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HCR CONCEPT - TEMPERATURE STUDY

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B, D, F, DR, H REACTOR NEW ALUMINUM HCR

CONCEPT - TEMPERATURE STUDY

July 28, 1964

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B, D, F, DR, H REACTOR NEW ALUMINUM HCR
CONCEPT - TEMPERATURE STUDY

INTRODUCTION

The horizontal control rods presently installed in the older Hanford Reactors have inadequate heat transfer characteristics for present and predicted future operation of the reactors. Continued graphite stack distortion, coupled with higher graphite temperatures, has resulted in HCR failure during reactor operation, such as swelling of the outer aluminum sheaths to the extent that rod movement in the graphite channel is severely restricted. Continued graphite stack distortion will tend to further aggravate the problem of rod operation.

A new HCR design concept, shown in Figure I, was developed by P. H. Hutton of Reactor Design, IPD, to alleviate some of the pressing operational problems. Prior to the acceptance of such a design, the important rod operating parameters should be known to some degree of accuracy.

This study was conducted to determine, by calculational methods, the temperature distributions that could be expected to occur in such an HCR when used at the present operating power levels and at 120% of the present power levels.

SUMMARY

A study has been completed in which the temperature characteristics and the accompanying coolant flow demands of a conceptual design of an aluminum HCR for the older Hanford Reactors have been determined. These characteristics were determined for the generally accepted reactor system conditions. The purpose of this study was to bracket the characteristics of the rod, shown in Figure I, for the most stringent system conditions to be expected and to illuminate any problems associated with the heat transfer portion of rod operation. The results of the study indicate that no such problems will exist with the temperature of the aluminum components of the control rod. The highest calculated temperature of the aluminum for a fully inserted rod in the maximum neutron flux zone is 200°F, shown in Figure III. This temperature is located on the rod sheath at the interface between the graphite channel and the rod.

The coolant flow demands for the control rod will range between 40 gpm per rod to 12 gpm per rod for a fully inserted rod in the maximum flux zone; the flows are shown in Figure IV. The flow demand is based upon the coolant outlet temperature, the graphite temperature, and upon the value of the contact coefficient between the graphite and the rod sheath. The inclusion of a physical separator between the rod and the graphite, in the order of sliding rails, would significantly enhance the heat transfer characteristics of the rod.

The calculated temperatures for the 120% power level case are not significantly different than those calculated for the normal power level. The ground rule of constant graphite temperature during the power increase eliminated a large potential increase in the heat flow to the cooling water.

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DISCUSSION

Generally, the mathematical solution of a heat transfer problem with concentric cylindrical geometry, such as the control rod under consideration, can be obtained with the appropriate energy balance equations in differential form. However, the exact solution of the equations becomes increasingly more difficult as small but significant complexities are introduced into the system. These complexities are in the form of two or three dimensional heat flow, multiple materials with different heat generation rates, multiple heat sinks, and multiple heat flow resistances in series. Certain simplifying assumptions and lumping procedures can be used to solve the problem but the use of a numerical solution method will allow accurate results without making the simplifications.

Two dimensional relaxation was used to calculate the temperature distribution throughout the horizontal rod complex. The system was subdivided into temperature nodes, and the resulting heat balance equations were solved simultaneously by an iterative method with the use of a FORTRAN coded heat transfer program written for the IBM 7090.*

The ground rules were chosen to reduce the number of calculations that would be necessary to produce a useful result. The calculations were systematically made in a parametric style. The geometry of the rod was fixed as shown in Figures I and II. The system parameters that were varied are power level, graphite temperature, and the value of the contact coefficient between the rod sheath and the graphite. This contact coefficient is a significant parameter, especially for a horizontal control rod of this configuration. Notably the large area of contact or the close proximity of the bottom of the rod with the graphite channel, and the low resistance through the aluminum sheath into the outer cooling annulus are the determining factors. Other system parameters, such as pile gas composition and coolant sink temperatures were fixed at values that are average. The inner and outer cooling water temperatures were chosen as average temperatures over the complete length of the rod. The pile gas composition was assumed to be 100% He. The relationship of the coolant temperature to the sheath temperature is practically a one-to-one ratio.

As mentioned earlier, the control rod and graphite channel geometries were fixed for the entire spectrum of calculations and the system geometry is shown in both Figures I and II. The inner cooling tube position would normally vary between the two extremes of actually touching the poison at one point or touching at the opposite point. The centered geometry was chosen to simplify the node geometry calculations and would have very little affect on the actual outer sheath surface temperature. The temperature of the poison would be slightly higher on one side or the other with the extreme geometries and would consequently affect, to a small degree, the local heat split to the inner and

* HW-73668, "User's Manual For STHTP - A Steady State Heat Transfer Program for the IBM 7090 Computer," F. J. Mollerus, Jr., May 21, 1962.

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FIGURE I
HCR CONCEPT

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FIGURE II
NODE BREAKDOWN

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outer coolant streams. Similarly, the position of the poison pieces would vary from touching the outer tube on one side to touching on the other side. Here again the centered geometry was chosen with little detriment to the calculated outer sheath-outer surface temperature. The local heat split would again be affected but not to a significant extent.

The system geometry that was chosen shows the control rod resting on the graphite. This may not occur at more than about 20% of the fully inserted rod length; however, the magnitude of the bottom contact coefficient was varied during the sequence of calculations. This, in essence, allowed the rod to become disassociated with the graphite while remaining juxtaposition to the graphite. Large separations of the rod from the graphite channel were not considered because of the accompanying reduction in the heat load to the rod coolant and, although this may occur, the maximum possible sheath temperatures are of primary interest.

The importance of the value of the contact coefficient between the control rod outer sheath surface and the graphite juxtaposition to the rod can readily be seen when the modes of heat transfer to the rod coolant streams are studied. The controlling resistance to heat transfer from the graphite to the outer coolant stream in the rod is that through the gas film between the graphite and the outer surface of the rod. The resistance through the outer aluminum sheath rightfully can be neglected in this case. The water side film coefficient for the inner coolant channel was calculated at $2,400 \frac{\text{BTU}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$ using the Dittus Boelter Equation. The outer coolant channel film coefficient for the water side was calculated to be $4,900 \frac{\text{BTU}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$ using a modification to the Dittus Boelter Equation incorporating an equivalent diameter term and a diameter ratio form. Both equations can be found in reference 1.* Both values were calculated for an average flow rate of 22 gpm, using the bulk average coolant temperature for the respective coolant channel. Significantly, the heat transferred from the graphite can amount to 70% of the total transferred to the coolant channel in the rod. Heat is transferred by radiation, conduction and convection through the contact gas layer at the bottom of the rod. Heat transfer at the other faces of the rod is primarily by radiation from the graphite because of the distances involved. By far the largest portion of heat from the graphite is transferred through the bottom face of the rod. Thus, since the controlling resistance at the bottom is through the gas film, increasing this distance by the use of a runner plate or rails would insure a significant reduction in amount of heat transferred to the coolant.

To show the effect of the contact coefficient between the rod and the graphite, the value was varied from $10 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$ to 500 during the calculations. The results are plotted in Figure III.

* Ref. 1 - "Fluid Dynamics and Heat Transfer," Knudsen, J. G., Katz, D. L., McGraw Hill Inc., pp. 394, pp. 403, 1958.

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Graphite temperature in the vicinity of the rod channel was varied between 1,800°F and 1,300°F for the calculations. Each rod channel and adjacent graphite can be examined separately from the other horizontal rod channels. Since the majority of the heat generated in the graphite is removed by the process tube coolant, the heat removed by any one rod has a very localized affect on the graphite temperature as a whole. The graphite temperature gradient is completely unaffected by the horizontal rod coolant at a distance of from .3" to 5" from the rod channel in a radial direction. The results of varying the graphite temperature are shown in Figure III and in Figure IV.

The pile gas composition was assumed to be 100% helium during the calculations. The major effect of varying the composition during the calculations would be to alter the amount of heat energy transferred from the graphite at all faces of the rod other than that face juxtaposition to the graphite, which is the bottom surface of the rod in the calculations. A correction factor for gas composition would encompass only the heat energy transferred by conduction, a small percentage of the whole. Varying the contact coefficient at the bottom of the rod, in a sense, takes into account a different gas at the interface between the rod and the graphite. The difficulty of ascertaining the actual temperature of the rod at any one position is entirely contained in the difficulty of determining the actual value of the contact coefficient. If it can be determined, either by purposely constructing sliding support rails or by actual observation of channel distortion, that the rod is significantly supported or removed from the graphite, then the determination of the actual temperature becomes one of routine calculations easily programmed on the IBM 7090.

The gas atmosphere in the rod proper, i.e., between the position and the inner and outer sheaths, is assumed to be 100% helium. Proper purging during construction of the rod will ensure the resulting lower poison temperature as calculated with the assumed atmosphere.

Two reactor power levels were assumed during the calculations. The present operating limit of 2090 MW was assumed for one set of calculations and 120% of this power level was assumed for the second set. As mentioned earlier, the rod was assumed to be completely or fully inserted into the channel. The heat generation rates of the various materials were determined for these power levels by assuming a flat side-to-side neutron flux distribution.

The physical constants used in the calculations are presented in Tables I, II and III.

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FIGURE IV

ROD COOLANT FLOW

REACTOR LEVEL 2090 MM

MAX. FLUX REGION

ROD FULLY INSERTED (26')

CONTACT COEFFICIENT:

--- 500 BTU/HR-FT²-°F

--- 50 BTU/HR-FT²-°F

--- 10 BTU/HR-FT²-°F

INLET TEMPERATURE 70°F

ROD FLOW (GPM)

GRAPHITE TEMPERATURE (°F)

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Table I

Physical Constants

<u>Item</u>	<u>Value</u>
Graphite Emissivity	0.85
Aluminum Emissivity	0.20
Boron Carbide Emissivity	0.65
Aluminum Thermal Conductivity	119 BTU/hr-ft-°F
Boron Carbide (Compacted) Thermal Conductivity	10.7 BTU/hr-ft-°F
Inner Coolant Film Coefficient (Water Side)	2,420 BTU/hr-ft ² -°F
Outer Coolant Film Coefficient (Water Side)	4,870 BTU/hr-ft ² -°F

Table II

Gas Thermal Conductivity - 100% Helium

<u>Temperature (°F)</u>	<u>K(BTU/hr-ft-°F)</u>
212	0.103
392	0.119
572	0.135
752	0.150
932	0.166
1,111	0.182
1,290	0.198

Table III

Graphite Thermal Conductivity

<u>Temperature (°F)</u>	<u>K(BTU/hr-ft-°F)</u>
140	15.0
356	17.0
464	17.5
572	18.0
662	18.0
752	18.0
842	18.0
1,111	17.0
2,160	15.0

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The results of the calculations are summarized in Figures III, IV, and V. Figure III is a plot of the maximum aluminum sheath surface temperature versus the maximum graphite temperature of the stack. The maximum aluminum temperature occurs at the bottom of the rod in all of the geometries that were considered. This temperature represents the highest skin temperature and most certainly the highest temperature of the aluminum components of the rod that would occur at the given power level. The calculations performed for 120% of the "normal level" of 2090 Mw indicate that no appreciable change in skin temperature would occur. The restrictive assumption of no increase in graphite temperature with the increase in power level essentially dictates such a result. Two system parameters are used in plotting the temperature values in Figure III. One is the contact coefficient at the bottom of the rod and the other is the outer channel coolant temperature. The coolant temperatures used is a point temperature and not to be misconstrued as the coolant outlet temperature. However, the 150 F line would closely approach the outlet portion of the rod.

The effect of the value of the contact coefficient between the rod and the graphite can be seen in Figure III. As the value of the contact coefficient is reduced, the effect of a change in the graphite temperature becomes noticeably small. At a value of 500 BTU/hr-ft²-°F and with a maximum graphite temperature of 1,800 F, 68% of the total heat load to the rod coolant is transferred from the graphite moderator. When the value of the contact coefficient is reduced to 10 BTU/hr-ft²-°F, the contribution from the graphite is correspondingly reduced to 27% of the total heat load to the coolant.

The calculated rod coolant flow rates versus graphite temperature with the coolant outlet temperature and the bottom contact coefficient values as system parameters are shown in Figure IV. These flow rates are those required to maintain the given coolant outlet temperature. The flow rate calculations are based upon a power level of 2,090 Mw, the rod fully inserted in the maximum flux region, and a coolant inlet temperature of 70 F. The heat flux to the rod coolant was assumed constant over the active length of the rod. This latter assumption may be slightly over pessimistic. Rods only partially inserted or located in flux regions other than the maximum region would require lower flows to maintain the same outlet temperature.

Figure V is a graphical representation of the longitudinal temperature gradient of the rod coolant for a given set of system conditions. A power level of 2090 Mw was assumed, with a coolant inlet temperature of 70 F and an outlet temperature of 150 F. The rod was assumed to be fully inserted in the maximum flux region; however, the value of the contact coefficient between the rod and the graphite was assumed to be only 50 BTU/hr-ft²-°F. The flow was assumed to be 19.8 gpm. The temperature gradient would change for other system conditions, although the general shape of the curve would remain the same.

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CONCLUSIONS

The results of this temperature study are as specific as one can get with a rather general approach to a design conception. Further calculations and, ultimately, comparison of actual test data from a prototype rod with calculated values should follow as the design and construction of the rod progresses. The following conclusion can be made based on these preliminary calculations:

1. The temperature of the aluminum components of the rod, for operating conditions normally expected during future operation of the old piles, will be adequately low for sustained operation.
2. Coolant flow rates necessary to maintain a coolant outlet temperature at about 150 F are reasonably low with contact coefficient between the rod and the graphite of about 50 BTU/hr-ft²-°F or lower.
3. No particular problem is expected by heat interchange between the inner and outer coolant streams of the rod.
4. A significant decrease in the coolant flow rate demand for the rods would accompany the inclusion of sliding rails or a track upon which the rod would rest when fully inserted.

J. D. Agar

Reactor Design Analysis

JD Agar:bw

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APPENDIX

The descriptions of the following cases are included for use with the individual node temperatures that are listed in the appendix. Each case represents a set of system parameters that were inserted into the input data of the FORTRAN coded program.

- Case 1 Reactor power level 2090 Mw
 Maximum graphite temperature 1800 F
 Bottom contact coefficient 500 BTU/hr-ft²-°F
 Rod fully inserted in maximum flux zone
 Average inner coolant temp. 76 F
 Average outer coolant temp. 123 F
- Case 2 Same as Case 1 except:
 Average outer coolant temp. 150 F
- Case 3 Same as Case 1 except:
 Contact coefficient 50 BTU/hr-ft²-°F
- Case 4 Same as Case 1 except:
 Contact coefficient 10 BTU/hr-ft²-°F
- Case 5 Same as Case 1 except:
 Contact coefficient 10 BTU/hr-ft²-°F
 Graphite temperature 1300 F
- Case 6 Same as Case 1 except:
 Contact coefficient 50 BTU/hr-ft²-°F
 Graphite temperature 1300 F
- Case 7 Same as Case 1 except:
 Graphite temperature 1300 F
- Case 8 Same as Case 1 except:
 Graphite temperature 1300 F
 Average outer coolant temperature 150 F

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Case No.

Node No.	Case No.		Node No.	Case No.		Node No.	Node No.
	1	2		3	4		
1	85.9	86.4	85.9	85.9	85.9	85.9	86.4
2	95.2	96.4	95.2	95.2	95.2	95.2	96.4
3	96.2	97.4	96.2	96.2	96.2	96.2	97.5
4	96.2	97.4	96.3	96.3	96.2	96.2	97.5
5	95.2	96.4	95.3	95.3	95.2	95.2	96.4
6	85.9	86.5	85.9	85.9	85.9	85.9	86.5
7	86.7	87.3	86.7	86.7	86.7	86.7	87.3
8	95.9	97.1	96.0	97.0	95.9	95.9	97.2
9	96.9	98.2	97.0	97.0	96.9	96.9	98.2
10	96.9	98.2	97.0	97.0	96.9	96.9	98.2
11	95.9	97.1	96.0	97.0	95.9	95.9	97.2
12	86.7	87.3	86.7	86.7	86.7	86.7	87.3
13	305	317	305	305	305	305	317
14	312	326	312	312	312	312	327
15	313	328	313	313	313	313	328
16	313	328	313	313	313	313	328
17	312	326	312	312	312	312	327
18	305	317	305	305	305	305	317
19	316	329	316	316	316	316	329
20	322	337	322	322	322	322	337
21	322	338	322	322	322	322	337
22	322	338	322	322	322	322	338
23	322	337	322	322	322	322	337
24	316	329	316	316	316	316	329
25	307	320	307	307	307	307	321
26	314	329	314	314	314	314	329
27	314	330	314	314	314	314	330
28	314	330	314	314	314	314	330
29	314	329	314	314	314	314	329
30	307	320	307	307	307	307	321
31	127	154	127	127	127	127	154
32	127	154	127	127	127	127	154
33	127	154	127	127	127	127	154
34	127	154	127	127	127	127	154
35	127	154	127	127	127	127	154
36	127	154	127	127	127	127	154
37	127	154	127	127	127	127	154
38	126	153	126	126	126	126	153
39	126	153	126	126	126	126	153
40	126	153	126	126	126	126	153
41	126	153	126	126	126	126	153
42	127	153	127	127	127	127	153
43	169	196	139	126	126	134	196
44	129	156	126	125	125	125	156
45	128	155	126	125	125	126	155
46	126	152	126	124	124	124	152
47	124	151	124	124	124	124	151
48	126	153	126	125	124	124	153
49	129	156	126	125	125	127	156
50	128	156	128	128	126	126	156
51	126	153	126	125	125	125	153
52	124	151	127	123	124	124	151
53	126	153	127	124	124	124	153

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