions were considered in the analysis of the second and third configurations.

With the installation of these various configurations in the lower grid plate holes a variety of clearances would result. To these could be added an eccentric position and, as a limiting thermal condition, no clearance at all. These cases, 1-6, are listed in Table 1. Clearances are those at Section 2 of Figure 1.

TABLE 1
CLEARANCE CONDITIONS ANALYZED

<u>Case</u>	<u>Configuration</u>	<u>Clearance, Inches</u>		<u>Remarks</u>
		<u>Radial</u>	<u>Diametral</u>	
1	I	0.0	0.010	Eccentric
2	I	0.005	0.010	Minimum tolerances
3	I	0.010	0.020	Maximum tolerances
4	II	0.033	0.066	
5	III	Configuration per Dwg. 7537-71807		
6	I	0.0	0.0	Plugged hole

The metal between grid plate holes can be conveniently sectioned into the hexagonal pattern of Figure 2. Axial projections of these surfaces will be adiabatic; no heat will flow from one hexagon to the next. By symmetry the analysis is further simplified in considering one-sixth of the area bordered by the hexagon and the hole, as shown in Figure 2. All heat generated within the area ABCD will flow to the top or bottom surface of the grid plate or to the side of the hole, BC. The hottest radial locations will be on vertical axes at A and D. Temperatures at A and D near the center of the core have been determined in this study.

Because the area of the coolant passage varies from point to point between the upper and lower surface of the grid plate, the thermal model was divided into the sections shown in Figure 1. Sectioning of the lower portion was based on possible requirements for incorporating a shroud around the thermocouple junction to prevent mixing of leakage coolant with coolant from the element outlet thermocouple flow tubes. Requirement for the shroud has been obviated as a result of the evaluation of

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alternate designs, Section 9 (and Reference 4). Its affect has not been included in this study. The shroud is shown for reference only in Figure 1.

2. GAMMA HEATING

Heat generation rates were derived from Reference 5 which presented the axial distribution of gamma heating for an 35-element core operating at 45.5 mw. For the 41-element Piqua recovery core operating at 30 mw the rates were multiplied by the factor

$$\left(\frac{30 \text{ mw}}{41 \text{ elements}} \right) / \left(\frac{45.5 \text{ mw}}{85 \text{ elements}} \right) = 1.37$$

Reference 5 presents heating rates for a solid plate and for a homogenized region consisting of iron and organic coolant. Since higher rates were derived for the solid plate these were used (Figure IV of Reference 5) in the present study. For the sections indicated in Figure 1 these are listed in Table 2. Conversion from watts/gm to Btu/hr-in³ employed a factor of 439.6, in which the density of steel was taken as 7.86 gm/cc.

TABLE 2

GAMMA HEATING RATES IN CENTER OF LOWER GRID PLATE

<u>Section*</u>	<u>Ref. (5) Rate w/gm</u>	<u>Recovery Core Rate</u>			<u>Btu/hr</u>
		<u>w/gm</u>	<u>Btu/hr-in³</u>	<u>Vol, in³**</u>	
1	0.1	0.137	60	2.625	158
2	0.066	0.0904	40	1.312	53
3	0.036	0.0493	22	6.562	144
4	0.014	0.0192	8	7.218	58
5	0.0084	0.0115	5	3.281	16
6	0.0067	0.0092	4	3.281	13
7	0.0061	0.0084	4	7.218	29

* Identified in Figure 1

** Of area AOD, Figure 2

A flat source was assumed in this study; no effect of power skewing by control rod position was considered.

3. COOLANT VELOCITIES

To determine heat transfer coefficients at metal-liquid interfaces, coolant velocities must be known or assumed. For the top of the grid plate it was assumed that 242 gpm was being discharged from the window openings in the base of each fuel element, producing a radial flow with a velocity of 2.85 ft/sec at the intersection with the adiabatic axis A-D (Figure 2).

Velocities in the leakage annulus, Figure 1, were determined for a pressure drop across the lower grid plate of 1.43 psi for all close-fitting elements. Since the fluted design⁽³⁾ would permit increased flow at decreased pressure drop a differential pressure of 1.32 psi was assumed for this condition (Case 5).

Within the annulus bordering section 2 (Figure 1) flow rates were determined from the orifice equation:

$$Q = 300 AK \sqrt{\Delta p / \rho} \quad (\text{gpm}) \quad (1)$$

in which A = flow area, in²

K = discharge coefficient, taken as 0.60

Δp = differential pressure, psi

ρ = coolant density, 55.54 lb/ft³

The resultant volumetric flow were then applied to the flow areas bordering sections 2, 3 and 4 (Figure 1). Flow rates in sections 5, 6 and 7 were augmented by an efflux of 48 gpm from the lower outlet thermocouple flow tubes. Flow rates and velocities for each section are listed in Table 3 (Section 6).

4. COOLANT TEMPERATURES

For core operation at 30 Mw with coolant flow provided by the small pump impellers the effective coolant temperature near the center of the core at the upper surface of the lower grid plate and in the leakage annulus, sections 1, 2, 3 and 4 of Figure 1, would be 589.5F (Reference 6). For sections 5, 6 and 7 the effective coolant temperature would be 600.1F; the mixed mean of the 589.5F leakage flow and the efflux -- 48 gpm at 610F -- from the outlet thermocouple flow tubes. These temperatures are specifically applicable to an element in position F-11 and within a few degrees for elements in other high-powered positions: F-9, E-10, etc. Coolant temperature at the lower surface of the lower grid plate is assumed to be that of the reactor mixed mean outlet, 575F. This is a conservatively low value, producing a conservatively high differential temperature across the grid plate, since coolant temperatures near the center of the plate will be higher than the lower plenum average.

5. COOLANT PROPERTIES

Physical properties were evaluated at 575°F with 5%
H.B. content⁽⁷⁾.

Density:	55.54 lb/ft ³
Thermal conductivity:	0.0677 Btu/hr-ft-°F
Viscosity:	1.05 lb/hr-ft
Specific heat:	0.56 Btu/lb-°F
Prandtl number ($c_p \mu / k$):	8.69

6. HEAT TRANSFER COEFFICIENTS

Conductivity of the steel in the grid plate is 25 Btu/hr-ft-°F at about 575°F (Reference 3, Table A-2).

The film coefficient at the liquid-to-metal interface in the annulus, sections 2 thru 7 inclusive, was determined from the correlation,

$$N_{Nu} = 0.027 N_R^{0.8} N_{Pr}^{0.33} \left(\frac{\mu_B}{\mu_w} \right)^{0.14} \dots (2)$$

This is derived from equation (9-10c) of Reference 3, with the coefficient modified according to the footnote, page 219. N_R is the local Reynolds number in the section of the annulus under consideration; N_{Pr} is the Prandtl number. Since the temperature difference between the metal surface and the coolant is not large the viscosity ratio term in equation (2) has been reduced, conservatively, to a value of 1.00.

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For the top surface the coolant velocity was conservatively assumed to be that across plane AD issuing from an opening 1.5 inches high in the lower end fitting of the element at BC, Figure 2. For a calculated total outflow of 242 gpm⁽⁶⁾ this velocity was determined to be 2.35 ft/sec. The effective hydraulic diameter for segment ABCD of the top surface was assumed to be equal to that of the outer moderator region between element outer process tubes, 3.665 in. For all lower end plug configurations (Cases 1 thru 6) the value of the film coefficient is constant: 184 Btu/hr-ft²-°F.

For the bottom surface natural rather than forced convection cooling was assumed, for which the following expression, (7-8b) from Reference 3, is applicable:

$$h L/k = 0.27 X^{0.25} \quad \dots (3)$$

where

$$X = \frac{L^3 \rho^2 g \beta \Delta t C_p}{\mu k}$$

and

$$L = 1 \text{ ft.}$$

β , coefficient of volumetric expansion

$$= 5.8 \times 10^{-4} \text{ per } ^\circ\text{F}$$

Δt , temperature potential = 45°F

(determine from a trial run: 620°F - 575°F)

C_p , μ and k are listed in section 5

When the proper values are substituted,

$$X = 2.684 \times 10^{11}$$

and $h = 12.96 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$

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Table 3 lists flow rates, velocities and heat transfer coefficients for a pressure drop across the lower grid plate of 1.48 psi. No foulant film deposit on top or bottom surfaces or in the holes has been assumed. Inspection has revealed⁽⁹⁾ that these surfaces are clean. The thermal analysis yields conservative results since a foulant film would reduce the thermal gradient in the metal.

TABLE 3

HYDRAULIC AND THERMAL PARAMETERS

Case	Gap Width (in) at Section 2	Diametral Clearance (in)	Section ⁽²⁾	Flow Area (in) ²	Flow (gpm)	Velocity (ft/sec)	h (Btu/ hr-ft ² -°F	TC Mixing ⁽³⁾ Error, °F
1	0.0 ⁽¹⁾	0.010	1	---	---	---	184	
			2	0	0	0	0	
			3	---	0	0	0	
			4	9.809	2	0.07	10.5	
			5,6,7	15.749	50	1.02	77.8	
			L ⁽⁴⁾	---	---	---	13.0	0.44
2	0.005	0.010	1	---	---	---	184	
			2	0.069	2	9.43	1564	
			3	0.764	2	0.85	141	
			4	9.309	2	0.07	10.5	
			5,6,7	15.749	50	1.02	77.8	
			L	---	---	---	13.0	0.44
3	0.010	0.020	1	---	---	---	184	
			2	0.137	4	9.43	1360	
			3	0.833	4	1.43	215	
			4	9.309	4	0.13	13.3	
			5,6,7	15.749	52	1.06	80.3	
			L	---	---	---	13.0	0.35
4	0.033	0.066	1	---	---	---	184	
			2	0.450	13.2	9.43	1072	
			3	1.146	13.2	3.70	422	
			4	9.309	13.2	0.43	47.4	
			5,6,7	15.749	61.2	1.25	91.4	
			L	---	---	---	13.0	2.38

(1) Eccentric element

(2) Identified in Figure 1

(3) Element F-9 at maximum power (1.026 Mw), 100% flow, no

(4) Lower surface of grid plate shroud

Table 3 Continued

<u>Case</u>	<u>Gap Width (in) at Section 2</u>	<u>Diametral Clearance (in)</u>	<u>Section</u>	<u>Flow Area (in)²</u>	<u>Flow (gpm)</u>	<u>Velocity (ft/sec)</u>	<u>h Btu/ hr-ft²-°F</u>	<u>TC Mixing Error, °F</u>
5	Conf. per Dwg. 7537- 71807		1	---	---	---	184	4.11
			2	1.076	29.7	8.85	779	
			3	1.910	29.7	4.99	4.61	
			4	9.809	29.7	0.97	90.6	
			5,6,7	15.749	77.7	1.58	110.6	
			L	---	---	---	13.0	
6	0.0	0.0 ⁽⁶⁾	1	---	---	---	184	0.0
			2	0	0	0	0	
			3	---	0	0	0	
			4	---	0	0	0	
			5	---	0	0	0	
			6,7	15.749	48	0.98	75.2	
			L	---	---	---	13.0	

(5) At 1.32 psi Δp

(6) Plugged hole

7. DETERMINATION OF TEMPERATURES

The TAP 3-F computer code (Reference 10, revised for FORTRAN IV) was used to determine steady-state temperatures at several nodes in the thermal model, including the liquid-metal interface (periphery of the hole: B-C, Figure 2) and along the vertical axes of those points where temperatures were the maximum (A and D, Figure 2). Heat inputs are from Table 2 and local values of the film coefficient from Table 3. The axial temperature profile at A (or D) is plotted in Figure 3.

8. CONCLUSIONS

a. The maximum differential temperature for the limiting, plugged hole, condition, is 51F (Curve 6 of Figure 3).

b. For this gradient the maximum deflection near the center of the grid plate would be 25 mils, using the conservative method of analysis developed by Mouradian (Reference 11).

c. A 25-mil deflection at the center of the plate is acceptable: it is too small to unseat any elements or induce bending stresses in the elements by angular displacement of hole axes produced by plate bowing.

d. From thermal and hydraulic considerations the element end fitting providing minimum clearance is acceptable.

9. EVALUATION OF ALTERNATE DESIGNSa. Objective

The design selected should minimize the difference between the temperature of the coolant discharged from the element outlet thermocouple flow tubes and that monitored by the pedestal-mounted thermocouple in the lower plenum. It should accomplish

this by reducing, to the greatest extent practicable, the admixture of coolant discharged from the flow tubes with that leaking through the annulus formed by the hole in the lower grid plate and the element lower end fitting. Minimizing thermocouple mixing error is essential in the determination of element performance and flow reduction resulting from film formation. At 100% element flow the error is limited to 1°F (Reference 12).

b. Alternative Designs

(1) Lower end fitting having a cylindrical diameter of 4.358 in, (Configuration 1) providing a nominal diametral clearance, cold, of 0.020 in, and permitting a maximum leakage of 4 gpm, used without the shroud.

(1a) The same, incorporating the shroud.

(2) Lower end fitting having a cylindrical diameter of 4.312 in, (Configuration 2) providing a nominal diametral clearance, cold, of 0.066 in, and allowing a leakage flow of about 13 gpm, used without the shroud.

(2a) The same, incorporating the shroud.

(3) Lower end fitting having the fluted design (Configuration 3) used in original Core I, permitting a leakage flow of about 30 gpm in the 41-element Recovery Core, used without the shroud.

(3a) The same, incorporating the shroud.

c. Evaluation of Alternatives

The shroud was proposed to channel the flow from the four element outlet tubes, diverting it over the thermocouple, and preventing the grid plate leakage flow from reaching the thermocouple. As element flow is reduced -- a condition in which the accuracy of the thermocouple becomes increasingly important -- the pressure

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between the element outlet and the thermocouple may be decreased sufficiently to permit some leakage flow or lower plenum coolant to reach the thermocouple. The degree of this coolant admixture cannot be accurately predicted by analytical methods.

(1) End fitting Configuration I, with 0.020 in. diametral clearance, used without shroud, is the optimum alternative. Maximum thermocouple mixing error with 4 gpm grid plate leakage flow is considered acceptable. This is plotted in Figure 4 as a function of relative flow, Q/Q_0 , for elements in the two highest powered positions, F-11 and F-9 with the reactor at 30 Mw. Coking or sticking in the constricted annular passage is considered a possibility. If the fitting is concentric in the hole velocities at the land (section 2, Figure 1) of about 9 ft/sec and at the enlargement below the land (section 3) of about 1 ft/sec, should be adequate to prevent the formation of a coke mass sufficient to plug the hole. An eccentric fitting, however, would greatly reduce the flow around an arc of about 120° , permitting the deposition of foulant film in this volume. To achieve burnup by implementing a fuel management program (Reference 13) all of the higher powered elements will be moved at least once during the year of core lifetime at 20 Mwt. This would provide existence of a coking problem. From Reference 4: "It was concluded that the flux levels and velocities in the area of concern were of the order to allow the judgement to be made that coking and sticking should not be considered a high risk situation."

(1a) Use of the shroud with the end fitting of Configuration 1 would decrease T/C mixing error at 100% element flow. When element flow is reduced the pressure at the outlet of the flow tubes is also reduced, permitting some lower grid plate leakage coolant or

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coolant from the lower plenum to reach the thermocouple junction.

The shroud becomes less effective as element flow decreases.

This alternative is acceptable but not optimum.

(2) End fitting of Configuration 2 having 0.066 in. diametral clearance would permit a calculated mixing error of 2.38F at 100% element flow (Table 3). Since this exceeds the 1F limitation, alternate (2) is unacceptable.

(2a) Incorporation of the shroud would probably reduce the error, at 100% element flow, to an acceptable value. At reduced element flows, as discussed in (1a) it becomes less effective. Alternate (2a) is inferior to alternate (1).

(3) Original end fittings of Configuration 3, conforming to drawing 7537-71807, would permit a calculated mixing error of 4.11F at 100% element flow (Table 3). Since this exceeds the 1F limitation, alternate (3) is unacceptable.

(3a) Incorporation of the shroud might reduce the error to acceptable limits at 100% element flow, but its benefits might be marginal at reduced element flows. Alternate (3a) is inferior to alternate (1).

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MODIFIED FUEL ELEMENT AND THERMOCOUPLE SHROUD			
DRAWN	ED [Signature]	2/17	DWG. SIZE C
CHECKED			SCALE FULL
ENGINEER	ED [Signature]	2/17	FIGURE 1
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FIGURE 2
TOP VIEW OF LOWER GRID PLATE

MIXING ERROR

AT ELEMENT OUTLET FOR MAXIMUM
LEAKAGE AT LOWER GRID PLATE

41-ELEMENT CORE AT 30 MW
SMALL PUMP IMPELLERS

FIGURE 4