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PWR CORE 2 MODEL STUDIES TO IMPROVE INLET-
PLENUM-CHAMBER MIXING

by

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PWR CORE 2 MODEL STUDIES TO IMPROVE INLET- PLENUM-CHAMBER MIXING

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In the course of the PWR Core 2 study program, studies to improve mixing in the lower plenum were carried out using a quarter-scale air-flow model. By use of vanes to form a strong vortex in the lower plenum, excellent lower-plenum mixing was obtained with only slight increase in pressure drop.

For the studies relating to a 9-ft core design, the model core was extended downward 4-1/2 in. below the Core 1 position. The flow baffle used for this configuration extended below the four inlets, with the result that considerable pressure loss occurred in the lower plenum. It was found that mixing could be greatly improved by use of deflectors to divert the inlet flow in a tangential direction. Data on lower-plenum mixing, core-flow distribution, thermal-shield-flow directions and velocities, flow-baffle orifice coefficients, and pressure losses were obtained for the 9-ft core configuration both with flow deflectors and without them. The flow deflectors greatly improved mixing at the expense of increased lower-plenum pressure loss.

For the studies relating to a 7.5-ft core design, the core was extended downward 2-1/4 in. The flow baffle used for this core design extended to about the center line of the inlets, so that restriction of inlet flow was less than for the 9-ft core. Data for the basic configuration were obtained, following which many types of mixing devices were studied. Use of a vaned ring to produce a strong vortex in the lower plenum resulted in excellent mixing with only slight increase in pressure drop. A similar vaned ring was designed for the prototype by Westinghouse and incorporated in the quarter-scale model. Detailed studies of model performance proved this design satisfactory.

INTRODUCTION

Model studies of the PWR with Core 1 had shown that mixing of coolant from the four inlets was not completed in the lower plenum. This would result in temperature gradients at the core inlet in case of unequal coolant temperatures at the four inlets. Accordingly, in the course of developing a reference design for Core 2, model studies to improve mixing in the lower plenum were carried out. Two lower-plenum designs were investigated in the model studies, one suitable for a core length of 9 ft, and the other suitable for a core length of 7.5 ft. Mixing devices were developed in the model studies which resulted in greatly improved mixing, with only slight pressure drop.

DESCRIPTION OF QUARTER-SCALE FLOW MODEL

General Description

The quarter-scale flow model was designed to simulate flow conditions throughout the PWR with the exception of those in the fuel assemblies; these were simulated with orificed tubes having proper flow resistances. The model was constructed of aluminum and stainless steel throughout with the exception of the upper and lower domes which were constructed of glass-fiber-reinforced plastic. The model was designed at the Bettis Laboratory of the Atomic Energy Commission, operated by Westinghouse Electric Corporation, and was constructed by the Aviation Gas Turbine Division of Westinghouse.

Figure 1 is a photograph showing the quarter-scale model setup for air-flow studies. Four centrifugal blowers were used to supply air to the model through the upper duct above the panel board. Air leaving the model was discharged through the roof of the building. The large manometer panel at the right was used to record pressures throughout the model. The inlet piping was made similar to that for the prototype with provision for equalizing flow in inlets and outlets. For tests with two or three loops, the inactive inlets and outlets were blocked with plates installed between piping flanges.

Figure 2 is a vertical cross section of the model showing the general arrangement of the pressure vessel, the inlets and outlets, the thermal shields, the core, the control-rod guides, the hold-down barrel, and the internal instrumentation.

Figure 3 is a horizontal cross section of the model showing the arrangement of the thermal shields, the core fuel assemblies, and the shield-passage instrumentation.

Air, simulating reactor coolant, entered through two or more of the four inlets at the bottom of the model. About 85 per cent of the air flowed upward through the perforated flow baffle under the core, and 15 per cent was diverted through the thermal-shield coolant passages. Air from the shield passages discharged under the core where it mixed with air coming through the flow baffle and passed upward through the core and into the upper plenum. From the upper plenum, it passed into the space between the pressure vessel and the hold-down barrel, and then discharged through two or more outlets.

Lower Plenum

The lower plenum of the flow model, shown in Figure 2, is the hemispherical space below the core, into which the inlet nozzles discharged. The plenum provided space for dissipation of jet momentum and mixing of coolant from the inlets. The flow baffle was located inside the plenum and was attached to the outer thermal shield. This baffle provided flow resistance which, in addition to diverting coolant through the thermal-shield passages, reduced the velocity gradients directly under the core and directed the flow in a generally upward direction.

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FIGURE 1. QUARTER-SCALE MODEL OF PWR SETUP FOR AIR-FLOW STUDIES

FIGURE 2. VERTICAL SECTION OF QUARTER-SCALE FLOW MODEL OF PWR

FIGURE 3. HORIZONTAL SECTION THROUGH CORE OF QUARTER-SCALE
FLOW MODEL OF PWR

Two flow-baffle configurations were studied; one simulating a 9-ft core design, and the other simulating a 7.5-ft core design. The flow baffle for the 9-ft core design extended below the inlets, reducing the effective lower-plenum volume to one-fourth that for Core 1. The flow baffle for the 7.5-ft core design extended to the center line of the inlets, reducing the plenum volume to about 50 per cent of that for Core 1. Details of lower-plenum design are discussed with the results of the studies.

Core

Description

The core of the model contained 145 simulated fuel assemblies arranged in five regions as shown in Figure 3. Coolant flow was proportional to heat flux in the prototype, and was highest in the seed region, lower in Regions 2 and 3, and lowest in Regions 1 and 4. All fuel assemblies within one region were designed for equal flow.

Each simulated fuel assembly in the model consisted of a 3/4-in. -OD tube having a flow-measuring orifice installed near the middle of the tube, as shown in Figure 2. All orifices within one region were of nominally equal diameter, but orifices in different regions were of different diameters. Upstream and downstream orifice-pressure taps were connected to a 360-tube water manometer, shown in Figure 1. In addition to the flow-measuring orifice, each tube had an inlet orifice to provide additional pressure drop. These orifices were recessed into a large plate which was bolted to the bottom of the core assembly. The two orifices in each tube had similar pressure drops, except for those in the seed region, where the inlet orifice was slightly larger than the tube diameter, and most of the pressure drop was taken at the measuring orifice. This core arrangement simulated Core 1 in over-all pressure loss and in distribution of flow, but does not necessarily simulate flow distribution or pressure loss in Core 2. However, it is felt that the simulation was sufficiently close that differences would not influence greatly the interpretation of results.

Calibration of Core Orifices

The inlet orifice-retaining plate was bolted to the bottom of the core and was sealed with a large rubber gasket having a hole for each core tube. Each of the 145 inlet orifices was held in place by two small screws and sealed with a rubber gasket. In preparation for studying flow distribution, mixing, and pressure loss, the gaskets between the inlet orifice and the retaining plate and between the retaining plate and the core were replaced to prevent leakage. An in-place calibration of the inlet orifice and the measuring orifice in each fuel assembly was made over a range of flows.

Model Setup and Operation

The model was set up to permit close control of flow to individual inlets and outlets and to minimize the leakage of SO_2 tracer to the work area. The general arrangement of test equipment is shown in Figure 1. Four centrifugal blowers, connected in series, provided air at pressures to 6 psi and flow rates to 5.5 lb per sec. Air filters and an intake orifice for measuring air flow were attached to the inlet of the first blower. The air, after compression, entered the model through vertical approach piping and 90-deg elbows to simulate the prototype installation. A flow-measuring nozzle was installed at each inlet to measure flow and to determine when flow to inlets was equal. Flows to individual inlets were adjusted by varying the depth of insertion of 3/8-in. rods into the air streams in the elbows. For tests with less than four loops operating, plates were installed between flanges of inactive inlets and outlets.

The outlets were fitted with short flow-measuring sections as shown in Figure 1. The model outlets were connected to exhaust piping which carried the SO_2 -contaminated exhaust to the roof.

Instrumentation and Test Procedures

Pressure taps for the 145 measuring orifices and for 70 static pressures throughout the model were connected to a specially constructed manometer board having 360 tubes, each suitable for measurement of pressures up to 170 in. of water. The manometer board consisted of six well-type manometers, each having one leveling tank and a number of manometer tubes. The tubes were connected to headers at the bottom of the board and the pressures to be measured were applied at the top. The manometer tubes were made of translucent polyethylene plastic. Orifice differentials and reading accuracy were such that flow measurements could be reproduced to ± 0.3 per cent.

Lower-plenum pressures were obtained with 30 static pressure taps installed in the surface of the lower dome.

Flow directions and velocities in the outer thermal-shield coolant passage were measured with cylindrical two-hole yaw probes using inclined manometers sensitive to 0.002-in. of water.

Mixing studies were conducted by injecting measured concentrations of SO_2 into Inlet 2-3, and determining the concentration of SO_2 in the air passing through each of the 145 simulated fuel assemblies in the core. The SO_2 was supplied from a pressurized gas cylinder. Because of the extremely low volume of SO_2 required, it was mixed with a much larger volume of compressed air, and the mixture injected into the inlet piping. The injector consisted of five 1/8-in. stainless steel tubes, having 21 holes, 0.021 in. in diameter, located at the centers of equal areas. It was located 11 ft upstream from the model inlet in the vertical run of pipe. With this arrangement, mixing ahead of the model was such that the deviations from the average concentration of 10 ppm of SO_2 at the model inlet were always less than 5 per cent.

Samples of air from each of the 145 simulated fuel assemblies were bled continuously from the upstream pressure taps of the flow-measuring orifices. The

manometer tubes previously used for pressure measurement were detached from the headers and allowed to vent air continuously. A sample for analysis was drawn from each manometer tube in turn, and analyzed immediately in a Titrilog, which recorded the concentration of SO_2 . With this procedure, it was possible to traverse the entire core in about half a day, with frequent checks of inlet concentration and of background level in a second inlet which nominally contained no SO_2 .

The Titrilog, which was used to measure SO_2 concentration, is manufactured by the Consolidated Electrodynamics Corporation. In this instrument, SO_2 is titrated with electrolytically generated bromine at a potentiometric balance point. A feedback amplifier controls the rate of generation of reacting bromine above a set reference level so that it is at all times equal to the rate of absorption of SO_2 in the titration cell. The current flow in the electrolytic cell serves as a measure of SO_2 concentration. The instrument scale has a range 0 to 10 ppm of SO_2 with a reading accuracy of ± 1.5 per cent of full-scale reading. The threshold sensitivity is 0.1 ppm; about 10 sec is required to reach equilibrium after a change in concentration.

RESULTS OF STUDIES USING 9-FT CORE LENGTH

Outline of Studies

The objective of studies with the 9-ft core length was to improve lower-plenum mixing with minimum increase in pressure drop, and without adversely affecting core-flow distribution or shield flow. Eight different configurations were screened by studying mixing and pressure drop for four-loop operation. At the conclusion of these screening studies, complete data were taken for the basic configuration without any mixing devices, and for the best flow-deflector configuration.

Mixing studies were carried out by use of SO_2 as a tracer in one inlet. Samples of air from each simulated fuel assembly were analyzed and the percentage of air from the traced inlet was then computed. Accuracy of mixing data was within ± 5 per cent.

Results of Screening Studies

Figure 4 shows lower-plenum arrangements for the 9-ft core. The configurations shown illustrate the various mixing devices used in the screening studies discussed below.

Screening studies were begun with tests of the basic 9-ft core design having a core extension and a perforated flow baffle, as shown in Figure 4a. The detailed design of the perforated flow baffle is shown in Figure A-1 in the Appendix. No mixing devices were used. The maximum concentration of air from the traced inlet found in the core was 89 per cent. With perfect mixing, a value of 25 per cent would have been obtained for every fuel assembly.

When the core extension was removed to increase the space for mixing above the flow baffle from 2.7 in. to 7.2 in., the maximum concentration of air from the traced inlet was 85 per cent, indicating that only a slight amount of mixing took place in the additional space above the flow baffle.

A thin sheet-metal conical extension was added to the flow baffle, extending $1/2$ in. below the bottom of the baffle, as shown in Figure 4b. This sharp-edged extension was expected to reduce the Cowanda effect, which would result in flow around the rounded bottom edge of the baffle. With this configuration the maximum concentration of air from the traced inlet was 98 per cent, representing the poorest mixing measured in any test.

With a conical extension on the flow baffle extending $1-3/4$ in. below the flow baffle, the maximum concentration of air from the traced inlet was found to be 95 per cent, which was not as good as for the basic configuration.

Finally, a conical extension reaching from the flow baffle to the bottom dome, with a clearance of $1/8$ in., as shown in Figure 4c, was installed. Four openings, each 6.5 by 2.75 in., were located at the bottom of the extension, each midway between two inlets. With this configuration, the maximum concentration of air from the traced inlet was 84 per cent.

a. Basic configuration.

b. 3/4-in. flow-baffle extension.

c. Slotted flow-baffle extension.

d. Tangential flow deflectors.

FIGURE 4. ARRANGEMENTS OF LOWER PLENUM FOR 9-FT CORE

Since conical extensions of the flow baffle did not improve mixing, means of admitting the coolant tangentially to generate a strong vortex in the lower plenum, and thus provide a longer path for mixing, were investigated. Because of the very limited space between the inlets and the flow baffle, the first approach was to install a semi-circular flow deflector around each inlet, as shown in Figure 4d. Each deflector extended from the outer shell to the flow baffle and was semicircular in shape, with a radius $1/2$ in. greater than that of the inlet. Deflectors of this design were used in two positions, the first directing the inlet flow downward 25 deg to just clear the adjacent deflector, and the second directing the inlet flow horizontally, so that it passed both below and above the adjacent deflector.

With the tangential deflectors directed downward 25 deg, the maximum measured concentration of flow from the traced inlet was 63 per cent, compared to 89 per cent for the basic configuration. With the deflectors directed horizontally, the maximum measured concentration of flow from the traced inlet was 51 per cent, a further improvement.

Although mixing was greatly improved for the two configurations having semi-circular flow deflectors they seriously restricted flow, resulting in excessive pressure loss. For identical flow rates, the static pressure drop from the inlet nozzle to the downstream side of the flow baffle was 3.80 in. of water for the Core 1 configuration, 7.32 in. of water for the basic 9-ft core configuration, and 51.7 in. of water for the first 9-ft core configuration with flow deflectors. Corresponding prototype pressure losses would be 5.44, 6.18, and 23.05 psi, respectively, based on an assumed four-loop flow rate of 23,700,000 lb per hr.

To reduce pressure loss the flow-deflector radius was increased to be $3/4$ in. greater than the radius of the inlet nozzle. This resulted in a reduction of static pressure drop to 14.60 in. of water at the flow rate used for comparison above. The corresponding prototype pressure loss would be 9.45 psi. Mixing was such that the greatest concentration of air from the traced inlet found in the core was 66 per cent. As this configuration appeared to offer a considerable improvement in mixing with a moderate increase in pressure loss, it was selected for more detailed study.

Results of Studies Without Mixing Devices

Core-Flow Distribution

Figures 5, 6, and 7 show data which were obtained with the basic 9-ft core design without any mixing devices. Each assembly location is marked with a value of flow through that assembly. Flow is expressed as the percentage of average mass flow through the region in which the assembly is located. Arrows indicate positions of operating inlets. No data were obtained for Assembly 87 (lower right corner of seed region in Figures 5, 6, and 7) because an orifice pressure tap was plugged.

Figure 5 is a map of the core showing flow distribution with four-loop operation. In this test, flow for each assembly was within ± 1.5 and -1.2 per cent of the average flow for each region.

FIGURE 5

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 9-FT CORE CONFIGURATION USING FOUR LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

FIGURE 6

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 9-FT CORE, USING THREE LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

Numbers in each simulated fuel assembly show percentage of average flow for region.

Figure 6 shows flow distribution with three-loop operation. The flow for each assembly is within +1.2 and -2.3 per cent of average flow for each region.

Figure 7 shows flow distribution with two opposed loops in operation. In this test, flow through each assembly was within +1.5 and -3.3 per cent of the average flow for the region.

Flow in Thermal-Shield Coolant Passages

Since part of the reactor coolant bypasses the flow baffle and flows through the thermal-shield coolant passages, it is necessary to measure the flow in these passages in order to evaluate pressure-loss data for both flow paths. In addition, it is important to determine that all surfaces of the thermal shields are adequately cooled. Previous studies made for Core 1, had shown that flow disturbances could be expected in the outermost shield passage only, as flow was generally downward in other passages regardless of operating conditions. Accordingly, in Core 2 studies, measurements of air velocities and directions were made in the outermost shield passage only, using two-hole cylindrical yaw probes of conventional design.

Figure 8 is a data plot showing a cross section of the shield passages, and a development of the outermost passage, Channel 1, showing the directions and velocities of air flow with four loops operating. Arrows are located at yaw-probe locations and indicate directions; numbers indicate flow velocities. Velocities of water flow in the prototype would be smaller than air-flow velocities shown by a factor of 6.2. The data plot is scaled to model proportions.

Figure 9 shows the flow pattern in Channel 1 with three loops operating. In this figure a region of disturbed flow is shown above Inlet 2-3, the middle operating loop.

Figure 10 shows the flow directions and velocities in Channel 1 with two opposed loops in operation. Although directions of flow depart from the vertical, mass transfer exists throughout the cooling annuli. Velocity and direction measurements could not be obtained at the two lower-elevation locations above the closed inlets because of extreme turbulence.

Lower-Plenum Mixing

Mixing studies were conducted by injecting measured concentrations of SO_2 into Inlet 2-3 and determining the concentration of SO_2 in air passing through each of the 145 simulated fuel assemblies in the model core.

Figure 11 shows mixing data with Inlet 2-3, the inlet into which SO_2 was injected, plus three loops in operation. The figure represents a cross section of the core of the flow model with the numbers indicating the percentage of flow in each simulated assembly which came from Inlet 2-3. With perfect mixing in the lower plenum, a value of 25.0 per cent would be obtained in every assembly. It will be noted, however, that concentrations in the quadrant of Inlet 2-3 were generally high, with peak values occurring nearest the inlet and decreasing with distance from the inlet. A maximum value of 89 per cent was found.

FIGURE 8. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE CONFIGURATION USING FOUR LOOPS

Arrows indicate flow direction and numbers indicate air velocity, fps.

FIGURE 9. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE USING THREE LOOPS

Arrows indicate flow direction and numbers indicate air velocity, fps.

FIGURE 10. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE USING TWO OPPOSED LOOPS

Arrows indicate flow direction and numbers indicate air velocity, fps.

Figure 12 shows mixing data using Inlet 2-3 plus two opposed loops. With this configuration, one third of the flow entered Inlet 2-3, so that perfect mixing would result in a concentration of 33.3 per cent in each simulated assembly. Again, the highest concentration was found nearest the traced inlet. The maximum value measured was 99 per cent.

Figure 13 shows mixing data using Inlet 2-3 plus two adjacent loops. This arrangement of operating inlets resulted in a shift in the pattern due to the unbalanced loop 90 deg from the other two operating loops, which produced lower peak concentrations. The maximum concentrations occurred between Inlet 2-3 and Inlet 3-4, the blocked inlet. The maximum value measured was 94 per cent.

Results of Studies With Flow Deflectors

In order to improve mixing, semicircular flow deflectors, as previously described, were installed around each inlet to generate a strong vortex in the lower plenum, and thus provide a longer path for mixing. Each deflector covered an included angle of 180 deg and was made with a radius $3/4$ in. greater than the radius of the inlet nozzle. With this change in lower-plenum geometry, the flow studies made with the basic configuration were repeated.

Core-Flow Distribution

The core-flow data shown in Figures 14, 15, and 16 were obtained with the flow deflectors installed.

Figure 14 is a map of the core showing flow distribution with four-loop operation. In this test, flow for each assembly was within +2.1 and -1.6 per cent of the average flow for each region.

Figure 15 shows flow distribution with three-loop operation. Flow for each assembly was within +3.2 and -3.8 per cent of the average flow for the region.

Figure 16 shows flow distribution with two opposed loops in operation. In this test, flow to all assembly was within +4.1 and -5.5 per cent of the average flow for the region.

A comparison of Figures 5, 6, and 7 with Figures 14, 15, and 16 shows that the maximum deviations from average flow were somewhat greater for the deflector configuration than for the basic configuration.

Flow in Thermal-Shield Coolant Passages

Figures 17, 18, and 19 are schematic diagrams of the Channel 1 thermal-shield passage showing flow velocities and directions.

FIGURE 15

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 9-FT CORE WITH FLOW DEFLECTORS, USING THREE LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

FIGURE 16

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 9-FT CORE WITH FLOW DEFLECTORS, USING TWO OPPOSED LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

FIGURE 17. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE AND FLOW DEFLECTORS FOR OPERATION WITH FOUR LOOPS

Arrow indicate flow direction and numbers indicate air velocity, fps.

FIGURE 18. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE AND FLOW DEFLECTORS FOR OPERATION WITH THREE LOOPS

Arrows indicate flow direction and numbers indicate air velocity, fps.

FIGURE 19. FLOW DIRECTIONS AND VELOCITIES IN OUTERMOST THERMAL-SHIELD COOLANT PASSAGE OF MODEL WITH 9-FT CORE AND FLOW DEFLECTORS FOR OPERATION WITH TWO OPPOSED LOOPS

Arrows indicate flow direction and numbers indicate air velocity, fps.

Figure 17 shows the flow pattern in Channel 1 with four loops operating. The direction of flow is uniform but deviates from vertical due to the effect of the tangential flow in the lower plenum caused by the deflectors.

Figure 18 shows the flow pattern with three loops operating. The flow is nearly horizontal immediately above the inlet adjacent to the closed inlet in the direction of flow. As can be seen from a comparison of this figure with Figure 9, no area of recirculation exists with the deflector configuration.

Figure 19 shows the flow pattern with two opposed loops operating. Immediately above the two operating loops the flow direction is nearly horizontal. Otherwise, the flow is generally upward throughout the channel.

Lower-Plenum Mixing

Figures 20, 21, and 22 are core maps showing the mixing data obtained with three different loop configurations.

Figure 20 shows mixing data obtained using Inlet 2-3 plus three loops. The maximum concentration of air from Inlet 2-3 measured in the core was 66 per cent. This peak occurred 180 deg from the traced inlet. Mixing over a large part of the core was good with values approaching the ideal value of 25 per cent.

Figure 21 shows mixing data using Inlet 2-3 plus two opposed loops. Again the peak concentration occurred 180 deg from the traced inlet. The maximum concentration of air from Inlet 2-3 was 73 per cent.

Figure 22 shows mixing data using Inlet 2-3 plus two adjacent inlets. The maximum concentration of air from Inlet 2-3 found in the core was 68 per cent. This occurred about 40 deg from the traced inlet in the direction of flow.

A comparison of Figures 11, 12, and 13 with Figures 20, 21, and 22 shows that the effect of the flow deflectors on mixing is to reduce the maximum concentration of air from Inlet 2-3 found in the core and to distribute the air from this inlet over nearly all of the core, rather than having it concentrated in the quadrant adjacent to the inlet.

Flow Rates in Thermal-Shield Coolant Passages

All of the thermal-shield coolant flows upward in the outermost passage, after which it divides and flows downward in other passages. The total flow through the shield passages was computed for each test using the flow velocity and direction data of Figures 8, 9, 10, 17, 18, and 19. These velocities were measured at the center of the flow passage, and were not necessarily vertical. Accordingly, the vertical components of velocities at the top measurement position were corrected by factors of 0.86 to 0.87 to account for the velocity profile across the passage thickness.

FIGURE 20

LOWER PLENUM MIXING WITH 9-FT CORE
CONFIGURATION WITH FLOW DEFLECTORS
USING INLET 2-3 PLUS THREE LOOPS

Numbers in each simulated fuel assembly show
percentage of air from inlet 2-3.

FIGURE 21

LOWER PLENUM MIXING WITH 9-FT CORE
WITH FLOW DEFLECTORS, USING INLET 2-3
USING INLET 2-3 PLUS TWO OPPOSED LOOPS

Numbers in each simulated fuel assembly show
percentage of air from Inlet 2-3.

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

Table 1 summarizes the shield flow rates both with and without flow deflectors. For the configuration without flow deflectors the shield flow rate increased sharply with a decrease in the number of operating loops. The flow rate for two-loop operation was 56.0 per cent higher than that obtained with four-loop operation. The addition of flow deflectors around the inlets substantially reduced the variation in flow rate with the number of loops in operation. For this configuration, the two-loop flow rate was only 6.3 per cent higher than the four-loop flow rate.

TABLE 1. FLOW RATES IN THERMAL-SHIELD COOLANT PASSAGES OF THE QUARTER-SCALE FLOW MODEL

Loops Operating	Flow, per cent of total	
	Without Flow Deflectors	With Flow Deflectors
Four	19.1	25.3
Three	23.8	25.7
Two opposed	29.8	26.9

Distribution of Flow Among Core Regions

Table 2 summarizes the distribution of flow among core regions in the model for the 9-ft core design both without flow deflectors, and with flow deflectors.

TABLE 2. DISTRIBUTION OF FLOW AMONG CORE REGIONS

Model Location	Flow Distribution With Indicated Number of Loops Operating, per cent of total					
	Without Flow Deflectors			With Flow Deflectors		
	Two	Three	Four	Two	Three	Four
Region 1	6.45	6.47	6.52	6.61	6.48	6.53
Region 2	16.10	16.16	16.10	15.81	16.22	16.09
Region 3	24.05	23.93	23.81	23.66	24.13	23.64
Region 4	5.92	5.95	6.02	6.10	5.98	6.07
Seed region	47.47	47.49	47.53	47.80	47.18	47.65

Distribution of flow among core regions varied only slightly with the number of operating loops without flow deflectors. The variation was slightly greater with the flow deflectors installed but not significantly so. The flow rate for each region followed closely the rates measured in Core 1 flow studies.

Lower-Plenum Static Pressures

Figure 23 is a schematic drawing showing the locations of the 30 static-pressure taps which were installed in the lower plenum of the model to study the effect of various changes in lower-plenum geometry on pressure distribution.

FIGURE 23. SCHEMATIC DRAWING OF BOTTOM DOME OF MODEL SHOWING LOCATIONS OF PRESSURE TAPS USED TO MEASURE LOWER-PLENUM PRESSURES

Table 3 summarizes the pressures measured in the lower plenum of the model both with and without flow deflectors.

A comparison of the pressures obtained with four-loop operation for the two geometric configurations best shows the effect of the flow deflectors. Without flow deflectors the static pressure in the bottom of the plenum, Taps 15 through 28, was quite uniform, but with flow deflectors a definite pressure gradient from edge to center resulted from the vortex flow.

Flow-Baffle Pressure Loss

Flow through the thermal-shield coolant passages has as its driving force the pressure drop across the perforated flow baffle under the core. Therefore, in order to design a baffle to obtain the desired shield-passage flow it is necessary to know flow-baffle pressure losses. These were determined with simulated two-loop, three-loop, and four-loop operation using several values of air flow for each condition. For each determination, the pressure differential across the flow baffle was measured with an inclined manometer, the flow through Channel 1 of the shield passages was measured with the yaw probes at the top of the channel, and the total model flow was measured at the model inlets. The flow through the flow baffle was determined as the difference between total model flow and shield-passage flow.

Total pressure loss for the entire lower plenum from the inlet nozzles to the bottom of the core and pressure loss across the perforated flow baffle were both measured. The total lower-plenum pressure loss included the effect of the restriction caused by extension of the baffle below the level of the inlets, and any vortex pressure loss in the lower plenum. It is reported as a loss coefficient, C_L , which is defined as

$$C_L = \frac{\Delta P}{q},$$

where, in consistent units,

ΔP = measured loss in total pressure

q = velocity pressure, $\frac{V^2}{2g}$

V = velocity in inlets

g = gravitational constant.

Thus, the loss coefficient is the number of velocity heads lost between the inlet nozzle and the space between the flow baffle and the core, expressed in terms of velocity pressure in the inlet nozzle. The pressure loss used was the difference between the total pressure in the inlet nozzle and the total pressure in the space between the flow baffle and the bottom of the core.

Figure 24 shows the relation of lower-plenum loss coefficients to Reynolds number in the inlet nozzle for the 9-ft core design, with and without flow deflectors.

TABLE 3. STATIC PRESSURES IN LOWER PLENUM OF 9-FT CORE MODEL

Pressure Tap	Static Pressure With Indicated Number of Loops Operating, in. of water					
	Without Flow Deflectors			With Flow Deflectors		
	Four (Test 143)	Three (Test 142)	Two (Test 141)	Four (Test 148)	Three (Test 151)	Two (Test 150)
1	121.1	80.0	64.1	123.6	78.7	61.3
2	113.1	74.8	58.3	120.9	76.6	52.5
3	121.1	82.5	64.4	123.6	80.5	59.1
4	113.7	74.4	65.7	121.2	76.6	59.1
5	121.1	82.4	64.6	124.0	80.2	61.2
6	113.2	73.8	57.0	121.6	75.5	55.6
7	120.7	80.0	64.5	123.4	78.0	60.1
8	113.1	81.4	65.5	121.3	76.6	58.2
9	114.1	75.6	64.4	123.6	80.2	60.9
10	120.0	78.3	63.7	122.9	78.6	60.4
11	120.0	81.4	62.7	122.8	79.1	59.6
12	116.4	81.3	58.7	120.3	76.0	56.2
13	113.7	74.6	57.2	114.7	70.9	50.8
14	114.7	75.8	58.7	117.9	73.4	54.3
15	115.8	75.9	58.0	118.1	74.3	55.6
16	115.4	76.2	59.2	116.8	74.2	55.0
17	115.8	77.3	58.1	117.8	75.0	55.9
18	115.2	76.9	60.9	116.7	73.9	55.9
19	115.6	77.4	58.2	118.0	74.7	55.9
20	115.3	76.0	58.6	117.0	73.0	55.1
21	115.6	76.6	58.2	117.4	73.7	56.1
22	115.4	78.0	60.9	116.6	73.7	55.4
23	115.7	76.5	58.8	114.9	71.8	54.5
24	116.2	77.7	59.9	112.6	71.4	53.8
25	116.3	77.8	59.9	112.5	71.4	53.8
26	116.2	77.4	59.8	112.7	70.5	53.8
27	116.3	76.8	59.9	112.8	70.7	53.8
28	116.2	77.8	60.9	111.6	70.1	53.3
29 ^(a)	113.0	75.1	57.9	112.7	71.2	53.9
30 ^(b)	120.6	77.4	64.5	128.9	86.8	58.4

(a) Above flow baffle.

(b) In inlet nozzle.

FIGURE 24. RELATION OF LOWER-PLENUM LOSS COEFFICIENTS TO REYNOLDS NUMBER IN INLET NOZZLES

The loss coefficients were found to be constant over a wide range of flows for each inlet arrangement, but varied for different arrangements. The addition of flow deflectors increased the loss coefficient about 50 per cent for each inlet arrangement.

The pressure loss across the perforated bottom of the flow baffle is expressed as an orifice coefficient from

$$V = CA \sqrt{2gh}$$

where

V = volume rate of flow through baffle

C = orifice coefficient of baffle

A = total orifice area of baffle

g = acceleration of gravity

h = fluid head across baffle.

The upstream orifice pressure was measured with pressure taps 14 through 28 located in the bottom of the pressure vessel at the locations shown in Figure 23. The measured pressures were presented in Table 3. For the deflector configuration, where a large pressure gradient existed in the lower plenum, an integrated pressure was used. The downstream orifice pressure was measured with a piezometer ring installed in the bottom of the baffle. Flow-baffle orifice coefficients are summarized in Table 4.

TABLE 4. AREA COEFFICIENTS FOR FLOW-BAFFLE ORIFICES

Loops Operating	Area Coefficient	
	Without Deflectors	With Deflectors
Four	0.70	0.61
Three	0.64	0.65
Two opposed	0.56	0.74

Prototype Pressure Drops

Table 5 summarizes the total lower-plenum pressure loss for the prototype with the 9-ft core design, with and without flow deflectors. The values were determined as the product of the lower-plenum loss coefficient, from Figure 24, and the appropriate prototype inlet velocity pressure. Values for Core 1 are included for comparison.

TABLE 5. TOTAL PRESSURE DROP IN LOWER PLENUM OF PROTOTYPE

Loops Operating	Prototype Inlet Velocity Pressure ^(a) , psi	Total Pressure Drop, psi		
		Core 2 (9 Ft)		Core 1 (6 Ft)
		Without Deflectors	With Deflectors	
Four	4.04	6.18	9.45	5.44
Three	4.81	6.93	10.58	6.07
Two opposed	6.57	8.87	12.68	7.59

(a) Based on nominal flow rates of 23,700,000, 19,400,000, and 15,100,000 lb per hr for operation with four, three, and two loops, and an inlet nozzle diameter of 15 in., which did not include a thermal sleeve.

The pressure drop for the 9-ft core design was 0.74 to 1.28 psi higher than that for Core 1. For the 9-ft core design with flow deflectors, the pressure loss was 4.01 to 5.09 psi higher than for Core 1.

RESULTS OF STUDIES USING 7.5-FT CORE LENGTH

Sequence of Studies

The objective of these studies was improvement of mixing in the lower plenum with minimum added pressure drop. Nine configurations were evaluated by studying mixing and pressure drop using four loops, with SO_2 used as a tracer in one loop. Detailed studies were then carried out for the basic design without mixing devices, and for the best configuration with mixing devices.

In an extension of the original program, pressure drop and mixing for four-loop operation were evaluated for 17 additional configurations, with the objective of optimizing the lower-plenum design. Further improvement in mixing was obtained with a reduction in pressure loss. The final arrangement of swirl vanes and flow deflectors developed was considered for the prototype reference design by Westinghouse personnel, making such changes as required for manufacture. Detailed performance of equipment made from the reference drawings was then checked in the quarter-scale model and found satisfactory.

Screening of Mixing Devices

Screening studies of nine configurations were carried out by evaluating mixing and pressure drop for four-loop operation only.

Figure 25 shows the lower plenum of the PWR flow model, including the core extension, perforated flow baffle, swirl vanes, shroud rings, and shield flow deflectors. The core extension, shroud rings, and shield flow deflectors were added after completion of the first detailed flow studies.

In tests with only the perforated flow baffle for the 7.5-ft core installed; the maximum concentration of air from the traced inlet found in the core was 99 per cent. A core extension was not used for these tests. The flow baffle contained 439 holes of 1/2-in. diameter.

As a first approach toward forming a single large vortex in the lower plenum, 45-deg vanes were placed over each inlet. Each vane assembly consisted of a 4-in.-ID ring, to which straight vanes 1 in. wide spaced 11/16 in. apart and inclined 45 deg were attached, to direct inlet air tangentially. The maximum concentration of air from the traced inlet found in any simulated fuel assembly in the core was 79 per cent. However, flow restriction in the vanes was excessive.

As a second approach, a similar vortex was formed in the lower plenum, using a ring of swirl vanes, as shown in Figure 25. Sixty vanes, each 13/16 in. wide and spaced at 1-in. intervals, were attached to a ring 18-3/4 in. in diameter. This assembly was fastened to the flow baffle with the vanes extending from the flow baffle to a circle on the bottom dome tangent to the bottom of the inlets, as shown in Figure 25. This ring covered many holes in the baffle. The shroud rings shown at the roots and tips of the vanes were not installed for these tests.

Figure 26 is a photograph of the model with the bottom dome removed, showing the final configuration of swirl vanes and flow deflectors attached to the flow baffle. The vanes are shown at an angle of 30 deg from a radius. With 60-deg

FIGURE 25. SKETCH OF THE LOWER PLENUM OF THE PWR FLOW MODEL WITH SIMULATED 7.5-FT CORE, SHOWING MODIFIED SWIRL VANES AND SHIELD FLOW DEFLECTORS

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FIGURE 26. PHOTOGRAPH OF PWR AIR-FLOW MODEL WITH BOTTOM DOME REMOVED, SHOWING MODIFIED SWIRL VANES AND SHIELD FLOW DEFLECTORS INSTALLED ON FLOW BAFFLE

vanes, the maximum concentration of air from the traced inlet found in the core was 65 per cent. A number of holes in the flow baffle which fell outside the vaned ring were open so that flow through them was not well mixed. With these holes plugged the maximum concentration found in the core was reduced to 58 per cent. For these and subsequent tests there were 312 holes in the flow baffle, arranged as shown in Figure A-2 in the Appendix.

In an attempt to provide better mixing between adjacent inlets, horizontal dividers which extended from the top of one inlet to the bottom of the adjacent inlet were fastened to the vanes. These proved unsatisfactory, as the maximum concentration found in the core was 70 per cent.

To determine the effect of thermal-shield coolant flow on mixing, a test was run with the outermost thermal-shield coolant passage blocked with sponge rubber. With the 60-deg vanes and no shield flow, the maximum concentration of air from the traced inlet found in the core was 51 per cent. A comparison of tests with and without shield flow showed that the flow through the shield passages caused an area of high concentration in the core near the traced inlet. To further study the effect of thermal-shield flow on mixing, one study was made with SO_2 injected from a point source into the inlet of the outermost shield passage. It was found that nearly all the shield coolant entered the fuel assemblies at the edge of the core.

Measurement of flow in the thermal-shield passages using the installed yaw probes showed that the shield-coolant flow rate was about 32 per cent of total model flow instead of the desired 15 per cent. This was the result of blocking of a number of holes around the periphery of the baffle to force all flow through the swirl vanes. Because of the rather high pressure loss with the 60-deg vane angle, the effect of three additional vane angles on mixing and on pressure drop was studied before enlarging the holes in the flow baffles to reduce shield flow and baffle pressure drop.

Vane angles of 60, 45, 37.5, and 30 deg, were studied for four-loop operation with flow from one inlet traced. Shield flow was blocked for this study so that results would not be influenced by excessive shield flow, and only lower-plenum effects were observed. The data are presented on core maps with the concentration of air from the traced inlet measured in each fuel assembly shown at the location of the assembly.

Figure 27 shows mixing data obtained with a vane angle of 60 deg. The maximum concentration of air from the traced inlet found in any simulated fuel assembly in the core was 51 per cent.

Figure 28 shows mixing data obtained with the vanes turned 45 deg from a radius. The maximum concentration was 58 per cent.

Figure 29 shows mixing data obtained with a 37.5-deg vane angle. The maximum concentration was 60 per cent.

Figure 30 shows mixing data obtained with a 30-deg vane angle. The maximum concentration was 63 per cent.

Table 6 summarizes the results of the studies made to determine the effect of vane angle on mixing in the lower plenum. The 60-deg vanes were most effective, followed by 30-deg, 37.5-deg, and 45-deg vanes. Lower-plenum pressure drop was highest for the 60-deg vanes, decreasing as vane angle was reduced. Because the 30-deg vane angle appeared to provide good mixing with moderate pressure loss, it was

FIGURE 27

LOWER-PLENUM MIXING WITH 7.5-FT CORE WITH 60-DEG VANES AND NO SHIELD FLOW, USING INLET 2-3 PLUS THREE LOOPS

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

FIGURE 28

LOWER-PLENUM MIXING WITH 7.5-FT CORE WITH 45-DEG VANES AND NO SHIELD FLOW, USING INLET 2-3 PLUS THREE LOOPS

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

TABLE 6. EFFECT OF VANE ANGLE ON LOWER-PLENUM MIXING

Vane Angle, deg	Model Pressure Drop ^(a) , in. of water	Concentration of Air From Traced inlet, per cent					
		Core Maximum	Core Average	Deviation of Quadrant Average From Core Average			
				Quadrant 3-2 ^(b)	Quadrant 2-1	Quadrant 1-4	Quadrant 4-3
60	23.9	51	25	-0.1	7.6	-1.7	-6.0
45	22.8	58	25	1.4	13.7	-5.5	-9.9
37.5	21.2	60	25	3.7	10.7	-5.4	-9.1
30	19.5	63	25	8.9	6.3	-5.3	-9.2
Without vanes	7.3	99	25	41.0	-14.9	-19.1	-7.6

(a) Difference between static pressure in inlet duct and static pressure downstream of flow baffle.

(b) SO₂ injected into Inlet 3-2.

selected for studies to determine the effects of the large vortex in the lower plenum on shield flow, flow distribution in the core, flow-baffle pressure loss, and mixing for operation with two, three, and four loops.

Before starting the detailed flow studies, the 312 holes in the flow baffle were enlarged from 1/2 in. to 19/32 in. to reduce pressure loss and shield flow.

The apparent mixing performance was influenced substantially by the discharge of poorly mixed flow from the thermal-shield coolant passages into the region of highest concentration in the core. To impart angular momentum to the shield flow and, thus, cause rotation of the traced flow in a direction opposite from the rotation of flow in the lower plenum, a small deflector vane was placed over each inlet. The location of these vanes is shown in Figure 25. This directed the high concentration of traced flow in the shield passages into what had been a region of low concentration on the periphery of the core. The effects of angular position of the vanes over the inlets and of the location, measured from the edge of the inlet, on mixing and pressure loss were studied. With the vanes located 1 in. from the edge of the 3-3/4-in.-diameter inlets, at an angle of 45 deg, some improvement in mixing was obtained with no increase in pressure drop.

In preparation for enlarging the holes in the flow baffle to study performance with reduced lower-plenum pressure loss, the aluminum core extension shown in Figure 25 was added to simulate the 7.5-ft core. This reduced the space between the flow baffle and the core bottom from 5.9 in. to 3.3 in. This change had no effect on flow distribution in the core, but mixing between the inlets and the bottom of the core was reduced somewhat. The core extension was used in all subsequent tests.

The 312 holes in the flow baffle were enlarged from 19/32 in. to 11/16 in. This reduced the lower-plenum pressure drop by 27 per cent, with a slight improvement in mixing.

To determine the effect of flow in the center of the baffle on pressure drop, the center holes were blocked for one test. Pressure drop increased, indicating that flow area near the center of the baffle was effective in spite of the low pressure at the center of the lower-plenum vortex.

The effect of reducing the flow area through the swirl vanes was investigated by adding a shroud ring of masking tape around the base of the swirl vanes. Five shroud-ring configurations were studied. The optimum configuration consisted of a 3/4-in.-wide ring which blocked 27 per cent of the flow area. With this configuration, the pressure drop across the lower plenum was unexpectedly reduced about 25 per cent below that with no shroud ring, and mixing was improved.

The lower-plenum configuration selected as the best compromise between mixing and pressure drop consisted of the flow baffle with 312 11/16-in.-diameter holes, 30-deg swirl vanes with a 3/4-in.-wide shroud ring at the base, and 45-deg deflectors for shield flow, positioned 1 in. from the edge of the inlets.

Based on these results, Westinghouse personnel considered similar swirl vanes and shield-flow deflectors for the prototype, making only such

changes as were required by manufacturing and stress considerations. This design was then incorporated in the quarter-scale air-flow model to verify its performance with two, three, and four loops in operation. Figure 25 shows the swirl vanes and shield flow deflectors modeled from the prototype design.

Core-Flow Distribution

Basic Configuration

Figure 3 showed the arrangement of the core into five regions. The flow rates in all simulated fuel assemblies within each region were nominally equal, but flow rates in different regions differed. This core arrangement simulated Core 1 in overall pressure loss and in flow distribution, but did not necessarily simulate Core 2. However, it was felt that the simulation was sufficiently close that differences would not influence greatly the interpretation of results.

Figures 31, 32, and 33 show flow data which were obtained with the basic 7.5-ft core design, without any mixing devices. Each assembly location is marked with a value of flow through that assembly. Flow is expressed as the percentage of average mass flow for each assembly in the region in which the assembly is located. Arrows indicate positions of operating inlets. No data were obtained for Assembly 87 (lower right corner of seed region in Figures 31, 32, and 33) because an orifice pressure tap was plugged.

Figure 31 is a map of the core showing flow distribution with four-loop operation. In this test, flow for each assembly was within +1.6 per cent and -1.5 per cent of the average flow for each region.

Figure 32 shows flow distribution with three-loop operation. The flow in each assembly was within +2.2 per cent and -3.4 per cent of average flow for each region.

Figure 33 shows flow distribution with two opposed loops in operation. In this test, flow was within +3.1 per cent and -4.9 per cent of the average flow for each region.

Swirl Vanes

The core-flow data shown in Figures 34, 35, and 36 were obtained with swirl vanes only.

Figure 34, is a map of the core showing flow distribution with four-loop operation. In this test, flow for each assembly was within +2.4 per cent and -5.4 per cent of the average flow for each region.

Figure 35 shows flow distribution with three-loop operation. Flow for each assembly was within +2.5 per cent and -3.3 per cent of average flow for each region.

FIGURE 33

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH
7.5-FT CORE, USING TWO OPPOSED LOOPS

Numbers in each simulated fuel assembly show per-
centage of average flow for region.

FIGURE 34

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH
7.5-FT CORE WITH SWIRL VANES, USING
FOUR LOOPS

Numbers in each simulated fuel assembly show per-
centage of average flow for region.

FIGURE 35

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 7.5-FT CORE WITH SWIRL VANES, USING THREE LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

Figure 36 shows flow distribution with two opposed loops in operation. Flow to each fuel assembly was within +3.3 per cent and -4.3 per cent of average flow for each region.

Modified Swirl Vanes and Shield Flow Deflectors

Figures 37, 38 and 39 show the core-flow distribution data obtained with the modified swirl vanes and shield flow deflectors.

Figure 37 is a map of the core showing flow distribution for operation with four loops. Flow for each assembly was within +2.4 per cent and -4.0 per cent of the average flow for each region.

Figure 38 shows core-flow distribution with three-loop operation. In this test, flow to all fuel assemblies was within +3.6 per cent and -4.0 per cent of average flow.

Figure 39 shows flow distribution with two opposed loops in operation. Flow for each assembly was within +4.6 per cent and -5.8 per cent of average flow.

A comparison of Figures 31, 32, and 33 with Figures 34, 35, 36, 37, 38, and 39 shows that the maximum deviations from average flow were somewhat greater for the vaned configurations than for the basic configuration.

Flow in Thermal-Shield Coolant Passages

Basic Configuration

Because part of the reactor coolant bypasses the flow baffle and flows through the thermal-shield coolant passages, the flow in these passages was measured to evaluate pressure-loss data for both flow paths. In addition, velocities and flow directions in shield passages were measured to insure that all of the thermal-shield surfaces were adequately cooled. Previous studies made for Core 1 had shown that flow disturbances could be expected only in the outermost passage, as flow had been downward in the other passages regardless of operating conditions. Accordingly, in these studies, measurements of air velocities and directions were made only in the outermost shield passage, using two-hole cylindrical yaw probes of conventional design.

Locations of the yaw probes are shown in Figures 2 and 3, and Figures 7, 8, and 9 show a development of the outermost passage, Channel 1.

For operation with four loops, flow directions were within 7 deg of vertical with a maximum velocity of 59 fps and a minimum velocity of 49 fps. The average velocity was 53 fps, which would correspond to a water velocity of 9 fps in the prototype.

For three-loop operation the flow directions at the upper elevation were within 12 deg of vertical, with a velocity range of from 23 to 74 fps and an average velocity of 51 fps. Flow in the area above the center operating loop was generally upward, with a maximum deviation from vertical of 48 deg. Previously an area of downward flow had

FIGURE 37

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 7.5-FT CORE WITH MODIFIED SWIRL VANES AND SHIELD FLOW DEFLECTORS, USING FOUR LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

FIGURE 38

DISTRIBUTION OF FLOW IN CORE OF MODEL WITH 7.5-FT CORE WITH MODIFIED SWIRL VANES AND SHIELD FLOW DEFLECTORS, USING THREE LOOPS

Numbers in each simulated fuel assembly show percentage of average flow for region.

Numbers in each simulated fuel assembly show percentage of average flow for region.

been found above the center operating loop in both the Core 1 studies and the studies of the 9-ft Core 2 configuration.

With two opposed loops in operation, flow directions were within 15 deg of vertical at the upper elevation and within 45 deg of vertical at the lower elevation. Measured velocities were between 20 and 83 fps, with an average velocity of 48 fps.

Swirl Vanes

Flow velocities and directions in the outermost thermal-shield coolant passage were measured using two-hole cylindrical yaw probes.

For operation with four loops, flow directions were within 15 deg of vertical, and flow velocities varied between 47 and 79 fps, with an average of 67 fps. This corresponds to an average velocity in the prototype of about 11 fps.

With three loops operating, flow directions were also within 15 deg of vertical. The maximum velocity measured was 79 fps and the minimum was 45 fps. The average velocity was 64 fps.

When operating with two opposed loops, flow directions were within 20 deg of vertical with a velocity range of from 43 to 95 fps, with an average of 58 fps.

Modified Swirl Vanes and Shield Flow Deflectors

During four-loop operation, flow direction varied from vertical to 24 deg from vertical in the direction opposite to the induced swirl in the lower plenum. The flow velocities varied between 38 and 104 fps, with an average of 68 fps. This corresponds to an average velocity in the prototype of about 11 fps.

With three loops operating, flow directions were between 5 and 65 deg from vertical in the direction opposite to the swirl in the lower plenum. The maximum velocity measured was 122 fps and the minimum was 30 fps. The average velocity was 66 fps.

When operating with two opposed loops, flow directions were between 8 and 48 deg from vertical opposite to the swirl in the lower plenum. The velocities ranged from 33 to 140 fps, with an average of 70 fps.

Lower-Plenum Mixing

Basic Configuration

Mixing studies were conducted by injecting measured concentrations of SO₂ into Inlet 2-3 and determining the concentration of SO₂ in air passing through each of the 145 simulated fuel assemblies in the model core, as described previously.

Figure 40 shows mixing data with Inlet 2-3, the inlet into which SO_2 was injected, plus three loops in operation. The figure represents a cross section of the model core with the numbers indicating the percentage of flow in each fuel assembly which came from Inlet 2-3. With perfect mixing in the lower plenum, a value of 25 per cent would be obtained in every assembly. It will be noted, however, that concentrations in the quadrant of Inlet 2-3 were generally high, with peak values occurring nearest the inlet and decreasing with distance from the inlet. A maximum value of 84 per cent was found.

Figure 41 shows mixing data obtained using Inlet 2-3 plus two opposed loops. With this configuration, one third of the flow entered through Inlet 2-3, so that perfect mixing would result in a concentration of 33.3 per cent in each assembly. Again, the highest concentration was found nearest the traced inlet. The maximum value measured was 89 per cent.

Figure 42 shows mixing data using Inlet 2-3 plus two adjacent loops. This arrangement of operating inlets caused a shift in the pattern due to the unbalanced loop 90 deg from the traced loop, which produced higher peak concentrations. The maximum concentration of 90 per cent occurred near Inlet 2-3.

Swirl Vanes

Figures 43, 44 and 45 are core maps showing the mixing data obtained with 30-deg swirl vanes installed.

Figure 43 shows mixing data obtained using Inlet 2-3 plus three loops. The maximum concentration of air from Inlet 2-3 measured in the core was 62 per cent. This peak occurred in assemblies adjacent to the traced inlet. Mixing over a large part of the core was good, with values approaching the ideal value of 25 per cent.

Figure 44 shows mixing data obtained using Inlet 2-3 plus two opposed loops. As before, a region of high concentration was found adjacent to the traced inlet, with a maximum value of 82 per cent. With perfect mixing a value of 33 per cent would be obtained for each simulated assembly.

Figure 45 shows mixing data obtained with Inlet 2-3 plus two adjacent inlets in operation. Again, the peak concentrations occurred adjacent to the traced inlet. The maximum value measured was 78 per cent.

Modified Swirl Vanes and Shield Flow Deflectors

Figures 46, 47, and 48 are core maps showing the mixing data obtained with modified swirl vanes and flow deflectors installed.

Figure 46 shows mixing data obtained using Inlet 2-3 plus three loops. The maximum concentration of air from Inlet 2-3 measured in the core was 65 per cent. This peak occurred in the outermost subassemblies between Inlets 2-3 and 3-4. With perfect mixing a value of 25 per cent would be obtained for each simulated assembly and outlet.

FIGURE 40

LOWER PLENUM MIXING WITH 7.5-FT CORE, USING
INLET 2-3 PLUS THREE LOOPS

Numbers in each simulated fuel assembly show per-
centage of air from Inlet 2-3.

FIGURE 41

LOWER PLENUM MIXING WITH 7.5-FT CORE, USING
INLET 2-3 PLUS TWO OPPOSED LOOPS

Numbers in each simulated fuel assembly show per-
centage of air from Inlet 2-3.

FIGURE 44

LOWER-PLENUM MIXING WITH 7.5-FT CORE WITH SWIRL VANES, USING INLET 2-3 PLUS TWO OPPOSED LOOPS

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

FIGURE 45

LOWER-PLENUM MIXING WITH 7.5-FT CORE WITH SWIRL VANES, USING INLET 2-3 PLUS TWO ADJACENT LOOPS

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

2

Numbers in each simulated fuel assembly show percentage of air from Inlet 2-3.

Figure 47 shows mixing data obtained using Inlet 2-3 plus two opposed loops. As before, a region of high concentration was found between Inlets 2-3 and 3-4, with a maximum value of 79 per cent. Since three loops were in operation, the ideal value would be 33 per cent.

Figure 48 shows mixing data obtained with Inlet 2-3 plus two adjacent operating inlets. Again the peak concentrations occurred between Inlets 2-3 and 3-4, but closer to Inlet 3-4. The maximum value measured was 87 per cent.

Summary of Mixing Data for 7.5-Ft Core

Table 7 summarizes mixing data for the 7.5-ft core design. In addition to data taken directly from preceding data plots, quadrant averages are shown.

Table 7 shows that the modified swirl vanes with shield flow deflectors considerably reduced the highest quadrant average for all operating conditions. However, in terms of lowering maximum concentration, the performance of the modified vanes with deflectors and the swirl vanes was nearly the same.

Flow Rates in Thermal-Shield Coolant Passages

All of the thermal-shield coolant flows upward in the outermost passage, after which it divides and flows downward in other passages. The total flow through the shield passages was computed for each test using the flow velocity and direction data discussed previously. These velocities were measured at the center of the flow passage and were not necessarily vertical. Accordingly, the vertical components of velocities at the upper elevation were corrected by factors of 0.865 to 0.870 to account for the velocity profile across the passage thickness.

Table 8 summarizes the shield flow rates both with and without mixing devices. For all three configurations the shield flow rate, expressed as percentage of total model flow, increased with a decrease in the number of operating loops.

Distribution of Flow Among Core Regions

Table 9 summarizes the distribution of flow among core regions in the model for the 7.5-ft core design both with and without mixing devices. Distribution of flow among core regions varied only slightly with the number of loops operating. The variation resulting from addition of swirl vanes was of the same order of magnitude as the variation due to the number of loops operating. The flow rate for each region followed closely the rates measured in the Core 1 flow studies.

TABLE 7. SUMMARY OF MIXING DATA FOR 7.5-FT CORE DESIGN

Configuration	Figure Number	Concentration, per cent of fluid from traced inlet									
		Ideal Concentration	Maximum Concentration Found in Core	Average for Indicated Quadrant				Concentration at Indicated Outlet			
				2-1	1-4	4-3	3-2	2-1	1-4	4-3	3-2
<u>Four Loops</u>											
Basic(a)	34	25.0	84	10.9	7.8	18.2	63.1	(b)	(b)	(b)	(b)
Swirl vanes(a)	43	25.0	62	24.9	15.7	16.2	43.2	27	21	18	34
Modified swirl vanes with shield flow deflectors(c)	46	25.0	65	27.6	15.0	23.7	33.7	30	20	21	29
<u>Traced Loop plus Two Opposed Loops</u>											
Basic	35	33.3	89	19.3	22.0	23.1	68.9	--	--	--	--
Swirl vanes	44	33.3	82	31.5	25.2	24.7	51.9	31	Blocked	27	42
Modified swirl vanes with shield flow deflectors	47	33.3	79	31.9	24.5	38.9	37.9	31	Blocked	32	37
<u>Traced Loop plus Two Adjacent Loops</u>											
Basic	36	33.3	90	31.1	8.2	20.2	74.0	--	--	--	--
Swirl vanes	45	33.3	78	42.1	24.9	17.6	48.7	Blocked	31	27	42
Modified swirl vanes with shield flow deflectors	48	33.3	87	37.0	25.5	35.5	35.5	Blocked	32	32	36

(a) Flow baffle had 312 holes of 19/32-in. diameter.

(b) Data not taken.

(c) Flow baffle had 312 holes of 11/16-in. diameter.

TABLE 8. FLOW RATES IN THERMAL-SHIELD COOLANT PASSAGES OF THE QUARTER-SCALE FLOW MODEL WITH 7.5-FT CORE

Loops Operating	Flow for Configuration Indicated, per cent of total		
	Without Mixing Devices	With Swirl Vanes	With Modified Swirl Vanes and Shield Flow Deflectors
Four	15.5	19.6	19.9
Three	17.5	23.0	22.8
Two opposed	19.8	24.6	27.9

TABLE 9. DISTRIBUTION OF FLOW AMONG CORE REGIONS

Model Location	Flow Distribution With Indicated Number of Loops Operating, per cent of total								
	Without Mixing Devices			With Swirl Vanes			With Modified Swirl Vanes and Shield Flow Deflectors		
	Two	Three	Four	Two	Three	Four	Two	Three	Four
Region 1	6.50	6.44	6.48	6.45	6.39	6.41	6.62	6.49	6.52
Region 2	15.99	16.05	16.03	15.93	15.98	15.92	16.38	16.25	16.07
Region 3	23.79	23.84	23.68	23.68	23.89	23.62	23.54	24.22	23.84
Region 4	5.95	5.75	5.96	5.85	5.81	5.95	6.02	5.97	6.00
Seed region	47.78	47.86	47.84	48.11	47.94	48.10	47.44	47.07	47.57

TABLE 10. STATIC PRESSURES IN LOWER PLENUM OF 7.5-FT CORE MODEL

Pressure Tap	Static Pressure With Indicated Configuration and Number of Loops Operating, in. of water								
	Without Mixing Devices ^(a)			With Swirl Vanes ^(a)			With Modified Swirl Vanes and Shield Flow Deflectors ^(b)		
	Four (Test 170)	Three (Test 171)	Two (Test 172)	Four (Test 167)	Three (Test 178)	Two (Test 179)	Four (Test 208)	Three (Test 212)	Two (Test 213)
1	119.64	72.12	58.80	120.24	73.44	60.24	126.60	78.24	62.76
2	113.58	72.50	59.53	112.30	74.67	60.92	118.10	80.84	67.32
3	120.27	72.36	59.61	120.99	73.29	60.24	126.60	82.62	68.76
4	113.87	66.49	49.12	113.24	65.04	46.74	119.85	72.34	50.96
5	120.17	73.22	59.50	120.89	74.36	60.34	127.85	81.94	64.01
6	111.39	63.77	59.36	112.11	66.04	60.84	119.35	76.74	66.01
7	120.27	73.67	58.80	120.80	74.59	60.62	127.16	83.34	68.56
8	111.76	63.12	43.60	111.06	66.34	48.62	120.54	74.44	54.46
9	117.64	70.90	59.10	115.99	71.89	58.54	121.41	77.49	62.26
10	118.08	70.99	59.27	119.09	72.86	60.24	123.97	79.44	66.76
11	119.49	72.52	58.90	120.56	74.34	61.24	124.41	80.64	66.45
12	118.29	70.72	58.80	119.86	74.06	61.04	127.85	80.04	66.07
13	118.26	70.32	59.24	119.30	72.99	60.96	118.66	81.24	64.51
14	118.70	71.65	59.36	117.86	71.26	59.09	122.10	77.24	64.88
15	118.96	71.68	58.62	118.74	72.14	59.87	122.19	78.24	64.88
16	118.64	71.87	59.74	118.74	73.02	60.44	123.13	78.94	65.26
17	119.01	71.80	58.76	118.80	73.32	59.39	122.54	79.64	64.16
18	118.64	71.56	58.80	118.62	73.24	58.91	123.22	79.64	63.66
19	119.01	71.82	58.68	118.93	73.44	60.04	122.51	78.74	65.20
20	118.64	71.59	59.70	118.86	73.24	61.32	123.04	78.84	65.14
21	119.06	71.92	58.62	118.99	72.46	59.69	122.85	78.64	64.64
22	118.61	71.52	58.75	118.71	71.67	58.54	123.10	78.64	63.86
23	118.64	71.62	60.10	117.28	71.61	57.44	122.85	78.24	63.86
24	119.11	73.37	60.30	113.93	69.04	55.26	122.10	76.64	61.56
25	119.08	72.22	58.80	114.49	70.34	55.80	122.41	78.34	61.76
26	119.14	72.02	60.36	114.68	69.47	55.44	122.72	78.24	61.64
27	119.08	72.12	58.70	114.42	68.06	55.64	122.57	76.34	61.83
28	119.43	72.64	60.34	112.43	67.93	54.94	118.22	77.74	61.32
29 ^(c)	113.58	68.52	56.50	112.11	68.14	55.19	119.54	76.34	61.36
30 ^(d)	120.92	74.22	62.90	121.99	76.44	64.09	127.10	84.74	72.01

(a) Flow baffle had 312 holes of 19/32-in. diameter.

(b) Flow baffle had 312 holes of 11/16-in. diameter.

(c) Above flow baffle.

(d) In inlet nozzle.

Lower-Plenum Static Pressures

Figure 49 is a schematic drawing showing the locations of the 30 static-pressure taps which were installed in the lower plenum of the model to study the effect of various changes in lower-plenum geometry on pressure distribution.

Table 10 summarizes the pressures measured in the lower plenum of the model for the three configurations.

A comparison of the pressures obtained during four-loop operation both with and without mixing devices best shows the effect of the swirl vanes. Without vanes the static pressure in the bottom of the plenum, Taps 15 through 28, was quite uniform, but with swirl vanes a definite pressure gradient from edge to center resulted from the vortex flow. With the modified swirl vanes the gradient was steeper but did not start at the edge. Instead, a large area of uniform pressure surrounded a small area of low pressure at the center containing Tap 28.

Flow-Baffle Pressure Loss

Flow through the thermal-shield coolant passages has as its driving force the pressure drop across the perforated flow baffle under the core. Therefore, in order to design a baffle to obtain the desired shield passage flow it was necessary to know flow baffle pressure losses. These were determined for simulated two-loop, three-loop, and four-loop operation. For each determination, the pressure differential across the flow baffle was measured with a water manometer, the flow through the outermost thermal-shield passage was measured with the installed yaw probes, and the total model flow was measured at the model inlets. The flow through the flow baffle was determined as the difference between total model flow and shield-passage flow.

Total pressure loss for the entire lower plenum from the inlets to the bottom of the core and pressure loss across the perforated flow baffle were both measured. The total plenum pressure loss is reported as a loss coefficient, C_L , as previously defined.

Table 11 summarizes the loss coefficients obtained for two-, three-, and four-loop operation with the three geometric configurations.

TABLE 11. LOWER-PLENUM LOSS COEFFICIENTS

Loops Operating	Loss Coefficient for Configuration Indicated		
	Without Mixing Devices	With Swirl Vanes	With Modified Swirl Vanes and Shield Flow Deflectors
Four	1.48	1.73	1.55
Three	1.36	1.59	1.54
Two opposed	1.28	1.44	1.53

FIGURE 49. SCHEMATIC DRAWING OF BOTTOM DOME OF MODEL SHOWING LOCATIONS OF PRESSURE TAPS USED TO MEASURE LOWER-PLENUM PRESSURES

The addition of swirl vanes increased the loss coefficient by about 17 per cent for each loop configuration. When the swirl vanes were modified, the flow-baffle holes enlarged, and the shield flow deflectors added, the loss coefficient for four-loop operation was reduced to a value only about 5 per cent greater than the original coefficient without mixing devices. The loss coefficient with the modified swirl vanes was nearly independent of number of loops operating.

The pressure loss across the perforated bottom of the flow baffle is expressed as an orifice, or area, coefficient as previously defined.

The upstream orifice pressure was measured with the pressure taps located in the bottom dome at the locations shown in Figure 49. The measured pressures, using Taps 14 through 28, were presented in Table 10. For the configurations with mixing devices where a large pressure gradient existed in the lower plenum, an integrated pressure was used. The downstream orifice pressure was measured with a piezometer ring installed in the bottom of the baffle, Tap 29. Flow-baffle orifice coefficients are summarized in Table 12.

TABLE 12. AREA COEFFICIENTS FOR FLOW-BAFFLE ORIFICES

Loops Operating	Orifice Coefficients for Configuration Indicated		
	Without Mixing Devices	With Swirl Vanes	With Modified Swirl Vanes and Shield Flow Deflectors
Four	0.63	0.61	0.60
Three	0.60	0.58	0.55
Two opposed	0.55	0.51	0.38

Before the lower-plenum pressure data were taken for the modified swirl vanes, additional static-pressure taps were installed on the upper surface of the flow baffle to determine the pressure distribution downstream of the baffle. In four-loop operation, there was a pressure gradient downstream quite similar to the upstream gradient in the lower plenum. Thus the pressure drop across the flow baffle was nearly uniform.

When the number of operating loops was reduced and the total flow through the baffle decreased, the downstream pressure gradient decreased. With two-loop operation the downstream pressure was nearly uniform while a pressure gradient existed upstream of the baffle.

Prototype Pressure Drops

Table 13 summarizes the total lower-plenum pressure loss for the prototype with the 7.5-ft coil design, with and without mixing devices. The values were determined as the product of the lower-plenum loss coefficient, from Table 10, and the appropriate inlet velocity pressure.

TABLE 13. TOTAL PRESSURE DROP IN LOWER PLENUM OF PROTOTYPE WITH 7.5-FT CORE

Loops Operating	Prototype Inlet Velocity Pressure(a), psi	Core 1 (6 Ft)	Total Lower-Plenum Pressure Drop With Indicated Configuration, psi		
			Without Mixing Devices	With Swirl Vanes	With Modified Swirl Vanes and Shield Flow Deflectors
Four	4.04	5.44	5.98	6.99	6.26
Three	4.81	6.07	6.54	7.65	7.41
Two opposed	6.57	7.59	8.41	9.46	10.05

(a) Based on nominal flow rates of 23,700,000, 19,400,000, and 15,100,000 lb per hr for operation with four, three, and two loops, and an inlet-nozzle diameter of 15 in., which did not include a thermal sleeve.

The pressure drop for the 7.5-ft core design without mixing devices is about 9 per cent higher than the pressure drop for Core 1 based on differences in total pressures. For the 7.5-ft core design with swirl vanes, the pressure loss is about 26 per cent higher than for Core 1. With modified swirl vanes the pressure loss for four-loop operation is only about 15 per cent higher than for Core 1. However, as the number of operating loops was reduced from four to two, there was an increase of 61 per cent in the pressure loss. This increase was about 40 per cent for the other two configurations as well as for Core 1 and the 9-ft Core. Thus, as Table 12 shows, the modified swirl vanes are the more efficient mixing device for four-loop and three-loop operation. The relatively higher pressure loss for two-loop operation appears relatively unimportant as the reactor is then operating at a low output.

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APPENDIX

FLOW-BAFFLE DESIGNS

APPENDIX

FLOW-BAFFLE DESIGNS

Detailed layouts of the flow baffles used for model studies are shown in Figures A-1 and A-2. All dimensions shown are those used for the 1/4-scale model; prototype dimensions would be larger by a factor of four. All holes were uniformly spaced with pitch lines forming equilateral triangles.

Figure A-1 shows the flow baffle for the 9-ft core configuration. The hole pattern covered the entire flat bottom of the baffle. The 516 holes were spaced on a triangular pitch with $3/4$ in. between centers, and were $1/2$ -in. diameter.

Figure A-2 shows the flow baffle used for studies of the 7.5-ft-core configuration. The perforated area was smaller than the flat bottom of the flow baffle, covering only that area enclosed by the ring of swirl vanes. The 312 holes were arranged in a triangular pitch with $15/16$ in. between centers. Data for two different hole sizes are included in this report. Data for studies without mixing devices, and for swirl vanes without shield flow, were obtained with a hole diameter of $19/32$ in. Data for modified swirl vanes and shield-flow deflectors were obtained with a hole diameter of $11/16$ in.

FIGURE A-1. LAYOUT OF FLOW HAFLE USED WITH 9-FT CORE SHOWING
DIMENSIONS AND HOLE PATTERN

FIGURE A-2. LAYOUT OF FLOW BAFFLE USED WITH 7.5-FT CORE SHOWING DIMENSIONS AND HOLE PATTERN