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NOZZLE STALL IN SAVANNAH RIVER REACTORS

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NOZZLE STALL IN SAVANNAH RIVER REACTORS

by

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ABSTRACT

Observed changes in the distribution of coolant to assemblies in the C reactor at Savannah River suggested that there was flow separation in the plenum inlet nozzles. Experiments with a water table model of a plenum nozzle and its associated vane system showed that the nozzle directs flow into the plenum with a tangential component. Tests with the reactor system confirmed that changes in plenum flow distribution are caused by alternate modes of nozzle stall. The stall mode is determined by the order of bringing pumping systems on line during reactor startup. Once the flow pattern is established, it remains stable unless deliberately perturbed. The different nozzle design used in K and P reactors promotes a more uniform flow distribution.

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INTRODUCTION

Heavy water coolant is distributed among the fuel assemblies in a Savannah River production reactor by a large flat manifold, or plenum, at the top of the reactor. In C reactor, the distribution of coolant is not uniform, and the distribution pattern occasionally has changed from that most often observed to one symmetrically opposite. The changes in the distribution pattern are caused by flow separation on alternate sides of the diverging nozzles supplying the plenum. This report describes an experimental investigation of this phenomenon. The results show that inlet nozzle flow disturbances can have an important effect on systems employing a large header supplying many assemblies; the results also show the extent to which studies reported in the literature on simple nozzles can be applied to more complex designs such as Savannah River nozzles.

THE REACTOR FLOW SYSTEM

An elevation view of a Savannah River reactor tank and associated piping is shown schematically in Figure 1. Heavy water coolant enters the plenum chamber at the top of the reactor through six nozzles and is distributed to a large number of tubular fuel assemblies (Figure 2). The coolant flows downward through the assemblies and is discharged into the bulk moderator tank. The effluent D_2O is removed from the bottom of the reactor tank through six nozzles, pumped through six pairs of heat exchangers, and returned to the plenum chamber. The discussion in this report will focus on the plenum inlet nozzles and the distribution of flow in the plenum.

The reactor plenum is approximately 18 ft in diameter, but only 8.75 in. high. It is filled by cylindrical permanent sleeves 5.25 in. in outside diameter, spaced 7 in. center to center in a triangular array. Coolant flows into each sleeve through three narrow slots, 5/16 by 8.75 in., as shown in Figure 2. A plenum inlet nozzle for C reactor, shown in Figure 3, has a flattened conical shape, diverging in the horizontal plane, and converging slightly from entrance to exit in the vertical plane. The cross-sectional area continuously increases. The entrance of a nozzle is circular, 15 in. in diameter, and is flanged to the 15-in. supply line from the pump. The exit plane is 8.75 in. high to match the plenum height and 48 in. wide. As shown in Figure 3, there are three vanes in each nozzle. The leading edges of the vanes begin a short distance downstream of the entrance.

Irregularities have been noted in the flow to certain assemblies in C reactor plenum. Fuel assemblies in the vicinity of the plenum nozzles have required special flow restrictors to assure equal coolant distribution. Without adjustment, flow to some assemblies would be higher than predicted; flow to others would be lower. Placing appropriately size orifices in individual assemblies is the most convenient correction. However, on several occasions, after the pumps had been started but before nuclear startup, assemblies which first required orifices to restrict flow now had abnormally low flow. Conversely, unrestricted assemblies now had very high flows, as much as 40% higher than normal. If the pumps were shut down and restarted one by one in another order, the assembly flows would revert to those for which the assemblies were orificed.

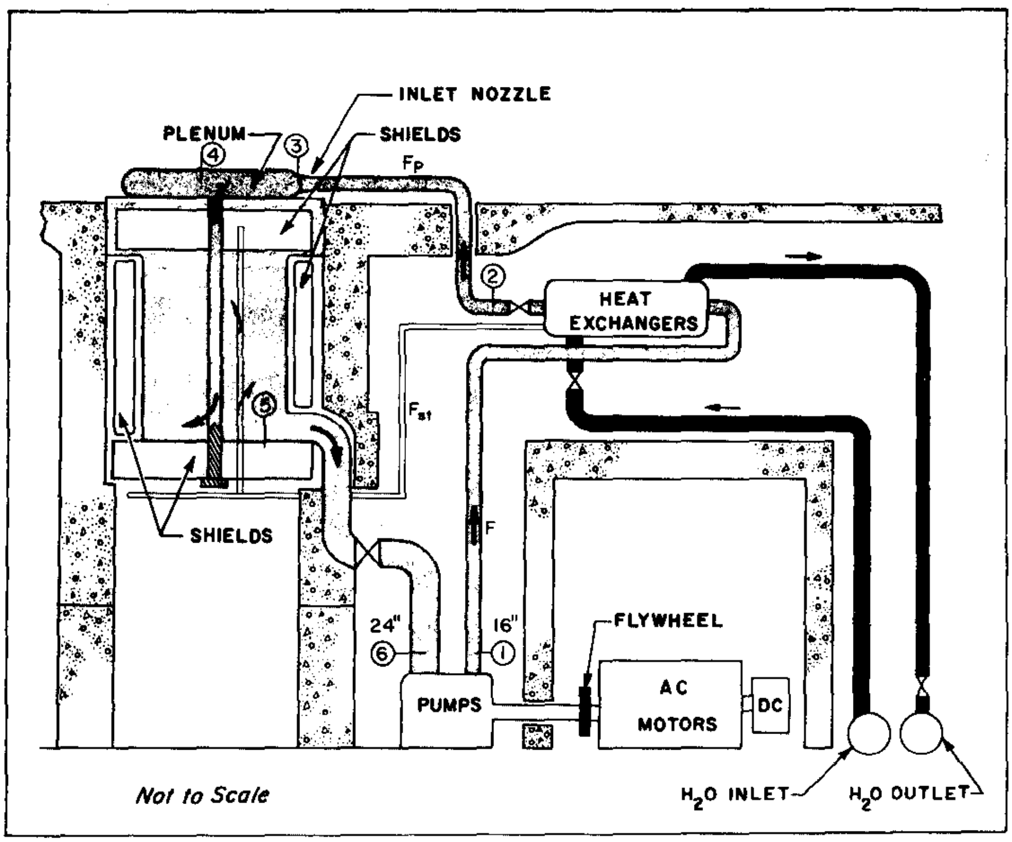


FIG. 1 ELEVATION SCHEMATIC OF REACTOR FLOW SYSTEM

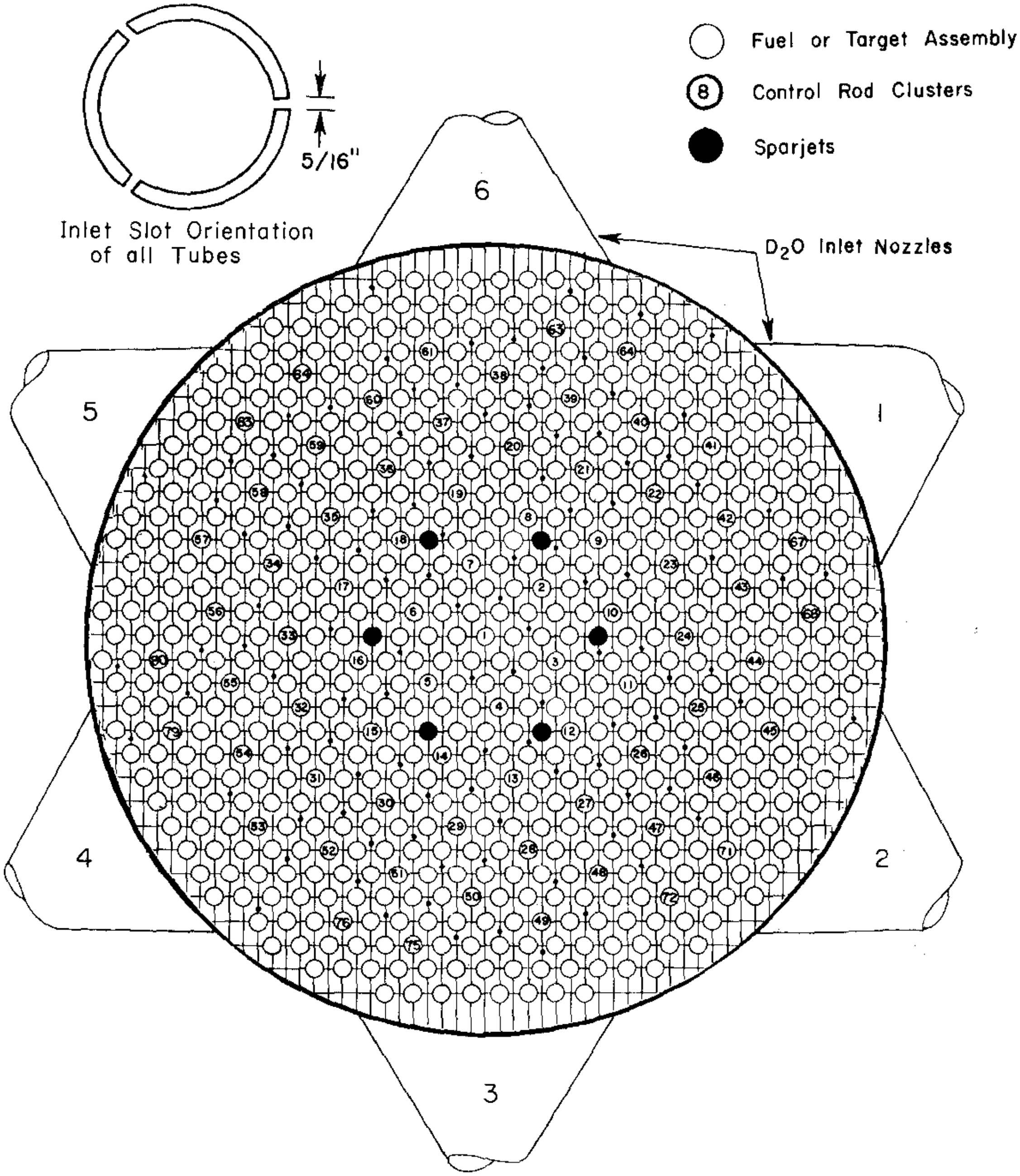


FIG. 2 PLAN VIEW OF REACTOR PLENUM, SHOWING TUBE PATTERN AND NOZZLES

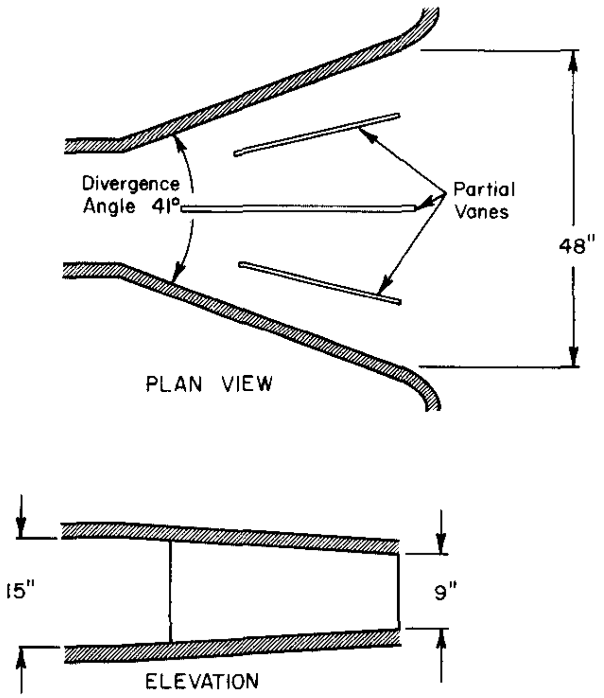


FIG. 3 C REACTOR PLENUM INLET NOZZLE

It was hypothesized that flow separation, or "stall,"[1] in the plenum inlet nozzles was responsible for the phenomena observed, and a test program was undertaken. The objects of the test were to determine:

- The extent of flow separation in the nozzles.
- The effectiveness of the existing vane system.
- The circumstances under which the nozzle stall pattern would "switch."

The test program was constrained by limited access to the reactor system. Extended shutdown for testing is not economical. Safety considerations prevent drilling holes to install velocity probes and pressure sensors directly in a nozzle. Therefore, simple experiments were first performed on a scale model nozzle. When these results reinforced the hypothesis of stalled nozzles, an in-reactor test was devised with existing reactor instrumentation which required short reactor downtime. The tests confirmed that the reactor nozzles were stalled and that different start-up procedures were effective in switching the stall pattern from one stable mode to the other. The revised order of starting the pumps provides a means of adjusting flow to match component orificing.

REVIEW OF DIFFUSER FLOW PHENOMENA

The flow distribution at the exit of a diverging nozzle is usually not uniform, but skewed to one side. The primary factor governing diffuser flow patterns is the angle between the diverging walls. Straight, two-dimensional diffusers are shown in Figure 4. If the divergence angle is small enough, the flow will be symmetric about the centerline (Figure 4a). If the angle is between approximately 8° to 14°, the flow pattern will be asymmetrical, with the greater flow rate near one or the other wall (Figure 4b). With an angle greater than 14°, the boundary layer will separate from one wall, causing backflow along the wall and the formation of eddies whose size and distribution will vary from moment to moment (Figure 4c). A nozzle in which this behavior is observed is said to be "stalled."

Kline and others[2,3] have refined this concept to include the length of the nozzle as a variable, and have classified the stall patterns into several flow regimes. Figure 5 is taken from Reference 3. The parameters are the divergence angle α and the aspect ratio (length/throat diameter). The Reynolds number does

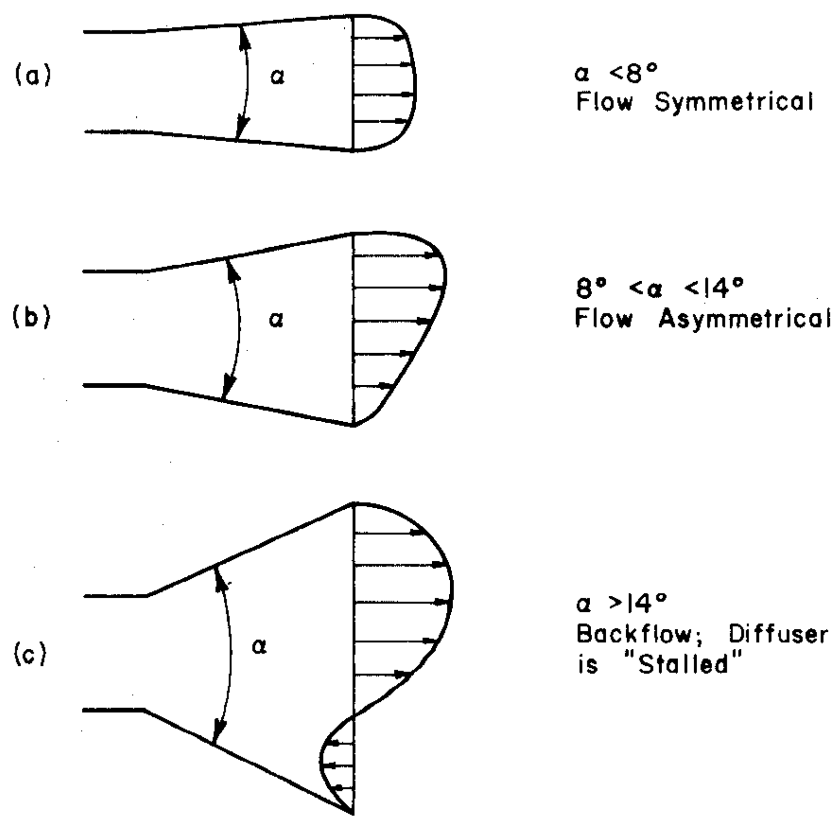


FIG. 4 VELOCITY PROFILES IN SIMPLE DIFFUSERS

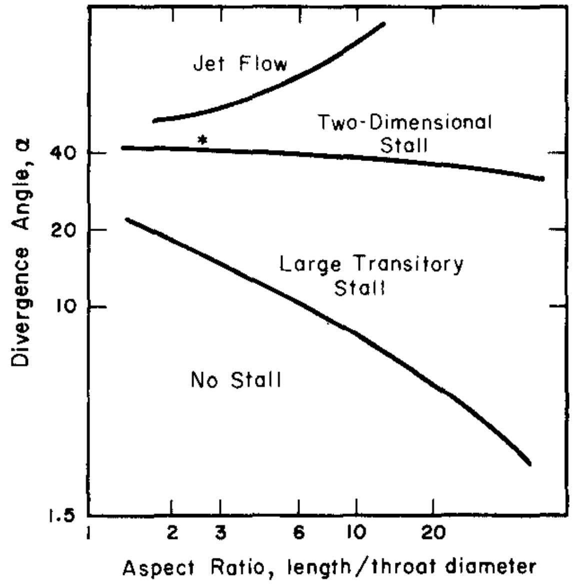


FIG. 5 FLOW REGIMES IN STRAIGHT-WALL, TWO-DIMENSIONAL DIFFUSER

not appear on this figure as an important variable. Diffuser flow patterns have been found to be almost independent of the Reynolds number based on inlet conditions above a Reynolds number of about 6000.[2] Because of Reynolds number independence, a simple scale model of the reactor nozzles will provide data that are applicable to the full-size nozzles.

Figure 5 was derived from data for a straight-wall, two-dimensional diffuser, without vanes. Neglecting vanes and the slight vertical convergence, the Savannah River C reactor nozzle design is indicated by an asterisk in Figure 5 at the point 2.6, 41°. This point is just within the regime designated "two-dimensional stall." In two-dimensional stall as defined by Kline,[2] the flow separates near the throat of the nozzle and preferentially follows one wall. Once established, the flow adheres to that wall and will not switch unless there is a large disturbance in the flow system. This contrasts with the regime labeled "large transitory stall" (Figure 5), in which the stall spontaneously switches from one wall to the other, at a rate roughly proportional to the mean inlet velocity.

Based on this information, the C reactor nozzles would be severely stalled with no vanes. The intent of placing vanes in a nozzle is to divide the nozzle into several subnozzles, each of which has a small divergence angle. However, the adverse pressure gradient which leads to stall begins at or near the entrance, and if the vanes do not begin at the throat, stall will develop.

NOZZLE MODEL ON A WATER TABLE

Experiments were conducted on a water table that mocked up a reactor nozzle on a 1/5 scale. Results from this simple model guided later in-reactor tests.

Figure 6 is a diagram of the free surface water table that was built. The flow from the pump entered at the left, passed through straightening tubes and developed in a 3-ft-long approach channel. This channel was 3 in. wide, but ran 10 in. deep to keep the Froude number less than 1. (Free surface flows with higher Froude numbers have standing waves and other surface effects.) The flow in the nozzle was turbulent, with a mean velocity of 0.6 ft/sec and an entrance Reynolds number of 2.6×10^4.

The model of the nozzle was approximately one-fifth reactor size in two dimensions, having the same divergence angle and length-to-throat-width ratio. Downstream of the test section was a bank of fifty tubes in a triangular lattice array simulating fuel positions in the plenum. The flow among these tubes was laminar and, therefore, did not properly model flow among the permanent sleeves in the plenum. However, the flow patterns observed in the nozzle were independent of the tube bank at the low velocities employed. Dye injection was used to study the flow patterns. Dye could be injected in single streams at various points of interest, or introduced in bulk from upstream.

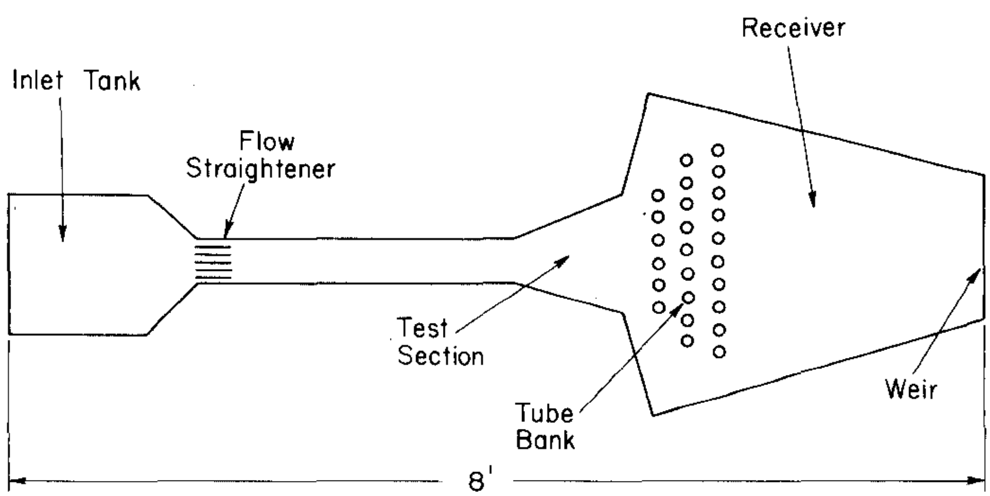


FIG. 6 PLAN VIEW OF FREE SURFACE WATER TABLE

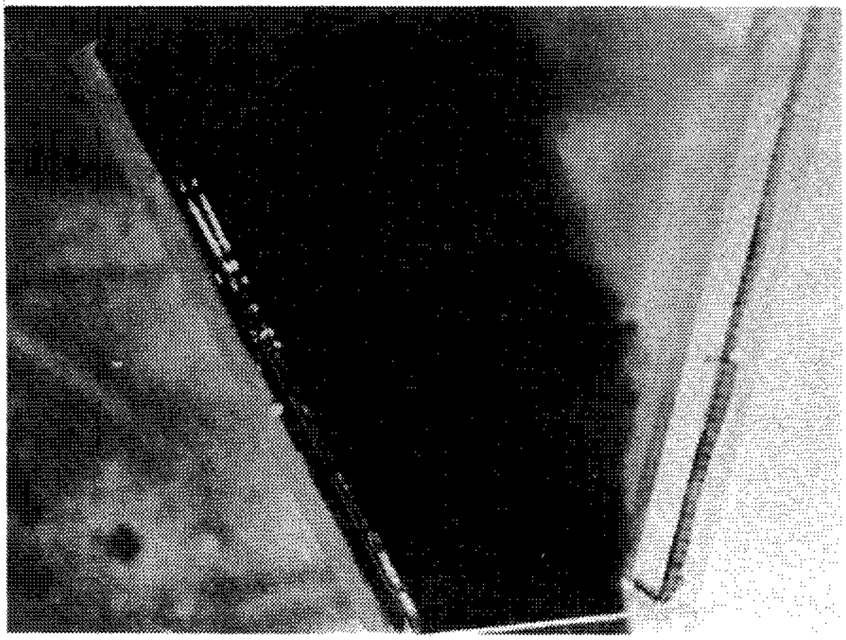
Some typical results of the experiments are illustrated in Figures 7 and 8. A motion picture was made to record the details of the eddies and the general unsteadiness of the flow patterns. The still pictures included in this report show the dye pattern produced when a large quantity of dye is released upstream of the throat.

Figure 7a shows the case with no vanes. Figure 7b is a sketch illustrating the details of the flow pattern in 7a, as revealed by motion pictures sequences and point injection. Note the extent of the nozzle cross section occupied by the eddy.

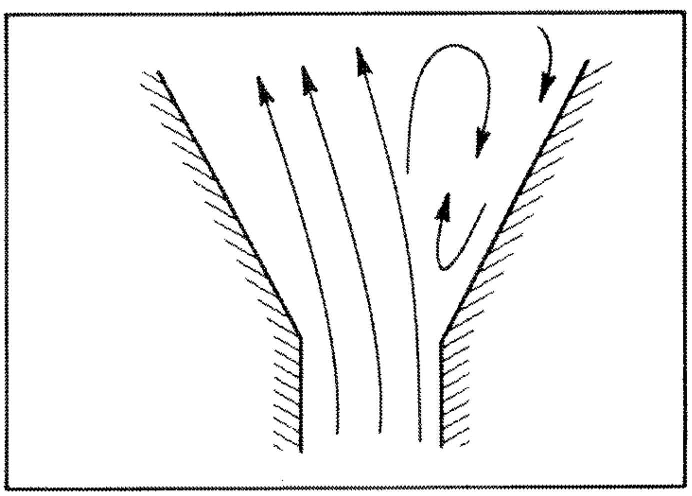
Figures 8a, b, c, and d show the sequential movement of a dye front moving through a nozzle having vanes that mock up those in the existing nozzles of C reactor. The nozzle still exhibited stall, although the size of the eddy is limited by the partial vane compared to a nozzle without vanes (Figure 7). As illustrated in Figure 9, backflow was observed in the passage formed by the outer vane. This phenomenon is consistent with the observations of other investigators.[2]

In all tests the side to which the flow first attached when the pump was started was fortuitous. The side of the nozzle exhibiting stall could be changed by unbalancing or perturbing the upstream flow.

These experiments demonstrated that the existing vane system is not effective in preventing stall in a two-dimensional straight wall diffuser. It is possible, however, to correct nozzle stall by certain modifications. For example, tests on the water table showed that stall could be prevented by moving the vanes forward into the throat (Figure 10), or by boundary layer suction.[1] There are other vane configurations[4,5] which will achieve the same purpose. Because the cost of mechanical modification of the reactor nozzles probably exceeds the gains from improved hydraulic performance in current programs, optimization of stall control methods was deferred.

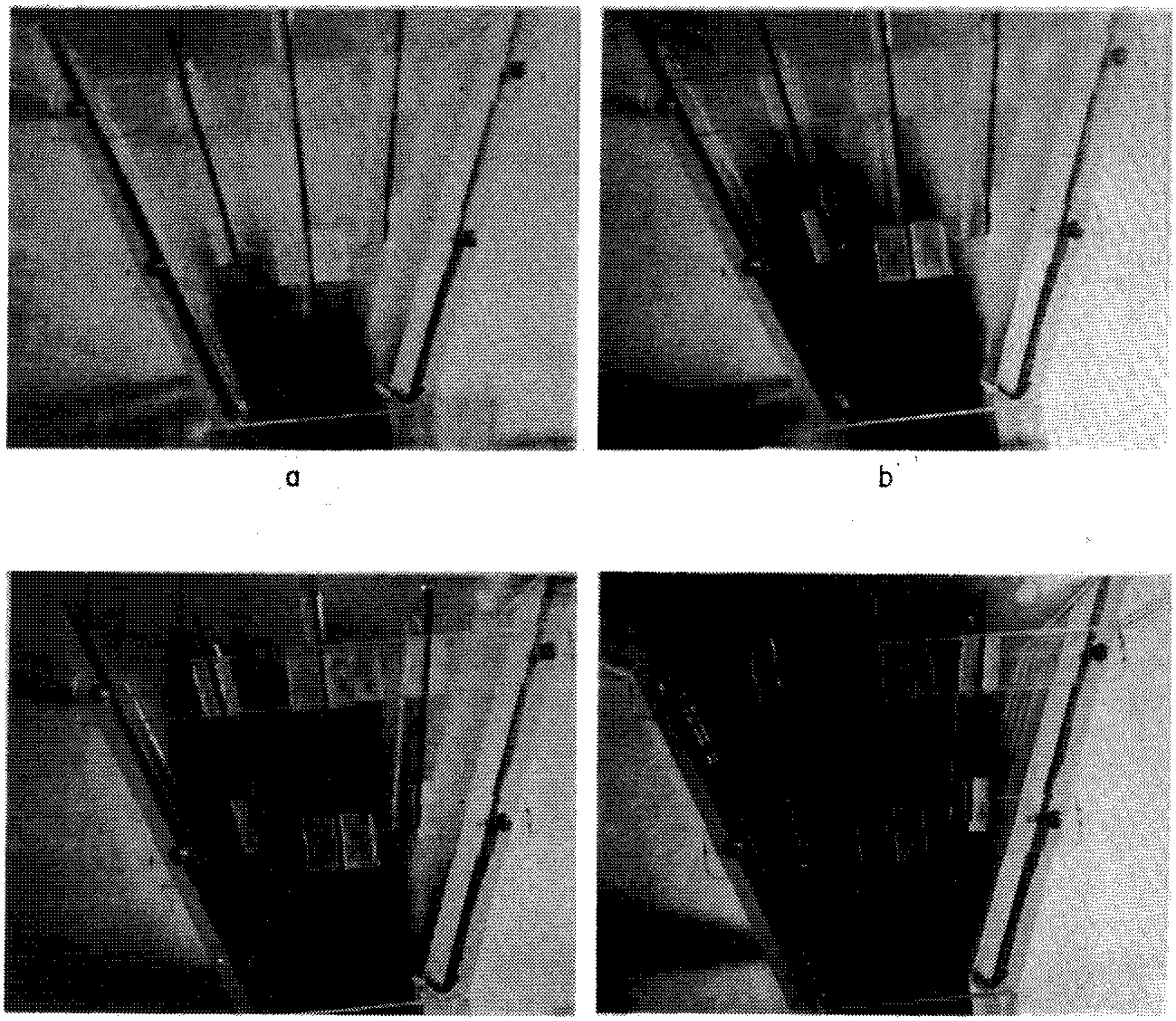


a



b

FIG. 7 STALL IN NOZZLE MODEL WITH NO VANES



a b

c d

FIG. 8 PROGRESS OF DYE THROUGH NOZZLE MODEL WITH VANES

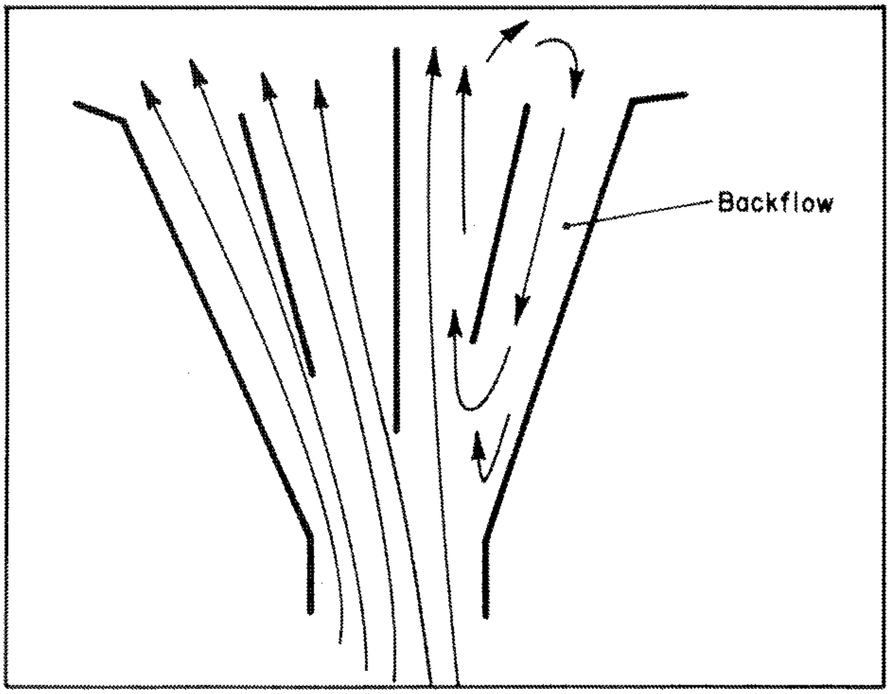


FIG. 9 OBSERVED FLOW PATTERN IN NOZZLE MODEL

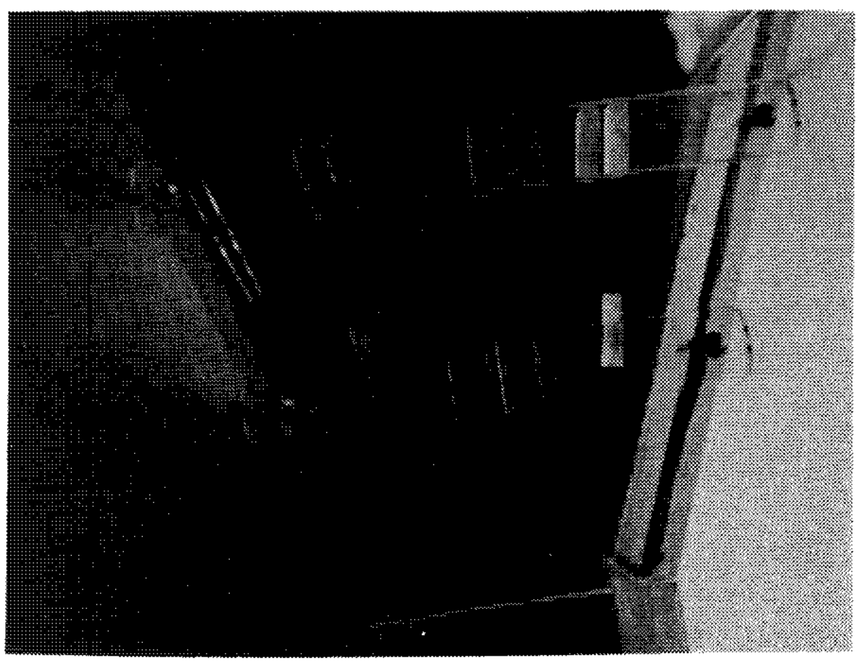


FIG. 10 FLOW IN NOZZLE MODEL WITH VANES MOVED TO THROAT

EXPERIMENTAL PROCEDURE FOR IN-REACTOR TESTS

The results of the model studies indicated that the C reactor plenum nozzles were probably running stalled. This condition would lead to non-uniformity in the plenum flow distribution. Then, if some mechanism were available to cause the stall pattern to switch in the nozzle, the plenum distribution could be altered. To verify these conclusions, a test in the reactor was devised. The objectives of the test were to:

- Demonstrate that the reactor nozzles were stalled.
- Determine the mechanism causing a nozzle to switch.
- Determine the interaction between the six plenum inlet nozzles.

Direct measurement of nozzle flow patterns with velocity and pressure probes was not possible without jeopardizing the integrity of the nozzles. Hence, data were obtained by heating the reactor primary cooling water (during a nuclear shutdown) with pump heat, suddenly cooling one system, and examining the resulting flow and temperature maps obtained from existing reactor instrumentation by the on-line computer, which can rapidly scan all positions in the reactor. In effect, cold water was being substituted in the reactor for dye used in the water table model, except that only nozzle effluent distribution among fuel assemblies could be seen, not flow inside the nozzle. However, interpretation of the reactor test results was aided by the earlier water table experiments.

The test procedure was to heat the reactor coolant slowly to 60°C with pump heat by reducing the secondary coolant flow to the heat exchangers in all six coolant supply systems. Then, the secondary coolant was admitted to the heat exchanger in one system, cooling the primary water some 10°C relative to the other systems. Assembly coolant temperatures were then scanned by the on-line computer at the rate of two positions per second and the results were printed. In addition, assembly flow rates were recorded.

A complete scan required approximately five minutes. During this time, gradual intermixing of water from the cooled system with the warm water from other systems in the moderator space caused the average temperature to decline at a rate of about 1°C per minute. Knowing the scan sequence and rate at which the computer scanned all the reactor positions, it was possible to correct the data for the mean change in water temperature. This procedure was repeated for each of the six inlet nozzles. Results of the tests are discussed in the next section.

The next step in the test was to attempt to make the nozzle stall switch from one side to the other side. In a normal reactor startup D_2O coolant pumps are turned on sequentially, in the same order each time (Hydraulic Systems 2-5-1-4-3-6, Figure 2). Starting the pumps in another order had produced the abnormal flow pattern, as had temporarily throttling and re-opening one system at full reactor flow. These events were duplicated as nearly as possible in the experiments.

EXPERIMENTAL RESULTS IN C REACTOR

NOZZLE STALL

Figure 11 shows the effluent temperature data from fuel assemblies (uncorrected) when System 3 (at bottom) is being cooled relative to the other systems. The data are typical of each of the six systems. Even without correction it is apparent that the bulk of the flow issues from the right hand side of the nozzle as evidenced by the lower temperatures.

In the analysis, the measured temperatures were first corrected for the slow temperature decrease in all systems due to partial mixing in the moderator space during the five minutes required for the data scan. A linear change was assumed based on plenum inlet temperatures measured at intervals during each run. Next, the corrected temperatures were used to estimate the fraction of flow in each assembly that came from the cold system. Assemblies directly in front of a nozzle should receive 100% of their flow from that nozzle, while between two nozzles, the assembly flow might be a mixture of coolant from the two nearest nozzles. The measured temperatures recorded during the scan are those of the mixture. Knowing the inlet temperatures at the nozzles, the percent of the flow to an assembly that came from the cold nozzle is easily calculated by an energy balance (Appendix). Results presented in terms of the percent cold flow clearly depict the flow pattern.

Figure 12 shows the percent of cold flow to assemblies in front of System 3 when System 3 was cooled. The bulk of the flow from the nozzle evidently adheres to the right side of the nozzle because assemblies located somewhat to the right of the nozzle exit receive flow from System No. 3 only. It appears that some of the cold water is drawn into the left side of the next nozzle counterclockwise (System 2). This is in agreement with the water table results (Figure 9).

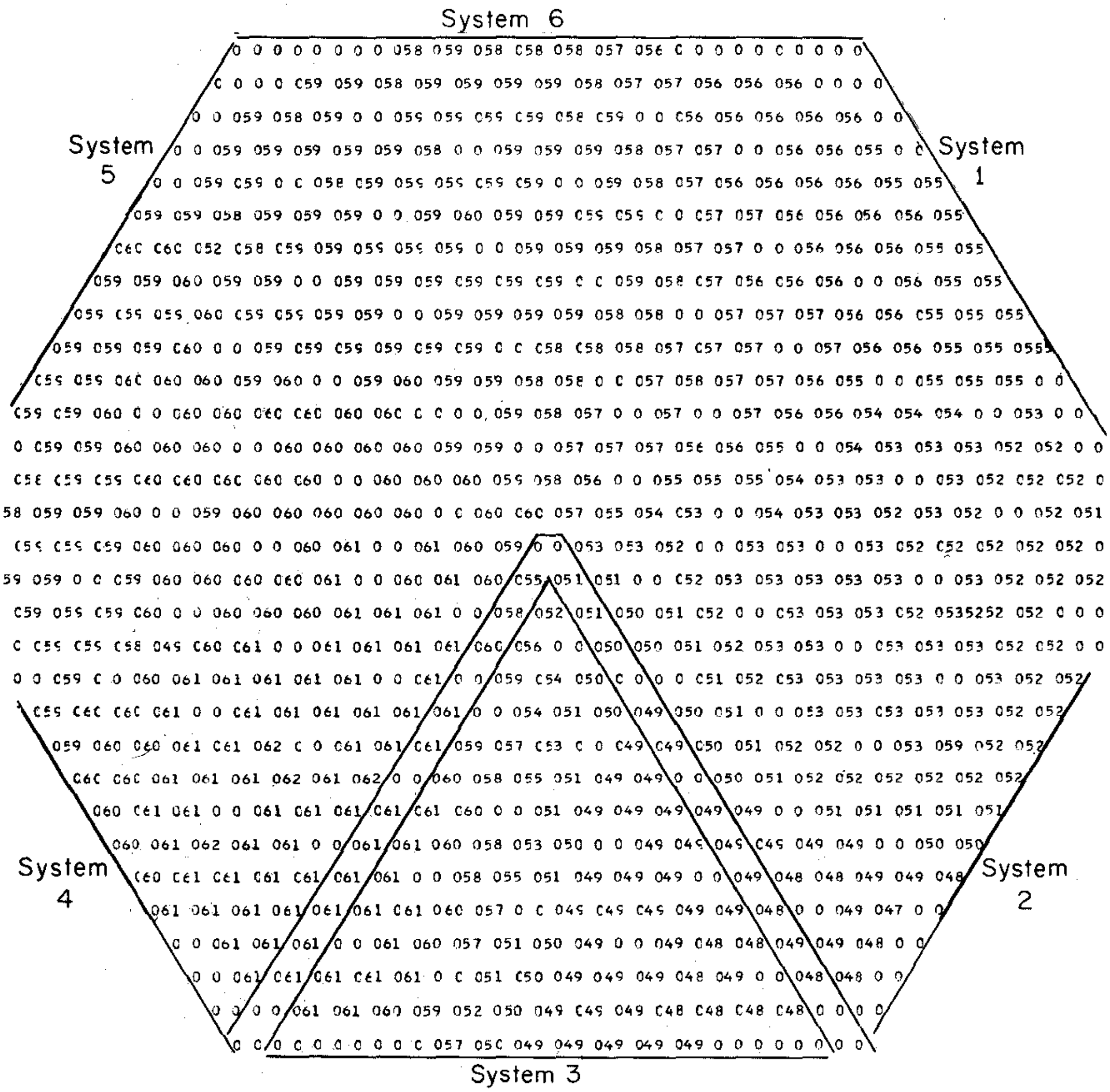


FIG. 11 TEMPERATURE DATA FOR EFFLUENT FROM FUEL ASSEMBLIES

At time = 0, all systems hot; At time = t_1, System 3 cold. Temperature under influence of System 3 hot on left and cool on right, indicating flow attached to right side of nozzle.

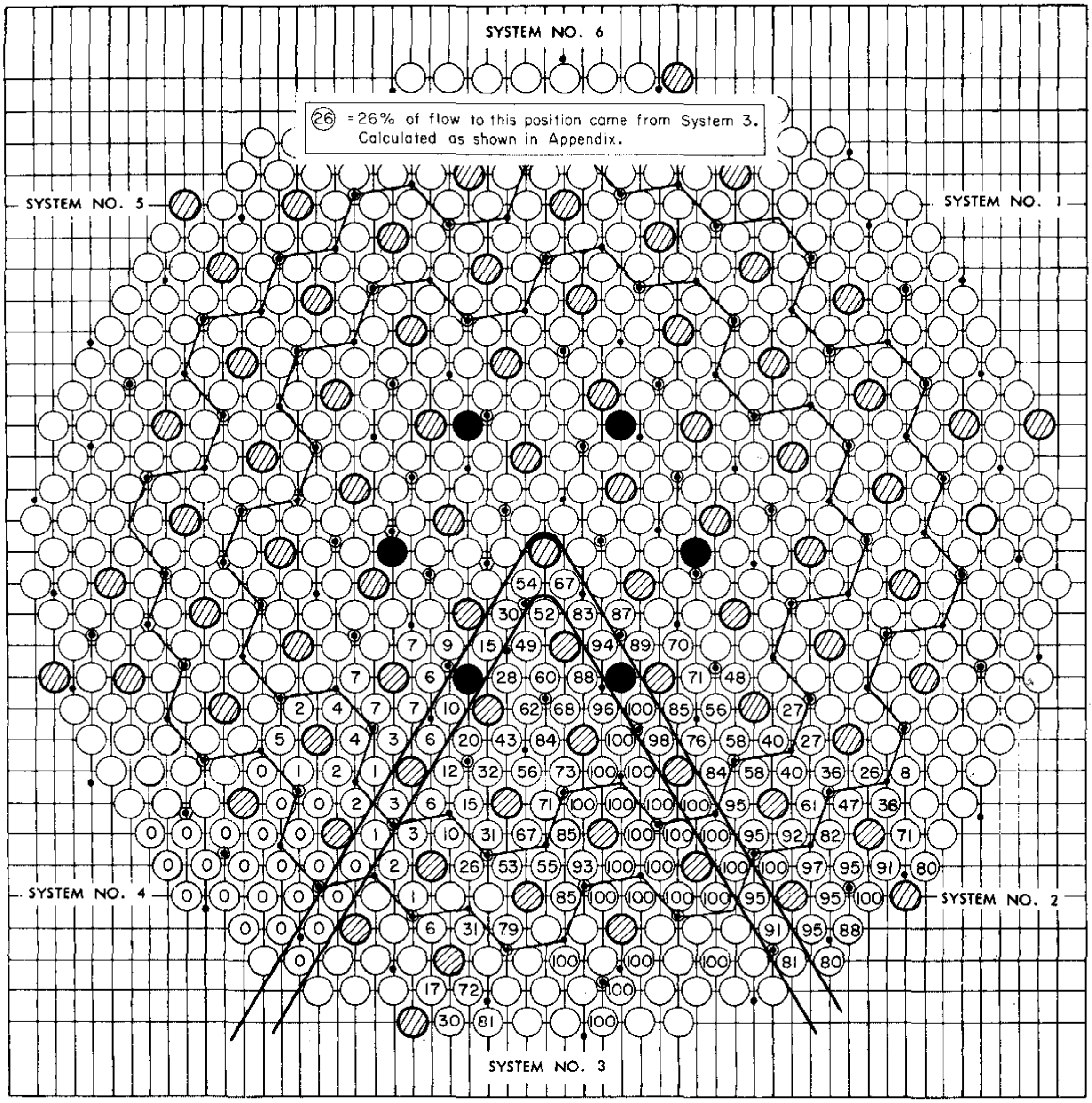


FIG. 12 FLOW DISTRIBUTION FROM NOZZLE 3 (C-REACTOR WITH NORMAL FLOW PATTERN)

The pattern shown in Figure 12 is typical of that in the other nozzles. The result is that in all the nozzles flow attaches to the right side of the nozzle, giving a slight counterclockwise motion to the coolant in the plenum. The asymmetric effluent from each nozzle affects the flow to positions near the nozzle exits. The plenum pressure in the first rows of positions on one side of the nozzle would be different from the other side because of the disparity in coolant velocity. The difference in plenum pressures leads to the difference in assembly flow rates observed.

NOZZLE STALL SWITCHING

After establishing the coolant distribution following a "normal" startup (Hydraulic Systems 2-5-1-4-3-6), the primary coolant pumps were stopped and restarted in a different order (Systems 3-6-4-1-2-5). The heating-cooling procedure was repeated to determine the flow distribution. The data (Figure 13) show that the coolant distribution changed in all nozzles. Coolant now adhered to the left

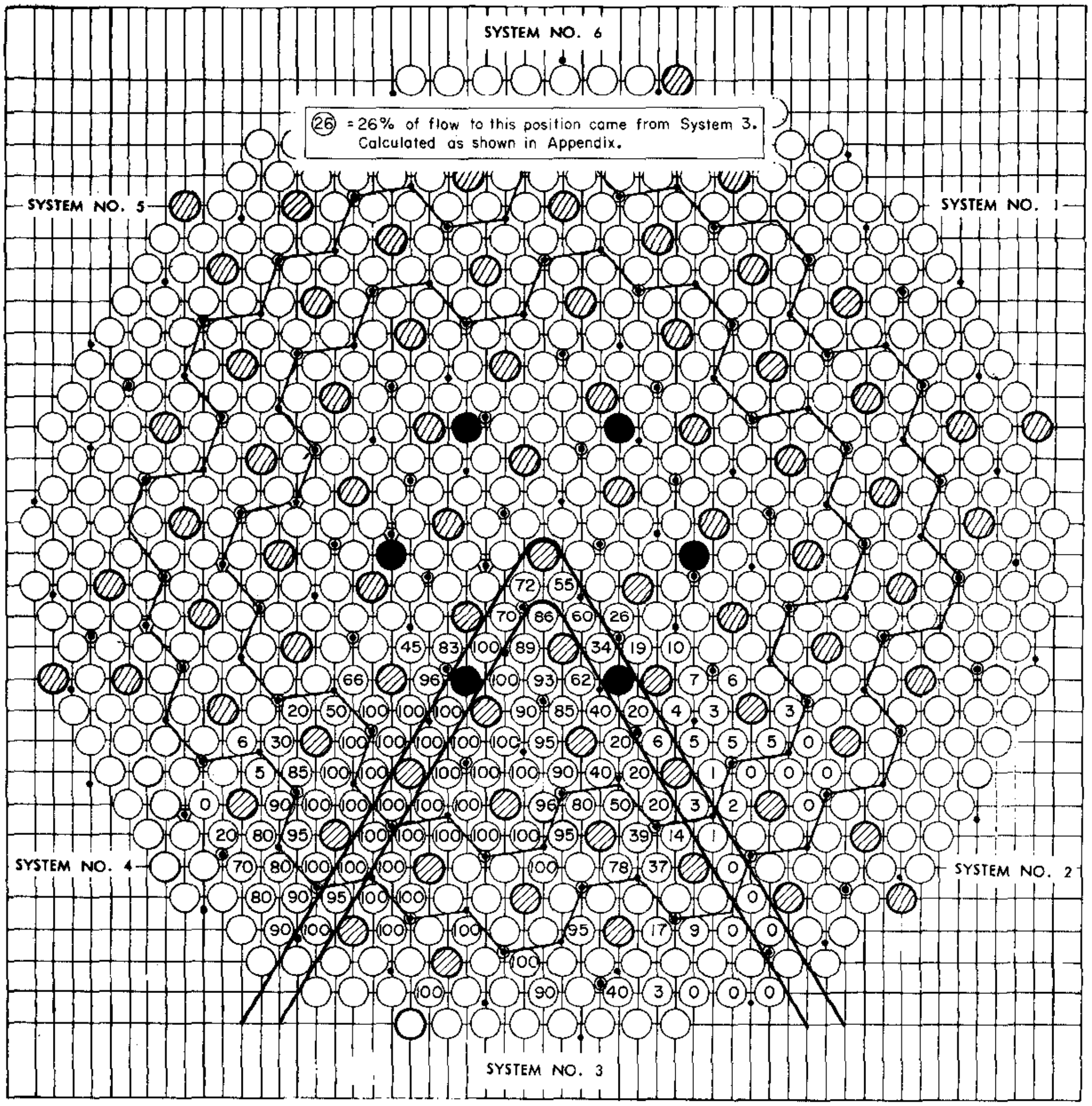


FIG. 13 FLOW DISTRIBUTION FROM NOZZLE-3 (C-REACTOR WITH ABNORMAL FLOW PATTERN)

sides of the nozzles, and imparted a slight clockwise swirl to flow in the plenum. The measured flow rates through assemblies near the nozzle exits changed. The side to which the flow adheres is determined by the nozzle of the first system start ed, e.g., the coolant from System 3 nozzle preferentially adheres to the right side, whereas the coolant from System 2 nozzle preferentially adheres to the left side.

Each coolant system has two heat exchangers, arranged in parallel, upstream of the plenum nozzle. Flow through a heat exchanger can be shut off by means of a large valve downstream of each heat exchanger. These valves provide a means for quickly restoring a normal flow pattern. After recording all data, one of the two valves in each system was closed, reducing the flow to the plenum. Then, the valves were re-opened in the normal order (Hydraulic Systems 2-5-1-4-3-6). The flow pattern in the plenum switched back to normal. This procedure has been adapted for use when the plenum flow pattern appears to be abnormal prior to nuclear startup.

EXPERIMENTAL RESULTS IN K REACTOR

The results previously discussed have pertained only to the C reactor at SRP. The other operating reactors, P and K, have not experienced bulk flow changes in the plenum. This is due to their slightly different plenum nozzle design. Figure 14 shows the P and K nozzle design. The nozzles have an initial divergence angle of 20°, one-half that of the nozzles in C reactor. There is a secondary divergence with 40° total included angle near the nozzle exit. Figure 5 indicates that this nozzle configuration should also be stalled. A mockup of the P, K nozzle on the water table exhibited stall, with separation on one side of the nozzle inlet, and back flow in the subchannel on that side, just as in the C nozzle model.

A series of tests were conducted in K reactor similar to those described in C to determine if stall in the K nozzles had as much effect on the plenum distribution pattern. It was found that the flow in K was nearly radial; that is, each nozzle supplied water only to the 60° segment of the plenum directly in front of the nozzle exit. The presence of nozzle stall was indicated, however, by slight asymmetry in the flow distribution at the exit of the nozzles. The effect was lost in the central area of the plenum.

It was concluded that the closely spaced sleeves in the K plenum act as a baffle, tending to even out an asymmetric flow pattern and countering the stall. The stabilizing effect of a large downstream resistance is mentioned in Reference 3. In C reactor, the angle of divergence is too large initially for the plenum tubes to correct an asymmetric flow pattern.

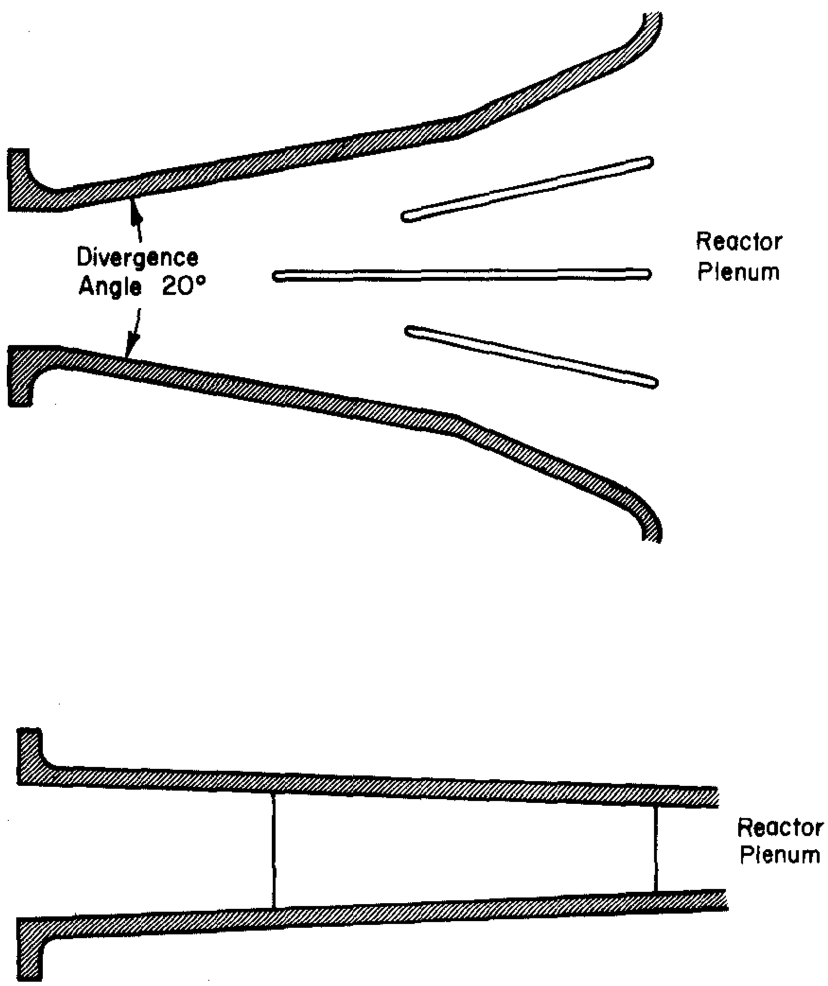


FIG. 14 P AND K REACTOR PLENUM INLET NOZZLE DETAIL

APPENDIX

FRACTION OF ASSEMBLY FLOW COMING FROM COOLED SYSTEM

An energy balance can be made on the coolant flow to a given assembly, assuming that the flow comes from the two nearest nozzles:

$$\dot{M}_{tot} T_{mix} = \dot{M}_{cold} T_{cold} + \dot{M}_{adj} T_{adj} \tag{1}$$

where: $\dot{M}_{tot}$ = total assembly mass flow rate

$\dot{M}_{cold}$ = mass flow that came from cold system

$\dot{M}_{adj}$ = mass flow that came from system adjacent to cold system

$$\dot{M}_{tot} = \dot{M}_{cold} + \dot{M}_{adj} \tag{2}$$

Let:

$$X = \dot{M}_{cold}/\dot{M}_{tot} \tag{3}$$

then:

$$(1-X) = \dot{M}_{adj}/\dot{M}_{tot} \tag{4}$$

Then substituting Equations (3) and (4) into (1) and rearranging gives:

$$X = \frac{T_{adj} - T_{mix}}{T_{adj} - T_{cold}} \tag{5}$$

The fraction X is the fraction of the total assembly flow that came from the cold nozzle.

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