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CROSSFLOW CALCULATION FOR THE FORT ST. VRAIN NUCLEAR REACTOR CORE

Work done by:

M. J. Johnson
R. J. Kiefer
D. W. McEachern

Report written by:

R. J. Kiefer

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ERRATUM

GAMD-9984, CROSSFLOW CALCULATION FOR THE FORT ST. VRAIN NUCLEAR REACTOR CORE

by

R. J. Kiefer

August 1970

The following erratum should be noted in Gulf General Atomic Informal Report GAMD-9984:

Page 41, Fig. 21--

Change Gas Temperature (°F) to read Fuel Temperature (°F)

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INTRODUCTION

The core of the Fort St. Vrain reactor to be built for the Public Service Company of Colorado is composed of hexagonal graphite fuel elements 31 in. high and 14 in. across the flats. The active core consists of 247 columns, each containing six active fuel elements stacked vertically. The upper and lower reflectors are each composed of a stack of three 15-in.-long blocks. Core cooling is accomplished by helium coolant passing vertically from top to bottom through 108 5/8-in. coolant holes drilled through each of the fuel elements, which are aligned by dowels at each element interface. Reference 1 gives a more complete description of the Fort St. Vrain core.

The columns are grouped into refueling regions, which consist of 7 columns of fuel and reflector blocks. A coolant flow orifice valve at the top of each region regulates the flow of coolant through the region and achieves uniform outlet temperatures.

During the operating lifetime of fuel elements within the core, the graphite contracts up to a maximum of 3% axially and 0.7% radially due to accumulated fast neutron exposure. The radial dimensional changes cause the narrow vertical gaps between fuel block columns within a refueling region to enlarge and increase the gap bypass flow. A gradient in fast neutron flux near the periphery of the core causes unequal axial contraction across the width of the fuel elements adjacent to the core-reflector boundary. This leads to a slight bowing distortion of these elements. The warping causes small gaps to open up between the horizontal fuel and reflector block interfaces, opening a flow path between the coolant holes and the vertical bypass gaps. This flow is from gaps to coolant holes in heavily orificed regions and from coolant holes to gaps in regions that are lightly orificed. The horizontal flow reduces the effect of orificing and has been termed "crossflow."

The core performance code COPE,⁽²⁾ used for preliminary design calculations of core performance, does not include the effects of crossflow; therefore, results obtained by use of this code are optimistic on the effect of orificing. The general-purpose flow code FLAC⁽³⁾ solves flow problems where flow branches are hooked up in any random manner. It has been modified to include heat inputs to the flow branches, and a core with heated vertical branches interconnected by horizontal crossflow branches can thus be simulated mathematically. Several core flow orificing studies of various radial power profiles have been made using the FLAC code.

The FLAC code, however, is difficult to use as a general-purpose core performance code because of the large amount of input preparation required for all of the interconnected flow branches. Therefore, a new technique has been devised as a supplement to the FLAC code to account for crossflow. It is a crossflow correlation based on the flow data generated by refined FLAC flow models. The correlation is described and the results of its use are presented in this report.

APPROACH

It was postulated that crossflows in the Fort St. Vrain reactor core can be completely described by three characteristics of the refueling regions: (1) region orifice valve setting, (2) region radial power peaking factor (RPF), and (3) region age.

The orifice valve setting controls the coolant flow in the region and the coolant pressure profiles along the axial length of the coolant holes within the region. Since pressure differences between the coolant holes in different regions of the core are the driving forces for crossflows, it is reasonable to postulate that the orifice setting is important in characterizing crossflow. The region radial power peaking factor determines the heat that must be removed by the coolant passing through the region. The heat affects the gas density within the region, which will, in turn, affect the quantity of crossflow. The vertical bypass gaps between stacked

fuel elements are known to increase with age due to graphite shrinkage caused by fast fluence of the blocks. These vertical gaps thus change with the duration of residence time of the fuel block in the core, so crossflow can be expected to depend on the region's age. Other quantities that have been postulated to play a role in crossflows in the Fort St. Vrain core include (1) core static pressure loss, (2) orifice valve setting of regions adjacent to subject region, and (3) average orifice setting for the core.

The core static pressure loss, which is related to the average orifice setting for the core, was not considered because a larger or smaller pressure loss would be imposed across the bypass gaps (with which crossflow is being exchanged) as well as across the regions. Any resulting changes in pressure differences would then be proportional and would not significantly affect the crossflow factor. Therefore, the effect of core pressure loss was not taken as a contributing variable. However, subsequent studies have shown that core pressure loss does have an influence, and future correlations will take it into account.

Orifice settings of adjacent regions could conceivably affect crossflow since they would influence the pressure in the vertical gap with which crossflow is being exchanged. However, the time in-core (and hence power factor and orifice setting) of adjacent regions is representative of the core average condition. Additionally, low horizontal flow resistance in the vertical gaps would equalize pressure at any given horizontal location. Therefore, orifice settings of adjacent regions, if not insignificant, would surely be less significant than the three variables chosen and are therefore neglected.

Several rapidly converging FLAC models were devised to correlate mathematically the effects on crossflow of the above postulated quantities. Results obtained from these models are used to show that the three quantities are adequate to describe core crossflow.

Three models are necessary since the effects of these parameters on a region are dependent on the region geometry, and three geometry types are recognized: (1) 7-column regions, (2) 7-column regions at the core periphery, and (3) 5-column regions. Therefore, three separate correlations were made.

A crossflow factor has been defined as the ratio of the flow in the blocks in a region at any axial location, W_z , to the exit flow from that region, W_{out} :

$$CFF_z = W_z / W_{out} \quad (1)$$

The parameters of orifice setting, region peaking factor, and age were varied in such a way as to determine the effect of each on the crossflow factor. This correlation was then incorporated into the general purpose core performance code COPE to account for the effects of crossflow. The following equation demonstrates the direct effect of the crossflow factor on total core pressure drop:

$$\begin{aligned} \Delta P = & \frac{1}{2\rho_1} \left(\frac{W_{out} CFF_1}{A_1} \right)^2 \left(K_{orif} + K_{inlet} \right) \\ & + \frac{1}{2\rho_1} \left(\frac{W_{out}}{A_n} \right)^2 \left(K_{exit} \frac{T_{out}}{T_1} \right) \\ & + \frac{1}{2\rho_1} \sum_{i=1}^n \left[\left(\frac{W_{out} CFF_i}{A_i} \right)^2 \left(\frac{4f_i L_i T_i}{D_i T_1} + \frac{\Delta T_i}{T_1} \right) \right] . \end{aligned}$$

Other extensive improvements were made and the code was renamed the POKE computer program.

RESULTS

The correlating equation is the product of a constant and three parameter dependent functions:

$$CFF_z = C_z F_o F_p F_A$$

where C_z = constant for axial block z ,

F_o = function of orifice setting for axial block z ,

F_p = function of radial peaking factor for axial block z ,

F_A = function of age for axial block z .

Table 1 gives the values of the constant C_z for the three region types. For the 7-column regions the functions are plotted in Figs. 1, 2, and 3 for F_o , F_p , and F_A , respectively.* The curves are labeled by block number from the top of the core; curve 1R is the first reflector block, curve 1 is the first fuel block, and curve 6 is the last fuel block. For bottom reflector blocks the crossflow factor is assumed equal to 1.0.

Since the POKE code does not calculate individual pressure losses in each of the three reflector blocks, a single flow value for the top reflector must be determined. Therefore, the first three lines (representing the three reflector blocks) have been averaged by root-sum-squares (since Δp is proportional to the square of flow rate).

Figures 4 through 6 show identical data for the 7-column edge region and Figs. 7 through 9 are for the 5-column regions.

EXAMPLE OF USE OF RESULTS

Suppose the region exit flow were known and the top reflector flow rate were to be calculated. The following data are available:

7-column region

W_{out}	= 90 lb/hr
Orifice coefficient	= 200
Power factor	= 0.76
Age	= 6 years

* All figures are located at the end of the report.

TABLE 1
VALUES OF THE CONSTANT TO BE USED
IN THE CROSSFLOW CORRELATION EQUATION

<u>Block No.</u>	<u>7-Column</u>	<u>7-Column Edge</u>	<u>5-Column</u>
1R	1.564	1.460	1.0
2R	1.317	1.322	1.0
3R	1.190	1.248	1.0
Ref1. av.	1.368	1.346	1.0
1	1.127	1.190	1.0
2	1.086	1.129	1.0
3	1.071	1.077	1.0
4	1.053	1.040	1.0
5	1.035	1.018	1.0
6	1.020	1.009	1.0

From Fig. 1, $F_o = 0.765$; from Fig. 2, $F_p = 0.849$; from Fig. 3, $F_A = 0.873$; and from Table 1, $C_z = 1.368$. Then from Eq. 2,

$$CFF_{refl} = 1.368(0.765)(0.849)(0.873) = 0.776,$$

and the flow rate in the top reflector is

$$90(0.776) = 70 \text{ lb/hr.}$$

METHOD OF ANALYSIS

For each of the three region types (7-column, 7-column edge, and 5-column), 16 FLAC runs were made using the Latin square technique described in Ref. 4.

RPF	1.8	1.3	0.8	0.3
Age	Orifice Setting			
0	5	100	200	300
2	300	5	100	200
4	200	300	5	100
6	100	200	300	5

For the 7-column case, the results of these 16 runs for the top reflector block are shown in the square below (W_{refl}/W_{out}):

1.238	0.8370	0.6927	0.6097
0.6466	1.251	0.7781	0.6366
0.7172	0.6032	1.244	0.7374
0.8528	0.6693	0.5720	1.234

when W_{refl} is the average flow in the top reflector blocks.

If the antilogs of the average log of the above numbers are taken for each variable remaining constant, the effect of each is separated. Mathematically, the Y_i point is expressed as

$$Y_i = \exp \left[\frac{1}{4} \sum_{j=1}^4 \ln \left(\frac{W_{\text{refl}}}{W_{\text{out}}} \right)_{ij} \right] .$$

The results of this procedure give:

K	F _O	RPF	F _P	Age	F _A
5	1.2418	0.3	0.7710	0	0.8134
100	0.8000	0.8	0.7870	2	0.7956
200	0.6783	1.3	0.8063	4	0.7938
300	0.6073	1.8	0.8365	6	0.7968

These values form the plots for line 1R, the top reflector block, of Figs. 1 through 3. In Fig. 1 (and Figs. 4 and 7), the data on orifice setting were extrapolated using a power factor of 0.8 and an age of 2 years, with three additional FLAC runs using orifice K values of 400, 500, and 600.

A check on the validity of the form of the correlation equation can be obtained by computing the constant of proportionality for all 16 runs and comparing the results:

1.465	1.595	1.595	1.601
1.600	1.570	1.554	1.530
1.592	1.55	1.604	1.506
1.600	1.536	1.502	1.618

If the correlation were perfect, all of the above numbers would be equal. The average is 1.564. Using this value gives an absolute average error of 0.038, a standard deviation of 0.044, and a probable error of 3.06%. It should be kept in mind that this probable error is for the top reflector block, where crossflow is most severe. For subsequent blocks, the probable errors are:

<u>Block</u>	<u>Probable Error (%)</u>
1R	3.06
2R	1.14
3R	0.45
1	0.25
2	0.19
3	0.17
4	0.18
5	0.15
6	0.12

As can be seen, the equation is correlating the results extremely well-- a probable error of only 0.25% at the first fuel block and decreasing for subsequent blocks.

CROSSFLOW FLAC MODELS

Three analytical models were devised: one each for the 7-column, 7-column edge, and 5-column regions. To minimize the flow branches in each network, various channels having similar crossflow characteristics were combined into equivalent flow branches. Each of the three models includes a detailed modeling of a correlating refueling region and additional regions representing the adjacent regions.

7-COLUMN REGION

All 7-column regions not adjacent to the core edge (regions 1 through 19) were represented by the model as shown in Fig. 10. Because of symmetry of this type of region, only one-sixth of the region need be used. Coolant channels comprising this region are channels 4, 5, 6, 7, and the internal gap, channel 8. The remaining channels represent the surrounding regions and associated gaps. Figure 11 shows the vertical flow channel arrangement.

Branch 169 is the inlet orifice to the 7-column region and branch 170 is the equivalent inlet orifice to all surrounding regions. As the orifice loss coefficient was varied upward for branch 169, it was varied downward for branch 170 to keep the core pressure drop constant at about 10 lb/in.². Figure 12 shows crossflow branch interconnections for the first crossflow gap of the top reflector.

To illustrate the logic behind the grouping of many coolant holes into equivalent channels, the following examples are given:

1. Channel 4 (Figs. 10 and 11) represents coolant channels in the 7-column region more than two rows removed from the block edge and communicating by crossflow only with the internal gap.
2. Channel 5 represents coolant holes in the 7-column region in the first and second rows near the block edge and communicating with the internal gap.
3. Channels 6 and 7 are the same as 4 and 5, respectively, except that they communicate with the external gap.
4. Channel 8 is the internal gap.
5. Channel 16 is the external gap between the 7-column region and all adjacent regions.
6. Channel 15 is the internal gap of the adjacent regions.
7. Channel 10 represents coolant holes in all adjacent regions in the outer two rows of a block edge and crossflowing to the common external gap.

7-COLUMN EDGE REGION

In the 7-column edge regions, one-third of the region perimeter faces a side reflector and not other orificed regions, and there are large differential contractions in the blocks adjacent to the side reflector. These conditions eliminate symmetry, and a much more complex model is necessary. Figure 13 is a schematic representation of this type of region. To simulate the larger differential contraction of blocks adjacent to the side reflector, the half facing the reflector was assumed to have no crossflow; i.e., channels 12 and 30 were assumed to have no horizontal interconnections. Channels comprising the 7-column edge region are 4 through 13, and the remainder represent the surrounding regions and associated gaps. Figures 14 and 15 are the vertical and horizontal branch and node schematics as used by the FLAC computer program. Branches 373 and 374 are the orifices of the 7-column edge region and all adjacent regions, respectively.

5-COLUMN REGION

The 5-column regions are similar to the 7-column edge regions but, as an additional characteristic, have only 5 fuel columns. Figure 16 is the schematic for this case, and holes 4 through 13 comprise the 5-column region. The remaining holes represent the effect of all adjacent regions. Figure 17 and 18 are the vertical and horizontal numbering schemes for the node and flow branch hookups as used by the FLAC computer program. Flow branches 313 and 314 are the orifices for the 5-column region and all adjacent regions, respectively.

GENERAL ASSUMPTIONS

Interface gaps of 0.010 in. were assumed for all interfaces including reflector blocks. The K/A^2 values used were taken from Fig. 10 of Ref. 5.

The effect of age is limited to the width of the internal gaps; in general, the older the region, the wider this gap becomes as the blocks

within the region shrink due to fast flux exposure. These widths vary axially since, in general, flux is higher near the core midplane and in the top half of the core. These widths for ages up to 6 years have been calculated (see Table 2) and were used as the age function in the cross-flow models.

In the 7-column edge and 5-column models, it was assumed that the holes on the block half facing the reflector did not have crossflow. This assumption approximates the effect of the wedge-shaped interface gap which forms as a result of larger contractions on the core side of edge blocks.

Heat input to the external gaps is treated in FLAC by assigning axial temperatures to the gaps. These axial temperatures are a function of the radial peaking factors of the regions that bound the gap, shown in Fig. 19.

Only two orifice values were assigned: one to the region for which crossflow was determined and one to the region representing all adjacent regions. As the correlating orifice was adjusted upward, the orifice representing all orifices of adjacent regions was adjusted downward in an attempt to keep core pressure drop constant at about 10 lb/in.²

COMPARISONS BETWEEN POKE AND WHOLE-CORE FLAC CALCULATIONS

As pointed out in the preceding paragraph, the correlation is quite precise for the 7-column, 7-column edge, and 5-column models. The real test, however, is how the results of POKE, using the correlation, compare with the results of the FLAC code for the whole core. The example chosen to make this comparison is the case presented in Table 3, in which orifice setting, radial power factor, and region age are listed in columns 2, 3, and 4, respectively. In the original whole-core FLAC analysis, total flow (and hence the mixed mean outlet temperatures) was correct when the assumed pressure drop was 8.4 lb/in.², the nominal value for the Fort St. Vrain

TABLE 2
DESCRIPTION OF INTERNAL GAPS

	Age of Fuel Region (yr)								External Gap	
	0		2		4		6			
	Width (in.)	Area (in. ²)	Width (in.)	Area (in. ²)	Width (in.)	Area (in. ²)	Width (in.)	Area (in. ²)	Width (in.)	Area (in. ²)
Top reflector	0.053	3.90	0.0957	7.05	0.117	8.62	0.130	9.54	0.207	752
Fuel block 1	0.036	2.65	0.128	9.41	0.168	12.3	0.191	14.1	0.224	844
Fuel block 2	0.037	2.72	0.125	9.18	0.166	12.2	0.190	14.0	0.220	829
Fuel block 3	0.039	2.87	0.0903	6.65	0.116	8.55	0.131	9.66	0.196	714
Fuel block 4	0.037	2.73	0.0694	5.11	0.0854	6.29	0.0948	6.98	0.176	627
Fuel block 5	0.034	2.50	0.0662	4.87	0.0819	6.03	0.0910	6.70	0.173	615
Fuel block 6	0.034	2.50	0.0619	4.56	0.0763	5.62	0.0847	6.24	0.166	588
Bottom reflector	0.033	2.43	0.0515	3.79	0.0613	4.52	0.0670	4.93	0.159	553

TABLE 3

DATA COMPARISONS OF FLAC AND POKE CORE PERFORMANCE CALCULATIONS

										RESULTS OF POKE RECALCULATION OF ORIFICE SETTINGS			
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Region Number	Orifice Coeff	Radial Power Factor	Region Age (Years)	Inlet CFF (FLAC)	Inlet CFF (POKE)	Ratio Cols 5 to 6	T-TBAR (FLAC)	T-TBAR (POKE)	T-TBAR (POKE) No CF	Orifice Coeff With CF	T-BAR with CF	Orifice Coeff No CF	T-TBAR No CF
1	300.00	0.325	1		0.585		-263.1	-340.8	-248.2	300.00	-354.8	300.00	-206.4
2	41.72	1.083	3	1.053	0.971	1.084	35.6	-6.3	-36.6	60.42	43.0	39.40	10.9
3	49.75	1.120	4	0.855	0.937	0.912	35.3	59.4	39.5	53.18	43.0	35.79	10.9
4	72.53	1.036	5	0.775	0.856	0.905	34.8	78.9	97.2	71.03	43.0	44.58	10.9
5	300.00	0.765	6	0.518	0.593	0.873	14.5	189.6	422.4	199.14	43.0	95.72	10.9
6	300.00	0.685	1	0.513	0.594	0.863	-57.6	87.1	299.6	284.12	43.0	123.64	10.9
7	69.72	0.974	2	0.901	0.862	1.045	39.6	18.0	32.8	89.44	43.0	52.60	10.9
8	79.41	0.956	5	0.862	0.833	1.034	39.8	31.7	60.6	95.46	43.0	55.23	10.9
9	97.51	0.919	2	0.833	0.796	1.046	41.5	44.9	99.5	110.14	43.0	61.14	10.9
10	300.00	0.741	6	0.534	0.592	0.902	-2.9	159.9	385.5	220.09	43.0	103.15	10.9
11	14.40	1.425	3	1.170	1.150	1.017	38.6	4.0	-73.9	148.40	43.0	16.01	10.9
12	91.41	0.987	1	0.725	0.718	1.010	31.7	90.9	138.5	84.94	43.0	50.80	10.9
13	40.12	1.185	4	0.909	0.975	0.932	33.5	60.1	21.5	42.81	43.0	30.25	10.9
14	36.38	1.189	2	0.909	1.002	0.907	28.1	41.9	-2.8	42.13	43.0	29.93	10.9
15	38.96	1.200	5	0.893	0.982	0.909	28.7	65.7	23.3	40.56	43.0	29.09	10.9
16	12.50	1.479	3	1.163	1.197	0.971	40.8	9.7	-71.3	17.49	43.0	13.74	10.9
17	191.21	0.855	6	0.588	0.671	0.876	26.4	159.5	314.6	138.84	43.0	73.24	10.9
18	42.91	1.080	4	1.040	0.965	1.078	37.8	-2.7	-31.1	61.07	43.0	39.72	10.9
19	164.86	0.821	1	0.709	0.694	1.021	45.7	79.2	205.5	160.84	43.0	80.86	10.9
20	300.00	0.445	1	0.735	0.743	0.989	-131.2	-309.1	-246.2	300.00	-324.3	300.00	-203.8
21	300.00	0.500	6	0.633	0.551	1.149	-154.3	-186.4	17.1	300.00	-205.8	247.61	10.9
22	300.00	0.516	4	0.645	0.559	1.154	-125.6	-166.9	41.4	300.00	-187.0	231.38	10.9
23	300.00	0.490	2	0.704	0.742	0.948	-88.6	-267.0	-196.0	300.00	-283.8	300.00	-149.2
24	300.00	0.770	1	0.543	0.599	0.9065	26.8	128.7	430.1	230.00	43.0	94.26	10.9
25	12.08	1.466	5	1.176	1.319	0.8915	27.4	41.6	-83.3	14.39	43.0	14.27	10.9
26	17.51	1.103	3	1.190	1.329	0.895	33.5	-210.7	-280.4	93.94	43.0	71.36	10.9
27	37.08	1.190	2	0.943	1.077	0.875	36.2	81.5	3.0	35.98	43.0	29.86	10.9
28	300.00	0.535	6	0.546	0.554	0.985	-158.2	-147.9	70.4	300.00	-168.7	213.98	10.9
29	71.85	0.857	4	0.926	1.053	0.879	41.0	-169.8	-209.4	265.63	43.0	140.70	10.9
30	5.15	1.714	3	1.205	1.486	0.811	21.5	78.7	-57.9	6.29	43.0	6.29	10.9
31	80.00	1.069	1	0.730	0.893	0.817	50.4	142.5	161.1	57.27	43.0	40.88	10.9
32	74.20	0.851	5	0.917	1.035	0.885	42.6	-171.1	-207.0	276.27	43.0	143.18	10.9
33	23.81	1.301	4	1.040	1.162	0.895	28.8	69.1	-39.4	24.57	43.0	22.37	10.9
34	242.28	0.750	2	0.602	0.626	0.962	31.5	57.1	290.5	260.17	43.0	100.28	10.9
35	300.00	0.423	6	0.735	0.718	1.024	-157.0	-335.3	-270.7	300.00	-349.5	300.00	-230.5
36	61.01	1.021	5	0.935	0.929	1.006	46.9	39.2	28.1	73.045	43.0	47.27	10.9
37	16.50	1.349	3	1.190	1.272	1.015	30.6	26.9	-88.3	20.88	43.0	19.69	10.9

reactor. This pressure drop value was also assumed for the new whole-core FLAC analysis where all horizontal gaps were given a width of 0.01 in. The modification to the 0.01-in. gap width caused the flow to increase and the outlet temperature to decrease (to 1442°F from 1496°F) and hence the case no longer represents the condition at an actual operating point. It should, however, provide a useful comparison between the two methods of core calculation. For the FLAC case, the orifice coefficients were adjusted so that the outlet temperatures of as many regions as possible were nearly equal to the outlet temperatures of the high-powered region. (In regions where the orifices are fully closed, taken here to mean $K_{\text{orif}} = 300$, no further control is possible and the outlet temperature may be substantially less than the mixed mean.) This technique for orifice valve adjustment was reasonably successful in producing a coolant exit temperature that was equal for all core regions (it varied from 21.5 to 50.4°F from the mixed mean).

Two methods of comparison of the more complete FLAC results and the POKE approximation were used. The first was to calculate, using POKE, the region-plenum temperature difference using orifice settings identical to those used in FLAC. The second was to use the same radial power peaking factors and the POKE option to calculate the orifice valve coefficients, K , which yield outlet temperatures that are equal in all regions in which orifice control remains. For the first method, exit coolant temperatures obtained with FLAC and POKE should be compared; for the second, orifice settings should be compared. Table 3 entries allow both the temperature and orifice comparisons. When orifice settings are identical, the average difference between FLAC-estimated and POKE-estimated region outlet temperatures is 55°F in regions where the orifice is not fully closed (compare columns 8 and 9 in Table 2). This includes such regions as 17, 26, 29, and 32, where, as can be seen in Table 2, the comparison is quite poor.

When orifice settings are recalculated by POKE, the difference between region outlet temperature and the plenum mixed mean is 43.0°F (column 12)

for all regions in which orifice control remains (orifice not fully closed). This is within the range of values (21.5 to 50.4, column 8) calculated using the original orifice setting assumptions. The new calculated orifice values compare quite well with the original estimates (column 11 vs column 2) with the exceptions of regions 26, 29, and 32, where the POKE-calculated orifice values are much higher. These are the same regions that gave poor comparisons for region outlet temperatures. All of these are 5-column regions, and this indicates that the 5-column region crossflow correlations may not represent the whole-core model as accurately as the 7-column correlation. The average orifice coefficient difference is 27.0 including these three anomalous regions.

DIRECT COMPARISON OF POKE VS FLAC INLET CROSSFLOW FACTORS

To assess the effect of the crossflow factor on calculated outlet temperature, flow rates, and orifice settings, a direct comparison can be made between inlet crossflow factor, W_{1R}/W_{out} , as calculated by the whole-core FLAC and the factor calculated by POKE. These two numbers also appear in Table 2, and their ratio in column 7 of that table is an index as to how accurately this correlation reproduces whole-core FLAC results. For a partially open orifice ($300 > K > 5.15$), this number varies from 0.811 for region 30 to 1.078 for region 18. In regions where the ratio is near 1.0 (e.g., region 12) outlet temperatures compare no better than in other regions. The conclusion that may be drawn here is that non-agreement of temperature results cannot be attributed to nonagreement of crossflow factors alone. The ratio of crossflow factors for the 37 regions is plotted in Fig. 20 vs orifice K value. The shotgun nature of the data indicates that no further flow correction by crossflow factors is possible with existing parameters.

Since the correlation fits the model data so precisely, failure to reach exact convergence to the solution of the system of equations in the correlation model is not likely a contributing factor. The possibility

exists, however, that in some of the crossflow branches of the large whole-core FLAC model, adequate convergence was not reached. This suspicion is confirmed when fully closed regions whose orifices were fully closed ($K = 300$) are observed. Fully closed regions have identical orifice settings and should therefore exhibit similar crossflow characteristics since power factor and age have only a second-order influence. The variation in inlet crossflow factor (W_{1R}/W_{out}), however, is actually very wide--0.513 for region 6 to 0.735 for region 35. The age and power factor functions do not suggest that this wide variation should exist.

PRESSURE DROP CALCULATIONS

Core pressure drop is governed by the region with the wide-open orifice ($K = 5.15$). Flow in this region is greatest but is no more than adequate to give the mixed mean outlet temperature. For the particular case in question, this is region 30. Unfortunately, this region has the poorest agreement between POKE and whole-core FLAC crossflow factors. At inlet, these values are 1.486 and 1.205 for a ratio of 0.811--the lowest of all regions. Since the POKE number represents considerably greater flow in this region, the POKE result should give a correspondingly greater pressure drop and, indeed, this is the case. The 8.4 lb/in.^2 calculated by FLAC is increased to 9.9 lb/in.^2 by POKE. This difference does not represent a universal error to which a correction factor can be applied. There is an additional high-power region, region 11, for example, in which the POKE predicted inlet crossflow factor is less than the factor calculated by FLAC. If region 11 represented the highest power region, the predicted core pressure drop by POKE would be less than that predicted by FLAC.

EFFECT OF CROSSFLOW ON CORE PERFORMANCE CALCULATIONS

Crossflow decreases the ability of the orifice valve to control the region outlet temperatures since these flows enter or leave core regions in paths not directly controlled by the orifice valve. All regions require

a higher degree of orificing and a resulting higher inlet flow in the region with the fully open orifice. More orificing increases the core pressure drop, reduces the outlet temperature in regions of fully closed orifices, and increases the outlet temperatures of regions on which orifice control remains. Columns 11 and 13 of Table 3 list orifice coefficients required for respective cases including and neglecting crossflow. In comparing these columns, the greater degree of orificing in the crossflow case is evident. Columns 12 and 14 are deviations of region outlet temperatures from the mixed mean for respective cases including and neglecting crossflow. When crossflow is neglected, a much more uniform outlet temperature is possible--in regions where control remains, the outlet temperature is 11°F above the mixed mean in lieu of 43°F when crossflow is accounted for. The pressure drop decreases from 10.6 to 9.0 lb/in.²

The difference of 32°F will, of course, be reflected in the fuel temperature; crossflow causes a 32°F increase in the fuel temperature at the core outlet. In addition to this, the lower flow rate will cause a lower heat transfer coefficient and a further increase in fuel temperature. To illustrate the total effect of crossflow on fuel temperature, Fig. 21 shows fuel temperature profiles for a high-power and a low-power channel, both with and without crossflow. At the core exit, the fuel temperature in the high-power regions has risen from 1870°F to 1913°F, a 43°F increase. In general, this will be true at the exit for all regions whose orifices are not fully closed. For this particular region, it is interesting to note that the highest temperature does not occur at the outlet but at the core midplane, and at this point, crossflow has actually reduced the maximum fuel temperature by 22°F. The two lower curves of Fig. 21 show the effect of crossflow on fuel temperatures in regions with fully closed orifices. In this case, the already low fuel temperature of 1485°F is further reduced to 1230°F.

CONCLUSIONS

The crossflow factors derived by utilizing simple, easily converged FLAC models give crossflow factors that are consistent with the three parameters on which the crossflow correlation is based: orifice setting, radial power factor, and age.

Comparisons between a whole-core FLAC model and the POKE model utilizing the correlation agree well in most but not all regions. This has been attributed to the probable lack of complete convergence in data from the whole-core FLAC model.

NOMENCLATURE

A_i	cross sectional area of flow hole in block i
CFF_z	crossflow factor defined in Eq. 1
C_z	constant in correlation of CFF given in Eq. 2
D_i	diameter of flow hole in block i
f_i	friction factor of coolant hole in block i
F_A	correlating factor dependent on region age. The age function is given in Figs. 3, 6, and 9.
F_O	correlating factor dependent on region orifice K value. The orifice function is given in Figs. 4, 7, and 20.
F_P	correlating factor dependent on region power factor. The power factor function is given in Figs. 5, 8, and 10.
K	orifice coefficient, $\Delta P_O/q_c$
K_{inlet}	pressure loss coefficient associated with entrance into flow hole
K_{exit}	pressure loss coefficient associated with exit from core to bottom plenum
L_i	length of block i
ΔP	pressure drop across core
ΔP_O	pressure drop across orifice valve
q_c	velocity head in coolant hole at reflector inlet
K/A^2	lumped variable derived from flow experiments on small gaps between graphite blocks. A is not easily defined, but K/A^2 for various gap widths is given in Fig. 10 of Ref. 5.

T or T_{out}	region outlet temperature
T_i	temperature in axial block i of a region
T_{in}	inlet temperature, °F
TBAR	core mixed mean outlet temperature, °F
W_z	flow rate in axial block z of a region, lb/hr
W_{out}	flow rate at outlet of a region, lb/hr
W_{refl}	flow rate, average, in the top reflector of a region, lb/hr
W_{1R} or W_{in}	flow rate at inlet to a region, lb/hr
ρ_1	coolant density at inlet

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Fig. 1. Function F_o vs orifice coefficient (7-column region)

Fig. 2. Function F_p vs power factor (7-column region)

Fig. 3. Function F_A vs age (7-column region)

Fig. 4. Function F_o vs orifice coefficient ($7 \leftarrow$ column edge region)

Fig. 5. Function F_p vs power factor (7-column edge region)

Fig. 6. Function F_A vs age (7-column edge region)

Fig. 7. Function F_o vs orifice coefficient (5-column region)

Fig. 8. Function F_p vs power factor (5-column region)

Fig. 9. Function F_A vs age (5-column region)

Fig. 11. Schematic of vertical flow channels (7-column region)

Fig. 12. Schematic of crossflow connections at each fuel element interface (7-column region)

Fig. 13. Schematic of coolant channel representation (7-column edge region). Channels 4 through 13 represent flow channels for the 7-column edge region; the remainder represent surrounding regions. Coolant channels 12 and 30 have no crossflow interconnections.

Fig. 14. Schematic of vertical flow channels (7-column edge region)

Fig. 15. Schematic of crossflow connections at each fuel element interface (7-column edge region)

Fig. 16. Schematic of coolant channel representation (5-column region). Channels 4 through 13 represent flow channels for the 5-column region; the remainder represent surrounding regions. Flow columns 13 and 24 have no crossflow interconnections.

Fig. 17. Schematic of vertical flow channels (5-column region)

Fig. 18. Schematic of crossflow connections at each fuel element interface (5-column region)

Fig. 19. Bypass exit gas temperature vs region radial peaking factor

Fig. 20. Ratio of FLAC to POKE inlet crossflow factors vs orifice setting

Fig. 21. Effect on temperature of crossflow in high- and low-powered regions