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DETERMINATION OF SLUG TEMPERATURES FOR VARIOUS POWER LEVELS

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E. J. Burda
Design Division

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DETERMINATION OF SLUG TEMPERATURES

FOR VARIOUS POWER LEVELS

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Intent of Study

- 1.0 This study was undertaken to determine the maximum temperatures that may be expected in slugs under various operating power levels.
- 1.1 Information of this nature is required to properly evaluate the effects on the slug of pile operation at power levels higher than those currently in use.

References

- 2.0 (A) Document HW 10558, Woods and Jones, July 21, 1948, "Production Test No. 105-80-P, Measurement of Slug Temperatures."
- 2.1 (B) Document INDC 2393, "Temperature Map, 105-D, November 29, 1948."
- 2.2 (C) Document 7-2092, Woods, July 16, 1945, "Flow Rates in Tubes of 105 Piles."

Discussion of Method

- 3.0 The following calculations are based on equations presented, and supported by experimental data, in Document HW 10558 (Reference A above).
- 3.1 In using these equations certain assumptions, made in the original derivation, must be taken into account. These are listed below, in part, to illustrate the underlying limitations to the calculations.
 - (a) The heat flux density entering the water in the tube follows a cosine function distribution along the active length of the tube for a normal charge.
 - (b) The heat generated in the graphite and other materials outside of the uranium slug is 6% of the heat flux entering the water.
 - (c) The heat generation per unit volume in the uranium is proportional to the thermal neutron flux in this volume.
 - (d) The heat generation per unit volume in the slug is uniform along the length of the uranium and for all positions at the same radius, but varies with the radius as an I_0 Bessel's function. This assumption can be made because the derivation and calculations are concerned with conditions at the mid-point of the aluminum tube where the axial flow of heat in the slug is zero.

3.2 The present calculations introduce some further assumptions in addition to those listed above:

- (a) The relative distribution of heat generation throughout the pile remains unchanged as the higher power levels are considered.
- (b) Geometry of the outer dimensions of the pile remains unchanged for the various power levels and lattice spacings considered.
- (c) The flow of water through tubes of the pile remains unchanged as the various power levels are considered. Note that the actual water flowing through the individual tubes varies, because of the orifice pattern, with the zone in which the tube is located.
- (d) The highest axial temperature occurs in the center section of the tube ($n=0$). This is not strictly true since the rate of heat generation is a cosine function and the water temperature varies as a sine function. Axial temperature is the sum of these two factors which yields a maximum value slightly downstream from ($n=0$). Due to the small change in water temperature with the distance relative to the large change in temperature drop inside the slug calculations show that for a flow rate of 19.8 gpm the maximum temperature occurs 1.4 ft. from ($n=0$). This distance varies as an inverse function of water flow. The error introduced by this assumption at 19.8 gpm and a total water temperature rise of 41°C is only 1.7°C .

3.3 The temperature developed in a slug is proportional to the rate at which heat is generated in it. Present experience indicates that the neutron flux distribution in the pile should be purposely distorted by using poison columns to obtain a nearly uniform neutron flux distribution over a large central portion of the pile. Poison patterns now in use produce distortion chiefly in planes passed through the pile perpendicular to the water tubes. Distribution parallel to the tubes is very nearly that of the cosine distribution assumed in Par. 3.1 (a).

3.4 In addition to this intentional distribution in the rate of heat generation per tube in the present piles there is also a slight random variation in the amount of heat generated in neighboring tubes. This variation is due partly to physical distortion of slugs after exposure, formation of water film, obstructions to orifices, etc. Consequently, a study of the maximum temperatures to be encountered in a new pile design must take these random variations into account.

3.5 In order to select a reasonable maximum rate of heat generation per tube for design considerations data is taken from the Temperature Map, Figure 1, (also Reference B). The map shows temperatures actually encountered in one of the present piles at a 275 Kw power level. The

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FIGURE 2. WATER TEMPERATURE RISE AGAINST RADIAL POSITION OF THE TUBE. OPERATING POWER LEVEL 275 Kw. TEMPERATURES CORRECTED TO A UNIFORM RATE OF WATER FLOW CORRESPONDING TO AN ORIFICE OF 0.240 INCHES.

temperature rise obtained in each tube is plotted in Figure 2 against radial distance of the tube from the effective center of the pile. 41°C is selected as a reasonable maximum temperature rise for these normal conditions in the central zone, where the orifice size is 0.240 inch. The map, Figure 1, shows several tubes with a higher temperature rise (48°C , Tube 2975, which is due to the temporary use of an abnormally small orifice, and two tubes with 42° rise). However, the 41° figure appears to be most consistent with the objectives of this study.

- 3.6 For purposes of true indication of rate of heat generation Figure 2 shows the temperature rise in tubes of the outer zones corrected to uniform water flow, (uniform orifice size of 0.240 inch). This correction is accomplished by multiplying the actual temperature rise by the ratio of water flow rate, actual water flow rate over water flow rate with 0.240 inch orifice. The flow values are obtained from Reference (C). The random variation in temperature rise mentioned in Par. 3.4 is well illustrated by Figure 2.

Calculations

- 4.0 In order to show properly the effect of higher operating power levels the slug temperatures are determined for several levels to permit the presentation of data in graph form. Sample calculations are given only for the 275 Mw level.

- 4.1 The following data, obtained from Figure 1 is used in the calculations:

Operating level	275 Mw	
Inlet water temperature	9.2°C	
Outlet water temperature	50°C	(representative tube)

- 4.2 As the purpose of these calculations is to determine the highest uranium temperatures that may be encountered for the various operating levels it is necessary that conditions be selected that yield the highest normal values. Consequently, the calculations, though making use of data from Figure 1, will assume the inlet water temperature to be 20°C , the highest that past records show may reasonably be expected. Calculations in Paragraphs 4.3 to 4.8 incl., are therefore based on data taken directly from the temperature map while that in Paragraphs 4.9 to 5.4, incl., is based on an inlet water temperature of 20°C .

- 4.3 Water flow (orifice 0.240") 19.8 gpm

(This is obtained from
Reference C, for a head-
er pressure of 350 psi)

4.4 Total heat added to water = $900(\text{flow gpm})(\text{temp. rise } ^\circ\text{C})$
 $= (900)(19.8)(41)$
 $= \underline{730,000 \text{ BTU/hr}}$

4.5 Heat added to the water at any point in the active portion of the tube is given by Reference (A) as

$$q_n = \frac{\pi Q \cos \left[\frac{\pi n}{2 R_p} \right]}{4 R_p \sin \left[\frac{\pi N}{2 R_p} \right]}$$

where q_n is the rate of heat generation at distance n from the center of the pile, BTU/(hr)(ft)

(n is measured from the mid-section of the tube, positive downstream, in the same units as N and R_p .)

Q is the total heat generated in the tube, BTU/hr

N is the length of the active charge measured from the center of the pile (11.6 ft).

R_p is the effective distance from the center of the pile of the projected outer boundary of the neutron activity (13.1 ft).

Heat is generated at the maximum rate at $n=0$ so

$$q_m = \frac{\pi Q}{4 R_p \sin \left[\frac{\pi N}{2 R_p} \right]} \quad \text{where } q_m \text{ is the maximum value of } q_n.$$

Inserting numerical values this becomes

$$q_m = \frac{.0608 (\text{total heat generated in the tube}), \text{ BTU/(hr)(ft)}}{.0608 (730,000)}$$

$$= \underline{44,400 \text{ BTU/(hr)(lineal ft)}}$$

4.6 Since 6% of the heat added to the water comes from other sources, maximum heat generated in the slug

$$= (.94) (\text{heat added to water})$$

$$= (.94) (44,400)$$

$$= \underline{41,800 \text{ BTU/(hr)(lineal ft)}}$$

4.7 Neglecting the cooling effect of the solid aluminum slug ends, maximum heat generated in the uranium

$$= \frac{(4.375' \text{ overall length})(\text{heat from slug per lineal ft.})}{(4.000' \text{ uranium length})}$$

$$= \frac{(4.375)(41,800)}{4.000} = \underline{45,750 \text{ BTU/(hr)(lin ft)}}$$

4.8 Maximum heat emanating from the slug per unit surface area

$$= \frac{\text{BTU}/(\text{hr})(\text{lineal ft})}{\text{circumference, ft}}$$

$$= \frac{45.750}{0.377} = 121.000 \text{ BTU}/(\text{hr})(\text{sq ft})$$

4.9 Thermal coefficient of the water film (from Reference A)

$$h_w = 367(1.35 + .02 t)(\text{gpm})^{0.8} \text{ BTU}/(\text{hr})(\text{sq ft})(^\circ\text{C})$$

where t = local water temp., $^\circ\text{C}$

$$= \frac{50 - 9.2}{2} + 20$$

$$= 40.4^\circ\text{C}$$

gpm = water flow, gpm

$$= 367(1.35 + .81)(19.8)^{0.8}$$

$$= 8660 \text{ BTU}/(\text{hr})(\text{sq ft})(^\circ\text{C})$$

5.0 Temperature drop across the water film

$$= \frac{\text{BTU}/(\text{hr})(\text{sq ft})}{h_w}$$

$$= \frac{121,000}{8660} = 14.0^\circ\text{C}$$

5.1 Thermal coefficient of the aluminum jacket

(from Reference A for
normal slug wall
thickness)

$$h_j = 36,000 \text{ BTU}/(\text{hr})(\text{sq ft})(^\circ\text{F})$$

$$= 64,700 \text{ BTU}/(\text{hr})(\text{sq ft})(^\circ\text{C})$$

5.2 Temperature drop across the aluminum jacket

$$= \frac{\text{BTU}/(\text{hr})(\text{sq ft})}{h_j} = \frac{121,000}{64,700}$$

$$= 1.87^\circ\text{C}$$

5.3 Axial temperature of the slug above uranium surface temperature

$$= \frac{(\text{BTU}/(\text{hr})(\text{lineal ft}))}{k_u} \left[\frac{I_0(uR)}{2uR I_1(uR)} - 1 \right]$$

(From Reference A where
thermal conductivity, k_u
of uranium = 14.6)

For slugs of standard dimensions the
last portion of the expression has a
value of 0.0727.

$$= \frac{(45.750)(0.0727)}{14.6}$$

$$= 228^\circ\text{C}$$

5.4 Actual temperature of slug axis

$$\begin{aligned}
 &40.4^{\circ}\text{C local water temperature} \\
 &14.0^{\circ}\text{C across water film} \\
 &1.87^{\circ}\text{C across aluminum jacket} \\
 &\underline{228^{\circ}\text{C across uranium}} \\
 &= 284.3^{\circ}\text{C (for inlet water temperature of } 20^{\circ}\text{C} \\
 &\text{and power level of 275 Mw.)}
 \end{aligned}$$

- 5.5 Temperature values are then determined for the higher power levels by increasing the heat produced per tube in proportion to the increase in total power level. This is in agreement with the assumption of Par. 3.2(a). Values are obtained for total power levels of 400 Mw and 500 Mw.
- 5.6 The various values thus obtained are tabulated in Table I along with those obtained above. Temperature values are plotted in Figure 3 against the total heat generated per tube.
- 5.7 It should be remembered that this method of calculation obtains a figure for water flow from a chart which is correct only for an average tube. Differences in tube conditions may cause the flow in a particular tube to be somewhat different. A reduction in flow results in a greater temperature rise for a given heat load. Consequently the computed heat load and resulting temperature values may be somewhat different from actual values. Any effect of this condition probably will yield calculated temperatures that are too high. It is felt that the results are reliable chiefly because of the experimental results described in Reference (C) which indicates that the flow rates can be accurately predicted.

Discussion of Results

- 6.0 Inspection of Figure 3 shows that under conditions of pile geometry and water flow now in use in the present Hanford piles uranium temperatures near 496.4°C can be expected for an operating level of 500 Mw. Most of this temperature drop, 414°C , is in the uranium itself and is inherent in the type of slug used and the heat generated per unit linear length.
- 6.1 The total temperature difference between inlet water and uranium surface is only 62.4°C . Efforts to improve cooling by increasing water flow, changing cooling medium, fins on the jacket, etc. can reduce this value somewhat but even a big improvement here will still leave the axis of slug at very nearly the temperature shown above.
- 6.2 The uranium temperature can be materially reduced only by decreasing the lattice spacing of the pile, in effect providing more tubes to carry away the same amount of heat, or by selecting a different size or shape for the slug. The former lowers the heat produced in the uranium per unit linear length and consequently lowers the axis

FIGURE 3
MAXIMUM TEMPERATURES TO
BE EXPECTED IN URANIUM
SLUGS FOR VARIOUS POWER
LEVELS

TABLE I

Inlet Water Temperature 20°C
Water Flow (0.5" orifice) 19.8 gpm

Power Level	Total Heat From Tube	Max. Heat Added to Water	Max. Heat From Slug to Water	Max. Heat From Uranium to Water	Max. Heat From Uranium to Water	Outlet Water Temp.
Mw	BTU/hr	BTU/(hr)(lin ft)	BTU/(hr)(lin ft)	BTU/(hr)(lin ft)	BTU/(hr)(sq ft)	°C
275.	730,000	44,400	41,800	45,750	121,000	61.
400.	1,061,000	64,500	60,800	66,500	176,000	79.6
500.	1,330,000	80,600	76,800	83,100	220,000	84.6

Power Level	Local Water Temp.	Thermal Coeff. of Water Film	Temp. Drop Across Water Film	Thermal Coeff. of Aluminum Jacket	Temp. Drop Across Jacket	Temp. Drop Across Uranium	Slug Axial Temp. Above Inlet Water Temp.
Mw	°C	BTU/(hr)(sq ft)(°C)	°C	BTU/(hr)(sq ft)(°C)	°C	°C	°C
275.	40.4	8,660	14.0	64,700	1.87	228.	284.3
400.	49.7	9,350	18.8	64,700	2.72	331.	402.2
500.	57.0	10,000	22.0	64,700	3.40	414.	496.4

temperature accordingly. Changing the geometry of the slug, such as providing a water passage through the center, involves solution of some serious canning problems.

- 6.3 To determine the temperatures to be expected at smaller lattice spacings Figure 3 may be used directly with an appropriate value of heat generation per tube. For fixed outside dimensions of the pile the total number of tubes varies as follows:

$$\text{Total number of tubes} = \frac{K}{(\text{lattice spacing})^2}$$

Heat generated
per tube at

$$\text{spacing B} = \frac{(\text{lattice spacing B})^2 (\text{Heat generated with spacing A})}{(\text{lattice spacing A})^2}$$

Using this relation and the temperature values already determined for the 8-3/8" spacing the temperatures shown in Table II are obtained as those that may be expected for various operating levels and lattice spacings.

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TABLE II.

POWER LEVEL	LATTICE SPACING	AXIAL TEMPERATURE OF SLUG ABOVE SURFACE TEMPERATURE OF URANIUM
275 Mw	7" 7½" 8-3/8" ○	159.°C 183. 228.0
400 Mw	7" 7½" 8-3/8"	231.°C 265. 331.
500 Mw	7" 7½" 8-3/8" ○	289.°C 331. 414.