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**YANKEE ATOMIC ELECTRIC COMPANY
RESEARCH AND DEVELOPMENT PROGRAM**

**PRESSURE DROP, FLOW DISTRIBUTION
AND MIXING STUDIES FOR A MODEL
HETEROGENEOUS REACTOR VESSEL**

**R & D SUBCONTRACT NO. 1 UNDER
USAEC - YAEC CONTRACT AT (30-3) - 222**

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**WESTINGHOUSE ELECTRIC CORPORATION
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Yankee Atomic Electric Company
Research and Development Program

PRESSURE DROP, FLOW DISTRIBUTION AND MIXING
STUDIES FOR A MODEL HETEROGENEOUS REACTOR VESSEL

by

R. T. Berringer
A. A. Bishop

Reactor Engineering Section

December 1959

For The Yankee Atomic Electric Company
Under Research and Development Subcontract
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APPROVED:

W. E. Abbott, Manager
Reactor Development Department

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I. ABSTRACT

A series of hydrodynamic tests were conducted on a 1/12 scale model of the Yankee reactor vessel and core with four, three and two loop operation. There was no depression of flow in the center of the core due to the control rod shrouds or shroud support plate. With four loops operating, flow distribution tests at the core inlet indicated that for all operating conditions the highest velocities occurred in the center region of the core and were a maximum of 18% higher than the average velocities. The lowest velocities were in the region near the core baffle and were a minimum of 18% lower than the average velocities. The effective flow starvation at the points of high flux were less than the 7% design value. Mixing studies indicated that no inlet position of the core received more than 55% of its total flow from one loop. The flow distribution did not change appreciably for four, three or two loop operation. The measured pressure drop across the vessel correlated within 6% of the predicted value.

II. INTRODUCTION

To obtain rated power from a heterogeneous nuclear reactor, sufficient pumping power must be supplied to overcome the hydraulic resistance in the primary loop in order to deliver rated flow to the reactor core. The prediction of the magnitude of the pressure drops, flow distribution and mixing in the reactor vessel is a fundamental design problem. From both operating and economic standpoints, arbitrarily oversizing the pumps is not a solution to the problem of determining the hydraulic resistance which the pump must overcome. Pumps are designed with specific characteristics and should operate in the vicinity of the design point for maximum efficiency and stability. The flow distribution in a reactor core determines the temperature rises in the fluid for the reactor power distribution. Theoretically, it is desirable to have peak flow where there is peak power. The amount and extent of mixing in a reactor vessel is significant for extreme operating conditions such as a cold water accident. The complex relationships of pressure drops, flow distribution, and mixing in a heterogeneous reactor demand recourse to an experimental investigation in order to obtain the most efficient hydraulic design.

The primary objective of this experimental investigation is to obtain and correlate experimental data in a model reactor vessel. The experimental pressure drops in the model are compared to the pressure drops obtained by accepted theoretical analyses. The effect of modifying the geometry of several components is investigated. The effects of operating the reactor with less than four loops are studied with reference to the pressure drops, flow distributions and mixing.

A secondary objective is the use of experimental information obtained in the model to predict hydraulic behavior in the actual Yankee reactor. Although this practical application is a very important consideration, this report deals with data obtained in the model and so must first be interpreted in relationship to correlations used for the model before being used to predict hydraulic behavior in the reactor.

III. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The pressure drop across the vessel correlated within 6% to the pressure drop predicted by the correlations used to calculate the pressure drop across the Yankee reactor pressure vessel.
2. Pressure drops across the inlet nozzles and thermal shield were significantly higher than the predicted value (at 300 gpm this increase was 0.93 psi or 25%). The pressure drops from the upper plenum to the outlet were significantly lower than the predicted value (at 300 gpm this decrease was 1.2 psi or 50%). The discrepancy between the predicted and calculated pressure drops in the outlet plenum and nozzles was not unexpected since the correlations for the calculations in this region were conservatively chosen. The discrepancy between the predicted and experimental pressure drops for the inlet nozzle and thermal shield, however, has not been fully explained.
3. Under normal 4-loop operation the highest velocities were in the center of the core and the lowest velocities were at the outer edge of the core. The center velocities were a maximum of 18% higher than the average velocities; the velocities near the core baffle wall were a minimum of 18% lower than the average velocity. With three or two loop operation the flow rate variation was $\pm 20\%$ with a somewhat skewed distribution. Comparison of representative neutron flux distributions with the measured flow distributions indicated the net effect of the flow distribution on the enthalpy rise in the hot channel to be less than the 7% design value.
4. Three dimensional velocities studies in the lower plenum indicated higher downward flows around the shrouds than radial velocities towards the shrouds. No detrimental disturbance to the flow distribution in the lower plenum is caused by the control rod shrouds or the shroud support plate.
5. Four loop operation plenum mixing studies with salt injected into one nozzle indicated that no simulated fuel assembly received more than 55% of its total entrance flow from the nozzle in which salt was injected. The degree of mixing did not change significantly for three loop operation.

Recommendation

Based on the results of this study the best estimate of the pressure drop across the Yankee Reactor Vessel is 33 psi. However, by allowing a $\pm 6\%$ correlation factor, the pressure drop range is 31 to 35 psi. The original reported value of 34 psi across the vessel is an acceptable pressure drop design value.

IV. NOMENCLATURE

A	Area, ft^2
D_e	Equivalent Diameter. $(\frac{4A}{P})$, ft.
f	Friction factor $\Delta p/(L/D_e) (\rho V^2/2g)$, dimensionless
g	Acceleration of gravity, 32.2 ft/sec^2
G	Mass flow rate, lbs/hr ft^2
K	Form coefficient, dimensionless
L	Length, ft.
N_R	Reynolds Number $(\frac{D_v \rho}{\mu})$, dimensionless
N	Normality, gram equivalents/liter
p	Static pressure, psi
P	Total pressure, psi
Δp	Differential pressure, psi
Q	Flow rate, gpm
t	Time, seconds
T	Temperature, $^{\circ}\text{F}$
v	Velocity, ft/sec
$\bar{v}$	Vector velocity, ft/sec
W	Mass flow, lbs/hr
Z	Elevation, ft.
ρ	Density, lb/ft^3
ν	Kinematical Viscosity, ft^2/sec
μ	Absolute viscosity, lb sec/ft^2

Subscripts

1, 2, 3---n	Numerical reference designation
c	Contraction
e.	Expansion
r	Relative

FIG. 1 SCHEMATIC DIAGRAM OF MODEL VESSEL IN LOOP "E"

V. DESCRIPTION OF EQUIPMENT

A. Loop E

Loop E is a low pressure - low temperature test facility having two-1000 gpm centrifugal pumps connected in parallel. The main loop piping is six inch stainless steel pipe. Figure 1 is a schematic of the loop modified for the reactor vessel model. A 250 gallon tank supplies water to the inlet side of the pumps and is open to the atmosphere. This stainless steel tank accommodates variations in the loop volume, furnishes a plenum which allows air to rise out of the system, and contains cooling coils for maintaining the desired temperature. Six inch diaphragm type valves and three inch gate type valves are used to control the flow. Orifice meters are used to measure the loop flow. The loop performed very satisfactorily for the testing of the reactor model vessel.

B. Reactor Vessel Model

1. Original Vessel Model

The vessel model first used for testing consisted of a 1/12 scale acrylic plastic model. This was a model of an earlier reactor prototype design, which has the same geometrical features, including the location of the inlet nozzles and the principal internal components. The control rod guide tubes and shrouds and the core were simplified in the model and were not to scale. The exact simulation of the reactor core was not feasible from a fabrication and cost standpoint, but obstructions to the flow were inserted in the model core to simulate the resistance to flow. Ceramic packing configurations such as spheres, Raschig rings, and Berl saddles were used to provide a resistance to flow of the same order of magnitude as an actual prototype core. The original model was also used to study mixing in the vessel head. To minimize thermal stresses between the vessel head and the flanges 0.5% of the total flow is by-passed into the head to ensure positive circulation in this region. The driving force for flow into the vessel head is the pressure drop across the vessel.

2. Modified Reactor Vessel

As the hydraulic studies in the vessel progressed, the need for velocity and flow distribution information in the core became evident. Moreover, changes in the design of the prototype vessel internals including features of the core warranted design changes in the model. It was decided to modify the existing model with new internals to provide a means of obtaining data in a core simulated with seventy-six dummy fuel assemblies and to comply with the latest prototype design. Figure 2 shows the revised model. Seventy-six total head probes extended into the dummy assemblies in the core, to be available for obtaining total head data in the core. Static head probes were later inserted to check the static pressure across the core. These head probes are shown in Figure 4. Thirty-two control rod shroud tubes and the shroud supports were scaled for geometric similitude to the prototype.

FIG. 2 MODIFIED REACTOR VESSEL MODEL

FIG. 3 MODIFIED REACTOR MODEL

C. Instrumentation

Standard liquid filled U-tube manometers were used to indicate all differential pressures. A bank of sixty straight-tube glass manometer tubes having a common manifold connection indicated readings from sixty of the total head probes. Air under pressure was forced into the common manifold connections. The air was filtered and regulated; the associated regulator and pressure gauge were graduated in two-psi intervals and could be accurately adjusted in one psi intervals.

A set of pitot tube flow measuring devices were designed to measure inlet and outlet flow through the reactor vessel flow nozzles. These tubes are shown in Figure 4. Basically, the tube consists of a 4.5" length of 2" type L copper tubing. The inlet of the tube is tapered to provide a smooth flow transition as the water impinges on the tip of the 0.1875" O.D., 0.035" wall total head probe component of the tube. The static pressure was transmitted to a piezometer ring from four taps located 90° apart around the periphery of the tube. The pitot tubes were calibrated in place using eight flow values. The center of the tube was used as the reference calibration point. The primary flow measuring device for the calibration was the main line orifice, a moriam flange tap orifice meter.

Total head stainless steel probes 0.1875" O.D., 0.1175" I.D. were also designed for the tests. The probes, which were connected by plastic tubing to the 60 tube bank of manometers, were 24" long and had a 2" tapered flow transition length at the head of the probe. A centering disc was located 2.25" from the probe head. Stainless steel static pressure probes were designed for the tests. Essentially these tubes were 24.5" long, with a 3.0" section of 0.058" O.D., 0.0018" wall tubing having four, number 80 drill holes 0.5" from the probe head. The body of the probe was a 21.5" length of 0.1875" O.D. x 0.035" tubing.

A Hundstad stainless steel two hole, three dimensional spherical-head probe was used to chart the flow distribution in the lower plenum. (Figure 5)

D. Chemical Injection System in the Model

A knowledge of the degree of coolant mixing which occurs in a reactor is important. The extent of the mixing of cold coolant flowing through one inlet nozzle with hot coolant flowing in the vessel through the other nozzles is an important consideration in evaluating the existence of a cold water accident.

A pressurized bomb having a capacity of 200 cc was mounted on one of the four inlet nozzles. A chemical solution under pressure was injected from the bomb into the coolant as it flowed through a nozzle into the vessel. Comparitory and titration techniques were used to determine the concentration gradients. Tri-sodium phosphate and sodium chloride were the chemicals used. The total head probes were used for sampling flow at the desired positions.

FIG. 4 EXPERIMENTAL PRESSURE PROBES

FIG. 5 - HUNDSTAD 3-DIMENSIONAL PROBE

FIG. 6 MODIFIED VESSEL MODEL COMPONENTS

VI. PRESSURE DROP TESTS AND RESULTS

A. Pressure Drop in the Yankee Pressure Vessel Model

Pressure drop calculations in a reactor vessel are complicated by the three dimensional aspects of the different regions. In the Yankee reactor there are three such plenum regions; the inlet plenum, the lower plenum, and the outlet plenum.

Associated with the inlet plenum is the converging flow from the four inlet nozzles. As the water flows into the inlet plenum not only is there an enlargement but there is also a directional turn into an annulus type plenum. No correlations were found to enable the pressure drop to be calculated for this particular geometry. For the inlet enlargement and direction turn the pressure drop which is entirely form loss was calculated based on a coefficient of unity and the vectorial resultant of the linear velocity in the nozzle and the plenum. This is tantamount to assuming a resultant velocity based on the law of cosines. The total loss coefficient based on this method is 1.2 using the nozzle velocity.

In the lower plenum there are thought to be losses caused by vortex and eddy formations, and obstructions to flow such as the control rod shrouds and the shroud support plate. For the Yankee reactor the energy losses in the lower plenum were calculated using a total velocity head based on the resultant vectorial velocity of the exit velocity from the thermal shield and the linear velocity in the lower plenum. This effectively includes the pressure drop effect of the 180° turn experienced by the coolant as it flows through the lower plenum.

The pressure drop across the Yankee core was calculated based on standard pressure drop correlations using a roughness of 100 micro-inches for the rods and friction factors based on the Moody diagram and the Colebrook correlation. Verification of this assumption for flow parallel to rods was obtained by experimental data included in "Model Study of the Pressure Drop Relationships in a Typical Fuel Rod Assembly",¹ YAE-75. The data in this report indicated that the equivalent diameter concept and related equations for calculating pressure drop inside of pipe are valid for calculating the pressure drop along a parallel cluster of rods where flow is parallel to the rods. The experimental pressure drop across the fuel assembly model correlated within 5% of the calculated value. In the model of the pressure vessel used for the present studies, the prototype core is simulated by 76 cylindrical tubes located between two support plates. The surfaces of the plastic simulated fuel assemblies were considered to be smooth and the corresponding curve from the Moody diagram was used to obtain the friction factor.

One velocity head, based on the vectorial resultant of the velocities in the upper plenum and the outlet nozzles, was taken as the energy lost in the upper plenum. For the contraction loss into the outlet nozzle a loss coefficient of 0.4 was assumed in the reactor and 0.78 was used for the re-entry model configuration.

The entrance to the outlet nozzles is tapered and the corners of the inlet nozzles are slightly rounded. In addition the entrance to the outer thermal shield flow region is tapered. This streamlining would effectively reduce the pressure drop in these regions. However, any such effect has not been included in the calculations because of the uncertainty of the exact magnitude of this saving. The omission of this correction is a conservatism in the design analysis.

Another region in the reactor where experimental data was needed to verify the pressure drops calculated was the parallel flow paths consisting of the paths on either side of the thermal shield and the reflector. Calculation of the pressure drop in this region is by iteration since friction factors must first be obtained based on an assumed velocity for the three parallel sections. No more than several trial velocities are needed because the solution converges rapidly.

In the model, the inlet and outlet nozzles protrude into the flow path while the nozzles in the reactor vessel are flush with the vessel wall and core barrel. The effect of these projections is to increase the experimental pressure drops in the model. When calculating the pressure drop in the model the effect of the nozzle protrusions was compensated for by assuming a coefficient for a Borda tube for the inlet nozzle and an exit loss coefficient of 0.78 for the re-entry losses at the exit nozzle.

B. Discussion of Pressure Drop Data

A summary of the pressure drop data is shown in Appendix C. Using the correlations, methods and assumptions discussed in the previous section the pressure drop across the model vessel was calculated to be 10 psi (although the value is listed as 9.98 in Appendix C it is felt that the pressure drop calculations are at best accurate to two significant figures.) Sample calculations for the model pressure drop are found in Appendix A. It should be noted that the increase in pressure drop caused by the re-entry of the nozzles has been included in the calculations. An average of the pressure data for four loop operation at 300 gpm total flow rate is 9.9 psi. For these tests the control rod shroud plate was in place.

When the shroud plate was removed the total pressure drop decreased to 9.4 psi. The difference of 0.5 psi was not entirely caused by the shroud plate since in the latter tests two of the 76 probes were not inserted in the core because of faulty connections. The effect was to cause a corresponding pressure drop decrease across the core. Within the estimated experimental error and non-reproducibility of data the pressure drop caused solely by the control rod shroud plate was estimated to be $0.3 \text{ psi} \pm 0.1$ at 300 gpm and four loop operation.

Based on the error analysis discussed in Section IX the experimental pressure drop is estimated to be accurate within $\pm 7.5\%$ of the value measured at 300 gpm. Thus the maximum experimental pressure drops at 300 gpm are 10.6 and 10.1 psi respectively for tests with and without the shroud support plate. Based on the calculated value of 10 psi the pressure drop across the model is correlated within $\pm 6\%$.

Observe that at a given total flow rate the pressure drop is inversely proportional to the number of loops operating. On a log-log plot the pressure drops across the vessel are straight lines having slopes from 1.9 to 2.0 for 4, 3 and 2 loop operation. This is to be expected since both predicted and experimental pressure drop data indicated that the form losses across the vessel predominate over the skin frictional losses. For two opposed loop operation, the pressure drop was 3% higher than with two adjacent loop operation.

As seen by the pressure drop breakdown in Appendix C the correlation between the individual pressure drops as calculated and measured is not good for the inlet nozzles, thermal shield and outlet nozzles.

In the original pressure drop calculations for the Yankee vessel the effect of the pins and lugs which hold the thermal shield in place was not included. However, the total entrance and exit losses in the thermal shield regions was assumed to be 1.4. The calculation listed under this "Predicted" column in Appendix C includes the pressure drop effect of the pins and lugs. The enlargement loss into the lower plenum is actually calculated and not arbitrarily taken as unity. The results of this method gives a pressure drop of 33 psi across the Yankee reactor instead of the 34 psi originally reported. Including the $\pm 6\%$ correlation factor the pressure drop range across the Yankee reactor is 31 to 35 psi.

Dynamic similitude between the model vessel and the reactor vessel does not exist because of temperature, velocity and size differences. The Reynolds number ratio between the corresponding regions in the model and the reactor varies from 1/500 to 1/100 for the various geometries and flows. Research on turbulence has shown that the geometry of turbulence, jet shape, and eddy formation is nearly independent of the Reynolds number at values above 5000, except in boundary layers on surfaces.² The main Yankee model Reynolds numbers exceeded 10,000. Moreover, since the losses in the model and reactor are form losses resulting in separation rather than frictional losses due to surface phenomena extrapolation from the hydrodynamics of the model vessel to the reactor is thought to be valid. Additional validity for extrapolating the experimental pressure drop data to the actual reactor is that the experimental pressure drop across the simulated core of the model is the same percentage magnitude of the total drop as the pressure drop across the reactor core.

As previously mentioned the pressure drop across an actual model of the fuel assembly and support plates was experimentally determined and reported in YAE-75. The experimental pressure drop could be correlated within 5% of the calculated value using similar pressure drop correlations as were used to calculate the pressure drop across the reactor core and the simulated core in the model vessel of the reactor.

FIG. 7 LOCATION OF PRESSURE TAPS IN MODEL.

FIG. 8 PRESSURE DROP RELATIONSHIPS FOR THE ORIGINAL MODEL

FIG. 9 PRESSURE DROP CORRELATIONS ACROSS THE MODEL VESSEL

FIG. 10 PRESSURE DROPS FROM INLET TO LOWER PLENUM
AND EXTRAPOLATED PRESSURE DROP CHARGED TO NOZZLES

FIG. 11 PRESSURE DROP CORRELATIONS ACROSS
THE OPEN LATTICE CORE

VII. FLOW DISTRIBUTION TESTS IN THE REACTOR VESSEL MODEL

A. General

Flow distribution in the reactor vessel model was studied by visual methods and by velocity measurements. Flow paths in the transparent model were observed using air bubbles or a dye. The flow around the support blocks in the bottom of the thermal shield produced a high degree of turbulence as it entered the lower plenum. Considerable turbulence was noted in all plenum regions. Some of the turbulent flow in the inlet plenum passed through small holes up into the head plenum with a high velocity. High flow disturbances prevented the measurement of the velocity, even with the 3 dimensional probe. Visual studies showed that the flow washed the head as it entered the head plenum before it went down into the upper plenum of the vessel.

B. Tests in the Simulated Yankee Core

Figure 6 shows the total head probes in the modified vessel model. Sixty of the available 76 pressure probes were connected to vertical tubes on the manometer board where they were recorded photographically as in Figure 13.

Holes were drilled in the simulated fuel assembly channels to allow for flow between channels. Eight levels of holes, each level having two 1/8" holes, were drilled in each dummy fuel assembly tube. This simulated the ratio of lateral flow area to normal flow area existing in the Yankee Reactor. Flow rates from 200 to 475 gpm were tested in the simulated open lattice tests. The number of open nozzles was varied to simulate four, three and two pump operation. Six static pressure probes were inserted into representative positions across the core to obtain static pressure information. The probes were inserted to a height of two inches above the lower core support plate after completing tests with probes two inches below the upper core support plate. The data indicated velocities which varied from a maximum in the center, decreasing gradually toward the outer radius of the core. Figure 16 gives a representative sample of velocity variations in the model core.

C. Three Dimensional Studies in the Lower Plenum

The complex turbulent flow field existing in the lower plenum presents difficulties in flow distribution tests in the plenum. The 3-D velocity probe shown in Figure 5 was used to measure velocity magnitudes and directions in the lower plenum. The velocity pattern shown in Figure 12 was obtained within experimental limitations. The pitch angle could only be measured with the probe for pitches from $+ 50^\circ$ to $- 50^\circ$. Also many positions resulted in an erratic behavior of the pressures being measured. Since the use of the 3-D velocity probe is based on the theoretical pressure distribution on a sphere in a uniform flow field, any small vortices occurring at the probe location would explain the erratic pressure readings obtained. Sufficient velocity data was obtained to predict a flow distribution where most of the flow went down into the lower regions of the plenum and then up through the shrouds with coolant in the upper portion of the plenum going in toward the center of the vessel. This distribution supports the higher velocities measured in the central regions of the core.

D. Correlation of Flow Distribution Data

The ratio of the measured velocity in each channel to the calculated average core velocity was determined and plotted in the core flow grids. For ease in interpreting the flow distribution data, velocity ratio isograms were interpolated as closely as was feasible from the experimental points and drawn in the flow grids as shown in Figures 14 to 24. In this way the experimental flow distribution at various flow conditions is described. Although the variation in velocities across the core increased with higher flows through the model, the percentage of variation was independent of total flow. Figures 14 through 17 show the velocity ratio isograms at four different flows. Figures 15, 18, 19 and 20 indicate the effect of varying the number of pumps in operation, while Figures 21 through 24 can be used to compare the flow distribution in the upper and lower positions in the core.

Observe that in Figure 3, the geometry of the inlet nozzle connections and manifolds are not identical. Since the loops are in such a condition, variances occur in the flow rate and distribution in the inlet nozzles as is evidenced by the nozzle flow rates shown in Figure 14. In later tests, the loop flows were somewhat balanced by valving.

If the reactor loops are perfectly symmetrical with equal hydrodynamic characteristics it is felt that the core distribution shown in Figure 14 would be more nearly symmetrical.

SCALE 1" = 1"
VECTOR SCALE 1" = 8 FT/SEC.

FIG. 12 - THREE-DIMENSIONAL VELOCITIES
IN THE LOWER PLENUM

FIG. 13 CORE INSTRUMENT PANEL

200 GPM

4 PUMP OPERATION

OPEN LATTICE

PROBES 2" FROM THE BOTTOM

EXPERIMENTAL LIMITS

X (V/V_{ave}) max. = 1.18

O (V/V_{ave}) min. = 0.87

FIG. 14 VELOCITY RATIO ISOGRAMS IN CORE

BOTTOM PROBE POSITION, 4 PUMP OPERATION, 200 GPM

300 GPM

4 PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM THE TOP

EXPERIMENTAL LIMITS

$(V/V_{ave})_{max.} = 1.16$

$(V/V_{ave})_{min.} = 0.86$

FIG. 15 VELOCITY RATIO ISOGRAMS IN CORE
TOP PROBE POSITION, 4 PUMP OPERATION, 300 GPM

EXPERIMENTAL LIMITS

$(V/V_{ave}) \text{ max.} = 1.14$

$(V/V_{ave}) \text{ min.} = 0.87$

FIG. 16. VELOCITY RATIO ISOGRAMS IN CORE
TOP PROBE POSITION, 4 PUMP OPERATION, 400 GPM

4 PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM TOP

$(V/v_{ave})_{max} = 1.15$

$$(V/V_{ave})_{min.} = 0.86$$

FIG. 17 VELOCITY RATIO ISOGRAMS IN CORE
TOP PROBE POSITION, 4 PUMP OPERATION, 450 GPM

300 GPM

3 PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM TOP

EXPERIMENTAL LIMITS

$(V/V_{ave}) \text{ max.} = 1.12$

$(V/V_{ave}) \text{ min.} = 0.84$

FIG. 18 VELOCITY RATIO ISOGRAMS IN CORE

TOP PROBE POSITION, 3 PUMP OPERATION, 300 GPM

300 GPM

2 ADJACENT PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM TOP

EXPERIMENTAL LIMITS

$(V/V_{ave}) \text{ max.} = 1.14$

$(V/V_{ave}) \text{ min.} = 0.86$

FIG. 19 VELOCITY RATIO ISOGRAMS IN CORE

TOP PROBE POSITION, 2 ADJACENT PUMP OPERATION, 300 GPM

300 GPM

2 OPPOSED PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM THE TOP

EXPERIMENTAL LIMITS
(V/Valve)max. 1.14
(V/Valve)min. = 0.84

FIG. 20 VELOCITY RATIO ISOGRAMS IN CORE
TOP PROBE POSITION, 2 OPPOSED PUMP OPERATION, 300 GPM

300 GPM

4 PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM THE BOTTOM

FIG. 21 VELOCITY RATIO ISOGRAMS IN CORE
BOTTOM PROBE POSITION, 4 PUMP OPERATION, 300 GPM

300 GPM

3 PUMP OPERATION
OPEN LATTICE
TUBES 2" FROM THE BOTTOM

EXPERIMENTAL LIMITS

$(V/V_{ave}) \text{ max.} = 1.17$

$(V/V_{ave}) \text{ min.} = 0.81$

FIG. 22 VELOCITY RATIO ISOGRAMS IN CORE

BOTTOM PROBE POSITION, 3-PUMP OPERATION, 300 GPM

300 GPM

2 ADJACENT PUMP OPERATION

OPEN LATTICE

PROBES 2" FROM THE BOTTOM

EXPERIMENTAL LIMITS

$(V/V_{ave}) \text{ max.} = 1.16$

$(V/V_{ave}) \text{ min.} = 0.88$

FIG. 23 VELOCITY RATIO ISOGRAMS IN CORE

BOTTOM PROBE POSITION, 2 ADJACENT PUMP OPERATION, 300 GPM

300 GPM

2 OPPOSED PUMP OPERATION
OPEN LATTICE
PROBES 2" FROM THE BOTTOM

EXPERIMENTAL LIMITS
(V/V_{ave}) max. = 1.16
(V/V_{ave}) min. = 0.84

FIG. 24 VELOCITY RATIO ISOGRAMS IN CORE
BOTTOM PROBE POSITION, 2 OPPOSED PUMP OPERATION, 300 GPM

VIII. MIXING TESTS IN THE REACTOR VESSEL MODEL

A. General

Mixing in the vessel was visually studied by using dye tracing methods and quantitatively studied by using chemical injection and sampling tests. Visual dye tests indicated no dead spots or regions where the fluid recirculated without mixing with the surrounding fluid. Chemical injection tests were used to determine the degree of mixing in the vessel. Since some of the chemical injected into one nozzle was found at all points sampled in the core, it was deemed that considerable mixing exists in the lower plenum.

B. Chemical Injection and Sampling Tests

A saturated sodium chloride solution was injected in an inlet nozzle and samples were taken at representative positions in the core. The chloride in the sample was determined by titrating with mercuric nitrate. The chloride ions combine with an equivalent amount of mercuric ions forming the slightly dissociated mercuric chloride. The first excess of mercuric ions is shown by a color change in the indicator, diphenyl-corbazone. A sample calculation is included in the Appendix. An average concentration of the flow through the nozzle in which the salt was injected was calculated for the sampling duration time. The ratio of the normality of the additional salt sampled in one channel to the calculated average inlet concentration was then taken as the ratio of the flow through that channel coming from the inlet. The first series of chemical injection tests consisted of sampling at ten representative positions in the core. For a later series of tests thirty positions in the core were sampled at the same time. Figure 25 shows the sampling setup. Mixing data was obtained at flow rates of 200, 300 and 400 gpm at simulated four pump operation with injection at one of two different inlet nozzles. Data was also obtained with three pump operation with injection into one loop nozzle at full flow. One test was run by injecting the salt into the fourth loop as it was being gradually opened to simulate a cold water incident.* The flow through the simulated cold loop indicated better mixing when the loop was gradually opened than when full flow entered from the cold loop. Chemical injection into the simulated cold loop at full flow represents the worst possible case of a cold water incident as far as mixing is concerned.

* The reactor cold water incident occurs when the relatively cool water from an inactive loop is injected into the reactor vessel as the loop is started up.

FIG. 25 MIXING EXPERIMENTAL SETUP

C. Interpretation and Correlation of Mixing Studies

The mixing tests indicated a considerable amount of mixing in the lower plenum. The effect of total flow on mixing was tested with no definite effects discerned, probably due to the high degree of turbulence in the plenum. It was interpreted that the total vessel flow had no significant effects on mixing and subsequent tests were conducted at 300 gpm. The amounts of salt in the samples from the core were expressed as a percentage of the inlet flow based on a uniform concentration. This dimensionless correlation readily indicates the extent and degree of mixing when plotted in the flow grid of the core. Figure 27 through 29 shows the correlation for tests where thirty points in the core were sampled simultaneously. Although similar tests resulted in slightly different mixing distributions, general trends in the mixing pattern were evident. The variation could be explained by the flow paths in the turbulent lower plenum shifting slightly with time. In general, sufficient mixing was found so that seldom did any one channel have as much as half of its flow from one inlet. The tests often indicated about one-fourth of the flow in central channels coming from the inlet in which salt was injected. The maximum concentration was noted to occur at the middle of the radius from the center of the core to the inlet nozzle. The channels closest to the nozzle in which the salt was injected, did not contain the most salt, but obtained more flow from adjacent nozzles.

TABLE I
SAMPLE EXPERIMENTAL MIXING DATA

Sample Probe Number	Injection Through Nozzle 3I at Flow Rate of 300 gpm					
	Number of Valves Open - 4				Valves Open - 3	
	Run No. 1 ¹		Run No. 2		Run No. 4	
	Sample Volume mls	Sample N x 10 ³	Sample Volume mls	Sample N x 10 ³	Sample Volume mls	Sample N x 10 ³
P ₁	--	1.06	--	1.41	--	1.59
P ₂	--	1.06	--	1.76	--	1.59
4	--	6.19	81	4.24	113	3.18
6	--	5.30	77	2.47	110	3.71
7	--	4.95	76	2.82	105	5.65
8	--	4.95	71	3.18	103	6.00
9	--	7.42	74	3.88	86	6.70
11	--	4.78	74	4.59	106	4.76
17	--	2.65	72	2.47	103	2.30
19	--	2.65	76	2.29	107	1.94
24	--	5.66	79	5.13	112	5.82
26	--	8.83	79	8.12	108	7.42
29	80	3.18	81	3.18	91	3.71
31	85	5.13	86	3.18	114	2.47
34	87	1.59	84	2.65	118	2.82
39	86	1.94	81	2.30	114	1.94
42	89	1.94	80	1.94	118	3.70
44	79	2.48	75	2.30	108	3.36
47	87	8.83	81	10.10	114	6.70
49	89	9.55	80	7.40	116	5.82
50	73	7.42	72	6.70	100	4.94
53	82	3.72	76	3.18	118	2.82
56	80	2.65	78	2.30	107	2.30
59	61	1.94	60	1.76	81	1.59
61	65	1.76	63	1.76	92	1.76
63	66	1.59	64	1.94	90	2.29
65	67	1.94	62	1.59	88	2.12
66	67	3.00	64	2.30	88	4.23
68	83	8.83	80	7.05	114	5.83
70	67	3.0	64	3.18	113	3.53
73	67	1.94	64	2.12	89	2.12
74	66	1.76	63	1.94	109	2.12

1. Runs No. 1 and 2 are duplicates

4 PUMP OPERATION 300 GPM
 PROBES 2" FROM TOP
 INJECTION AT I_3

PERCENTAGE OF FLOW IN CHANNEL FROM I_3

FIG. 26 TOP PROBE POSITION, 4 PUMP OPERATION, 300 GPM

4 PUMP OPERATION 300 GPM
 SAMPLE PROBES 2" FROM BOTTOM
 INJECTION AT I_3

PERCENTAGE OF FLOW IN CHANNEL FROM I_3

FIG. 27 BOTTOM PROBE POSITION, 4 PUMP OPERATION, 300 GPM

4 PUMP OPERATION 400 GPM
 PROBES 2" FROM BOTTOM
 INJECTION AT I₃

PERCENTAGE OF FLOW IN CHANNEL FROM I₃

FIG. 28 BOTTOM PROBE POSITION, 4 PUMP OPERATION, 400 GPM

3 PUMP OPERATION 300 GPM
 PROBES 2" FROM BOTTOM
 INJECTION AT I₃

PERCENTAGE OF FLOW IN CHANNEL FROM I₃

FIG. 29 BOTTOM PROBE POSITION, 3 PUMP OPERATION, 300 GPM

IX. EXPERIMENTAL ERROR ANALYSIS

A. Pressure Drop Determinations

The flow metering devices were sharp edged plate orifices with pressure drop measurements being read from oil and mercury manometers. The two main line flow meters checked within 2% at 300 gpm and the absolute calibration accuracy of the Meriam flow meter used for most tests is taken as 2%. Static pressure drops across the model vessel were measured with a mercury manometer. The combined error in manometer calibration, capillary effect and ability to read the manometer was taken at $\pm 1\%$. Since only static pressures were read directly in obtaining the pressure drop across the vessel it was necessary first to determine the total pressure difference, or the pressure drop between the inlet and outlet nozzle pressure taps. To obtain the desired total pressure drop information necessitated determining the flow and velocity through the nozzles at the desired total flow rate. At 300 gpm, the calibration accuracy of the nozzles was estimated to be ± 5 gpm based on a weighted flow distribution for the four inlet and outlet nozzles. Thus the possible error in nozzle flow velocity is 2.5% of the total pressure drop. On an additive basis the total estimated error on the pressure drop versus flow across the vessel is 7.5%.

B. Flow Distribution Determination

The principal source of error would be due to local conditions and would not effectively alter the overall results. By local effects are meant the error in total head reading caused by eccentricity of a total head probe in its flow channel, partial clogging of a probe, or disturbance at the head of the probe caused by surrounding conditions. Periodical purging helped eliminate the possibility of crud formation in the total head probes. No quantitative error determination for local perturbations was established or though necessary. Moreover, errors in total flow determination did not appreciably effect the data reported in percent of average flow since they are relative.

C. Mixing Determinations

Errors inherent in these determinations are due to the inaccuracy of measuring nozzle flow, inaccuracies in measuring the amount of salt injected, and inaccuracies in time determination. These errors are estimated to be ± 5 gpm, ± 5 ml and ± 0.4 seconds respectively. For four loop operation the arithmetical average of the amount of coolant received at the point of maximum NaCl concentration in the core was $43.5\% \pm 11.5\%$ or a maximum of 55% including the estimated error.

X. REFERENCES

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APPENDIX A

Sample Pressure Drop Calculations for the Modified Yankee Hydraulic Vessel Model

Flow = 300 gpm T = 80°F ν = 0.932 x 10⁻⁵ ft²/sec
= 0.670 ft³/sec ρ = 62.2 lb/ft³

a. Inlet Nozzle

$$\text{Area}_1 = 0.0767 \text{ ft}^2 \quad v_1 = Q/A = \frac{0.670 \text{ ft}^3/\text{sec}}{0.0767 \text{ ft}^2} = 8.74 \text{ ft/sec}$$

b. Inlet Annulus

$$A_2 = 0.1143 \text{ ft}^2 \qquad v_2 = 5.87 \text{ ft/sec}$$

Assume expansion loss plus 90° turn with a hydraulic loss coefficient based on a borda tube.

$$\vec{v}_R = \vec{v}_1 + \vec{v}_2 = 10.55 \text{ ft/sec} \quad K = 1/0.82^2 = 1.49$$

$$\Delta p = K \frac{\rho v r^2}{2g} = 1.49 \times \frac{62.2 \times 10.55^2}{64.4 \times 144} = \underline{1.112 \text{ psi}}$$

c. Flow past the Thermal Shield

A reiterative calculation results in a flow of $0.335 \text{ ft}^3/\text{sec}$ through the outside region.

$$A_{3T} = 0.0687 \text{ ft}^2 \quad A_3 = 0.0355 \text{ ft}^2 \quad v_3 = 9.44 \text{ ft/sec}$$

$$A_{3T}/A_2 = 0.6 \quad K_c = .275$$

$$De = 0.026 \text{ ft.} \quad N_R = \frac{7.89 \times .026}{0.932 \times 10^{-5}} = 2.20 \times 10^4, \quad f = 0.025$$

$$\Delta p = \left(\frac{0.025 \times 1}{0.0303} + 0.275 \right) \frac{62.2 \times 9.44^2}{64.4 \times 144} = 0.645 \text{ psi}$$

Across Pins $A_p = 0.030 \text{ ft}^2$ $v = 11.05 \text{ ft/sec}$

$$A_p/A_3 = 0.854 \quad K_c = 0.114 \quad K_e = 0.03$$

$$A_p = 0.144 \times \frac{62.2 \times 11.05^2}{64.4 \times 144} = 0.118 \text{ psi}$$

Across Support Blocks $A_s = 0.286 \text{ ft}^2$ $v = 11.7 \text{ ft/sec}$

$$A_s/A_3 = 0.808 \quad K_c = 0.4$$

$$A_3/A_4 = 0.10 \quad K_e = 0.81$$

$$\Delta p = 0.95 \frac{62.2 \times 11.7^2}{64.4 \times 144} = 0.873$$

Across Shield $\Delta p = 0.645 + 0.118 + 0.873 = \underline{1.636 \text{ psi}}$

d. Pressure Losses in the Lower Plenum

Assume 1 relative velocity head due to 180° turn and turbulence losses

$$\text{Area} = 0.342 \text{ ft}^2 \quad v_4 = 1.96 \text{ ft/sec}$$

$$v_3' = 10.6 \text{ ft/sec (weighted average of shield outlet velocities)}$$

$$\vec{v}_r = \vec{v}_3' + \vec{v}_4 = 12.56 \text{ ft/sec}$$

$$\Delta p = 1.0 \times \frac{62.2 \times 12.56^2}{64.4 \times 144} = \underline{1.06 \text{ psi}}$$

e. Pressure Drop Across the Lower Core Support Plate

$$A_5 = 0.0584 \text{ ft}^2 \quad v_5 = 11.5 \text{ ft/sec}$$

$$A_5/A_4 = 0.171 \quad K_s = 0.455$$

$$\Delta p = 0.455 \times \frac{62.2 \times 11.5^2}{64.4 \times 144} = \underline{0.404 \text{ psi}}$$

f. Pressure Drop Across the Probes

$$A_6 = 0.0437 \text{ ft}^2 \quad v = 15.3 \text{ ft/sec}$$

$$A_6/A_5 = 0.75 \quad K_c = 0.18$$

$$A_6/A_i = \frac{0.0437}{0.283} = 0.155 \quad K_e = 0.72$$

$$D_e = 0.0156 \text{ ft}$$

$$N_R = \frac{15.3 \times 0.0156}{0.932 \times 10^{-5}} = 25,600$$

$$f = 0.024$$

$$\Delta p = (0.024 \times \frac{0.561}{0.0156} + 0.90) \times \frac{62.2 \times 15.3^2}{144 \times 64.4} = \underline{2.77 \text{ psi}}$$

g. Pressure Drop Due to Probe Spacers

$$A_7 = 0.0322 \quad v = 20.8 \text{ ft/sec}$$

$$A_7/A_6 = 0.738 \quad K_c = 0.19 \quad K_e = 0.07$$

$$\Delta p = 0.26 \times \frac{62.2 \times 20.8^2}{64.4 \times 144} = \underline{0.755 \text{ psi}}$$

h. Pressure Losses in the Upper Plenum

(Assume 1 relative velocity head)

$$A_8 = 0.283 \text{ ft}^2 \quad v_8 = 2.36 \text{ ft/sec}$$

$$\bar{v}_r = \bar{v}_8 + \bar{v}_9 \quad v_9 = 13.6 \text{ ft/sec} \quad v_r = 13.8 \text{ ft/sec}$$

$$\Delta p = 1.0 \times \frac{62.2 \times 13.8^2}{64.4 \times 144} = \underline{1.28 \text{ psi}}$$

i. Contraction into Outlet Nozzle

Total area for nozzles

$$4 \times 1.765 = 7.060 \text{ in}^2 \\ = 0.0471 \text{ ft}^2$$

$$V = Q/A = \frac{0.670}{0.0491} = 13.6 \text{ ft/sec}$$

Assume $K_c = 0.78$ for a re-entry tube

$$\Delta p = 0.78 \frac{(13.6)^2}{64.4} \frac{(62.4)}{144} \\ = 0.965$$

Total Pressure Drop

$$\Delta p_{\text{Total}} = 1.112 + 1.636 + 1.06 + 0.404 + 2.77 + 0.965 + 0.755 + 1.28 \\ = \underline{9.98 \text{ psi}}$$

Pressure drop charged to nozzles

$$1.112 + 2.245 = \underline{3.357 \text{ psi}}$$

APPENDIX B

Chemical Injection Mixing Tests - Sample Calculation

Run No. 1

Total Flow 300 GPM

55 ml of a saturated NaCl solution injected into No. 3 inlet

Flow into No. 3 inlet 84 GPM

Sample time 4 sec.

Measured concentration of the saturated salt solution 0.305 gms NaCl/ml solution

a. Volume flowing through No. 3 Inlet in 4 Seconds

$$84 \text{ gal/min} \times 4 \text{ sec} \times \text{min}/60 \text{ sec} \times 3.79 \text{ liter/gal} = \underline{21.2 \text{ liters}}$$

b. Average Inlet Concentration

$$(55 \text{ ml}/21.2 \text{ liters}) \times (0.305 \text{ gms NaCl/ml}) = 0.791 \text{ gms NaCl/liter}$$

$$\text{Normality} = \frac{0.791 \text{ gms}}{\text{liter}} \times \frac{\text{liter}}{58.5 \text{ gms}} = \underline{1.35 \times 10^{-2} \text{ Normal Solution}}$$

c. Presample Concentration

To determine the amount of salt in the loop prior to the addition of salt into No. 3 inlet, 30 ml of a sample was titrated to the end point by 0.4 ml of 0.05 Normal Mercuric Nitrate

$$\text{Normality of Salt} = \frac{0.4 \text{ ml} \times 0.05 \text{ N}}{30 \text{ ml}} = \underline{6.67 \times 10^{-4} \text{ N}}$$

d. Concentration of sample Taken at Position No. 2, Titrated with 2.6 ml of $\text{Hg}(\text{NO}_3)_2$ into 30 ml.

$$\text{Normality of Sample} = \frac{2.6 \text{ ml} \times 0.05 \text{ N}}{30 \text{ ml}} = \underline{4.33 \times 10^{-3} \text{ N}}$$

e. Increase in Concentration Due to Injection

$$4.33 \times 10^{-3} \text{ N} - 6.67 \times 10^{-4} \text{ N} = \underline{3.663 \times 10^{-3} \text{ N}}$$

f. Percentage of Sample at Position No. 2 Coming from No. 3 Inlet

$$\% = \frac{3.663 \times 10^{-3} \text{ N}}{1.35 \times 10^{-2} \text{ N}} \times 100 = \underline{27.1 \%}$$

APPENDIX C

Summary of the Experimental Pressure Drop Data with Shroud Support Plate in Place

Temp. GPM	Loops No.	Static Pressures (psi)								Total Pressure Drops (psi)			
		Pa *	P _h	P _b	P _c	P _d	P _e	P _f	P _g	Across Core ΔP_{b-g}	Across Vessel ΔP_{a-h}	Inlet to Lower Plenum ΔP_{a-b}	Upper Plenum to Outlet ΔP_{g-h}
350	4	7.8	2.8	6.0	5.41	5.23	4.54	3.68	3.82	1.64	4.643	2.980	0.336
350	4	11.6	3.74	8.94	7.89	7.76	6.66	4.94	5.48	2.92	7.303	3.723	0.660
300	4	15.8	5.0	12.08	10.76	10.44	8.89	7.30	7.35	4.19	10.03	4.900	0.940
250	4	20.6	6.05	15.90	14.03	13.72	11.58	9.49	9.48	5.88	13.49	6.010	1.600
200	3	8.5	2.82	7.44	5.0	4.77	4.04	3.45	3.45	3.45	5.255	2.160	0.355
250	3	12.9	3.90	9.92	8.96	8.83	7.64	6.64	6.74	2.64	8.361	4.417	1.310
300	3	18.1	5.23	13.68	12.27	12.04	10.40	9.04	9.18	3.96	12.04	6.240	1.740
350	3	24.4	6.7	18.38	16.40	16.13	13.86	11.99	12.03	5.81	16.41	8.32	2.300
200	2-Adj	11.6	2.81	8.80	8.12	8.25	7.16	6.57	6.66	1.60	7.48	4.34	1.640
250	2-Adj	17.0	3.80	12.88	11.88	11.70	10.47	9.60	9.65	2.69	11.30	6.22	2.390
300	2-Adj	23.7	5.13	17.78	16.37	16.14	14.19	13.14	13.18	4.06	15.84	8.70	3.080
200	2-Opp	11.8	2.97	9.08	8.49	8.35	7.26	7.03	6.90	1.64	7.76	4.36	1.720
250	2-Opp	17.8	4.15	13.48	12.43	11.93	11.07	10.16	10.11	2.83	11.89	6.56	2.500
300	2-Opp	24.9	5.70	18.56	17.19	16.92	15.24	13.92	13.96	4.06	16.73	9.38	3.290

* refers to probe locations as indicated in Figure 7.

APPENDIX C

Comparison of Measured and Predicted Pressure Drops

Pressure Drop Location	Predicted ¹ psi	Experimental ² psi	Experimental ³ psi
From inlet to lower plenum (a to b) ⁴	3.81	4.74	4.33
From lower to upper plenum (b to g)	3.93	4.09	3.70
Upper plenum to outlet nozzle (g to h)	2.24	1.03	1.30
Total across vessel (a to h)	9.98	9.88	9.39
Charged to nozzle flow	3.36	2.50	2.25

1. Predicted as given in the sample calculation.
2. Average of experimental tests with probes 2-3/4" up from the bottom of the lower core support plate and shroud support plate in place.
3. Average of experimental tests after the shroud support plate was removed and two additional probes left out of the core.
4. Refers to location of pressure taps as shown in Figure 7.

APPENDIX D

Sample Pressure Drop Calculation for the Yankee Reactor Vessel

Design Flow $W = 37.8 \times 10^6$ lbs/hr

Water Temperatures Inlet = 499°F $Q = 211.4 \text{ ft}^3/\text{sec}$

Avg. = 516°F $Q = 215.3 \text{ ft}^3/\text{sec}$

Outlet = 529°F $Q = 218.8 \text{ ft}^3/\text{sec}$

1. Inlet Nozzles $A = 4 \times 1.981 = 7.924 \text{ ft}^2$

$$v = Q/A = \frac{211.4 \text{ ft}^3/\text{sec}}{7.924 \text{ ft}^2} = 26.7 \text{ ft/sec}$$

$$N_R = \frac{Dvp}{\mu} = \frac{1.981 \times 26.7 \times 49.68 \times 3600}{0.2613} = 29.0 \times 10^6$$

$$\epsilon = \frac{0.000500}{19.0625} = 2.62 \times 10^{-5}$$

$$f = 0.0055 \left[1 + \left(\frac{20,000\epsilon}{D} + \frac{10^6}{N_R} \right)^{0.333} \right] = 0.0101$$

$$\Delta p = f \frac{L}{D} \frac{\rho v^2}{2g} = \frac{0.0101 \times 21 \times 49.68 \times 26.7^2}{19.0625 \times 64.4 \times 144}$$

$$\Delta p = \underline{0.0431 \text{ psi}}$$

2. Inlet Annulus Area $A_2 = 22.12 \text{ ft}^2$ $v_2 = 9.56 \text{ ft/sec}$

Assume expansion loss and 90° turn to be one relative velocity head

$$\bar{v}_r = \bar{v}_1 + \bar{v}_2 = 28.35 \text{ ft/sec}$$

$$\Delta p = K \frac{\rho v^2}{2g} = \frac{1 \times 47.68 \times 28.35^2}{64.4 \times 144} = \underline{4.305 \text{ psi}}$$

3. Pressure Drop Across Baffle and Thermal Shields

Region a Outside of Thermal Shield $A_a = 4.67 \text{ ft}^2$ (3.79 ft^2 at lugs)

Region b Inside of Thermal Shield $A_b = 4.49 \text{ ft}^2$

Region c Inside Reflector $A_c = 14.717 \text{ ft}^2$

Holes into Reflector $A_{d1} = 1.395 \text{ ft}^2$

Holes out of Reflector $A_{d2} = 1.80 \text{ ft}^2$

$$\Delta p = f \frac{L}{De} + \Sigma K \frac{\rho v^2}{2g}$$

$$g = \frac{2g \Delta p / \rho}{f L / De + \Sigma K}$$

A trial and error solution is followed whereby f is assumed and the pressure drops across the four flow passages equated.

$$v_a = 18.4 \text{ ft/sec} \quad v_b = 21.7 \text{ ft/sec} \quad v_c = 1.92 \text{ ft/sec}$$

$$\Delta p = \underline{4.174 \text{ psi}}$$

4. Pressure Losses in the Lower Plenum

Assume one relative velocity head due to 180° turn and turbulence losses.

$$A_4 = 51.83 \text{ ft}^2$$

$$v_4 = 4.08 \text{ ft/sec}$$

$$v_3 = 21.4 \text{ ft/sec (weighted average from thermal shield regions)}$$

$$v_r = v_3 + v_4 = 25.48 \text{ ft/sec}$$

$$\Delta p = K \frac{\rho v^2}{2g} = \frac{1 \times 49.68 \times 25.48^2}{64.4 \times 144} = 3.48 \text{ psi}$$

5. Pressure Drop Across the Lower Core Support Plate

$$A = 10.560 \text{ ft}^2$$

$$v = 20.39 \text{ ft/sec}$$

Directly above plate

$$A_5 = 29.6 \text{ ft}^2$$

$$A_5/A_4 = 0.204$$

$$K_c = 0.376$$

$$A_5/A_5 = 0.357$$

$$K_e = 0.42$$

$$\Delta p = (0.376 + 0.42) \frac{48.78 \times 20.39^2}{64.4 \times 144} = \underline{1.74 \text{ psi}}$$

6. Pressure Drop Across Fuel Assembly End Plates

$$A_6 = 8.44 \text{ ft}^2$$

$$v_6 = 25.51 \text{ ft/sec}$$

Flow area through core

$$A_7 = 15.4 \text{ ft}^2$$

$$A_6/A_7 = 0.285$$

$$K_c = 0.362$$

$$A_6/A_7 = 0.549$$

$$K_e = 0.2$$

$$v_7 = 14.0 \text{ ft/sec}$$

$$\Delta p = \frac{0.562 \times 48.78 \times 25.51^2}{64.4 \times 144} = \underline{1.90 \text{ psi}}$$

7. Pressure Drop in the Core

Along Fuel Rods $D_e = 0.0281$ ft.

$$N_R = \frac{0.0281 \times 14 \times 48.78 \times 3600}{0.2515} = 2.75 \times 10^5$$

Weighted average core roughness 65×10^{-6} in.

$$\epsilon/D_e = \frac{65 \times 10^{-6}}{12 \times 0.0281} = 1.93 \times 10^{-4} \quad f = 0.017$$

$$\Delta p = \frac{0.017 \times 6.958 \times 48.78 \times 14^2}{0.0281 \times 64.4 \times 144} = \underline{4.34 \text{ psi}}$$

Pressure Drop across Ferrule Supports for Compromise Fuel Assemblies

$$A_8 = 13.08 \text{ ft}^2$$

$$v_8 = 16.47 \text{ ft/sec}$$

$$A_8/A_7 = 0.851$$

$$K_c = 0.10$$

$$K_e = 0.03$$

$$N_R = \frac{16.47 \times 0.0104 \times 48.78 \times 3600}{0.2515} = 1.20 \times 10^5$$

$$\epsilon/D_e = \frac{64 \times 10^{-6}}{12 \times 0.0104} = 4.4 \times 10^{-4} \quad f = 0.0192$$

$$\Delta p = (0.0192 \times \frac{0.5}{0.0104} + 0.13 \times 6) \frac{48.78 \times 16.47^2}{64.4 \times 144}$$

$$\Delta p = 1.32 + 1.112 = \underline{2.432 \text{ psi}}$$

Across Rubbing Straps $A_g = 14.23 \text{ ft}^2 \quad v = 15.1 \text{ ft/sec}$

$$A_g/A_7 = 0.925 \quad K_c + K_e = 0.1$$

$$\Delta p = (f L/D + 0.1) \frac{4 \times 48.78 \times 15.1^2}{64.4 \times 144} = 0.1 + 0.48 = \underline{0.58 \text{ psi}}$$

8. Upper Fuel Assembly End Plates

$$A_6/A_7 = 0.549$$

$$K_c = 0.278$$

$$v_6 = 25.51$$

$$A_6/A_5^1 = 0.285$$

$$K_e = 0.52$$

$$\Delta p = (0.52 + 0.278) \frac{48.78 \times 25.51^2}{64.4 \times 144} = \underline{2.69 \text{ psi}}$$

9. Upper Core Support Plate

$$A_5/A_4 = 0.204$$

$$K_c = 0.346$$

Area above support plate

$$A = 23.66 \text{ ft}^2$$

$$A_5/A_{10} = 0.444$$

$$K_e = 0.3$$

$$\Delta p = \frac{(0.346 + 0.3) \cdot 48.78 \times 26.4^2}{64.4 \times 144} = \underline{1.40 \text{ psi}}$$

10. Upper Plenum

Assume 1 relative velocity head loss

$$v_r = v_{10} + v_{11} = 29.1 \text{ ft/sec}$$

$$\Delta p = \frac{1 \times 47.98 \times 29.1^2}{64.4 \times 144} = \underline{4.378 \text{ psi}}$$

11. Outlet Nozzle

$$\Delta p = (f L/D + 0.4) \frac{47.98 \times 27.61^2}{64.4 \times 144} = 0.05 + 1.58 = \underline{1.63 \text{ psi}}$$

Total pressure drop across the reactor vessel 33.1 psi

Pressure drop across the reactor core 15.1 psi