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TEMPERATURE CALCULATIONS
FOR A NEWLY DESIGNED FLEXIBLE HCR
FOR THE K REACTORS

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TEMPERATURE CALCULATIONS FOR A NEWLY DESIGNED
FLEXIBLE HCR FOR THE K REACTORS

January 27, 1964

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TEMPERATURE CALCULATIONS FOR A NEWLY DESIGNED
FLEXIBLE HCR FOR THE K REACTORS

INTRODUCTION

The steadily increasing graphite stack distortion in the K Reactors has caused serious operating problems with the existing horizontal control rods. To compound the seriousness of the problems, the high level of reactor operation today and the anticipated higher level of operation in the future demands a reliable control rod system. A flexible control rod has been designed by Reactor Design, IPD, to facilitate reliable operation of the HCR system in spite of channel bowing arising from graphite stack distortion.

This flexible control rod design is radically different from the existing K Reactor control rods and in fact, is more closely aligned to the control rods now in use at the older Hanford Reactors. The major difference of the new rod is the elimination of intimate contact between the poison-containing section of the rod and the cooling water.

Such a change in design as described above could result in significant changes in the operating temperatures of the rod proper. This study was undertaken to provide a calculated indication of the temperature changes and the relative magnitude of such changes relative to reactor power levels, graphite temperatures, coolant temperatures, etc. In addition to this basic information, the scope of the study has been somewhat enlarged to include the calculation of operating temperatures of the existing K Reactor control rods at present and forecasted future reactor operating conditions. The purpose of this latter work was to support an effort to better define limiting environmental conditions for use of the existing rods.

SUMMARY

Heat transfer calculations were made on the newly designed flexible control rod for the K Reactors at present and forecasted operating conditions, and on the present K Reactor control rods at the present operating conditions. The calculations were performed with the aid of a FORTRAN coded heat transfer program written for the IBM 7090.

One system geometry was considered for the flexible rod and three system geometries were considered for the present K Reactor control rod. The various system parameters, consistent with the geometries considered, were determined and the calculations were performed in a parametric manner.

The results of the calculations are presented in graphical form in Figures V through VIII. The following general conclusions were determined from the results of the study:

1. The maximum sheath temperature normally expected to occur in the flexible rod, with the one geometry considered, was calculated to be 1,000°F. This temperature is based upon a maximum graphite temperature of 1,900°F, which might occur after the completion of the K Retubing program, a contact coefficient 500, and upon a maximum poison to sheath gap of 5 mils.

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2. Close regulation of the poison-to-sheath distances should be made during the fabrication of the rods.
3. A maximum sheath temperature that could normally be expected to occur in the regular K Reactor HCR, after completion of the K Retubing Program, was calculated to be 420°F.
4. An increase in the reactor power level from 4,400 Mw to 5,000 Mw resulted in a calculated increase of 8% in the sheath temperatures of the two types of control rods.
5. The limiting resistances to heat transfer in the flexible control rod were the poison to sheath gap distance, the poison to cooling tubes distance, and the value of the contact coefficient between the sheath and the juxta position graphite.
6. The value of the contact coefficient between the flexible rod and the graphite was determined to vary between 10 and 500 Btu/hr-ft²-°F.

DISCUSSION

A. Analytical Procedures

The calculations for this study were performed with the aid of a FORTRAN coded heat transfer program written for the IBM 7090. Although the program is capable of handling a three dimensional heat transfer system, for ease of applying the system data the program was limited to a two dimensional approach, which is in the realm of actual possibilities. One would not expect sudden discontinuities in the physical makeup of the rod in a longitudinal direction; and, the flat neutron flux in both K Reactors in a side-to-side direction insures a fairly consistent heat generation rate down the length of the rod. Thus, the heat transferred in a longitudinal direction would be of questionable significance. This leaves a two dimensional heat transfer system with heat being transferred in a radial direction towards the cooling water channel, and around the periphery of the rod.

There are several ways to calculate the heat transfer in the fairly complex geometry of the rod, all of which lend themselves readily to numerical solution. The primary requirement for the results is to show a fairly complete temperature distribution in the cross section of the control rod. To arrive at such a result, a heat transfer program* was used which incorporates the relaxation method of heat transfer calculation. Briefly, the cross section of the rod proper and the contributing graphite is divided into a predetermined number of temperature nodes. An initial temperature distribution is assumed for the nodes and a two dimensional heat balance is made on each individual node. A new temperature is determined by the program procedure for each node

* HW-79392, "User's Manual For N-Heat, N-Reactor Lattice Heat Transfer Program For the IBM 7090 Computer," F. J. Mollerus, Jr., 1963.

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and the heat balance calculations are again completed for each node. This procedure is repeated until a predetermined maximum heat transfer error is reached for each node and at this point the program is terminated.

The geometry of the new flexible rod is shown in Figure I. Figures II, III, and IV show the different geometries considered for the existing K Reactor control rods. Only one geometry, the "worst case" geometry, was considered for the flexible rod, although there is one geometry that could conceivably be worse than the one that was considered. This one would assume the same rod cross section but with the rod sheath in direct contact with the bottom of the graphite channel and with the side of the channel. This latter system geometry was neglected on the basis of being improbable. From a materials design standpoint only the most probable geometry which would produce the highest rod sheath temperature is of immediate interest.

The flexible rod shown in Figure I represents only one-half of the actual rod. The uniformity of the rod design and the neutron flux allows the positioning of an imaginary adiabatic vertical plane to be placed in the center of the middle cooling tube. The temperature distribution shown in Figure I is a mirror image of that contained in the other one-half of the rod.

As mentioned above, three geometries were used to depict the most obvious positions of a regular K Reactor control rod during reactor operation. Figures II and III show the control rod centered in a side-to-side direction over the existing saddle block. Figure IV shows the rod resting against the side of the saddle block and as such, the complete rod cross section was needed to calculate the resulting temperature distribution. In the latter case the side-to-side concentricity was destroyed.

The modes of heat transfer from the surrounding graphite stack to both types of control rods are the same. Radiation heat transfer is the controlling mode in the upper portion of the rod periphery or around the complete periphery in the case of the regular rod suspended above the graphite. In the region of close positioning of the rod with the graphite, radiation and conduction through the surrounding gas medium are both important modes. In the case of contact with the graphite, 60° contact with the regular K HCR in geometry III, 30° contact with the regular K HCR in geometry IV, and complete contact on the bottom of the new HCR, conduction heat transfer is the main consideration. The limiting factor in this latter case is the actual value of the heat transfer contact coefficient between the graphite and the rod sheath.

Heat transfer within the two types of control rods is significantly different. The original K rod design is unique from a heat transfer characteristic with direct contact between the cooling water and the outer section of the rod containing the poison material. The modes of heat transfer in this rod are conduction through the rod proper and convection into the cooling water. The limiting resistances to heat transfer are the effective thermal conductivity through the vibration compacted poison material, and the heat transfer coefficient on the water side of the cooling channel.

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FIGURE II

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K REGULAR CONTROL ROD

MAX. GRAPHITE TEMPERATURE 1400°F

MAXIMUM POWER REGION

REACTOR POWER LEVEL 4400 MW

COOLANT INLET TEMPERATURE 75°F

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FIGURE III

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K REGULAR CONTROL ROD

MAXIMUM GRAPHITE TEMP 1400 °F

MAXIMUM POWER REGION

REACTOR POWER LEVEL 4400 Mw

COOLANT INLET TEMPERATURE 75 °F

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FIGURE IV
K. REGULAR CONTROL ROD

MAXIMUM GRAPHITE TEMP 1400 °F
MAXIMUM POWER REGION
REACTOR POWER LEVEL 4900 Mw
COOLANT INLET TEMPERATURE 75 °F

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The new rod, designed wholly for serviceability, is not as effective a heat transfer medium as the present rod. Therefore, the outer sheath temperatures can be expected to be higher than those experienced with the present rods. This is one reason for the use of Inconel as the structural material of the new rods, rather than extruded aluminum. As can be seen in Figure I, the new rod will be constructed with three separate and distinct parts--the Inconel cooling tubes, the sintered poison pieces, and the outer Inconel sheath. The gas spaces surrounding these parts will be filled with 100% helium during the construction of the rods and maintained by the radiation breakdown of boron during operation with the rod. The geometry used for the calculations can be construed as representing the maximum variations in the surface tolerances of the separate parts. Because of these allowed tolerances, the cooling tubes, poison, and outer sheath can be visualized as being separated from one another by individual gas films at some fixed point down the length of the rod. As mentioned earlier, this would represent the most probable "worst case" geometry of the rod, although not in existence the whole length of the rod.

The modes of heat transfer through the flexible rod are conduction through the Inconel sheath, conduction and radiation through the gas film surrounding the sintered poison blocks, conduction through the poison, conduction and radiation through the gas film surrounding the cooling tubes, conduction through the Inconel cooling tubes, and finally convection into the cooling water. This, of course, ignores the possibility of a crud film on the water side of the cooling tube walls.

The limiting resistances to heat transfer in the flexible rod are the conduction through the two gas films or the spacing involved, and the thermal conductivity of the poison material. In the case of this rod, the combined magnitudes of the limiting resistances mentioned above far outweigh the resistance of convective heat transfer into the cooling water. This may or may not hold true for the case of aging or fouling of the cooling tubes after continued use.

For the purpose of this study, the radial clearance between the outside surfaces of the three cooling tubes to the channel surface of the poison material was held constant at 0.009 inches. This stipulation is consistent with the fabrication specifications of the component parts. The radial clearance between the outer surfaces of the poison pieces and the inner surface of the Inconel sheath may not be as easily controlled during the fabrication of the rod. Therefore, this radial clearance was varied as a system parameter during the calculations. The results are reported as a function of this parameter among others.

B. Physical Properties and System Parameters

The following tables list the physical constants used in the calculations.

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TABLE I
PHYSICAL CONSTANTS

<u>Item</u>	<u>Value</u>
Graphite Emissivity	0.85
Aluminum Thermal Conductivity	119 Btu/hr-ft-°F
Aluminum Emissivity	0.20
Boron - Aluminum Thermal Conductivity (sintered)	16 Btu/hr-ft-°F
Boron - Aluminum Thermal Conductivity (vibration compacted)	10.7 Btu/hr-ft-°F
Boron - Aluminum Emissivity	0.65
Inconel Sheath Thermal Conductivity	13.2 Btu/hr-ft-°F
Inconel Cooling Tube Thermal Conductivity	9.1 Btu/hr-ft-°F
Inconel Emissivity	0.85

TABLE II
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
THERMAL CONDUCTIVITY - GRAPHITE

<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 present K-Reactor operating power level of 4,400 Mw was the basis for the determination of heat generation rates in the various materials. The original heat generation rate calculations of the materials, other than the boron carbide, were completed by W. L. Bunch*. The heat generation in the boron carbide for a maximum power region rod fully inserted was determined, from measured operating data, to be about 160 kw. A specific heat generation rate, in dimensions of $\frac{\text{Btu}}{\text{hr-ft}}$, calculated from this previously determined total heat generation rate will, in general, closely approximate a true specific rate because of the fairly flat side-to-side neutron flux in the K Reactors. The specific heat generation of other power regions in the reactor can then be determined from a ratio of average specific tube powers for the areas of interest.

The operating temperatures of the HCR's at a pile power level of 5,000 Mw are of interest. This power level, predicted for future operation, will undoubtedly be reached. The only significant change in the HCR system parameters will be the heat generation rates or the neutron flux level. These new heat generation rates were estimated from previously determined values by direct multiplication with the ratios of pile power levels.

For the purposes of these calculations, inlet water temperature was assumed to be 75°F at the inlet to rod tip. The variation of river water temperature with time throughout the year is of little interest in assessing possible temperature problems with the rod components.

Although the pile gas composition has been composed of various amounts of nitrogen and helium during past operating periods of the K-Reactors, the pile gas was assumed to be 100% helium during the calculations. This again is a "worst case" condition. Previous heat transfer calculations on similar systems have indicated that the actual composition of the pile gas can have a significant effect on the surrounding graphite temperature for small clearances between the sink and the graphite, and for high flux regions. As the clearance is increased, i.e., more dependence on radiation heat transfer, and/or the neutron flux is decreased, the effect of the pile gas composition on the graphite temperature is considerably reduced. However, in the case at hand, the sheath temperature is of primary interest and not the graphite temperature. The gas atmosphere within the rod proper is significantly more important because the clearance between the rod sheath and the graphite is large enough to regard heat transfer by radiation from the graphite as a limiting mode of transfer. The use of 100% helium as the pile gas composition will slightly increase the heat load from the graphite, thus providing a maximum heat load to the rod cooling system.

The heat generated in the graphite stack during reactor operation is normally transferred to three heat sinks consisting of the process tubes, the horizontal rods, and the thermal shield. The heat sink composed of the process tubes is, by far, the most significant of the three sinks. For the purposes of this study, the heat transferred to the thermal shield can be neglected. The heat transferred to the horizontal rod cooling system will affect the graphite temperature in the immediate vicinity of a rod. At some small distance from a rod channel, the graphite heat load is transferred almost 100% to the surrounding process tubes. Also, each control rod can be examined

* HW-67513, "An Evaluation of Five Possible HCR Sleeve Materials For K-Reactor," W. L. Bunch, J. R. Agar, 1960

REF ID: A55151

exclusive of the surrounding rods because of the distance between rods. This latter effect is produced by the low thermal conductivity of the graphite, combined with the proximity of the process tube channels.

The difficulty of proceeding with a two dimensional heat transfer program, as described earlier, is the problem of determining the effect of the rod cooling load on the graphite temperature surrounding the rod channel of interest. Also, once the surrounding graphite temperature has been determined for the series of runs, an index representing the graphite temperature has to be determined for a usable plot or presentation of the calculated results. The only known graphite temperatures, by measurement during reactor operation, is that indicated by the originally installed thermocouples in the graphite stack and/or by the thermocouples later installed in existing graphite channels. These thermocouples, by virtue of their positions, indicate maximum stack temperatures. Therefore, the usable index mentioned above must be the maximum graphite stack temperature at a given location in the stack. From henceforth, the graphite temperatures mentioned without further explanation will refer to the maximum temperature in the maximum flux zone in the K-Reactors. This temperature will normally occur in a longitudinal filler block unaffected by the horizontal rods.

A quasi-three dimensional view was taken of a module of the graphite stack around a horizontal control rod in an attempt to determine a realistic graphite temperature that could be used as a constant sink temperature in program. The solution was obtained in a trial and error method. Starting with a given volume and a graphite channel surface temperature, the percents of heat generated in the graphite that flowed to the rod and to the corresponding process tubes were calculated. The module volume was then increased in a linear direction, i.e., in a vertical direction, and the calculations were repeated until the percent of heat flow to the rod was insignificant. The corresponding temperature drop through the module of graphite was calculated and the original calculations were repeated with a corrected graphite channel surface temperature. The final resulting graphite channel surface temperature was then related to the maximum graphite temperature in the filler block. In the programmed calculations that followed, the maximum filler block temperature was varied with a corresponding variance in the graphite channel surface temperature. It was found that the graphite stack temperature was unaffected by the HCR cooling system at a distance of five inches from the rod channel surface.

An important system parameter, the heat transfer contact coefficient between the HCR and the graphite channel, prevents one from ascribing actual values to the temperature of the rod sheath. The calculated temperatures must be left as a dependent of the contact coefficient. This contact coefficient is a function of many system variables such as the position of the rod in the channel, the force, if any, applied to the interface between the channel surface and the sheath, the yield strength of the materials involved, the surface finish of the materials involved, and so forth. Good estimates can be made for most of the variables or material properties except the force applied to the interface. As one would expect, this force is critical to the analytical determination of the contact coefficient. The best that one can do in such an analytical study as this, with a limited amount of experimental data, is to use contact coefficient values that can be determined to

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be extreme limiting values. Thus if the rod were actually separated from the channel wall, the contact coefficient is determined by standard methods of heat transfer calculations. This would constitute the minimum value. If one were to use values for the contact coefficient above 500 Btu/hr-ft²-°F, other portions of the system become limiting, such as the transfer through the graphite stack, and so this value would constitute a maximum value. Using such an analysis, the value of the contact coefficient was varied between 10 and 500 $\frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$ in the program.

C. Calculated Results

All of the system parameters discussed thus far in the report are significant to the rod operating temperatures to varying degrees. Figures V through VIII present the calculated results in graphical form plotted versus the parameters. Figures V (A) and V (B) may be used for the following problems:

Problem I

Given:

- Coolant inlet and outlet temperature
- Reactor power level (4,400 Mw)
- Pile maximum graphite temperature
- Poison-to-sheath gap distance
- Contact Coefficient Value
- Allowable maximum sheath temperature

Determine:

- Minimum required coolant flow rate

Problem II

Given:

- Coolant inlet temperature
- Reactor power level (4,400 Mw)
- Pile maximum graphite temperature
- Poison-to-sheath gap distance
- Contact Coefficient Value
- Allowable maximum sheath temperature
- Coolant Flow Rate

Determine:

- Resulting Outlet Coolant Temperature

As mentioned earlier the calculated results, as presented, represent operating conditions at a pile power level of 4,400 Mw. The outlet coolant temperature represents that which would occur at the outlet end of the control rod tip. This temperature will possibly be higher than that measured in the reactor building. The distance from the rod tip to the point at which the temperature is measured is significantly long. No attempt was made during this study to determine the heat transferred, if any, from the outlet coolant line by convection and radiation after the coolant return line leaves the rod tip.

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FIGURE 2 (A)

H-FLEXIBLE FOOD

INLET COOLANT TEMP 75°F

RADIAL CLEARANCE 5 TO 25 MIL

CONTACT COEFFICIENT 10 TO 500 BTU/IN²·HR·°F

MAX SQUARE
 1000 °F

3000 °F

INDEX NUMBER

COOLANT OUTLET TEMP °F

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FIGURE 1 (M)

H-FLEXIBLE ROD

INLET COOLANT TEMP 95°F

RADIAL CLEARANCE .5 MIL

CONTACT COEFF +.500 STEEL/PTFE

CONTACT COEFF = .10

RADIAL CLEARANCE .15 MIL

CONTACT COEFF = .500

RADIAL CLEARANCE .25 MIL

CONTACT COEFF = .500

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FIGURE IV
 A. ALUMINUM ROD

INLET TEMPERATURE COOLANT = 75°F
 COOLANT FLOW = 12 TO 21 GPM

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FIGURE III

R FLEXIBLE ROD

INLET COOLANT TEMP = 75°F
GRAPHITE TEMP 1400 TO 2000 °F
RADIAL CLEARANCE .5 TO 2.5 MIL
COOLANT FLOW 12 TO 22 GPM

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The index number which represents the ordinate on Figures V (A) and V (B) is the facility for coordinating the combined use of both graphs. To solve problem I, entrance is made to the appropriate curve in Figure V (A) and with the corresponding index number, the answer is found on the curves of Figure V (B). The reverse technique is used to solve problem II.

Figure VI is used to determine either the maximum obtainable sheath temperature for a given poison to sheath gap or to determine the maximum allowable poison to sheath gap distance for a maximum allowable sheath temperature. The necessary basic data needed to solve these two problems is the maximum graphite temperature, the contact coefficient value determined from the rod position, and the reactor power level. Here again, the basis for the given curves is a reactor operating power level of 4,400 Mw. Since future reactor operation may include a rise in power level to 5,000 Mw, additional calculations were made to determine the effect on the sheath temperature of a flexible control rod, fully inserted and still located in the maximum flux zone. It was found that the rise in power level of 13.6% resulted in a blanketed rise in the sheath temperatures of 8%. This rise in sheath temperature can be attributed mostly to the increased graphite temperature and secondly to the increased heat generation rates in the Inconel sheath and poison material. Although calculations were not performed, a similar percent increase in temperature would be expected for the present K Reactor rods.

Figure VII presents a plot of the maximum sheath temperature at a point location versus the bulk average sheath temperature determined at the same cross sectional location as the former point. The only significant parameter in this relationship is the value of the contact coefficient between the rod sheath and the graphite. These calculations were based on the previously explained system geometry. A change in the internal geometry of the rod could significantly alter this relationship between the maximum and average sheath temperatures.

Figures VIII and IX represent the results of calculations for the present K Reactor horizontal control rods at the present operating conditions. The three included geometries were discussed earlier. The value of the contact coefficients for the two geometries that depicted the rod as in direct contact with the graphite was limited to 500 $\frac{\text{Btu}}{\text{hr-ft}^2 \cdot ^\circ\text{F}}$, which would represent the

"worst case" or the largest heat load from the graphite to the rod coolant. The temperatures of the rod coolant used in the calculations, and presented in Figure IX, were calculated for a constant heat load from the graphite stack down the length of the rod. This constant heat load does not really exist for the entire length of the rod tip but here again, the results would depict a "worst case". This discrepancy between the assumed case and the actual case would not warrant a detailed calculation of the variation of the heat load for this study.

CONCLUSIONS

The results of the calculations performed during this analytical study are wholly contained in graphical form on the Figures I through IX. A further breakdown of the results seems unwarranted at this time.

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The following generalized statements form the ground rules upon which the calculations were based:

1. The system geometry for the flexible control rod was restricted to a single centered geometry representing a "worst case"; i.e., the poison material and the Inconel cooling tubes were centered within the rod proper and the sheath was placed in contact with the graphite channel.
2. The pile gas composition was limited to 100% He.
3. The gas atmosphere within the flexible rod was assumed to be 100% helium.
4. The reactor operating pile power level was assumed to be 4,400 Mw for the calculations as plotted. However, a series of calculations was made with a pile power level of 5,000 Mw to determine the effect of the increased level on the sheath temperature of the flexible rod.
5. A flat neutron flux in the side-to-side direction at the K Reactors was assumed.
6. The flexible rod tip was wholly contained in the maximum flux region of the pile.

The following general conclusions can be made based upon the foregoing calculations:

1. The maximum sheath temperature of the flexible rod normally expected to occur was calculated to be 1,000°F for the maximum graphite temperature of 1,900°F that could occur at the present operating conditions and following the completion of the K Reactor retubing program. Also a contact coefficient of 500 was assumed. This temperature assumes a maximum poison to sheath gap of 5 mils which is expected to be maintained during fabrication of the rod.
2. The effect on the sheath temperature of allowing a large variation in the poison to sheath gap distance, i.e., from 5 mils to 25 mils, is significant enough to warrant close regulation during the fabrication of the flexible rod.
3. A maximum sheath temperature of the present K Reactor control rods was calculated to be 420°F for the maximum graphite temperature of 1900°F that could occur at the present operating conditions after the completion of the K Reactor retubing project. The geometry associated with this calculated temperature assumes the rod in direct contact with the tube saddle block and centered in the rod channel in a side-to-side direction (Figure III geometry). Figure IV geometry was neglected in favor of the more readily attainable geometry of Figure III.
4. An increase in reactor power level from 4,400 Mw to 5,000 Mw increased the calculated flexible rod sheath temperatures 8% over those associated with the lower power level. A similar increase is expected for the present rod.

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5. The limiting resistances to heat transfer in the flexible control rod were the poison to sheath gap distance, the poison to cooling tube gap distance, and the value of the contact coefficient between the rod sheath and the graphite.
6. The value of the contact coefficient between the flexible rod sheath and the graphite is difficult if not impossible to determine analytically. Therefore, the rod temperatures must be determined as a function of the contact coefficient. The probable maximum and minimum values of the coefficient were determined to be 500 and 10 Btu/hr-ft²-°F respectively.

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J. D. Agar

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