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**ANALYSIS OF THE MULTICOLUMN FLOW
DISTRIBUTION TEST DATA**

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ABSTRACT

Tests were made to determine the flow characteristics of an orificed core for an HTGR reactor of the type designed for the Public Service Company of Colorado (PSC). The tests were made to determine the effects of crossflow within the core on the ability of the orifices to maintain a uniform coolant outlet temperature from the core. The crossflow is due to a nonuniform graphite contraction of the individual fuel blocks caused by irradiation. The test specimen consisted of a 0.45 scale model simulating 3 fuel regions out of the 37 fuel regions in the prototype and 6 side reflector columns. The multicolumn flow model had a dual purpose:

1. Determine the flow and pressure distribution in the simulated portion of the core, including the effects of crossflow.
2. Evaluate the possibility of flow-induced vibrations in the simulated core.

This report deals only with the flow distribution part of the program; the results of the investigation of flow-induced vibrations are present in Ref. 2.

The main results obtained with the flow model test can be summarized as follows:

1. No crossflow at the block interfaces was detected for fuel elements without simulated graphite contraction.
2. An appreciable amount of crossflow was found in the top reflector region equalizing the pressure between the fuel elements and the orifice cavity. In a region orificed for minimum flow, this crossflow amounted to about 55% of the total outlet flow from the region.

3. An appreciable crossflow was found in the fuel elements with simulated graphite contraction. In a region orificed for minimum flow, the crossflow at the top reflector was 22% of the total outlet flow from the region. Crossflow at the block interfaces amounted to 40% of the total outlet flow.
4. An analytical model was derived for correlating the flow model tests. The agreement between test results and analytical results is within 10%. The analytical model can be used to extrapolate the test results to prototype conditions.

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1. INTRODUCTION

The core of the 330 Mwe PSC High Temperature Gas-cooled Reactor consists of 37 refueling regions which are orificed to produce a uniform gas outlet temperature. A typical fuel region consists of 7 fuel element columns, with each column comprised of 6 fuel elements and 6 reflector elements, 3 at the top and 3 at the bottom. Some of the coolant flow bypasses the primary coolant channels via the clearance gap between fuel element interface gaps which are caused by a nonuniform graphite contraction due to irradiation. The magnitude of crossflow is proportional to the degree of orificing required to achieve uniform coolant outlet temperature. In the PSC reactor, the region orifices create lateral pressure differentials up to 8 psi.

Crossflow in the core tends to decrease the effectiveness of the region orifices. Considerable effort has been made to analyze the effect of crossflow on the flow distribution with orifices at the inlet at the core; however, the analysis has suffered from lack of a realistic description of the crossflow paths. Therefore, two experiments were designed to produce quantitative information on the crossflow characteristics of the core. The first was to investigate the crossflow between individual coolant holes and the bypass channel between fuel elements via the block interfaces. The second was to investigate the gross crossflow between refueling regions and to serve as a check on the analytical methods for predicting crossflow in the core. This report describes the latter of the two experiments.

The specific objectives of the experiment were as follows:

1. Determine the core pressure drop characteristics as a function of flow so that an accurate prediction of core pressure loss in the reactor can be made.
2. Determine the magnitude of bypass flow and crossflow in the core associated with 3 different flow mechanisms:

- a) Bypass flow in gaps between fuel element columns.
 - b) Crossflow through gaps at the interfaces of fuel element blocks within a given column and region.
 - c) Gross crossflow between fuel regions which are orificed for different flow rates.
- 3. Determine the magnitude of bypass flow and crossflow in the core as a function of simulated nonuniform graphite contraction over core lifetime.
 - 4. Determine the degree to which the flow distribution in the test rig can be predicted and correlated by available analytical methods.

2. SUMMARY OF RESULTS

The results of the multicolumn flow distribution test are summarized in the following paragraphs.

1. The smooth tube friction correlation for the flow in the coolant holes and in the bypass gaps resulted in the best agreement with the test data. In addition, no additional pressure losses for misalignment of the coolant holes and/or gaps was detected. Curves of friction factor vs. Reynolds number are shown in Figs. 12 and 13 for the coolant holes and bypass gaps, respectively.
2. The fraction of flow which bypasses the coolant holes varies in a complex way with axial location and with the amount of simulated gap at the fuel element interfaces. With the 3 regions orificed for maximum, average, and minimum flow, the flow entering the external bypass gaps is approximately 40% of the total flow through the rig. About 50% of this flow enters the internal bypass gaps below the keyed top reflector block. A portion of the flow entering the internal bypass gaps flows upward into the orifice cavity, joins with the orifice flow, and subsequently flows down the coolant holes. This effect is most pronounced in regions orificed for a reduced flow. With the unshimmed core configuration (graphite contraction not simulated), crossflow at the fuel block interfaces could not be detected within the accuracy of the experiment. The source of the flow rate entering the 3 regions without the effects of simulated graphite contraction is as follows:

Orifice Settings	Flow Mechanisms	Fraction of Region Outlet Flow		
		Region A	Region B	Region C
1. All orifices full open	Inlet orifice	.87	.86	.82
	Crossflow in top reflector	.13	.14	.18
2. A=max. flow B=avg. flow C=min. flow	Inlet orifice	.87	.70	.45
	Crossflow in top reflector	.13	.30	.55

No gross crossflow between fuel regions was observed. The source of crossflow was the flow entering the external bypass gaps which subsequently feeds the fuel regions orificed for reduced flow.

- With shims placed under selected fuel elements to simulate the effects of nonuniform graphite contraction, an appreciable crossflow was detected at the fuel element interfaces. The source of flow rate entering the 3 regions in the shimmed configuration is as follows:

Orifice Settings	Flow Mechanisms	Fraction of Region Outlet Flow		
		Region A	Region B	Region C
1. All orifices full open	Inlet orifice	.87	.83	.82
	Crossflow in top reflector*	.10	.09	.11
	Crossflow at block interfaces*	.03	.08	.07
2. A=max. flow B=avg. flow C=min. flow	Inlet Orifice	.94	.63	.38
	Crossflow in top reflector*	.06	.15	.22
	Crossflow at block interfaces*	.00	.22	.40

* Note: The proportion of crossflow in the top reflector and at the block interfaces could not be determined directly from the experiment. Therefore, the reported results are based on the analytical model.

4. The results obtained with an analytical model designed to simulate the actual test flow model compare rather favorably with the measured data. In general, the agreement between the test and the analytical results is within about 10%.

3. EXPERIMENTAL METHOD

The basic approach of the experiment was to perform tests on a scaled model of a partial core which was geometrically and fluid dynamically similar, insofar as possible, to the reactor. Air at atmospheric pressure was circulated through the model to simulate the flow of helium in the reactor. Various reactor operating conditions were simulated by varying the air flow rate through the model and by providing different size gaps at the interface of individual fuel element blocks. The gaps between fuel element columns were adjusted to simulate 3 different fuel ages for the 3 fuel regions. The model instrumentation was designed to measure pressure and flow distribution in prescribed coolant channels and in the gaps between columns.

The scaling parameters affecting the fluid dynamic similitude of the model to the prototype are based on matching the following: (1) Reynolds number in the gaps; (2) Reynolds number in the coolant channels; and (3) leakage perimeter of the coolant holes along the outer edge of the block (assuming that leakage from a coolant hole remote from the gap is negligible). Considering the capabilities of the existing GGA flow model facility, it was not possible to match all three similarity requirements simultaneously and some compromise had to be made. The degree of similitude that can be achieved utilizing the GGA flow model facility is shown in Table 1.

Although similitude of the model to the prototype is not exact, it is believed to be sufficiently close so that the results will be applicable. Of the 4 quantities to match, the parameters which fall appreciably short of the objective are the gap Reynolds number and the relative fraction of cross-sectional flow area represented in bypass gaps. Generally, if the flow is clearly in the fully developed turbulent regime (e.g., Reynolds number greater than 10^4), the flow distribution is not strongly dependent on Reynolds number. When this is true, a Reynolds number match within 50% is generally acceptable. For the reactor conditions, the Reynolds number

Table 1

Degree of Similitude for the Flow Distribution Test

Conditions, model-to-reactor:

Block Scale Factor	.45
--------------------	-----

Fluid Dynamic Test Conditions:

Total air flow rate through model	13 lb/sec max.
Overall pressure drop across model	4.5 psi max.
Pressure drop across a wide open orifice	0.3 psi
Coolant holes per block	30
Maximum number of columns with internal flow channels	21

Degree of Similitude, model-to-reactor:

Reynolds No. in coolant channel	.89
Reynolds No. in gaps	.41
Leakage perimeter of coolant holes	~ 1.0
Relative fraction of cross-sectional flow area represented in bypass gaps	~ 3.0

(Note: For ideal similitude, each of the above ratios should be 1.0)

in the coolant channels varies between 1.6 and 5.4 times 10^4 . Therefore, flow similarity in the coolant holes is approximately satisfied. For the gap flow, the estimated Reynolds number at reactor conditions is approximately 5500, and for the model approximately 2400. This difference indicates that similarity for the gap flow may be marginal. However, analysis of the test data indicates that there is a relatively large uncertainty in the size and distribution of the bypass gaps. It is believed that the effects of this uncertainty are considerably greater than the effects of lack of similarity in the Reynolds number. In addition, the test results on the crossflow in the fuel element interfaces indicated that the pressure loss coefficients for crossflow were essentially independent of the flow in the gaps. Therefore, the fluid dynamic similarity in the model is considered to be reasonably satisfied. The fact that the fraction of cross-sectional flow represented in bypass gaps is much larger in the flow model than in the prototype means that the effects of crossflow are more pronounced in the model. However, the difference is corrected, in principle, by development of a satisfactory analytical model.

Basic flow measurements consisted of the total flow through the rig, the flow through the inlet orifice of each of three 7-column regions, and the flow in the discharge duct of each of the 21 columns. Pitot-static probes at the discharge end of the bypass gaps indicate the relative axial flow rate in the gaps between columns. Static pressure measurements in the gap along the length of the column and along the length of selected coolant holes determine a pressure gradient (dP/dz). Knowing the flow rate at one point in the channel and the pressure gradient along the full channel length is sufficient to determine the flow rate at any point. Information of this type in different regions of the model is then compared to determine which gaps are gaining or losing flow.

The gross crossflow from region to region cannot be determined by direct measurements in the model. However, two methods are available for evaluating gross crossflow indirectly. The first is to compare the flow input to each region (measured by the calibrated inlet orifice) vs.

the flow output (measured by the calibrated pitot-static tube in the discharge duct of each column). The second is to utilize the static pressure gradient (dP/dz) to determine local flow rate in a channel. The magnitude and direction of crossflow can be calculated or inferred by making an overall flow balance at several stations.

The determination of gross crossflow by the above methods is subject to numerous uncertainties. Each method may be expected to yield results with a precision of no better than $\pm 10\%$.

4. APPARATUS AND INSTRUMENTATION

4.1 DESCRIPTION OF THE MULTICOLUMN FLOW MODEL

The flow model installation comprises a model of a portion of the core as shown in Fig. 1, the air supply system, and the data acquisition system. The core model comprises a cluster of 27 core element columns (fabricated to a scale factor of 0.45) including top and bottom reflector, inlet orifice controls and control rod guide tubes, core support blocks and posts, and exit plenum. The top of the model is open to the atmosphere. Two blowers in series draw air downward through the model and subsequently discharge the air to the atmosphere. A plan view of the model is shown schematically in Fig. 2. Three 7-column fuel regions are shown in the figure with the remaining 6 columns consisting of simulated reflector elements. A column is comprised of 12 blocks, 3 blocks simulating the top reflector, 6 blocks simulating the active core length, and 3 blocks simulating the bottom reflector. The 3 fuel regions and the 6 side reflector elements are surrounded by the sidewalls, which simulate the core barrel as illustrated in Fig. 3. Each fuel region is equipped with an orifice to control the coolant flow into the region. The dimension across the flats of a fuel element are different in each region and at various axial locations. The dimensions are sized to reproduce the graphite contraction due to irradiation represented by a 0, 3, and 6-year old region.

Each fuel element column has 30 coolant holes which are arranged in a double row along the fuel element perimeter. The center column of each region is unique in that some of the 30 coolant holes are distributed around the perimeter of control rod holes. The 30 coolant holes merge into one hole in the bottom reflector and the coolant leaves each fuel column through the dump tube into the lower plenum. The top blocks are keyed together in order to maintain a stable system and to restrict the inlet gaps to fixed dimensions. Dowel pins are installed at the block

interfaces to prevent misalignment of the coolant holes from one block to the next one. Each 7 column fuel region rests on top of a core support block. The core support blocks are sized to simulate hot reactor dimensions. The simulation of the contracted graphite blocks was established with shims placed under selected fuel elements in the rig.

A typical view of a 7 column region with the orifice mechanism removed is shown in Fig. 4. An overall view of the multicolumn rig is shown in Fig. 5.

4.2 INSTRUMENTATION IN THE FLOW MODEL

Instrumentation in the flow model consisted of the following types: calibrated flow meters, static pressure taps, total pressure probes, displacement sensors and thermocouples.

Twenty-six different flow rates were measured. The three adjustable inlet orifices were each calibrated to measure flow rate as a function of angle of opening and pressure drop. The overall accuracy of the calibration was estimated at $\pm 5\%$. The total flow through the test rig was measured with two calibrated venturi meters in parallel with an estimated accuracy of $\pm 1\%$. The 21 discharge flows from the model core element columns were each measured by a calibrated pitot-static probe in the dump tube. It was found that the individual dump tube calibrations were dependent on the particular orientation of the fuel element transition block which merged the 30 coolant holes into a single outlet. This indicated that the flow in the dump tube was not fully developed. Therefore, each transition block was identified with its corresponding calibration, which is estimated to be $\pm 3\%$.

A total of 67 pitot-static probes and 104 static pressure taps were installed at a fixed position in the test rig. These numbers include the taps in the orifice cavities, in the simulated core regions, and in the discharge holes (dump tubes) of each region. In addition to the fixed pressure taps, a movable rake was provided with 20 static pressure taps. The rake could be placed in any axial position above a plane located 40

inches above the core support structure. For a detailed layout of the pressure taps excluding dump tube and venturi pressure taps, see Engineering drawings 90-SK-838-G and 90-SK-856-C. A top view of the model with instrumentation installed is shown in Fig. 6.

The accuracy of the static and pitot-static pressure measurements is ± 0.05 psi and ± 0.005 psi for the transducers rated at 5. psi and 0.5 psi, respectively. However, the recording of the data is less accurate than the reading ability from the pressure transducers. An explanation of this will be given later in the text.

Two different kinds of displacement sensors were used in the test, one with an accuracy of ± 0.001 inch and the other with an accuracy of ± 0.002 inch. The accuracy of the displacement sensors was not significantly influenced by the recording mechanisms. The location of the probes can be seen in the drawings mentioned previously.

Six copper-constantan thermocouples were installed in the test rig to measure air temperature. The thermocouples measured room temperature, inlet temperature at 2 of the orifice valves, outlet plenum temperature at 2 places, and the temperature at the main flow venturi meters. All the temperature measurements were within $\pm 2^\circ\text{F}$ of the room temperature and, therefore, did not influence the mass flow calculation.

4.3 DATA ACQUISITION

For each test run, all the data, such as the specified flow conditions, specified orifice settings, specified movable rake position, and the measured pressures, temperatures and fuel block displacements, were punched on paper tape by means of the data acquisition system. The output from the transducers and the potentiometers were recorded on a multichannel digital recorder. The recorder reads the data channel and punches the data on one paper tape and prints them onto a second one.

A Scanivalve system was used to provide rapid sensing and sequencing of the pressure measurements. The Scanivalve system consists

of 6 valves in which each valve rotates through 64 sensing ports per one revolution. The time to make one complete revolution can be adjusted; however, it was found that a minimum cycle time from one port reading to the next was about 2.5 seconds in order to insure true steady state conditions of each pressure reading. In the test model 5 valves were used. Valve numbers one and two were connected to a single sensitive transducer to record differential pressure between the 2 valve ports. This was used to measure the dynamic pressures, which had a maximum value of about 0.5 psi. The accuracy of the velocity head transducer was ± 0.005 psi except for the initial set of runs (runs 1 through 13 of Table 1) which had an accuracy of ± 0.02 . Valves 3, 4, and 5 were used for the static pressure measurements. At each port the same four transducers were used to convert the actual pressure reading into a voltage reading by means of the digital voltmeter. The accuracy of the voltmeter data recording was ± 0.05 mv which resulted in a static pressure inaccuracy of ± 0.015 psi. The transducers which measured the static pressures indicated the gage pressure relative to the atmosphere. In the pressure differential transducer, the total pressure was referenced to the static pressure of the probe and was, therefore, independent of the atmosphere. The voltage reading of the transducer was fed into the data acquisition system and punched and printed onto the paper tapes.

5. EXPERIMENTAL RESULTS

5.1 DATA REDUCTION

In order to handle the large amount of data generated in each test run, a computer program called MULTI was written in FORTRAN IV for the Univac 1108. A total of 306 milli-volt readings were punched on paper tape by the data acquisition system for each test run. These data were first transposed onto magnetic tape by the IBM 360. The magnetic tape was then used together with the program MULTI to perform the data reduction. The data reduction procedure in the MULTI code is as follows:

- a) Read and check the paper tape data and transform the raw data.
- b) Convert the thermocouple readings into temperatures, the potentiometer readings into relative displacements of the blocks, and the transducer readings into pressures.
- c) Calculate mass flows in the dump tubes, and velocities in coolant holes and gaps. Perform an overall mass balance in the test rig.

A rather frequent occurrence was to discover mispunched, missing, or too many characters on the paper tape. Different versions of the MULTI code had to be written to overcome these errors. The basic method of correcting errors on the paper tape was to replace the data which were in error with additional data cards. Most of the time the punch errors occurred in channel identifications which were not used by the program; however, that data was marked as an error element and had to be treated as such.

By means of calibration equations, the corrected set of data was converted into temperatures, displacements and pressures for the thermocouples, potentiometers and transducers, respectively.

Mass flow rates were found by applying calibration equations to the flow in the venturi meter, the inlet flow through each orifice and the outlet flow through each dump tube. The difference of total venturi meter flow and total orifice flow was the gap flow at the model inlet; the difference of total venturi meter flow and total dump tube flow was the gap flow at the test rig outlet. Based on the total pressure readings, the velocity and the mass flux were calculated in the coolant holes and gaps. It was not possible to calculate the actual mass flow in the gaps since the gap area, which is representative for the pressure pickup, is not known. Further, the total pressure probes in the gaps and coolant holes were not calibrated.

5.2 DISCUSSION OF TEST RESULTS

The experimental results consist of tabulated mass flow balances and several figures showing pressure distribution as a function of axial height above the core support floor for a number of flow conditions and for two core arrangements. The two core arrangements represent, respectively, a core with no shims under the fuel blocks and a core with shims placed under a selected number of blocks to simulate the effect of nonuniform graphite contraction. In both arrangements, the bypass gap system in the region was identical and simulated 0, 3- and 6-year old fuel regions. These results are summarized in Tables 2 and 3 and Figs. 8 through 11.

The significance of the test results is not readily apparent from a study of the Tables and Figures. Because of the complex nature of the experiment, the large number of variables that interact to produce a certain observed effect, and the fact that precise measurements are available for only a few gross effects, the significance of the test results were arrived at by deduction and by a careful application of fluid flow principles to the test data. In the following paragraphs those results which are relevant to the performance of the PSC reactor and/or of value in design are discussed in detail.

The core pressure drop characteristic in the coolant holes was determined for different Reynolds numbers. It was assumed that no cross-flow at the flock interfaces occurred and, therefore, the coolant flow in the coolant holes is constant from the top to bottom of the test rig. The validity of this assumption is demonstrated in Figs. 8 and 9 where the axial static pressure distribution in the coolant holes is plotted.

In the figures, no pressure gradient change was found in the coolant holes and no pressure drop due to momentum change could be detected at the interfaces. Based on the equation,

$$\frac{dp}{dz} = \frac{f}{d_h} \left(\frac{m}{A} \right)^2 \frac{1}{2 \rho g_c}, \quad (1)$$

where f = friction factor, $f = f(\text{Re})$
 d_h = hydraulic diameter (constant)
 m = mass flow rate
 A = coolant hole area (constant)
 ρ = gas density

it can be stated that the mass flow is constant with a constant pressure gradient $\frac{dp}{dz}$.

Since Reynolds number, $\text{Re} = \frac{m}{A} \frac{d_h}{\mu}$, is not affected by the static pressure, the friction factor is constant along the channel length. The decrease in air density with increasing probe insertion depth should cause an increase in the pressure gradient. Further, crossflow from the gaps into the coolant holes should increase the pressure gradient. The static pressure change from 13.5 to 11.5 psia with constant mass flow results in a pressure gradient change of

$$\frac{dp}{dz} (13.5) : \frac{dp}{dz} (11.5) = 1 : 1.17 .$$

Since the measured pressure gradient is constant, it must be concluded that in order to compensate for the density change crossflow should occur from the coolant holes into the gaps. This is not possible since, as shown in Fig. 8, the pressure in the gap is higher than in the coolant holes. No change in pressure gradient was detected; therefore, the mass flow in the coolant holes was constant from top to the bottom.

It was further assumed that the mass flow distribution through the coolant holes within one fuel element is uniform. Therefore, the mass flow in an individual hole is equal to the dump tube flow divided by the number of coolant holes in the element. The coolant holes are geometrically identical except for possible small changes in the alignment of coolant holes from one block to the next; however, this effect was not detected. A possible perturbation to the uniform flow split could be due to a different entrance angle of the flow into the coolant holes, but this was assumed to be a second order influence and, therefore, was neglected.

In Fig. 12 the friction factors are plotted vs. Reynolds number for some of the runs listed in Table 1 for two instrumented fuel elements per region. It can be seen that a significant scatter of the data exists, and that about half of the friction factor values are smaller than that obtained by the smooth tube friction correlation. It was therefore concluded that the friction correlation for smooth tubes may be applied to the test rig, and that losses due to misalignment of the fuel elements may be neglected.

The flow area represented by bypass gaps is not as well defined as the coolant hole flow area because the distribution of gap dimensions is not precisely known. For the purpose of calculating the pressure drop characteristics of the bypass flow, a theoretical gap area was determined from a number of considerations which are discussed in a subsequent section of this report. However, one consideration relevant to this discussion is that the theoretical gap area is sized so that the friction pressure losses correspond to smooth tubes. Thus, the theoretical gap area represents a

minimum area since additional pressure loss influences would require a larger flow area than that for smooth tube. In addition, it was assumed that the gap area was uniformly distributed at each axial elevation.

From Figs. 8 and 9 it can be seen that the static pressure gradient in the external and internal gaps is nearly constant over the length of the active core. Slight variations in the pressure gradient can be seen; however, these are attributed to a change in gap area at the first, third, and tenth block from the top of the rig. In the vicinity of the top few blocks, relatively large changes in pressure gradient occur due to crossflow which equalizes the pressure in the external and internal gaps. This crossflow will be described in more detail in a subsequent section of this report. For the purpose of determining the pressure drop characteristics of the bypass flow, only those data over the constant flow length were analyzed.

Figure 13 shows results of friction factor vs. Reynolds number in the bypass gaps. At large Reynolds numbers (greater than 4000) the friction factor is essentially that based on smooth tube data. In the laminar flow regime (Reynolds number less than 2500) the data points fall considerably higher than the theoretical curve,

$$f = \frac{64}{Re} .$$

However, at low flows the data are less reliable due to the limited sensitivity of the instrumentation. The general conclusion is that the core pressure drop characteristics can be correlated by smooth tube friction factors within the accuracy of the experiment.

5.4 CROSSFLOW WITHOUT SHIMS

In Table 2 the overall mass balances are shown for a selected number of test conditions. Additional runs with lower flows were also made. However, the accuracy of the inlet orifice calibration was such that

Table 2

Summary of Overall Flow Balance Without Shims (lb/sec)

Run	Total Flow	Orifice Setting			Orifice Flow			Dump Tube Flow			External Gap Inlet	External Gap Outlet	ΔP Rig (psi)
		A	B	C	A	B	C	A	B	C			
1	6.59	Max.	Max.	Max.	1.92	2.08	1.90	2.06	2.07	2.03	.70	.43	1.47
2	6.55				1.99	2.00	1.92	2.06	2.07	2.03	.64	.39	1.45
3	6.49				1.94	2.05	1.87	1.93	1.95	1.92	.62	.69	1.45
4	7.02				1.91	2.03	1.84	2.02	2.05	2.01	1.22	.93	1.46
5	8.76				2.39	2.38	2.24	2.51	2.51	2.44	1.75	1.31	2.23
6	8.85				2.49	2.38	2.25	2.48	2.52	2.44	1.73	1.40	2.25
7	8.31				2.35	2.31	2.29	2.62	2.62	2.52	1.36	.57	2.24
8	10.38				2.71	2.67	2.62	3.01	3.01	2.97	2.38	1.39	3.11
9	10.43				2.66	2.67	2.53	2.96	3.03	2.93	2.56	1.50	3.11
10	10.32				2.71	2.64	2.57	2.99	3.03	2.94	2.37	1.36	3.15
11	12.43				3.10	3.08	2.85	3.56	3.61	3.48	3.39	1.77	4.44
12	12.39				3.14	3.04	2.87	3.54	3.57	3.51	3.35	1.78	4.43
13	12.44				3.08	3.10	2.87	3.55	3.58	3.51	3.40	1.80	4.43
14	3.09		Avg.	Min.	1.11	.716	.424	1.09	.787	.647	.843	.509	.42
15	3.12				1.19	.718	.424	1.09	.796	.643	.780	.590	.42
16	3.07				1.14	.715	.423	1.09	.779	.636	.797	.568	.42
17	7.74				2.39	1.49	.807	2.73	2.03	1.63	3.04	1.34	2.45
18	7.77				2.49	1.49	.806	2.74	2.04	1.64	2.98	1.35	2.45
19	7.81				2.43	1.50	.806	2.74	2.04	1.64	3.08	1.39	2.45
20	9.63				2.92	1.80	.924	3.35	2.52	2.03	3.99	1.74	3.72
21	9.62				2.94	1.79	.923	3.35	2.50	2.02	3.96	1.75	3.71
22	9.70				2.98	1.81	.927	3.36	2.53	2.04	3.97	1.75	3.76
23	10.40				3.25	1.91	.972	3.68	2.74	2.21	4.27	1.78	4.64
24	10.50				3.22	1.91	.970	3.68	2.75	2.23	4.39	1.84	4.64
25	10.58	Max.	Avg.	Min.	3.16	1.91	.971	3.71	2.77	2.26	4.53	1.85	4.64
26	9.55	Min.		Max.	.959	1.82	2.66	1.97	2.53	3.40	4.11	1.65	3.95
27	9.68	Min.	Min.		.981	.974	2.95	2.13	2.31	3.71	4.77	1.53	4.09
28	5.7	Max.			1.83	.579	1.52	1.80	1.11	1.76	1.77	1.01	1.10

the uncertainty in the flow rate at low flows was quite large; e.g., in some runs the flow through the external gaps at the inlet and the gaps at the outlet were calculated to be negative which is, of course, not possible.

For two orifice settings, (1) all orifices wide open, and (2) orifice A set for maximum flow, B for average flow, and C for minimum flow, a pressure scan with the movable pressure rake was performed. The flow was set to maximum blower capacity (see Table 2 Runs 11 and 23). The static pressures in the coolant holes and gap as designated in Fig. 7 were plotted in Figs. 8 and 9 vs. the axial rig dimension.

The pressure distribution was obtained from the fixed instrumentation and movable pressure rake from the bottom of the rig to the 40-inch elevation, and from the 40-inch elevation to the top of the rig, respectively. The data from the fixed and the movable pressure probes agreed quite well.

From these figures it must be concluded that crossflow from one fuel region into another, or from one fuel element into another, cannot occur. The static pressure in the gaps surrounding the fuel element is everywhere higher than the coolant hole pressure, i.e., if crossflow occurs at the interfaces, then the direction of flow must be from the bypass gaps to the coolant holes. The preponderance of data indicates that this type of crossflow did not occur.

From Figs. 8 and 9, it can be seen that the pressure gradient in the coolant holes is constant and, therefore, as explained in the results section, "Core Pressure Drop Characteristics," no crossflow occurs at the block interfaces. An exception to this result was found in column B1 (see Fig. 9), which was orificed for average flow. From Fig. 9, it can be seen that an abrupt change in slope of static pressure vs. axial length occurs at the interface between the 3rd and 4th fuel blocks. This is attributed to the following. An eccentric motor was installed in the 3rd fuel block. This motor interfered with two of the coolant holes which were immediately adjacent to the instrumented coolant hole (B1). These coolant holes were plugged in the top three fuel blocks but were left open to flow

in the lower blocks. Sufficient crossflow occurred at the block interface to cause a local redistribution of the flow in coolant holes in the bottom half of the rig. This situation was corrected for the runs with shims by plugging the affected coolant holes above and below the motor.

The static pressure gradient in the bypass gaps is also seen to be constant over the major length of the rig. Further, the static pressure in the external bypass gaps and internal bypass gaps becomes equal within the top three reflector blocks, and remains equal throughout the remainder of the rig. An external gap refers to the bypass gap between the refueling regions and is open directly to the plenum above the core, while internal gaps refer to bypass gaps within a 7-column cluster which are open to the plenum below the orifice can. The constant pressure gradient in the bypass gaps supports the conclusion that no crossflow occurs at the block interfaces. In the bottom reflector region, the static pressure gradient in the gaps is not constant. Data points are spaced too far apart to deduce an accurate curvature of the pressure characteristic; however, it is most likely that the variation in pressure gradient is due to a change in the flow resistance and due to a change in the flow rate. This is particularly true since the flow in the inner gaps must find its way into the external gaps in order to exhaust into the lower plenum.

A unique situation occurs in the top reflector region. The pressure gradient in the internal gaps is reversed from that of the external gaps indicating that the direction of flow is upward. In addition, the pressure gradient in the external gaps is about 3.5 times as great in the top reflector block as in the active core. This implies that about 55% of the flow which enters the external gaps finds its way into the internal gaps within the top reflector region. This can occur only below the top keyed reflector blocks since the clearance around the keys is very small compared to the average clearance between columns. The negative pressure gradient in the internal gaps indicates that part of the flow which entered the internal gap via the external gap flows upward into the orifice cavity and ultimately joins the flow down the coolant holes. This effect is most

pronounced in the fuel regions which are orificed for minimum flow, e.g., Region C in Fig. 9.

The amount of crossflow between the external and internal gaps could not be determined on the basis of static pressure gradients alone because the cross-sectional flow areas are not precisely known. The indicated crossflow may be found from the difference between the flow in the dump tubes and the flow entering the inlet orifice. In the case of all orifices full open (Runs 11-13, Table 2), the net crossflow under the orifice cans amounted to 14% of the flow through the region. In the case of three inlet orifices set for maximum flow, average flow and minimum flow, respectively (Runs 23-25, Table 2), the net crossflow under the orifice cans amounted to 13%, 31%, and 56%, respectively.

5.5 CROSSFLOW WITH SHIMS

In order to simulate the effects of nonuniform graphite contraction due to irradiation, shims were placed under selected fuel elements. The nonuniformity of the contraction is greatest in the fuel elements located near the side reflector since the gradient in fast flux is quite large at the core-reflector interface. For the flow tests, the location and thickness of shims that were installed in the model are shown in Fig. 14. Table 3 presents a summary of the overall mass flow balances for the most important test runs. Runs 1-15 present data for 5 different flow conditions, each flow condition consisting of 3 test runs to determine the repeatability of test results. Runs 16-24 present data for special test conditions which were designed to verify some of the conclusions concerning crossflow in the rig.

Detail static pressure surveys were made with the movable pressure rake for two test conditions, one with all orifices set at full open, and one with the three orifices set for maximum flow, average flow and minimum flow, respectively. The results are shown in Figs. 10 and 11. The solid lines in the figures represent the pressure distribution in the

coolant holes whereas the points which are not connected represent the pressure distribution in the gaps. The location of instrumentation in plan view is shown in Fig. 7.

A study of the static pressure distribution in Figs. 10 and 11 shows that crossflow did occur in the rig and that the relative magnitude and location of the crossflow can be deduced from the local pressure gradients. The key results may be summarized as follows:

1. The pressure in the gaps is generally higher than the pressure in the coolant holes indicating that the direction of crossflow is from the bypass gaps into the coolant holes.
2. The pressure gradient in the coolant holes in columns which did not contain shims was constant indicating that no crossflow occurred at the fuel element interfaces.

The relative magnitude of the crossflow can be deduced from the change in pressure gradient that occurs at a particular block interface. For example, in Region C the pressure gradient is increased after each block interface with shims. The abrupt loss in static pressure at each interface is attributed to the momentum change due to flow addition into the coolant hole. As discussed in the section called "Core Pressure Drop Characteristics," the pressure gradient in a channel may be defined,

$$\frac{dp}{dz} = \frac{f}{d_H} \left(\frac{m}{A} \right)^2 \frac{1}{2 g_c \rho} = K m^2 \quad (2)$$

In the analysis of the test results the parameter K is assumed to be constant for all elevations. This is approximately true since, generally, f and ρ both decrease from top to bottom in the test rig. The crossflow at each interface in Region C was calculated from Eq. (2) as a fraction of the coolant hole inlet flow. The results are as follows:

S_1	S_2	S_3	S_4	S_5
$0.08 m_{in}$	$0.12 m_{in}$	$0.08 m_{in}$	$0.19 m_{in}$	- - -

where m_{in} = coolant hole inlet flow from the orifice cavity

S_1 to S_5 = shim locations as shown in Fig. 10

Applying the momentum equation to the flow in a coolant hole with crossflow at an interface (see sketch below) gives:

$$P_{1s} - P_{2s} = \frac{m_2^2 + 2m_2 m_1}{A^2 \rho} \quad (3)$$

Sketch for Crossflow at Interface

where

- P_{1s} = static pressure upstream of interface
- P_{2s} = static pressure downstream of interface
- m_1 = mass flow upstream interface
- $m_2 = c m_{in}$ = crossflow
- c = crossflow fraction; values for Region C are given in the preceding table
- ρ = average fluid density

The calculated values for $P_{1s} - P_{2s}$ always turned out to be less than the values obtained from the measured pressure distribution. This is probably due to the fact that the coolant hole inlet flow is determined only by the pitot-static probe in the top reflector block which was not a calibrated measurement.

From Fig. 11 it can be seen that, at an elevation below shim S5, the static pressure gradient in the gaps close to the fuel elements with shims is in the direction indicating upflow in these gaps. There are a sufficiently large number of data points to confirm this effect, however, on physical grounds, it must be concluded that the upflow can occur only in localized regions. In addition, the pressure pickups may not be giving a true indication of static pressure since lateral flow in the gaps contribute a total pressure component to the pressure readings.

It may be noted that some of the gap pressures shown on Fig. 11 are lower than the coolant hole pressures in Region A, indicating that crossflow can occur from the coolant holes into the gaps. However, the pressure distribution in the coolant holes in fuel Region A indicated that no crossflow occurred.

At the top portion of the core, the pressure gradient in a coolant hole with shims in Region C is very flat (see Fig. 11) indicating very small flow rate. It is possible that, within a region which has some fuel elements with large interface gaps, reverse flow (upflow) can occur in the coolant holes.

Tests were run with an inlet orifice completely closed in order to investigate the limiting case for crossflow in the test rig. The inlet orifice for Region C was completely sealed with rubber tape to avoid any flow entering the orifice cavity from the top. The results are summarized in Table 3, Runs 19-22. The mass flow which was found in the dump tubes in Region C was due entirely to crossflow. The crossflow into a closed region with shims amounted to 54% of the outlet flow in an unshimmed region with a wide open orifice. The crossflow in a closed region without shims amounted to 31% of the outlet flow in a shimmed region with a wide open orifice. Crossflow under the top reflector block keys and into the orifice cavity probably occurs in a region with wide open orifice. From Table 3 Run 19, it can be seen that the net flow out of Region A is greater than the flow through the inlet orifice, 3.63 vs. 3.23 lb/sec. Since Region A did not have shims, the evidence is sufficiently strong to conclude that crossflow did not occur at the fuel element interfaces, but must have occurred under the top reflector keys.

The crossflow under the top reflector block keys was qualitatively confirmed by injecting colored smoke in some of the external gaps close to a closed orifice. Traces of that smoke were found under the orifice cans at the inlet of the coolant holes and at the inlet of the internal gap.

Another test was then performed with a pitot-static probe. The probe was lowered into the internal gaps for different orifice settings. The results obtained with this method demonstrated that upflow in the internal gaps occurred down to about 8, 12, and 14 inches below the top of the orifice cans for the orifice settings corresponding to maximum, average, and minimum flow, respectively. Since the keys in the top block extend 7 inches below the top of the orifice cans, readings below this point are subject to error because the direction of the velocity vector is not known. With another probe the velocity vector was determined just below the keys and it was found that the velocity vector was horizontal.

Table 3

Summary of Overall Flow Balance With Shims (lb/sec)

Run	Flow	Orifice Setting			Orifice Flow			Dump Tube Flow			External	External	ΔP Rig (psi)		
		A	B	C	A	B	C	A	B	C	Gap Inlet	Gap Outlet			
1	13.00	Max.	Max.	Max.	3.12	2.77	2.65	3.49	3.76	3.59	4.45	2.16	4.47		
2	12.94	↓	↓	↓	3.13	2.80	2.69	3.48	3.76	3.62	4.32	2.09	4.47		
3	12.96				3.16	2.87	2.54	3.49	3.74	3.60	4.38	2.12	4.42		
4	3.21				Avg.	Min.	1.08	.637	.401	1.05	.881	.778	1.09	.507	.39
5	3.29				1.01	.630	.398	1.04	.888	.780	1.24	.569	.38		
6	3.28				1.04	.630	.397	1.06	.890	.793	1.21	.545	.38		
7	5.20				1.69	.982	.519	1.71	1.44	1.27	2.01	.784	1.00		
8	5.22				1.71	.991	.523	1.71	1.44	1.27	2.00	.806	1.01		
9	5.24				1.67	.988	.522	1.72	1.45	1.29	2.07	.787	1.01		
10	7.82				2.31	1.37	.711	2.54	2.15	1.87	3.42	1.25	2.16		
11	7.82				2.35	1.37	.710	2.55	2.15	1.86	3.39	1.26	2.18		
12	7.85				2.31	1.37	.711	2.55	2.16	1.87	3.47	1.28	2.16		
13	10.68				3.22	1.86	.944	3.53	2.91	2.53	4.65	1.71	4.72		
14	10.68	3.27	1.86	.948	3.55	2.94	2.50	4.61	1.70	4.72					
15	10.77	3.23	1.85	.950	3.56	2.95	2.45	4.74	1.80	4.70					
16	9.626	Min.	↓	Max.	.953	1.69	2.51	1.89	2.82	3.37	4.48	1.54	3.80		
17	10.22	↓	Min.	↓	.977	.955	2.90	2.17	2.62	3.65	5.39	1.77	4.72		
18	11.76	Max.	Max.	Min.	3.14	2.92	.941	3.58	3.79	2.50	4.75	1.89	4.60		
19	10.44	↓	Avg.	Closed	3.23	1.87	0.	3.63	3.02	1.97	5.33	1.82	4.70		
20	9.30	Avg.	↓	↓	1.98	1.89	0.	2.68	2.98	1.92	5.44	1.72	4.71		
21	10.03	Closed	↓	Max.	0.0	1.84	2.87	1.16	3.09	3.68	5.43	2.12	4.71		
22	8.29	↓	↓	Avg.	0.0	1.87	1.84	1.07	2.88	2.82	4.59	1.53	4.80		
23	3.83	↓	Closed	Closed	0.0	0.0	0.0	.643	1.11	1.14	3.83	.931	1.97		
24	3.44	↓	↓	↓	0.0	0.0	0.0	.534	1.05	1.08	3.44	.774	1.97		

5.6

CONCLUDING REMARKS ON THE FLOW MODEL TEST RESULTS

In general, it was found that two types of crossflow occur in the test rig: crossflow at the fuel element interface gaps, and crossflow under the top reflector block keys which subsequently flows upward in the internal gaps into the orifice cavity and down the coolant holes. The latter crossflow, shown schematically in Fig. 15, was the larger of the two. In addition, the latter crossflow is manifested at the very top of the fuel element columns while crossflow in the interfaces is a more gradual effect occurring over the whole length of the column. Therefore, it appears that corrective design action may be most fruitful if directed toward eliminating the crossflow between the external and internal bypass gaps. For example, the following methods may be worth investigating to accomplish this objective:

1. Install a flow restriction at the inlet to the external gaps.
2. Provide much longer keys to contain the external gap bypass flow further down into the core. In this way, the pressure drop of the flow path consisting of downflow in the external gaps and upflow in the internal gaps could be greatly increased.

Because of the complicated flow patterns in the orifice cavity, a possibility exists that the calibration of the core region inlet orifices is not valid for the conditions encountered during the test. The pressure pickup for the orifice flow determination is placed in a closed hole as shown in Fig. 15. At the time when the orifice calibration was performed the external gap inlets were sealed and no crossflow under the top reflector block keys occurred. However, when this crossflow occurs and there is upflow in the internal gaps into the orifice cavity, the flow pattern in the orifice cavity is changed. With a changed flow pattern, the calibration of the orifice may shift. The influence is more pronounced with closed orifices since the crossflow into the orifice is much larger than the flow through the orifice. It is believed that a possible shift in the orifice calibration cannot be large enough to change the basic conclusions from the test.

The quantitative crossflow results discussed in the preceding sections are not directly applicable to the PSC prototype conditions. This is primarily due to the fact that the fraction of total flow area represented by bypass gaps is considerably larger in the flow model than in the prototype, 0.25 vs. 0.09. Therefore, an analytical model of the flow network represented by the test rig was developed. Once confirmation of the analytical model is obtained with the flow model tests, the model can be applied to flow distribution analyses of the prototype. The analytical model was developed by using the FLOPSY computer code,⁽³⁾ which computes the flow distribution in flow networks on the basis of a constant density fluid.

The analytical flow network, which resulted from several iterations at correlating the experimental results, is shown in Figs. 16 and 17. The coolant hole area from each fuel region was divided into 4 vertical flow paths. Two flow paths simulated the coolant holes facing the internal gap system, and two flow paths simulated the coolant holes facing the external gap system. The two flow paths facing each gap system were used in order to simulate the shimmed and unshimmed fuel elements. Each coolant hole flow path was divided into 12 segments simulating the 12 blocks per fuel element column. The bypass gap system was divided into 3 internal and 3 external gap flow paths with 12 segments in each path. The internal gaps are connected to the appropriate orifice cavity to simulate the bypass flow. In Fig. 17, the connection branches from the bypass gap system to the coolant hole flow paths and from the internal to the external bypass gaps are shown for the top block only. However, similar connection branches are applicable to all the downstream block interfaces. The internal gap within each region is connected to its corresponding external gap, and the 3 external gaps are connected to each other at each block interface.

The coolant hole area in each flow line is well defined. An uncertainty in the gap area exists because the gap area determined from the engineering drawings did not agree with the gap area determined from

pressure gradients in the gap system. The external gap area was then determined by the following methods:

1. All the gap thicknesses at the top of the model were measured and multiplied by the gap length.
2. A static pressure scan was made along the top reflector block with all the orifice inlets closed with rubber tape. Based on the total flow measurement through the gaps and the friction correlation for smooth tubes, the external gap area was calculated.
3. Based on the static pressure gradient in the gaps along fuel blocks 4 through 10 in Fig. 8 and the friction correlation for smooth tubes, the total gap area was calculated. Since no crossflow occurred, the gap outlet flow was equal to the gap flow along these blocks.
4. A theoretical gap area which gave the best apparent correlation of the flow distribution calculated by the FLOPSY code with the measured flow distribution of test runs shown in Figs. 8 through 11.

A summary of the gap areas determined by the above methods is shown in Table 4. It can be seen that the gap area determined by the above methods is generally larger than the area based on dimensions shown on the engineering drawings. In order for the test results to be consistent with basic fluid dynamic principles, it was concluded that the actual flow area must be larger than that determined from the engineering drawings. Therefore, the values of bypass area which gave the best fit with the FLOPSY results was used for the analytical model.

In the analytical model, pressure loss coefficients of 0.2 and 1.0 were applied to the inlet and outlet, respectively, for the coolant holes, and loss coefficients of 0.3 and 1.0 were applied to the inlet and outlet, respectively, for the bypass gaps. The loss coefficients for the orifices were determined such that the orifice flow matched the values obtained in the flow model. This was done by calculating the static

Table 4

Summary of Possible Bypass Gap Areas in the Flow Model

Gap Area (in ²) Determined by Various Methods					
Block Number	Dimensions on Eng. Drawings	Gap Measurement at Top of Rig	$\left(\frac{dP}{dz}\right)$ Along Top Reflector Block	$\left(\frac{dP}{dz}\right)$ Along Blocks 4-10	Best Fit Using FLOPSY
1 (Top)	34.23	38.8	55.8	45.6	43.6
2-3	19.20	23.8	40.8	30.6	28.6
4-10	24.96	29.6	46.6	36.4	34.4
11-12	16.56	21.1	38.1	28.0	25.9

pressure in the orifice cavity based on the measured static and total pressure at the coolant hole inlets. The loss coefficients for crossflow at the fuel element interfaces were based on test results from a loss coefficient experiment on a full scale model of an interface between 2 fuel elements.⁽¹⁾ The crossflow loss coefficients were determined as a function of interface gap height and are included in this report in Fig. 18. For the newly machined fuel elements a gap width of 0.001 in. was chosen. For the case with the shims, the gap thickness was set equal to the shim thickness. It should be noted that the data for the crossflow loss coefficients include a rather large scatter as shown in Fig. 18. In the analytical model, a best fit of the multicolumn test data was found by using the largest crossflow loss coefficients of Fig. 18. This does not imply that the multicolumn test results can be used to better define the crossflow loss coefficients because the placement of shims created an effective crossflow path slightly different from that expected in the prototype. For all the vertical flow channels (including bypass gaps) the friction correlation for smooth tubes was used. The hydraulic diameter for the bypass gap system was determined as follows:

$$d_H = \frac{4A_G}{P_G}$$

where A_G = bypass gap area
 P_G = wetted perimeter

The wetted perimeter comprises the sum of all the fuel block perimeters plus the inside tank perimeter.

Four flow model test runs were investigated with the analytical model. The run conditions were those as presented in Figs. 8 through 11, and included results on both the shimmed and unshimmed core configurations. A comparison of the overall mass balances obtained from the experiment and the analysis is as shown in Table 5. The theoretical total mass flow through the rig is slightly higher than the test values when the momentum

Table 5

Comparison of Flow Model Test Results with Analytical Results
Flow Rate, lb/sec

Flow Path Description	No Shims		No Shims		With Shims		With Shims			With Shims		
	Analysis Model 1	Test, Run 12 Table 1	Analysis Model 1	Test, Run 23 Table 1	Analysis Model 1	Test, Run 1 Table 3	Analysis Model No.			Test, Run 13 Table 3	Analysis Model 2	Test, Run 19 Table 3
							1	2	3			
Crossflow Under Top Reflector Keys												
A	.35		.21		.38		.31	.19	.21		.17	
B	.35		1.02		.35		.94	.43	.44		.44	
C	.32		1.29		.43		1.18	.52	.53		.71	
Orifice A	3.23	3.14	3.61	3.25	3.29	3.12	3.51	3.35	3.44	3.22	3.45	3.23
B	3.23	3.04	1.81	1.91	3.30	2.77	1.81	1.86	1.87	1.86	1.94	1.87
C	3.29	2.87	.96	.97	3.09	2.65	.91	.96	.95	.94	.01	.00
Total Crossflow at Interfaces												
A	.15		.03		.13		-.04	.08	-.01		.02	
B	.14		.24		.29		.49	.65	.68		.66	
C	.14		.38		.28		.79	.91	1.01		1.37	
Dump Tube												
A	3.73	3.54	3.85	3.68	3.79	3.49	3.78	3.62	3.64	3.53	3.63	3.63
B	3.72	3.57	3.07	2.74	3.84	3.76	3.23	2.94	2.97	2.91	3.03	3.02
C	3.74	3.51	2.63	2.21	3.81	3.59	2.87	2.39	2.50	2.53	2.08	1.97
Total Flow	12.88	12.39	11.1	10.40	13.13	13.00	11.36	10.42	10.56	10.68	10.04	10.44
Gap Inlet	3.14	3.35	4.72	4.27	3.45	4.45	5.13	4.25	4.29	4.65	4.75	5.34
Gap Outlet	1.69	1.78	1.61	1.78	1.68	2.15	1.42	1.38	1.43	1.71	1.37	1.82

Table 5, continued

Flow Path Description	No Shims		No Shims		With Shims		With Shims			With Shims		
	Analysis Model 1	Test, Run 12 Table 1	Analysis Model 1	Test, Run 23 Table 1	Analysis Model 1	Test, Run 1 Table 3	Analysis Model No.			Test, Run 13 Table 3	Analysis Model 2	Test, Run 19 Table 3
							1	2	3			
Dump Tube Flow Minus Orifice Flow												
A	.49	.40	.242	.43	.51	.27	.27	.27	.20	.31	.19	.40
B	.49	.53	1.261	.81	.64	.99	1.42	1.08	1.12	1.05	1.10	1.15
C	.46	.64	1.672	1.23	.61	.83	1.96	1.43	1.54	1.58	2.08	1.97
ΔP Test Rig [psi]	4.42	4.42	4.64	4.64	4.47	4.47	4.72	4.72	4.72	4.72	4.71	4.71

NOTES

1. The pressure loss coefficients used in the 3 analytical models are as follows:

	Model No.	
	1	2 and 3
Coolant Hole Inlet	0	.2
Dump Tube Exit	1.0	1.0
External Gap Inlet	.25	.3
Gap Exit	1.0	1.0
Loss Factor for Crossflow in the Top Reflector	0	3.0

2. In Model 1, all momentum change losses were neglected.
3. In Model 2, all momentum change losses due to mass flow addition were considered.
4. In Model 3, the momentum change losses due to mass flow addition were considered only for the shimmed fuel columns.

change due to mass flow addition is neglected. When the momentum change losses were included in the theoretical model, the theoretical total mass flow came out slightly less than the measured test values. A possible explanation for the discrepancy in the measured and calculated mass flow is that the gap area in the test was not uniformly distributed as assumed in the analytical model.

For a given test rig pressure difference, the mass flow in a uniformly distributed bypass gap is less than for the case of a nonuniform bypass gap distribution. Measurements of gap thickness at the top of the core indicated bypass gap thickness ranging between 0.04 and 0.16 inches. With variations in bypass gap dimensions of this size, a larger than predicted mass flow rate in the test rig should be expected. No effort was made to incorporate a nonuniform bypass gap dimension into the analytical model since there is no way to determine the true gap dimensions in the interior of the core.

From the theoretical results, it was noted that crossflow occurs in fuel element interfaces in the unshimmed fuel regions as well as in the shimmed fuel regions. The experimental data indicated that no crossflow occurred at the fuel element interfaces in the unshimmed fuel regions. Apparently, the experimental data were not sufficiently accurate to detect the small crossflow rates. For example, in Region C, which had its inlet orifice set to minimum flow, the theoretical crossflow at an interface with no shims was typically the order of 0.009 lb/sec. This amounted to 1.5% of the flow in the coolant holes upstream of the interface. Therefore, the limiting crossflow at the interfaces that could be detected in the test must be greater than approximately 2%.

Table 5 presents a comparison of the predicted and measured mass flow rates in various flow branches in the test rig. The significant results from the table are as follows. In the case with all orifices full open and no shims, the predicted gross crossflow of about 0.49 lb/sec consisted of about 0.35 lb/sec crossflow under the top reflector keys and 0.14 lb/sec crossflow at the block interfaces. This compares favorably

with the measured gross crossflow of about 0.54 lb/sec. In the case where the orifices were set at maximum, average, and minimum flow, respectively, the predicted gross crossflow also compares reasonably well with the measured crossflow. However, the predicted crossflow tended to be slightly higher than the measured values. For example, in Region C which had its orifice set for minimum flow, the calculated gross crossflow was 1.67 lb/sec out of a total dump tube flow of 2.63 lb/sec, whereas the measured crossflow was 1.23 lb/sec out of a total dump tube flow of 2.21 lb/sec. The calculated gross crossflow of 1.67 lb/sec consisted of .38 lb/sec at the interfaces and 1.29 lb/sec under the top reflector keys. A similarly fair agreement between analysis and test was found with the shimmed core configuration. With all 3 orifices at full open, the predicted gross crossflow per region was about 0.60 lb/sec vs. 0.70 lb/sec measured. In the case of a shimmed core configuration with different orifice settings, the agreement between the analysis and test was improved when the additional pressure losses due to mass flow addition were included in the analysis. Generally, the calculated crossflow under the top reflector keys was larger than the crossflow at the fuel block interfaces in all regions, even with the shimmed core configuration. However, when the corrections to the pressure drop equation were added for mass flow addition, the calculated crossflow at the interfaces became the larger contributor to the overall crossflow. For example, in Region C which has its orifice set for minimum flow, the calculated gross crossflow was 1.96 and 1.43 lb/sec for the uncorrected and corrected pressure losses, respectively.

In summary, the discrepancies between the calculated and measured flows that appear in Table 5 tend to be in the range of 10% or less. Isolated examples of larger discrepancies appear to be the order of 20%.

A detailed presentation of the calculated crossflow at the fuel block interfaces is shown in Table 6. The results do not appear to display any unusual patterns. The most significant observation is that the axial gradation of crossflow into a given region is not at all systematic.

Table 6

Calculated Cross Flow for Shimmed
Fuel Blocks at the Fuel Block Interface
Flow Rate, lb/sec

Axial Shim Location Between Blocks	Run 1 ⁽¹⁾ Table 3 Fuel Region		Run 13 ⁽²⁾ Table 3 Fuel Region		Run 13 ⁽²⁾ Table 3 With Momentum Change Correction Fuel Region	
	B	C	B	C	B	C
4 and 5	.006	.029	.081	.120	.079	.125
5 and 6	-.005	.022	.098	.181	.106	.193
6 and 7	.008	.017	.060	.146	.087	.164
7 and 8	.037	.039	.052	.130	.094	.158
8 and 9	.040	.041	.042	.004	.071	.094

NOTES

- (1) All orifices set at full open.
- (2) Orifice settings as follows: Region A = max. flow,
Region B = average flow, Region C = min. flow.

Figures 19a and 19b show the calculated total pressure distribution for the simulated test runs presented in Figs. 8 and 9. It should be noted that the test measurements were obtained as static pressures; however, FLOPSY code calculates only total pressures. The dynamic pressures in the bypass gap and the coolant hole of Region A is about 0.07 psi and 0.5 psi, respectively. Taking this into account, the calculated pressure distribution compares favorably with the measured distribution.

Figures 20a, 20b, and 20c show the calculated total pressure distribution for the conditions corresponding to the test runs shown in Figs. 10 and 11, i.e., the shimmed core configuration. The agreement between the calculated and measured pressure distributions is generally good. However, a rather large discrepancy exists between the calculated and measured pressure distribution in the bypass gaps. For example, test results indicate a rather large transverse pressure gradient in the external gaps, about 0.9 psi maximum, while the analysis indicated a negligible transverse pressure gradient, about 0.05 psi. This difference cannot be explained by correcting for the dynamic pressure in the bypass gaps. It is possible that due to the limited number of flow paths in the analytical model, a large transverse pressure gradient is not detected. It is also possible, since the scatter in the pressure readings was quite large in these runs, that the pressure probes were giving faulty readings.

Figure 20c shows the total pressure distribution plotted for the case shown in Fig. 20a after including coolant hole inlet losses and momentum change losses. The results compare very favorably with the test results shown in Fig. 11.

In summary, the analytical results generally compare favorably with the measured data. The approximation of using constant average density in the analysis did not appear to have a strong adverse affect on the agreement between the analytical and test results. The largest uncertainty in deriving the analytical model is the flow geometry and the pressure loss characteristics. The bypass flow gaps are not well defined in the physical model. The evidence from the combined results of the analysis and test

gives strong support to the conclusion that the bypass gap area is much larger (approximately by a factor of 1.4) than predicted from the engineering drawings. The analysis indicates that the bypass flow area could even be larger, since the friction pressure losses were based on smooth pipe and no additional losses were assumed for possible misalignment of the coolant holes.

The effect of having reverse flow in the internal bypass gaps in the top reflector region may affect the calibration of the inlet orifices. The magnitude of this effect cannot be determined from the multicolumn test data. It is believed that the effect is probably small except perhaps near the full closed orifice setting.

6. REFERENCES

1. Malek, G. J., Gulf General Atomic, Inc., "Crossflow Loss Coefficient Test," unpublished data.
2. Prevenslik, T., Gulf General Atomic, Inc., "Analysis of Core Vibration Test Data," unpublished data.
3. Strain, B. L., "FLOPSY II - A Digital Computer Program for Calculating Flows and Pressure Drops in Hydraulic Networks," General Electric Co., Knolls Atomic Power Laboratory, Schenectacy, N. Y., Report No. KAPL-3030 (1965).

Fig. 1 - Schematic of multi-column flow model

Fig. 2 - Cross section schematic of test rig

Fig. 3 - Top view of model showing bottom reflector region

Fig. 4 - Top view of 7-column region with orifice removed

Fig. 5 - Overall view of flow model

Fig. 6 - Top view of the flow model

NOTE:

1. Data symbols correspond to results plotted in Figs. 8 through 11.

A = Fuel Region A

B = Fuel Region B

C = Fuel Region C

R = Side reflector elements

Fig. 7 - Schematic showing location of static pressure probes on the movable rake

Fig. 9 - Static pressure distribution with no shims, different orifice settings

Fig. 12 - Friction factor vs. Reynolds number for coolant holes

Fig. 13 - Friction factor vs. Reynolds number for the bypass gap system

Axial location between block	Shim thickness [in]	
	B3,B4,B5 C3,C4,C5	Reflector
4 and 5	1/32	1/64
5 and 6	1/16	1/32
6 and 7	1/16	1/32
7 and 8	1/16	1/32
8 and 9	1/32	1/64

Fig. 14 - Schematic showing location of shims

Fig. 15 - Sketch of inlet orifice and vicinity showing various flow paths into a fuel region

The numbers in this drawing refer to the main flow lines on Fig. 17

Fig. 16 - Vertical flow line description for analytical model

Fig. 17 - Network of analytical model

Fig. 18- Crossflow Loss Coefficient Factor for a 1/6 Fuel Element Sector

Fig. 19(a) - Calculated total pressure distribution without shims

Fig. 20(a) - Calculated total pressure distribution with shims

Fig. 20(c) - Calculated total pressure distribution with shims

NOTES:

1. Conditions correspond to Test run 13, Model 2, Table 5.
2. Orifices A, B and C = opened, half-opened and closed, respectively.
3. The dotted line at the coolant hole inlet shows the inlet loss into the coolant holes.

6. REFERENCES

1. Malek, G. J., Gulf General Atomic, Inc., "Crossflow Loss Coefficient Test," unpublished data.
2. Prevenslik, T., Gulf General Atomic, Inc., "Analysis of Core Vibration Test Data," unpublished data.
3. Strain, B. L., "FLOPSY II - A Digital Computer Program for Calculating Flows and Pressure Drops in Hydraulic Networks," General Electric Co., Knolls Atomic Power Laboratory, Schenectady, N. Y., Report No. KAPL-3030 (1965).