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K-REACTOR RETUBING PROGRAM GRAPHITE TEMPERATURE STUDY

AUTHOR

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K-REACTOR RETUBING PROGRAM

GRAPHITE TEMPERATURE STUDY

J. D. Agar
Reactor Design Analysis
N-REACTOR PROJECT

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K REACTOR RETUBING PROGRAM - GRAPHITE TEMPERATURE STUDY

INTRODUCTION

A project has been proposed and the funds allocated for the replacement of the central zone aluminum process tubes at both K Reactors with smooth bore zirconium process tubes of approximately the same outside diameter as the original tubes.^{(2)*} Associated with this project is the problem of relieving the present graphite stack distortion in the vicinity of the process tube channels and counteracting or prerelieving, at this time, the expected graphite stack distortion that will take place over the next ten years.⁽⁵⁾ Such relief becomes increasingly important when it is realized that long reactor life is required for the zirconium tubes in order to justify the cost of the project. This justification is also based upon the ability to charge normal sized, self supported fuel elements during the reactor life of the tubes.

Relieving the restrictions in the graphite process channels caused by stack contraction will be done by removing localized portions of the graphite from the tube blocks and trunion blocks with a guided cutting tool. This immediately brings up the question of graphite temperatures and the presently imposed maximum graphite temperature limits.⁽³⁾ Combined coring and graphite stack distortion could result in excessive graphite temperatures or localized hot spots.

This graphite temperature study was undertaken to permit predicting possible temperature problems that might be associated with the restoration of graphite channel straightness since the timing of the overall project completion will not allow time for extensive testing to determine such problem areas.

SUMMARY AND CONCLUSIONS

Temperature distributions for various process tube - graphite system geometries were determined for the K-Reactors with the aid of a FORTRAN two dimensional, steady state heat transfer program. The results of the study are presented in parametric form with maximum graphite temperature as the dependent variable. The maximum graphite temperature is located in the extreme upper corners of that portion of the filler block shown in Figure I.

The various system geometries considered were basically composed of the normal K-Reactor graphite lattice with a Zircaloy-2 process tube located in various spatial positions within a tube block channel. The diameter of the tube block process channel was changed to conform to the present coring pattern at the K Reactors with different amounts of graphite removed eccentrically from the original channel.

Calculations were performed for assumed reactor operating levels of 4,000 MW and 5,000 MW, each with two different pile gas compositions of 100% He and 70% He - 30% N₂. The heat generation rates in the two principle materials, graphite and Zircaloy-2, were varied to correspond to the points of minimum and maximum neutron flux in the high powered region of the K Reactors.

The following conclusions are based upon the two dimensional heat transfer calculations described above:

*Numbers in parenthesis refer to Bibliography.

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- (1) A graphite temperature of 1100°C is possible for 5,000 MW operation at the K-Reactors anytime within six years after the completion of the retubing project, based on predicted graphite contraction models and a pile gas composition of 100% He.
- (2) This 1100°C graphite temperature will far exceed the presently imposed maximum graphite temperature limit of 700°C. Both the temperature limit and the calculated maximum temperature are point values.
- (3) Graphite temperatures at points of maximum neutron flux will exceed the present maximum limit by some finite amount with reactor operation at 5,000 MW or above regardless of whether or not the reactors are cored and retubed. This temperature excess will depend upon the system parameters of the geometry in question.
- (4) The volume average graphite temperature of the two reactors following completion of zirconium retubing program will remain sufficiently below 1,000°C to retard the deleterious graphite water gas or oxygen reactions in the bulk of the graphite for 4,000 MW or 5,000 MW power level operation.
- (5) A re-evaluation of the present maximum graphite temperature limits as imposed on a measured temperature point value should be made to determine the need for such a limit.
- (6) The two dimensional heat transfer study, as conducted, is sufficient to obtain a facility for evaluating possible graphite temperature problems that may occur during reactor operation following the completion of the retubing project at the K Reactors. A three dimensional study, at this time, would provide little additional information.

DISCUSSION

A. Method of Approach to the Problem

The original coring pattern of the graphite process channels at the K Reactors, in a front to rear direction, was designed to cause an extremely flat graphite temperature profile in the axial direction during reactor operation. The existing coring pattern in the central zone region of the reactors varies from a 52 mil diametral tube-to-channel clearance in the three center most tube blocks to a 432 mil diametral clearance in the front and rear tube blocks. The process tube was originally held in a concentric position with respect to the graphite channel diameter by trunion block collars situated between two adjacent tube blocks. Unfortunately, the pattern was originally designed for a given neutron flux pattern or fuel element location in the channel.

Since the original startup of the K Reactors three related events have taken place. The power level has been increased at both reactors beyond the originally designed level, the position of the neutron flux peak in the central portion of KE reactor has been skewed towards the front and a large percentage of the originally placed thermocouples in both graphite stacks have failed to function properly. Peak graphite temperatures at the K Reactors and particularly at KE Reactor are presently approaching unpreferred values. Although not of direct concern in this study, the means for measuring and monitoring these temperatures is not presently available at either reactor. Nevertheless, maximum

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graphite temperature limits of 700°C in the bulk of the graphite and 850°C in the 130 coring region are imposed at the reactors⁽³⁾ and of necessity must be adhered to during normal reactor operation.

With the above facts in mind, an approach to the problem of determining graphite temperatures was formulated. A realistic approach was to incorporate the different modes of heat transfer and the available paths of heat transfer that would be present. A FORTRAN heat transfer program⁽⁴⁾ was used to calculate the temperature distributions for various geometries. The program is capable of handling either two or three dimensional heat transfer but because of the relative ease with which the two dimensional program can be used to vary system parameters and the apparent insignificance of axial heat transfer in the graphite tube blocks and filler blocks, the two dimensional approach was adopted.

Figure I shows the model of the system that was used. The type and direction of graphite removal and the position of the process tube in the graphite channel was changed from that shown in Figure I as needed. Shown in the model is a downward eccentric coring case with the process tube located on the bottom of the revised channel.

The FORTRAN program is based upon the standard relaxation method of calculating temperatures at various locations in a system as shown in Figure I. The entire system is arbitrarily divided into temperature nodes. A first guess temperature distribution is assumed for the node distribution and heat transfer balances are made for each node. Temperature changes automatically are made as the calculations proceed. Heat transfer is assumed to be by conduction and/or radiation to a single heat sink, the process tube coolant. The heat transfer path is assumed to be in the XY plane only although the system model is constructed as a thin three dimensional figure of unit length in the axial direction. Because of the symmetry of the process channel - graphite stack geometry, equal heat transfer to each process tube coolant stream in an appropriate process tube array in the center portion of the reactor is assumed. Thus, the single heat sink used in the calculations is of realistic value when a process tube is surrounded by tubes of the same power and coolant flow rate.

As mentioned earlier, the three dimensional approach would be of little value at this point. The reason for this is based upon several significant items. First, such an approach must be based upon a specific system geometry that would be expected to occur at some time after the completion of the retubing project. The variance of such system parameters as tube location in the distorted graphite channel and the continuity of the bulk graphite in a front to rear direction would result in a significant change in the amount of heat transferred in the axial direction. A tube block and filler block separation of an inch or more in the front to rear or Z direction could result in essentially no heat transfer in this direction. Since it would be extremely difficult to predict the condition of the graphite after the completion of such a project, the results of a three dimensional study would be of questionable value.

The interacting effect of various system parameters such as heat generation rate, gas composition and geometry is very important in assessing the possible significance of potential problems associated with the coring operation. The two dimensional program is entirely adequate for determining such effects. A three dimensional program would be extremely difficult and time consuming to apply to the task of a parametric study.

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FIG. 1

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By applying Fourier's equation of heat transfer, $q = -K \frac{dT}{dx}$ to a calculated temperature distribution based upon measured tube and graphite distortion data⁽⁷⁾, it was estimated that about 10% of the heat generated in the region of maximum flux could be transferred in an axial direction. This assumes no separation of graphite blocks in the front to rear direction. The 10% value is, at best, an approximation of the maximum rate of transfer that would be realized under ideal conditions within six years after the project completion.

B. Cases or Geometries Calculated

The various geometries that were used in the calculations are based upon a given cutting tool. The tool, although still in the design stage at this writing, is assumed to consist of a four foot straightening bar, guided on both ends, with circular, revolving cutters mounted on the bar. The OD of the cutters are assumed to be 1.818 inches, resulting in a circular cut in the graphite with an ID of 1.818 inches.

The various geometries were chosen to represent the extremes with regards to tube spatial location in the channel. The depth of cut in either the upward or downward direction was varied from 1/8" to 5/8" and the size of the original channel was varied to include all of the original cored diameters. The removal of the graphite from the process channel in an upward or downward direction will be defined as upward or downward eccentric coring. Concentric coring of graphite from the process channel, a way of describing the original coring that was done to the tube blocks, will be defined as concentric coring.

For each of the coring methods described above, a series of cases were examined in which all of the system parameters such as heat generation rate, gas composition and sink temperatures were varied over the range anticipated for operation of the reactors following completion of the project. For each series of calculations the process tube was located in each one of three spatial locations; in the center of the original channel, resting on the channel bottom and just touching the channel at the top.

C. Presentation of Results

The calculated results of the study are presented primarily in the form of a parametric study. The results can be applied to predicted tube-graphite profiles as the data becomes available. These predicted profiles will be determined with the existing experimental apparatus that has been constructed specifically to distort a representative row of tube blocks to that expected at a given time as determined by a graphite contraction rate.⁽⁷⁾ Means for measuring the position of a process tube in the experimental channel at predetermined front to rear locations has been incorporated into the apparatus. One set of measured data has been received which depicts the system geometry six years after the project completion. The results of the parametric study have been applied to these measured data and the plot is shown in Figure II. The plotted temperature points for this case are not connected by lines because of the uncertainty of the tube position in the channel at intervening locations. In other words, the exact shape of the temperature profile is unknown for the reasons discussed earlier although a good indication of the shape can be seen.

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FIGURE II

MAXIMUM GRAPHITE TEMPERATURE PROFILE

Six year measured distortion data for
the 58th tube row
Applied to 50th tube row
100% He
Power Level 5,000 MW

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The experimental six year tube location data, discussed above, was measured for graphite distortion that would be seen at the 58th tube row at the K Reactors. In order to apply this data to a maximum heat generation rate zone, it was assumed, in lieu of additional data, that this measured distortion would also occur at the 50th tube row. An adequate flux distribution was obtained for the latter tube row and the ensuing graphite temperatures were determined. A maximum temperature of about 1,100°C could be expected for these conditions assuming no front to rear heat transfer. With ideal conditions for front to rear heat transfer, i.e. good tube block contact, this maximum temperature could be reduced to slightly below 1,000°C.

Tables I, II, III and IV show the values of physical constants that were used in the calculations. The values of conductivity for the pile gas mixtures were taken from an experimental study by J. M. Davidson.⁽⁸⁾ The conductivity values for graphite were obtained from an extrapolation of existing experimental data.

An important phase of the study was the determination of the effects of the various system parameters on the graphite temperature. The parameters investigated were process tube coolant temperature or sink temperature, heat generation rate, pile gas composition, diameter of the original process channel, position of the tube in the channel and the amount of graphite removed for each coring operation. It was found that for an increase in sink temperature of 50°C there was a corresponding increase of 25°C in the graphite temperature for the minimum diametral tube to graphite clearance of 52 mils. As the diametral clearance is increased to 500 mil the effect of a small change in sink temperature becomes negligible. The reason for this correlation to diametral clearance is the corresponding change in the mode of heat transfer across the gas gap surrounding the tube. As the diametral clearance is increased the mode of heat transfer changes from one of conduction and radiation to one primarily of radiation. The fourth power of the graphite temperature that appears in the radiation equation reduces a small change in sink temperature or tube wall temperature to a negligible effect. The changes in the modes of heat transfer are graphically shown in Figure III. In this plot, calculated data were used in which the tube was positioned in the center of each channel of a given size; the channel diameter was enlarged concentrically with respect to the channel axis. This type of geometry corresponds to the originally designed K Reactors prior to any stack distortion.

The effect on graphite temperature of varying the heat generation rate in the graphite is by far the most significant of the parametric effects. Over the range of heat generations used, the maximum graphite temperature was changed about 700°C. The range of heat generation rates used is bounded by the lowest rate that would appear at the point of maximum flux in the fringe tubes and the maximum rate that would normally be expected in a high powered tube, the latter for a reactor power level of 5,000 MW. The method of plotting these heat generation rates as parameters or as variables incorporated an index rate. The heat generation rates of the two primary materials, Zircaloy-2 and graphite, are inserted into the FORTRAN program as input data. The rates are functions of a given neutron flux distribution and as such are symmetrical with respect to each other. Thus, in reporting the data, the heat generation rates of either material can be used as an index rate. The graphite heat generation rate is used throughout this report. Figures IV to VII show the range of heat generation rates used and the method of using an index rate in presenting the data.

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TABLE I
PHYSICAL CONSTANTS

<u>Items</u>	<u>Value</u>	<u>Units</u>
Contact coeff. of tube block (bottom)	500	Btu/hr-ft ² -°F
Emissivity of graphite	0.98	_____
Emissivity of Zircaloy-2	0.50	_____
Heat transfer coefficient - waterside	∞	Btu/hr-ft ² -°F
Thermal conductivity of Zircaloy-2	6.5	Btu/hr-ft ² -°F/ft

TABLE II
GRAPHITE THERMAL CONDUCTIVITY
Btu/hr-ft²-°F/ft

<u>T(°F)</u>	<u>K</u>
140	2.10
356	4.60
464	7.00
572	7.98
662	8.61
752	8.96
842	8.84
1110	8.33
2160	6.44

TABLE III
PILE GAS THERMAL CONDUCTIVITY
Btu/hr-ft²-°F/ft

<u>T(°F)</u>	<u>K@100% He</u>	<u>K@70% He - 30% N₂</u>
32	.081	.046
261	.103	.061
621	.137	.083
981	.171	.106

TABLE IV
HEAT GENERATION RATES
Btu/hr-in³

<u>Graphite</u>	<u>Zircaloy-2</u>
5	29
10	57
15	83
20	114
30	160

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GRAPHITE REMOVAL WITH CONSTANT HEAT GENERATION RATES

Concentric Coring
 Tube Located in Channel Center
 100% He
 Sink Temperature 66°C
 Parameter - Graphite Heat Generation Rate

359 14

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10 X 10 1000 M 359.14
10 X 10 1000 M 359.14

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ECCENTRIC DOWNWARD CHANNEL CORING

FIGURE VII

EGCENTRIC UPWARD CHANNEL CORDING

Tide at Top of Channel
Sink Temp. 55°C
100% H₂O
Depth of Cut 1/8" to 5/8"

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Two different pile gas compositions were used in the calculations, 100% He and 70% He - 30% N₂. This is the range of compositions that would normally be expected during reactor operations. The change in the graphite temperature over the range of gas compositions given is also related to the other parameters; heat generation rate, diametral clearance and the position of the tube in the graphite channel. This interrelationship can best be seen in Figure IV and it follows the same pattern for the other geometries considered, although this data is not included in the remainder of the graphs. The maximum effect of changing the compositions from 100% He to 70% He occurs in the maximum flux zones and amount to about 140°C.

Earlier in the report the various coring methods, such as concentric coring, were defined without attempting to explain the reason for considering each method. Such an explanation is needed at this point. The graphite growth in the front and rear fringes of the stack coupled with graphite contraction in the center portion of the stack causes an S-shaped front to rear channel profile. When the cutting tool, which was described earlier in the report, is drawn through the channel the graphite is removed either from the top of the channel or the bottom but never from both locations during the same pass. It should be remembered that the diameter of the cutting tool is smaller than the diameter of the graphite channel.

At the K Reactors eight tube blocks and seven trunnion blocks make up a single front to rear process channel. Different tube blocks make up definite coring regions. That is to say, the diameter of the process channel through the tube blocks varies from 2.238" for the first tube block to 1.858" for the three center tube blocks. The diameter of the channel in each tube block remains constant throughout the length of the block.

After the eccentric coring operation has been completed, the channel diameter will no longer be constant throughout the length of the tube block. The depth of the cut will vary from zero to a maximum of 5/8" depending upon the extent of distortion of the channel or upon the location of the cut with respect to the S-shaped curve discussed earlier. It must be clearly understood that the channel in any one tube block will not be distorted but individual tube blocks will be displaced or cocked at an angle thus causing the S-shaped channel.

The effect of the original channel diameter on the graphite temperature, for downward eccentric coring, is shown in Figure VI. The resulting changes in graphite temperature vary between a 120°C temperature difference and no temperature difference, depending upon whether the tube is centered in the original channel or whether the tube is located at the bottom of the new channel. The 120°C ΔT change, associated with the centered tube geometry, reflects a concentric change in the channel size caused by the presently existing coring pattern. For example, if the neutron flux or heat generation rate is the same in the number three tube block and the number four tube block then the temperature of block three will be about 32°C higher than that of block four; this assumes equal graphite removal by the tool for both blocks and in the downward direction. This can be varified in Figure VI; tube block #3 has an original channel diameter of 1.918" and block #4 has an original channel diameter of 1.858".

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If the same procedure is followed on Figure IV, which would reflect the case of no graphite removed by the straightening bar or cutting tool, then the corresponding change would be significantly larger. This suggests that the eccentric removal of graphite in the downward direction counteracts or overshadows the effect of increasing the original channel size when the process tube is centered in the original channel. The explanation is related to the mode of heat transfer that would be present. If the depth of the eccentric cut is $1/8$ " or more, the mode of heat transfer is primarily by radiation to the centered tube. A small increase in the upper distance between the tube and the tube block caused by going from one channel size to another would not significantly decrease the amount of energy transported from the filler block. This explanation places a large importance on the lower heat path and this importance can be seen readily by examining the system model in Figure I. The partial gas gap around the outer surface of the tube block causes a large percentage of the filler block energy to be transported through the lower portion of the tube block and into the heat sink. When the process tube is removed from the channel bottom, a large increase in heat flow resistance is realized.

This increase in heat flow resistance is not realized when the tube remains on the channel bottom after downward eccentric coring. Therefore, the effect on graphite temperature in going from one tube block to another is insignificant as can be seen by the dotted line in Figure VI.

The calculations for upward eccentric coring, with the process tube resting against the top of the process channel, show a small variation in maximum graphite temperature related to changes in original channel diameter. This effect, shown in Figure VII, is explained analogous to that for the downward eccentric coring case.

The effect of process tube spatial position in the tube block channel on graphite temperature is shown most clearly in Figure VI and by comparing Figures IV and V. This parameter becomes increasingly important as the heat generation rate becomes greater. In any case, the effect of varying the tube spatial position from a centrally located position to one of an extreme upper or lower position is significant on the maximum graphite temperature. This effect is the direct result of increasing or decreasing the length of the path for conductive heat transfer through the tube gas gap and through the tube block. When the tube is moved to the bottom of the channel, the conduction path through the lower portion of the gas gap around the tube is significantly shortened and the resulting effect is the same as described earlier. This spatial position of the tube then, favors a significant increase in heat transfer, thus reducing the graphite temperature.

When the process tube is positioned in the upper extreme of the process channel accompanied by upward eccentric coring the maximum graphite temperature is again lowered over that associated with the centered geometry. The conduction path through the upper portion of the tube gas gap is significantly shortened along with the conduction path through the upper portion of the tube block. Since the point of maximum graphite temperature is located in the upper extreme corners of that portion of the filler block shown in the model, this reduced heat transfer path is conducive to lower maximum graphite temperatures.

Finally, the amount of graphite removed during the eccentric coring operation with the straightening bar or the depth of cut has a significant effect on

graphite temperature. Regardless of the position of the tube in the renovated process channel, unless the tube is touching the graphite, the significant conduction heat transfer path at some position on the tube periphery has been increased in length. As mentioned above, the position of the tube may well limit the magnitude of the graphite temperature change but the change is significant. Figure III shows the effect of increasing the channel diameter at a given heat generation rate. The maximum amount of graphite that will be removed from any one point in the channel during the eccentric coring operation is limited by the cutter diameter, the amount of channel distortion and the length of the straightening bar⁽⁷⁾. At a point of inflection of the channel the minimum depth of the cut will be about 1/8". This amount of graphite removal corresponds to the point of 170 mil diametral clearance in the concentric case of Figure II. The comparison between the eccentric coring case and the concentric case was made by comparing the resulting temperatures. Examination of the curves in Figure III shows that further removal of graphite will not change the maximum graphite temperature significantly. The reason, as explained in a previous section, is based upon the change in the mode of heat transfer. The primary mode of heat transfer in the region of the 1/8" cut, with the tube centered in the channel, is by radiation. As the depth of the cut is increased to the possible maximum of 5/8", the maximum graphite temperature increase is in the range of 30°C to 60°C ΔT which is well within the accuracy of the calculations.

In summarizing the discussion above, the composite results of changing the system parameters can be seen in Figures III through VII. The graphs appearing in these figures, as discussed above, are in parametric form. These results as applied to a specific geometry and a specific set of operating data can be seen in Figure II.

Care must be taken in applying the calculated results of the study to additional experimentally measured data, as the measured data become available. The various parameters discussed above must be carefully evaluated for the specific case in question. Some interpolation between curves presenting the calculated results must be made because of the limited number of cases that were calculated. No distinctive advantage would have been gained by calculating temperatures for a multitude of geometries. The assumptions that must be made in applying the calculated results to a specific geometry overshadow the need for an extensive network of temperature cross plots.

The purpose of this graphite temperature study must be kept in mind when comparing the results of the study to measured in-pile temperatures or when evaluating the graphite temperatures as applied to an experimentally measured tube-channel geometry. The primary purpose for the study was to obtain a facility for evaluating the effects of system parameters on graphite temperatures following the completion of the retubing project of the K reactors.

The study shows that with certain possible geometries and at the maximum operating conditions forecasted, graphite hot spots can and will be present. Tables V and VI show a comparison of maximum graphite temperatures for a variety of geometries. A small degree of minimizing of the magnitude of hot spots can be obtained by controlling a limited number of system parameters such as pile gas composition and the magnitude and location of peak heat generation rates. The absolute control of graphite temperature hot spots can only be gained with a sacrifice in power level, and then a sudden shift in neutron flux peak location during operation could cause a momentary hot spot.

TABLE V

MAXIMUM GRAPHITE TEMPERATURE

Sink Temp. 60°C
 Gas Comp. 100% He
 Tube Row 50th
 Reactor KE-KW

Block No.****	S _n * (Btu/hr-in ³)	Graphite Temperature (°C)				
		Case 1	Case 2	Case 3	Case 4	Case 5
3	9	330	330	380	620	380
4	9	330	330	380	510	380
3	18	680	620	600	900	600
4	18	540	530	600	820	600
3	23**	840	760	720	1090	740
4	23	660	640	720	1000	740
3	29***	1000	880	860	1270	860
	29	800	760	860	1180	860

TABLE VI

CASE DESIGNATION

- Case 1 - Present coring configuration with tube ideally in center of channel
- Case 2 - Present coring configuration with tube resting on bottom of channel
- Case 3 - Minimum downward coring 1/8" with tube resting on channel bottom
- Case 4 - Minimum downward coring 1/8" with tube centered in original channel
- Case 5 - Minimum upward coring 1/8" with tube located at top of channel - just touching the graphite.

*S_n = volumetric rate of heat generation in the graphite.

**Peak value for a reactor power level of 4,000 Mw.

***Peak value for a reactor power level of 5,000 Mw..

****Tube block #3 has an original channel diameter of 1.918" and tube block #4 has an original channel diameter of 1.858.

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Such momentary hot spots do exist now and the retubing project should not increase the frequency of occurrence of these hot spots, only the magnitude of the resulting graphite temperature. What must be assessed now is whether or not a high level of reactor operation can be maintained with the possibility of permanent high graphite temperatures at given locations. It must be remembered that these fairly high temperatures will be localized and that the bulk average graphite temperature will be considerably below those peak temperatures.

Water gas reactions and reactions of the graphite with oxygen will also be localized with respect to the high temperature regions. Thus, if the bulk of the graphite is below a reaction threshold temperature then possibly the amount of deterioration of the graphite stack in the vicinity of the hot spots can be ignored.

The presence of graphite temperature hot spots during reactor operation, following the completion of the retubing project, cannot be detected without extensive graphite temperature measurement. Such a program can be prohibitively expensive. The series of calculations included in this study should be valuable for supplementing feasible temperature measurements.

J. D. Agar

Reactor Design Analysis
N-REACTOR PROJECT

JD Agar:bsm

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