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Section C-II

J. E. Willard, Sootien Chief

ESTIMATES REGARDING GAS FLOW AND HEAT TRANSFER IN A HIGH
TEMPERATURE OXIDE PILE

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Abstract

Final design of the proposed BeO moderated pile, for operation at high temperatures to produce useful power, requires a choice of the optimum interrelated values of a number of values concerning pressure drops and heat transfer characteristics. To clarify the problems involved, estimates have been made of: 1) pressure drops for six different shapes of "fuel rods"; 2) the effect of variation in alignment of the rods on the pressure drop; 3) the fraction of pile power required for circulating the coolant gas; 4) the effect of diameter of a hole in the fuel rods on gas flow distribution, total pile voids, and temperature distribution in gas streams and in the solid; 5) the effect of assumed variation in heat production rates across the pile on the temperature difference between the fuel rods and coolant gas; 6) the effect of the emissivity of BeO on the temperature difference between the fuel rods and the coolant gas; 7) the effect of pile power on temperature variation between coolant gas streams and walls of fuel tubes.

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I. Introduction:

The high-temperature oxide pile (MUC-JDN-63) is being designed for the purpose of producing heat from nuclear reactions under such conditions that the heat energy may be used to produce useful power. The nuclear energy is released by the action of neutrons in causing fission of ²³⁸U atoms in "fuel rods". These fuel rods will consist of cylinders about 1-1/2" diameter by 6" long, made of 90% BeO and 10% UO₂. A group of rods will be placed in each of the channels through the beryllium oxide moderator bricks and the heat of the fission reaction removed from the surface of the rods by circulating helium as the coolant gas. In order to allow optimum design of such a pile it is necessary to make a series of calculations on gas pressure drop, gas pumping power, and temperatures to be expected in the gas heating channels. Since a number of vital factors such as, pile size, number and arrangement of control rods, and good emissivity data on beryllium oxide, are only approximately known, such calculations can only be of a tentative nature. However, calculations have been made, the results of which are presented in this report, which show the trend to be expected in the characteristic under study when other variables, such as pile size or power output are changed. The results of calculations presented in this report should, therefore, be considered as estimates rather than final design calculations.

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II. Assumptions for Calculations:

1. Pile. The pile is to consist of an assembly of beryllium-oxide bricks arranged in such a manner that a large number of cylindrical channels are present. These channels will receive the heater rods which contain the fissionable material. An annular or other shaped space remains between the heater rod and the brick. This space is used as a channel for the flow of the gas which removes the heat from the pile. The nominal size of pile assumed for calculations has 504 parallel gas channels each being 6 feet long. Such a pile would be roughly 6 feet in diameter.

The beryllium-oxide moderating brick has been tentatively decided upon as of hexagonal cross section three inches between flats and three inches overall in length. The bricks so far produced have had cylindrical holes, along their axes, two inches in diameter. These holes serve as receptacles for the fuel rods and as gas passage channels.

The various shapes of fuel rods which have been considered are shown on Chart 1. The reasons for the choice of these shapes may be summarized as follows:

Design A. This is one of the simplest designs

Design B. This is a possible practical modification of A. Fins have been added as a centering mechanism.

DESIGN	A	B	C	D	E	F
CROSS SECTION AREA	.0122 FT. ²	.0130	.0167	.0134	.0122	.0139
GAS PASSAGE AREA	.0096 FT. ²	.0088	.0051	.0094	.0096	.0079
EQUIV. DIA. ROD & BRICK	.0416 FT	.0356	.0208	.043	.038	.0316
HEATING SURFACE-ROD ONLY	2.35 FT. ² *	2.778	2.75	2.55	2.65	2.82
HEAT. SURFACE ROD & BRICK	5.50 FT. ² *	5.928	5.90	5.70	5.80	5.97
WEIGHT VEL. †	.489 $\frac{\text{LBS}}{\text{SEC. FT.}^2}$	.531	.915	.497	.489	.593
% VOID	18.1%	16.67	9.65	17.8	18.1	14.9

* FOR 6' CHANNEL

† BASED ON 504 CHANNELS-4000 KW.

ISOMETRIC VIEWS & SOME DATA FOR VARIOUS FUEL ROD DESIGNS.

864-005

CHART I
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Design C. Another simple cylinder of larger diameter

Design D. This is the design on which calculations have been based. The square section is a centering mechanism while the cylinder at each end prevents serious contraction losses at the joints. This design is the only one presented which will maintain a constant contraction loss between different fuel rods in a channel. The good characteristics may be maintained if the cylinder is at only one end.

Design E. This is a simple rod of square cross section providing the same gas channel area as design A.

Design F. This is a simple square cylinder that will just pass through the two inch hole in the brick.

The coolant gas chosen is helium. This was chosen because of its inert character and good thermal properties. It has been tentatively decided to operate with the gas being heated from 500°F at the low temperature end to 1800°F at the outlet. This results in a total gas flow rate of 2.56 pounds per second at the nominal full load of 4000 kw. The gas pressure has been chosen to be atmospheric at 4000 kw. At higher power levels the mass flow of gas must be increased in proportion to the increase in power if the gas operates through the same temperature range. Two possibilities have been considered for the pressure: First, that the gas pressure is increased directly with the power level, and secondly that the gas pressure remains constant at one atmosphere as the power level changes.

2. Critical Constants which have been Used.

A. Helium

Specific heat $C_p = 1.24 \text{ BTU/lb } ^\circ\text{F}$

Thermal conductivity $k_{500^\circ\text{F}} = .125 \text{ BTU ft/ft}^2\text{ } ^\circ\text{F hr}$

$k_{1800^\circ\text{F}} = .232 \text{ BTU ft/ft}^2\text{ } ^\circ\text{F hr}$

Viscosity $\mu_{500^\circ\text{F}} = 1.88 \times 10^{-5} \text{ lb/sec ft}$

$\mu_{1800^\circ\text{F}} = 3.48 \times 10^{-5} \text{ lb/sec ft}$

Gas constant $R = 386 \text{ ft lb/lb}^\circ\text{F}_{\text{abs}}$

The data on helium have been taken from Report CP-3061, "Physical Constants of Proposed Coolants".

B. Beryllium Oxide

Specific heat C_p (mean, 70-1000°F = .40 BTU/lb°F

Thermal conductivity $k_{1800^\circ\text{F}} = 8.73 \text{ BTU ft/hr } ^\circ\text{F ft}^2$

Specific gravity or density $\rho = 2.75$

Emissivity $\epsilon_t = 0.86$ (This value is subject to considerable doubt.)

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III. Pressure Drop Calculations

The pressure drop experienced by the gas during circulation through the pile will be determined by the sum of pressure losses from various sources. Some of the more important sources may be listed as follows:

- A. Fluid friction as determined by the Fanning equation.
- B. Change of kinetic energy of gas due to expansion.
- C. Enlargement and contraction loss at fuel rod joints.
- D. Entrance and exit losses from the gas headers.
- E. Entrance and exit losses from the piping to the gas headers.

These have been listed in approximate order of importance. The equations used for their determination are given below.

A. Fluid Friction

$$\Delta p_F = \frac{2f_a G^2 v_a N}{g D_{eq}} \quad (1)$$

B. Kinetic energy change

$$\Delta p_{KE} = \frac{G^2 (v_2^2 - v_1^2)}{g} \quad (2)$$

C. Fuel rod joint loss

$$\Delta p_j = \frac{\rho (J=1)}{2g} \left[(v_2 - v_1)^2 + K_o v_2^2 \right] \quad (3)$$

D. Entrance contraction loss

$$\Delta p_o = \frac{\rho}{2g} \left[v_2^2 - v_1^2 + K_o v_2^2 \right] \quad (4)$$

Exit expansion loss

$$\Delta p_o = \frac{\rho}{g} (v_2^2 - v_1 v_2) \quad (5)$$

E. Expansion and contraction losses from the gas lines to headers use equations (4) and (5).

The symbols have the following significance:

Δp = Pressure drop in flowing from region 1 to region 2. Subscript denotes cause of loss (lb/ft²)

f_a = Average friction factor for Fanning equation between regions 1 and 2. (dimensionless)

G = Mass flow velocity of fluid = $V\rho$. ($lb/ft^2 \text{ sec}$)

v = Specific volume at regions 1 or 2 as indicated by subscript. (ft^3/lb)

v_a = Average specific volume of fluid between regions 1 to 2. (ft^3/lb)

L = Length of fluid passage. (ft)

g = Acceleration of gravity. (ft/sec^2)

D_{eq} = Equivalent diameter, equal to diameter of gas passage if channel is circular, or if an annulus or other shape, equal to four times the hydraulic radius. (ft)

ρ = Density of gas. (lb/ft^3)

j = Number of fuel rods in gas channel.

V = Velocity of gas, subscript 1 and 2 refer to upstream and downstream regions respectively. (ft/sec)

K_c = Contraction loss constant depending on area ratio, see McAdams, 2 ed. p 122

As the final dimensions of the pile have not as yet been determined, it is impossible to give a definite value for the pressure drop. However, the calculations have been made in such a manner that effects of variation in pile size on the pressure drop can be readily estimated. When it has become necessary to use some particular pile to permit study of some other variable, the pile size chosen is that mentioned in the introduction, namely 504 channels, six feet long.

Figure I shows the pressure loss per foot length of channel, due to fluid friction. This has been estimated by the use of equation (1). The pressure loss is plotted against total number of gas channels. The heat removal rate is of course 4000 kw. These curves may be used in estimating differences between different fuel rod designs so far as pressure drop is concerned.

Figure II shows total pressure loss due to fluid friction and kinetic energy changes (equations 1 and 2) to be expected in piles of various sizes. The optimum length-radius ratio of 1.85 has been used. These calculations have been made on the assumption of 4000 kw. power level and the use of fuel rods having design D, Chart I.

Chart II shows the comparable pressure losses resulting from misalignment of the fuel rod joints. All of these pressure drops are estimated by the use of equation (3). It should be noticed that all of these pressure losses, with the exception of that produced by the design D, are variable from zero to the maximum values shown.

CHART II.

FRICTION LOSSES DUE TO CONTRACTION & EXPANSION
(CALLED ORIFICE LOSSES) WERE CALCULATED USING THE
FORMULA :

$$\text{FRICTION LOSS} = \mu \frac{V-1}{2g} [(V_1-V_2)^2 + KV_2^2]$$

THE ORIFICES ARE FORMED AT THE JOINTS BY
MISALIGNMENT OF RODS, OR BY THEIR DESIGN AS
IS THE CASE IN "D."

AVERAGE ORIFICE LOSSES FOR 504 HOLE X 6' PILE.
LBS. PER FT.²

4 8 12 16 20

A

B

D

E

E'

F

2" DIA.

TOP VIEW SHOWING GAS PASSAGE AREAS AS EFFECTED BY POSITIONING OF VARIOUS FUEL RODS.

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In order to reduce thermal stresses in the fuel rod it may be desirable to place an axial hole down the center of this rod. This will also tend to lower the pressure drop in the channel. Figure III shows both pressure drop and gas flow rate distribution between the two resulting parallel channels for design D fuel rod. The effect of such holes on the percentage voids in the pile is shown on Figure IV. It will be shown later that best temperature equalization of the gas leaving such a fuel rod requires a hole size of about one-half inch diameter. This size gives 20% voids.

Figures V and VI show the effect of pile operating load on the gas pressure drop and compression horsepower. Two different operating conditions have been assumed in drawing these curves.

A. That the blower suction pressure remains constant at one atmosphere and that one boiler is used which produces a pressure drop of ten inches of water when helium is circulated at a rate to remove 4000 kw. and is heated from 500°F to 1800°F. At other loads the boiler drop is assumed to increase as the square of the gas mass flow velocity.

B. In these curves the blower suction pressure is assumed to vary at the same rate as the power level of the pile varies. It is further assumed that the pressure drop in the boiler remains constant at ten inches of water. This latter condition can only be maintained by adding boilers to the system. This is not too unreasonable an assumption since one boiler would never carry the range of loads contemplated here.

The curves of blower horsepower have been calculated from the usual adiabatic compression formula

$$HP = \frac{WRT}{k-1} \frac{\left[\frac{P_2}{P_1} \right]^{\frac{k-1}{k}} - 1}{550} \quad (6)$$

Where: HP = Theoretical adiabatic horsepower

W = Weight rate of fluid, lb/sec

R = Gas constant, $386 \frac{\text{Ft lb}}{\text{lb}^\circ\text{Rankin}}$ for helium

T = Absolute temperature at compressor inlet, °Rankin

k = Ratio of specific heats, 1.66 for helium

P₁ & P₂ = Initial and final pressures

The curves marked input horsepower have been calculated the same way with the assumption that the overall blower efficiency is 70%.

Assumption A comes close to indicating performance with the equip-

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EFFECT OF FUEL ROD HOLE SIZE
ON GAS FLOW CONDITIONS
DESIGN D FUEL ROD
504 CHANNELS 6 FT LONG
4000 KW OPERATION

STO 798 864 015

11 Fig-V

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FIGURE V

12 Fig-VI

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FIGURE VI

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ment proposed by Allis Chalmers. At 8000 kw. the input or motor power would be about 145 horsepower. This could probably be carried for very short periods by two blowers operated in parallel, each of which would be powered by a 60 horsepower driver. Conditions as proposed by them would be less severe, however, since they intend to use two boilers while maintaining atmospheric pressure.

For operation under conditions as outlined under "B" a sixty horsepower blower unit could probably carry the pumping load up to about 20,000 kw.

A breakdown of the pressure losses for design A has been made for all but entrance and exit losses at piping connections to the unit. These may be listed as follows.

	<u>lb/ft²</u>	<u>Atm.</u>
a. Fluid friction	$\Delta P_f = 13.4$	.00632
b. Kinetic energy	$\Delta P_{KE} = 1.85$	.00087
c. Joints in fuel rods	$\Delta P_j = 0.00^*$	.00000
d. Entrance and exit	$\Delta P_o = .54$	.00026
	$\Delta P_e = -.67$	-.00032
Total pressure loss	15.12	.00713

From this break down it will be noticed that the two losses listed under d, the contraction and expansion at the ends of the pile, nearly offset each other and thus the most significant losses are those for fluid friction and kinetic energy change.

IV. Heat Transfer Introduction:

Optimum design of the gas heating channels does of course involve more than pressure drop calculations. In fact, channels giving low pressure drops will in general be rather inefficient for heating the gas. Factors of interest with respect to heat transfer are; the magnitude of h (the heat transfer coefficient) for different rod shapes and sizes, the effect of emissivity of beryllium oxide in controlling the size of the heat transfer surface, the effect of non-uniform heat generation within the pile in creating local hot spots, and the effect of the heat capacity of the pile acting as a stabilizer in preventing rapid fluctuations in temperature.

As in the case of pressure drop calculations the uncertainty of, pile size, neutron flux distribution, and reliable emissivity data on beryllium oxide prevents a definite statement of the thermal conditions within the pile. However, calculations have been made which will assist in visualizing how thermal conditions may change as,

* This assumes the rods are lined up coaxially.

neutron flux distribution, fuel rod design, emissivity of pile material, power level of pile, etc. are varied. These factors as well as others will be discussed in turn.

The rate of heat removal from any part of the pile will be exactly equal to the rate of generation of heat in that same part of the pile. The temperature difference between the heating surface and cooling medium ($T_2 - T_g$) will be proportional to the rate of heat generation. Several possibilities may be considered with respect to the uniformity of heat generation.

1. The heat generation is uniform and equal in all fuel channels and all points along the lengths of a channel.
2. The heat generation rate is equal in all channels but varies from a minimum to maximum and then back to a minimum again along the length of the channel.
3. The heat generation varies from channel to channel across any diameter of the pile in much the same way that it also varies along the length of the channel.

The effects of these different modes of heat generation in modifying pile and gas temperatures are illustrated in Figures VII, VIII and IX. The case of uniform generation through the pile is illustrated in Figure VII. Here the temperature difference between heater surface and gas is constant along the length of the heating channel. And maximum pile temperatures occur at the gas exit end.

Figure VIII illustrates the case in which the heat generation is equal in all channels but varies along the length of the channel. In drawing these curves, it has been assumed that the power output varies as a sinusoidal function along the length of the rod. It is recognized that this is not an entirely accurate method of indicating the power variation. It is believed to be reasonably close for a first approximation. The exact shape of the curve will depend on the shape and size of the pile, the temperature distribution within the pile, and the type of reflector or absorbing blanket used around the pile. Figure VIII shows that for this Case 2 the maximum value of temperature difference between heater surface and gas occurs at the center of the rod and is equal to 1.57 times the similar temperature difference in Case 1. The maximum heater surface temperatures are reduced a hundred degrees or so and now occur within the heater channel rather than at the end as in Case 1.

Case 3 is presented in Figure IX. This again is based on the assumption of sinusoidal variation in power output along the length of the heater channel but in addition it is assumed that the power output also varies as a sinusoidal function across any diameter of the pile. This leads to the result that if equal weights of gas flow through all channels the heat picked up by the gas in the central channel of such a pile will be equal to about 2.16 times the average of heat absorbed in all channels. If the average temperature rise of the gas in passing through the pile is from 500°F to 1800°F or a total of 1300°F , the gas leaving such a center channel will have undergone a rise of 2800°F to give a maximum temperature of 3300°F . The maximum temperature difference between heating surface and gas will occur at the center of this channel and will be equal to 3.39 times the value for linear power generation. This results in a temperature difference of 945°F and a maximum rod surface temperature of about 3580°F . Since this case comes much

GAS AND HEATER TEMPERATURES
vs.
POSITION IN HEATER CHANNEL
ILLUSTRATING CASE OF UNIFORM
GENERATION OF HEAT THRU PILE
FUEL ROD DESIGN D
4000 KW OPERATION

FIGURE IX

closer to indicating conditions as they will actually exist in the pile, (the effect of temperature on the reactivity of the pile has been neglected), it is obvious that some modifications will have to be made either to make the rate of heat generation more uniform within the pile or to modify the gas flow channels in such a manner that the gas leaving the various channels is uniform in temperature. This latter could be accomplished by the use of orifices in the channels.

Another uncertainty that is also important in determining the maximum pile temperatures is the value of the emissivity of beryllium oxide. This becomes important in determining the extent of the surface from which heat is transferred to the coolant gas by controlling the amount of heat radiated from the fuel rod to the wall of the gas passage. A value of the emissivity, ϵ , of beryllia was estimated, in the absence of other data, from Table XIII of "Heat Transmission" by McAdams, second edition. The value chosen for the calculations that have been made is 0.86 as being roughly representative of other seemingly similar materials for which he gives the following values:

<u>Material</u>	<u>Emissivity</u>
Silica brick	.80-.95
Marble light gray	.93
Porcelain glazed	.92
Refractory materials 40 different (1110-1830°F)	.75-.90

Very recently, results of preliminary experimental determinations of the emissivity of beryllium oxide seem to indicate that the value chosen may be high by a factor of 3 to 10. In order to make an estimate of the effect of such a change in the value of emissivity, Figure X has been included. This curve shows that if the emissivity is reduced by a factor of 10, the temperature difference between rod and brick wall is increased by about 330°F. This will result in an increase in the fuel rod wall temperature of about 200°F.

The uncertainty here can only be settled by more accurate determinations of the emissivity, or from experimental data on the mock-up unit. It is important to remember, therefore, that maximum temperatures for the fuel rod may be increased considerably while those for the beryllia brick may be reduced from the values presented.

V. Heat Transfer Calculations:

The calculation of heat transfer coefficients has been in accordance with McAdams recommended procedure in most cases. However, it has been assumed that even for very low values of Reynold's number, the heat transfer coefficients may be calculated by the formula:

$$h = 0.023 \frac{k}{D} \left(\frac{DG}{\mu} \right)^{0.8} \left(\frac{Cp\mu}{k} \right)^{0.4} \quad (7)$$

19 Fig-X

KEUFFEL & ESSER CO., N. Y. NO. 359-71
Semi-Logarithmic, 3 Cycles x 10 to the inch, 10th lines accented
MADE IN U. S. A.

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FIGURE X

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which for helium reduces to:

$$h = 0.019 \frac{k}{D} \left(\frac{DG}{\mu} \right)^{0.8} \quad (8)$$

McAdams recommends this only for cases where flow is turbulent. For streamline flow of gases he recommends the formula:

$$h = 1.62 \frac{k}{D} \left[\left(\frac{\mu}{\mu_f} \right)^{1/3} \left(1 + 0.015 Z^{1/3} \right) \left(\frac{4W_{op}}{\pi KL} \right)^{1/3} \right] \quad (9)$$

In these formulae:

h = Heat transfer coefficient from heating surface to gas. (BTU/ft² °F hr)

D = Diameter or equivalent diameter of gas passage, (ft)

k = Thermal conductivity of gas, (BTU ft/ft² °F hr)

G = Mass flow velocity, (lb/ft² sec)

μ = Absolute viscosity of gas at average temperature after mixing (lb/sec ft)

μ_f = Absolute viscosity of gas at temperature of film at heating surface, (lb/sec ft)

Z = Grashof number, see McAdams, 2d ed., p 191

W = Mass flow rate, (lb/sec)

L = Length of heating channel, (ft)

A comparison of the values of h calculated by formulae (8) and (9) for a solid fuel rod of design D and power level of 4000 kw indicates that h , as determined by equation (9) is about 28% larger than the value found when equation (8) is used. Since the difference in values of h is small and in consideration of the fact that there is considerable doubt as to the existence of streamline flow at low values of Reynold's number for the channels used, especially for design D, it has been decided that all calculations of h will be made with formula (8). This decision if in error will result in slightly higher values of temperature drop than actual and is, therefore, on the conservative side so far as pile temperatures are concerned. That is, the procedure will indicate higher than actual heater surface temperatures. Data obtained in the tests on the mock-up unit should indicate the validity of this assumption.

The equation for heat transfer from heating surface to gas which has been used is:

$$Q = hA(T - T_g) \quad (10)*$$

*The value of h used in equation (10) has been calculated from equation (8). The values of h used when the rod alone is used as a heater are based on a value of $Deq.$ equal to four times the hydraulic radius based on total wetted perimeter. The values of h when applied to the wall are based on a hydraulic radius calculated with just the perimeter of the wall rather than total perimeter.

Where:

Q = Total heat transfer (BTU/hr)

h = Heat transfer coefficient for gas in particular channel (BTU/hr ft² °F)

A = Heat transfer to which h is applicable (ft²)

T = Temperature of heating surface (°F)

T_g = Bulk temperature (average temperature) of gas at heater (°F)

Where radiation effects have been involved, a simplified form of radiation equation is used, see MoAdams, second edition, p. 62:

$$Q_r = F h_r A_s (T_s - T_w) \quad (11)$$

Q_r = Radiant energy loss from surface s to w , (BTU/hr)

F = Emissivity factor as shown in equation:

$$F = \frac{1}{\left(\frac{1}{\epsilon_s} + \frac{1}{\epsilon_w} \right) - 1}$$

h_r = Radiant energy transfer coefficient (BTU/ft² °F hr, see p. 63 MoAdams)

A_s = Area of radiating surface (ft²)

T_s = Temperature of source (°F)

T_w = Temperature of receiving wall (°F)

ϵ_s = Emissivity of radiator

ϵ_w = Emissivity of receiving wall

No radiant heating of the helium coolant has been considered since only electronic energy levels would be affected with this gas and heat transfer through such a process would be very small.

Equations (10) and (11) have been combined in various forms to obtain the results given in the remainder of this report.

Consideration of equations (8) and (10) indicates the trends to be expected in values of h and $(T - T_g)$ when the power and gas flow is increased by a factor k while keeping terminal gas temperatures and gas flow channel dimensions constant. If this is done the value of h will increase by the factor $k^{0.8}$. Therefore, the temperature difference $(T - T_g)$ will increase as $k^{0.2}$.

If the gas flow velocity is increased by a factor k but the power level remains the same, then the value of h will increase by $k^{0.8}$ and the temperature difference $(T-T_g)$ will change by a factor of $k^{-0.8}$. These relationships are convenient for estimating effects of changes in flow rate on values of h and on temperature differences to be expected between heating surface and the gas.

Figure XI presents estimates of temperature conditions that may be expected at the top of a pile operating at a power level of 4,000 kw. The calculations have been made, as mentioned before, on the assumption that heat is liberated at an equal rate in all fuel channels and the rate of liberation is uniformly constant along the length of the channel. They are also based on an emissivity of 0.86 for beryllia. The curve shows the effect of size of central hole in the fuel rod on the temperature conditions. If a hole is used it should be roughly 1/2 to 5/8 inch in diameter for the design chosen. Other sizes of hole produce large temperature differences in the two gas streams. Data have been calculated for 10,000 and 40,000 kw and similar results found.

Figure XII shows the effect of operation at various power levels on temperature conditions to be expected in the pile and gas streams when the fuel rod is provided with a 1/2 inch axial hole. The same assumptions were made in making these calculations as were necessary for curve XI. In addition it has been assumed that when the operation power level is modified from the standard of 4,000 kw the gas pressure is also modified in the same manner. Although the problem has not been solved for the case in which gas pressure remains constant, Assumption A, it is believed that temperatures will not vary significantly from those shown.

The actual heat capacity of the pile is of considerable interest from an operating point of view. Thus, the time required to change the temperature of the pile during operation will determine the speed with which safety as well as operating controls will need to function. The effect of the negative coefficient of pile reactivity with respect to temperature might cause difficulty with hunting if the pile does not have considerable heat capacity. Another condition under which high heat capacity is desirable would occur during shut-down periods. During such periods there will still be considerable heat generation caused by decay of radio-active products built up during operation. Thus a large heat capacity will allow shutting down the coolant supply during periods when fuel rods are being changed.

Accurate analysis of this problem for full power operation is difficult since the problem heat transfer from the heater rod to the moderator brick must take place by conduction, convection and radiation. However, the thermal stability at low power generation rates, say from one to ten per cent of rated power, is fairly simple to treat. Equation (12) which follows, has been derived to indicate expected performance.

$$Q = 0.0063 \frac{W}{\phi} \text{ (hr/100°F)} \quad (12)$$

where:

Q = Time for pile temperature to rise 100°F (hr/100°F). 864 626

W = Weight of beryllium oxide in pile (short tons)

ϕ = Fraction of normal heat liberation rate. (dimensionless)

24 figure XII

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FIGURE XII

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This equation is based on the assumption of an average specific heat of beryllium oxide of 0.43 BTU/lb °F between 70 and 1800°F. Equation (12) indicates that when the pile is shut down and heat generation is one percent of that at full load the pile will require 43 hours to rise 100°F. This is based on a pile having 7 tons of material.

VI. Conclusions:

✓ In conclusion it may be stated that the results of calculations presented here tend to confirm the feasibility of the construction of such a power pile. ✓ Furthermore, they furnish design information to assist in a quick realization of the effects of changes in pile size, heat generation rate, etc. on such things as gas pumping power, pressure drop, and pile temperatures.

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