JUL 11 1966 853

MASTER

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

Westinghouse Atomic Power Division

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

WCAP-3269-62

WCAP-3269-62
UC-80 Reactor Technology
Special Distribution

CFSTI PRICES

H.C. \$ 3.00; MN. .50

HYDRAULIC DESIGN OF A ROD CLUSTER CONTROL

FUEL ASSEMBLY

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

R. A. Dean

Reactor Engineering

September 1965

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

Prepared for the U. S. Atomic Energy Commission
Under New York Operations Office Contract AT(30-1)-3269

WESTINGHOUSE ELECTRIC CORPORATION
Atomic Power Division
Box 355
Pittsburgh, Pennsylvania 15230

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "Person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

EXTERNAL DISTRIBUTION

	<u>No. of Copies</u>
USAEC, New York Operations Office, 376 Hudson St., New York 14, N.Y., Director, Reactor Development Division	3
USAEC, New York Operations Office, 376 Hudson St., New York 14, N.Y., Attn: D. F. Streinz, Project Engineer, Reactor Development Division	1
USAEC, Division of Reactor Development and Technology, Washington 25, D. C., Attn: W. R. Voigt	3
USAEC, Division of Technical Information, P. O. Box 62, Oak Ridge, Tennessee	15
USAEC, Assistant General Counsel for Patents, Germantown, Maryland Attn: R. A. Anderson	1
General Electric Atomic Power Equipment Dept., 2151 South First St., San Jose, California, Attn: Aileen Thompson	2
The Babcock & Wilcox Co., Atomic Energy Division, 1201 Kemper St., P. O. Box 1260, Lynchburg, Virginia, Attn: J. W. Landis	2
Allis-Chalmers Manufacturing Co., Nuclear Power Dept. - Greendale, P. O. Box 512, Milwaukee 1, Wisconsin, Attn: C. B. Graham	2
Combustion Engineering, Inc., Nuclear Division, Windsor, Connecticut, Attn: A. F. Miller	2
Hanford Atomic Products Operations, General Electric Co., Richland, Washington, Attn: W. S. Dowis	2
Argonne National Laboratory, P. O. Box 299, Lemont, Illinois, Attn: A. V. Crewe	2
United Nuclear Corporation, Development Division, 5 New Street, White Plains, New York, Attn: Librarian	1
Yankee Atomic Electric Co., 441 Stuart St., Boston 16, Massachusetts, Attn: R. J. Coe	1
Yankee Atomic Electric Co., 441 Stuart St., Boston 16, Massachusetts, Attn: D. E. Vandenburg	1
Los Angeles Dept. of Water & Power, 207 South Broadway, P. O. Box 3669, Terminal Annex, Los Angeles 54, California, Attn: S. B. Nelson	1
Connecticut Yankee Atomic Power Co., P. O. Box 2010, Hartford 1, Connecticut, Attn: S. R. Knapp	1
Southern California Edison Co., P. O. Box 351, Los Angeles 53, California, Attn: J. F. Davenport	1
Southern California Edison Co., P. O. Box 351, Los Angeles 53, California, Attn: J. B. Henderson	1
San Diego Gas & Electric Co., P. O. Box 1831, San Diego 12, California Attn: C. M. Laffoon	1
TOTAL	<u>43</u>

TABLE OF CONTENTS

	<u>Page No.</u>
List of Figures	iv
Abstract	v
Introduction	1
Experimental Program	3
Test Results	13
Conclusions and Recommendations	28
References	29
Appendix	30
Acknowledgements	43

List of Figures

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
1	Test Cell-General Assembly	4
2	Fuel Assembly	5
3	Control Rod Assembly	6
4	Guide Tube Assembly	7
5	Photograph of Test Cell	8
6	Photograph of Test Loop	9
7	Photograph of Mixing Devices	11
8	Pressure Drop of Lower Core Plate and End Plate	14
9	Pressure Drop of Fuel Rods and Grids	15
10	Pressure Drop of Outlet of RCC Assembly	16
11	Pressure Drop of Outlet of Standard Assembly	17
12	Effect of Spider Location on Outlet Pressure Drop	19
13	Photograph of Optimized Mixing Device	21
14	Annular Friction Factor, $D_e = 0.028"$	22
15	Annular Friction Factor, $D_e = 0.046"$	23
16	Annular Friction Factor, $D_e = 0.106"$	24

Appendix

1	Dependence of Vena-Contracta Flow Area on Upstream Conditions	34
2	Effect of Rounded or Chamfered Entrance on Contraction Coefficient	38
3	Correction Factor for Rounded or Chamfered Entrance	39

Abstract

A test program was conducted to evaluate the hydraulic characteristics of the RCC control rod system. Two fuel assemblies, one containing a RCC control rod system, were positioned side by side in a single test cell. Tests were run which determined the resistance required to balance the outlet flows from the two assemblies. Flow patterns, made visible by dye injection, indicated the lack of mixing between the outlet of the fuel assembly and the upper core plate. A dual purpose mixing device was developed which balanced the outlet flows in addition to mixing the coolant so that the average outlet temperature could be recorded by the in-core instrumentation.

An analytical model for predicting the pressure loss coefficients for components with rounded or chamfered entrances is presented. Pressure loss coefficients for the various core components were obtained and agree well with this model.

Pressure drop measurements were also made to determine the friction factor for flows in annuli with the radial gaps varying from 0.014" to 0.053". These data are presented for flows in the laminar region and for turbulent flows with Reynolds numbers up to 15,000.

Introduction

A new concept of control rod design for pressurized water reactors has been selected for the San Onofre plant. The standard cruciform shaped control rod which was located between fuel assemblies has been replaced with rod clusters which disperse the neutron poison throughout the fuel; hence, the nomenclature of Rod Cluster Control (RCC) was adopted. With this design, the absorbers are guided inside the fuel assembly by guide thimbles which replace selected fuel rods. When an absorber is inserted in the core, there must be sufficient flow in the annulus formed by the absorber and thimble to prevent excessive temperatures of the absorber material. No followers are attached to these absorbers, and when the absorber is withdrawn to the upper section of the thimble, the coolant bypass flow in the thimble must be evaluated.

This design has control rod guide tubes located directly over selected fuel assemblies. At these locations, the hydraulic resistance at the upper core plate is increased since the guide tube decreases the available flow area. This causes a flow redistribution to occur; i.e. some flow leaves the assemblies below the guide tubes and exits through the core plate via the flow holes above the adjacent assemblies. The net result would be a decrease in the mass flow rate and an increase in the enthalpy rise in those fuel assemblies below the guide tubes. Both these factors have an adverse effect on the DNB ratio which determines the allowable core power. It was decided to prevent this flow unbalance from occurring by increasing the flow resistance of the upper core support plate above those fuel assemblies which do not have control rods. This requires a knowledge of the additional hydraulic resistance of the guide tube. Due to the complex geometry of the flow path in the guide tube vicinity, an analytical analysis would not be capable of supplying the value of this resistance with the accuracy required for design purposes.

An experimental program was then undertaken to measure the hydraulic resistance of the RCC guide tube. These data were used to design the upper core support plate and guide tubes so that the flow distribution would be uniform at the exit of the core. During these tests, it was observed that very little mixing occurred between the end of the fuel rods and the upper core plate. In the reactor, thermocouples will be located near the upper core plate, and it is desirable to have these thermocouples record the average outlet temperature of each instrumented fuel assembly. Thus a mixing

device was designed to serve a two fold purpose: (a) balance the outlet flows and (b) mix the flow so an average assembly outlet temperature could be measured.

An analytical model was developed to predict the pressure loss coefficients when the upstream edge of a flow restriction is rounded or chamfered. The pressure drop across the various core components was obtained experimentally and compared with the calculated values using this model.

The following conditions must be satisfied if the design of the RCC absorber guide thimble is to be optimized:

- (1) There must be sufficient flow in the thimble to cool an inserted absorber.
- (2) The bypass flow through the thimble is minimized when the absorber is withdrawn.
- (3) Rapid control rod scram times must be obtained.

Preliminary analysis indicated the radial gap in the annulus formed by the absorber and the thimble should be about 0.040". Very little experimental data could be found for the friction factor for turbulent flow in such small annular gaps. The uncertainty resulting from extrapolation of these data were too great to optimize the design. Bypass flow must be evaluated using the lowest value of the friction factor, while the absorber cooling calculation is performed using the highest value. Therefore, experimental measurements were made to evaluate the friction factor for flows in annuli with the radial gaps varying 0.014" to 0.053". These friction factors were obtained for Reynolds numbers ranging from 200 to 15,000.

Experimental Program

A test cell was designed to house two fuel assemblies, one complete with the RCC control rod system, in a low pressure water loop. These fuel assemblies were full size in cross-section but only four feet long, as this length was sufficient to duplicate the flow conditions in the core at the outlet of the assemblies.

The details of the test cell, fuel assemblies, control rod, and guide tube are shown in Figures 1, 2, 3, and 4. Note that only one fuel assembly had guide thimbles for the control rod absorbers, the other contained 196 dummy fuel rods. Hereafter these assemblies will be referred to as the RCC assembly and the standard assembly respectively. A photograph of the test cell is shown in Figure 5, and Figure 6 is a photograph of the test loop.

The test cell had a common inlet plenum which supplied flow to both fuel assemblies. The upper plenum had a baffle separating the flow leaving the two assemblies; these enabled a measurement of the difference in the outlet pressure drop of the two assemblies.

Calibrated orifices were placed in each of the outlet legs of the test section. These orifices were fabricated at WAPD and calibrated by the University of Pennsylvania to an accuracy of $\pm 0.3\%$. Each orifice section consisted of an orifice, a 13 feet entrance length of pipe with flow straightening vanes, and a 5 feet exit length of pipe. From the time of calibration, each orifice section remained intact; this prevented any misalignment of the orifice which could affect the calibration curve.

The fuel rod support grids in the two assemblies were staggered, i.e. located at different elevations. Dye injection taps were located in the fuel rods to permit a visual study of the flow patterns in the flow channels near the periphery of the assemblies in the vicinity of the staggered grids. These flow patterns were observed and photographed through plexiglas windows in the sides of the test cell.

Dye injection taps and windows were also provided near the top of the assembly to observe the flow patterns in the assembly outlet and the upper plenum.

H
G
F
E
D
C
B
A

FUEL TUBES FOR RCC ASSY

TUBE NO.	DIAM.	PATTERN
1, 3, 4	31.00	X
5, 6, 7	26.00	X
8, 9	16.750	Y
10, 11, 12	13.750	Y
13, 14	13.750	Y
15, 16, 17	13.750	Y
18, 19	13.750	Y
20, 21	13.750	Y

FUEL TUBES FOR STANDARD ASSY

TUBE NO.	DIAM.	PATTERN
19, 4, 15	21.750	X
31, 38, 39	34.851	Y
40, 17, 18	37.000	X
41, 20, 31	37.000	X
22, 33, 14	11.500	Y
33, 37	11.500	Y
34, 38	11.500	Y
36	12.016	Y
40	12.750	Y
41	17.000	Y
42	18.440	Y
43	19.150	Y
44	13.750	Y

SECTION C-C

SECTION B-B

BILL OF MATERIAL			
ITEM NO.	DESCRIPTION	QTY	REMARKS
1	BOTTOM PLATE	1	
2	SIDE PLATE	2	
3	FLOW SCREEN	1	
4	LOWER CORE PLATE	1	
5	WINDOW	4	
6	STANDARD FUEL ASSEMBLY	1	
7	RCC FUEL ASSEMBLY	1	
8	SPRINGS	1	
9	TOP CORE PLATE	1	
10	REINFORCING PLUG	1	
11	WINDOW	4	
12	GUIDE TUBE ASSEMBLY	1	
13	TOP PLATE	1	
14	OUTLET PIPE	1	
15	GUIDE TUBE ASSEMBLY	1	
16	INLET PIPE	1	
17	CLAMPING ASSEMBLY	1	
18	CLAMPING ASSEMBLY	1	
19	O-RINGS	2	NEOPRENE

647J238
SUB 2

647J238
SUB 2

Figure 1

WESTINGHOUSE ELECTRIC CORPORATION
ATOMIC POWER DIV., PITTSBURGH, PA., U.S.A.
647J238
SUB 2
1:1
DO NOT SCALE

Figure 3

Control Rod Assembly for Hydraulic Test

ESK 318666-0

Photograph of Test Cell

Figure 5

Photograph of Test Loop

Figure 6

Pressure taps were located throughout the test assemblies and test cell to determine the hydraulic resistance of the various components. These taps were connected to either differential manometers or multi-tube manometer boards. The data on the multi-tube manometers were recorded photographically to insure the readings were taken simultaneously.

Three orifice type restrictions, which could be placed in the upper core plate above the standard assembly, were designed to be installed through the windows in the upper portion of the test cell. During the testing of these orifice type restrictions, the flow mixing in the outlet of the assembly was found to be unfavorable for the thermocouples which will be part of the in-core instrumentation package. The scope of the program was then increased to develop an outlet mixing device which would mix the coolant while balancing the outlet flows.

The objective of this portion of the program was to determine what types of mixing devices would be feasible, and from these types determine which would be the most efficient, i.e. induce the maximum mixing per unit pressure drop. Five basic types of devices were tested: solid plates, stacked plates with a large central hole, tubular vanes, stacked curved blades, and propellers. Some of these devices are shown in Figure 7.

Physics analyses performed since the start of these tests indicated it would be more advantageous to have all fuel assemblies of one type, RCC, rather than have some with guide thimbles and others completely loaded with fuel rods. An analytical study was performed and indicated modifications could be made to the mixing devices which would plug the empty guide thimbles, such that the additional pressure drop of these thimble plugs and supports could be calculated with sufficient accuracy. Therefore, it was decided to test the outlet mixing device on the standard assembly and, in the plant design, allow for the increase in pressure drop due to thimble plugs and supports.

Annular friction factor data were obtained in a low pressure water loop from a vertical test section three feet long with an inside diameter of 0.465". Solid rods with diameters of 0.359", 0.419", and 0.437" were inserted in the test section. These configurations yielded friction factor data

Figure 7

for annuli with equivalent diameters of 0.106, 0.046, and 0.028 inches respectively. Tests were conducted with the rods centered, 100% eccentric, and diagonally located in the test cell, i.e. the rod contacted the top of the test cell at a position diametrically opposite the point of contact at the bottom. Static pressure measurements were made at the following distances above the entrance: 6, 15, 24, and 33 inches. At each elevation, 4 static taps, spaced 90° apart, were located to insure that an average pressure would be recorded. The "calming length" from the inlet to the first tap varied from 57 to 222 equivalent diameters. The static taps were connected to a ten feet U-tube manometer filled with 2.95 specific gravity oil. Data were collected from all combinations of the taps, except on some runs when the pressure drop between the bottom and top taps were off the scale of the manometer.

Test Results

A. Pressure Loss

Pressure drop data were obtained for the inlet of the assembly, the fuel rods and grids, and assembly outlet with and without an RCC guide tube. The variation of pressure drop with flow rate for the various components is shown in Figures 8, 9, 10, 11, and Table I lists the pressure loss coefficients.

Table I
Pressure Loss Coefficients (Based on the Velocity Along the Fuel Rods)

<u>Component</u>	<u>Measured Loss Coefficient</u>
Lower Core Plate and End Plate	3.15
Spacer Grid	1.06
Standard Assembly Retaining Plate and Core Plate	2.0
RCC Assembly Retaining Plate and Core Plate (Absorber Withdrawn)	3.46

An analytical model for predicting the pressure loss coefficients for non-abrupt contractions and expansions is presented in the Appendix. Using this model, the predicted pressure loss coefficient for the inlet of the assembly was 2.99, 5% lower than measured. The calculated loss coefficient for the outlet of the standard assembly was 1.78, 11% lower than the measured value. One reason for the larger discrepancy in the coefficient for the assembly outlet could be the 3/4" gap between the nozzle plate and core plate, as the analytical model does not account for the disturbance created by such a gap.

Comparison of the pressure drop at the outlet of the RCC assembly with the pressure drop at the outlet of the standard assembly with no orificing indicated a severe flow maldistribution, approximately 15%, would occur near the assembly outlet. This maldistribution could be prevented by increasing the pressure drop at the outlet of the

LOWER CORE PLATE AND END PLATE PRESSURE DROP

Figure 8

PRESSURE DROP ACROSS 4 GRIDS AND 32.8" OF FUEL ROD

Figure 9

FLOW IN UPPER CORE PLATE OF RCC ASSEMBLY (GPM)

PRESSURE DROP FOR THE OUTLET OF THE RCC ASSEMBLY

Figure 10

standard assembly. The most feasible way of accomplishing this in the core design would be to reduce the flow area in the upper core plate at the locations which did not have RCC guide tubes.

In these tests, this reduction in core plate flow area was simulated by inserting three different size orifice type restrictions in the upper core support plate above the standard fuel assembly. The data obtained with these orifice type restrictions indicated the flow area in the core plate should be reduced 12.8 in² to balance the outlet flows. During these tests, the control rod was in the fully withdrawn position. The pressure drop at the outlet of the RCC assembly was then determined as a function of the control rod position. This variation in pressure drop is illustrated in Figure 12 which shows the maximum variation is 1.2 psi.

B. Flow Patterns

Studies of the flow patterns, made visible by dye injection, indicated there was no cross flow induced by the staggered grids which would cause fuel rod vibration as a result of vortex shedding. Dye injected near the outlet of the fuel assembly indicated very little mixing occurred between the fuel rods and the upper plenum. In the design of the core, thermocouples are used extensively in the in-core instrumentation package, and it is desirable to have these thermocouples record the average outlet temperature of the fuel assembly. These tests indicated that the present design, with the thermocouples in the upper core plate, will record local temperatures not the average temperature. Since the pressure drop at the outlet of the non-RCC assemblies had to be increased to balance the flows, it was decided to develop a device which could be inserted in the top of the assembly to mix the coolant while balancing the pressure drop. The test cell was not designed for this purpose, and with the existing design only a qualitative evaluation of the device could be performed by observing the flow patterns made visible by the dye injection. A major modification of the test facility would be required to install a dye sampling system. The resulting cost and delay in the loop

EFFECT OF SPIDER LOCATION ON RCC ASSEMBLY OUTLET PRESSURE DROP

Figure 12

schedule prohibited such a modification; hence, only a qualitative evaluation was conducted. The relative performance of the five basic designs (Figure 7) which were tested are listed below.

Performance of Mixing Devices

Solid plate	Good mixing when located near the retaining, plate, excessive pressure drop
Stacked perforated plate	Fair mixing, reasonable pressure drop
Tubular vanes	Fair mixing, very low pressure drop
Stacked curved blades	Good mixing, reasonable pressure drop
Propellers	Good mixing, low pressure drop

The results of the tests on the basic types of devices indicated the propellers' performance was superior, and it was decided to optimize the design of the propeller. Various modifications were then tested; varying the bend angle, curving the blades, drilling holes in the blades, and removing material from the trailing edge. Curving the blades increased pressure drop without improving the mixing. Drilling holes in the blades decreased pressure drop but also decreased the amount of mixing. Removing material from the trailing edge reduced pressure drop slightly without any sacrifice in the mixing. Increasing the bend angle (defined as the maximum angle between the propeller blade and the horizontal) up to an angle of approximately 50° decreased pressure drop without affecting the mixing. The final design, Figure 13, was established as a straight propeller with a bend angle of 50° with the trailing edge of the blade scalloped. The pressure drop with this device was 0.45 psi less than the RCC guide tube; therefore, this 0.45 psi will be allowed in the plant design for the plug thimbles and supports.

C. Annular Friction Factors

The friction factor data obtained for annuli with diametral gaps of 0.028", 0.046", and 0.106" are presented in Figures 14, 15, and 16.

Photograph of Optimized Mixing Device

Figure 13

Figure 14

Figure 15

Figure 16

respectively. In all cases, the flow behavior changed from laminar to turbulent at a Reynolds number of approximately 1300. From the data for flows in concentric annuli, the following empirical correlations were obtained. The correlations fit the data to $\pm 10\%$ in the range of applicability.

Table II
Concentric Friction Factor Correlations

Diametral Gap (inches)	d_o/d_i	$f = \frac{2dp}{dx} \frac{D_e}{\rho V^2}$	Range of Correlation
0.106	1.29	$0.300 (Re)^{-0.25}$	$1400 \leq Re \leq 13,000$
0.106	1.29	$70.0 (Re)^{-1.0}$	$800 \leq Re \leq 1400$
0.046	1.11	$0.276 (Re)^{-0.25}$	$1300 \leq Re \leq 6000$
0.046	1.11	$59.0 (Re)^{-1.0}$	$300 \leq Re \leq 1300$
0.028	1.06	$0.270 (Re)^{-0.25}$	$1150 \leq Re \leq 2400$
0.028	1.06	$53.0 (Re)^{-1.0}$	$220 \leq Re \leq 1150$

These correlations are plotted on their respective figures. The coefficient α in the correlations for turbulent flows, $f = \alpha Re^\beta$, was found to vary linearly with the diameter ratio, d_o/d_i . This dependence may be expressed as

$$\alpha = 0.132 + 0.13 d_o/d_i$$

Thus in the turbulent flow region, these experimental data for concentric annuli can be correlated by

$$f = (0.132 + 0.13 d_o/d_i) Re^{-0.25}$$

Davis⁽¹⁾ proposed the following equation for correlating the friction factor in concentric annuli

$$f = 0.22 (\text{Re})^{-0.2} \left(\frac{d_o/d_i - 1}{d_o/d_i} \right)^{0.1}$$

Knudsen and Katz⁽²⁾ state that most experimental results can be represented by the equation

$$f = 0.304 \text{Re}^{-0.25}$$

However, there have been cases where the deviations from this equation has been as great as 35%. The data obtained in this test were bracketed by these correlations. They were generally about 10% higher than the predicted values according to Davis and from 2% to 15% lower than those using the equation of Knudsen and Katz.

The Navier-Stokes' equation can be solved exactly to obtain the friction factor as a function of Reynolds number for both circular pipes and concentric annuli, when the flow is laminar. These solutions indicate that, at a given Reynolds number, the friction factor for an annulus should be approximately 50% greater than that for a circular pipe, when the diameter ratio (d_o/d_i) of the annulus is greater than 0.75. However, these data agree better with the predicted values for circular pipes. Similar results have been obtained by other investigators.^(3,4,5) The reason for this discrepancy has not been resolved. Since the flows in the RUC absorber thimble will be turbulent, further investigation of the above behavior in the laminar region could not be justified. The data were presented and discussed to stimulate thinking in this area which may result in a solution of this apparent discrepancy.

For the test section with the smallest gap, $D_e = 0.028"$, the friction factor data for the eccentric annulus in laminar flow were approximately 20% greater than those for the concentric annulus; however in turbulent flow they agreed within the experimental error. The concentric and eccentric data obtained from the tests with $D_e = 0.046"$ agreed for both laminar and turbulent flows. The test section with the largest gap, $D_e = 0.106"$, yielded friction factors for the eccentric annulus which were about 15% less than those for

the concentric case. Table III lists the empirical correlations for the eccentric annuli.

Table III
Eccentric Friction Factor Correlations

Diametral Gap (inches)	d_o/d_i	$f = 2 \frac{dp}{dx} \frac{D_e}{\rho v^2}$	
0.106	1.29	$55.0 \text{ Re}^{-1.0}$	laminar
		$0.255 \text{ Re}^{-0.25}$	turbulent
0.046	1.11	$59.0 \text{ Re}^{-1.0}$	laminar
		$0.276 \text{ Re}^{-0.25}$	turbulent
0.028	1.06	$65.0 \text{ Re}^{-1.0}$	laminar
		$0.270 \text{ Re}^{-0.25}$	turbulent

In all cases the factors obtained for the diagonal annuli essentially agreed with those for the concentric cases. The data scatter for the diagonal condition was greater ($\pm 15\%$ instead of $\pm 10\%$ for the concentric and eccentric annuli). This is believed to be the result of the varying axial geometry in the test cell caused by the diagonal core, i.e. the core was fully eccentric at the top and bottom of the test cell but concentric at the mid-plane. Hence, we would not expect a uniform pressure gradient along the length of the test cell; and this variation would be reflected as an additional variation in the friction factor.

Conclusions and Recommendations

A propeller type outlet mixing device was developed for fuel assemblies without control rods. This device balances the resistance of the RCC guide tube and mixes the coolant so that a temperature nearer the average outlet temperature of the assembly could be recorded by the in-core instrumentation. These tests indicated a local temperature, instead of an average temperature, would be recorded if an outlet mixing device is not incorporated in the design. Without this mixer, the assembly power or enthalpy rise, as obtained from the in-core thermocouples, could be very misleading. The mixing effectiveness of the propeller type device was only evaluated qualitatively. It is recommended that further studies be conducted to obtain a quantitative evaluation; this would reduce the uncertainty in determining the enthalpy rise across an assembly from the measured outlet temperature.

An empirical correlation was developed for the friction factor for annuli with very small gaps; the experimental data being obtained for annuli with equivalent diameters of 0.028, 0.046, and 0.106 inches. The equivalent diameter of the RCC absorber-thimble is approximately 0.080 inches and it is recommended that this correlation, with an uncertainty of $\pm 10\%$, be used in the evaluation of;

- (a) The temperature distribution of an inserted absorber.
- (b) The coolant bypass flow when the absorbers are withdrawn.

A semi-empirical correlation was derived for the pressure loss coefficients for non-abrupt contractions and expansions. This correlation permits full advantage to be taken of a partially rounded (or partially chamfered) entrance in reducing the pressure drop of a given component. It eliminates the "individual judgement" which usually results in overly conservative loss coefficients. It also illustrates the consequences of "over-chamfering" this entrance section. It is suggested that this correlation be used for future design calculations.

References

1. Davis, E. S., Heat Transfer and Pressure Drop in Annuli, Transactions ASME Vol. 65, 1943.
2. Knudsen, J. G., and Katz, D. L., Fluid Dynamics and Heat Transfer, McGraw-Hill, 1958.
3. Nootbar, R. F., and Kinter, R. C., Proceedings of the Second Midwestern Conference on Fluid Mechanics, Ohio State University, 1952.
4. Kratz, A. P., MacIntire, H. J., and Gould, R. E., Flow of Liquids in Pipes of Circular and Annular Cross-Sections, University of Illinois Engineering Experiment Station, Bulletin No. 222, 1931.
5. Atherton, D. H., Fluid Flow in Pipes of Annular Cross-Section, Transactions ASME, Vol. 48, 1926.

APPENDIX

PRESSURE LOSS COEFFICIENTS FOR NON-ABRUPT CONTRACTIONS AND EXPANSIONS

Introduction

Reactor performance is strongly influenced by the pressure drop of the reactor vessel since this pressure drop is the largest in the primary system and the coolant flow rate is determined by the total pressure loss. Upon startup of a plant, the coolant flow rate is generally found to be higher than the design flow rate and the pressure drop across the vessel is lower than predicted. If the uncertainty in predicting the pressure losses can be reduced, the benefit of a higher flow rate can be utilized during the design of the plant. Approximately 70% of the pressure loss in the vessel is due to losses which occur when the flow area changes; these losses are generally referred to as form losses or contraction and expansion losses. Pressure loss coefficients for abrupt contractions and expansions have been determined by many investigators and, in general the agreement of the various results is good. However, very few data are available for the case when the entrance of the contraction is chamfered or rounded, with the exception of the well rounded entrance where it is usually accepted that the pressure loss coefficient is in the neighborhood of 0.04. Qualitatively, it is known that a "small degree of rounding" will significantly reduce the loss coefficient. The coefficient for a "slightly rounded" entrance has been reported as ≈ 0.23 , but this "slightly rounded" entrance is not defined. Designers have correction factors which they apply to the abrupt contraction loss to account for the shape of the entrance, but these factors are usually based on their individual judgement and hence are probably conservative. The reactor internals have many short contractions and expansions and the effect of the shape of the entrance of the expansion loss is often completely overlooked. A quantitative evaluation must be performed if full advantage is to be made of partially rounded entrances by removing unnecessary conservatism from the design calculations. A semi-empirical model has been developed to predict pressure loss coefficients for partially rounded or partially chamfered entrances.

Abrupt Expansion

Before discussing the effect of rounding the entrance, the model for predicting the pressure loss at an abrupt expansion is reviewed. Consider the following abrupt, axisymmetric expansion

Applying the one dimensional steady state momentum equation between sections (1) and (2), and assuming the shear stresses on the walls are negligible, yields

$$\int_s \rho u^2 \frac{\partial x}{\partial n} ds = - \int_s P \frac{\partial x}{\partial n} ds \quad (1)$$

If we further assume

- (i) uniform velocity distribution at sections (1) and (2)
- (ii) uniform pressure at the point of expansion, i.e. the static pressure of the main flow stream is applied on the vertical walls at this location

we obtain the solution

$$\rho V_2^2 A_2 - \rho V_1^2 A_1 = P_1 A_2 - P_2 A_2$$

Bernoulli's energy equation between these same sections yields

$$\frac{\rho V_1^2}{2} + P_1 = \frac{\rho V_2^2}{2} + P_2 + \Delta P_l$$

where ΔP_l is the unrecoverable pressure loss

Combining these solutions we obtain

$$\Delta P_l = \frac{\rho}{2} V_1^2 \left(\frac{A_1}{A_2} - 1 \right)^2$$

Expressing this pressure loss in terms of a pressure loss coefficient K_e and the dynamic head $\frac{\rho V_1^2}{2}$ yields

$$K_e = \left(\frac{A_1}{A_2} - 1 \right)^2$$

Many observations of flows at high Reynolds numbers ($> 10^4$) have agreed with the loss coefficients calculated in this manner, even when the expansion is not axisymmetric.

Abrupt Contraction

The flow pattern at an abrupt axisymmetric contraction is sketched below

SKETCH B

The fluid is accelerated from V_1 to $V_{v.c.}$ (the velocity at the vena-contracta) and then decelerated to V_2 . Considering the loss due to the deceleration from $V_{v.c.}$ to V_2 as an expansion loss we obtain

$$\Delta P_{dec} = \frac{\rho}{2} V_{v.c.}^2 \left(\frac{A_{v.c.}}{A_2} - 1 \right)^2$$

The flow area of the vena-contracta will depend on the flow area upstream of the contraction, as shown in Figure 1.⁽¹⁾ The total loss due to the contraction should then be the sum of the losses due to the acceleration and deceleration (or expansion). The momentum equation will not be helpful in this situation as the pressure distribution on the face of the contraction is required to obtain the solution. However, the total loss measured experimentally can be compared with the calculated deceleration loss and the difference will be considered as the acceleration loss. This approach was proposed by Streeter⁽¹⁾ in his discussion of abrupt contraction losses. A review of experimental data^(2,3) on contraction losses at high Reynolds numbers indicated the acceleration loss coefficient, based on the average velocity for fully developed flow, $\frac{\rho V_2^2}{2}$, may be approximated by

$$K_{acc} = .065 \left(1 - \frac{A_2}{A_1} \right)$$

Hence

$$\Delta P_{acc} = .065 \left(1 - \frac{A_2}{A_1} \right) \frac{\rho V_2^2}{2}$$

Chamfered Entrances

The approach outlined above is now extended to contractions with chamfered entrances.

(a) Single Vena-Contracta

Consider first the following axisymmetric non-abrupt contraction where reattachment takes place downstream of the chamfer.

SKETCH C

DEPENDENCE OF VENA-CONTRACTA FLOW AREA ON UPSTREAM CONDITIONS

Figure 1

The flow then separates from the wall at section (e) the same as it would if this were an abrupt contraction with a diameter $d_2 + 2r$.

The pressure loss due to the acceleration of the fluid from V_1 to $V_{v.c.}$ is then a function of the upstream flow area A_1 and the entrance flow area A_e (or $A_2\delta$, where $\delta = 1 + \frac{4r}{d_2} + \frac{4r^2}{d_2^2}$)

$$\begin{aligned}\Delta P_{acc} &= .065 \left(1 - \frac{\delta A_2}{A_1}\right) \frac{\rho V_e^2}{2g_c} \\ &= .065 \left(1 - \frac{\delta A_2}{A_1}\right) \frac{\rho V_2^2}{2g_c} \left(\frac{1}{\delta^2}\right)\end{aligned}$$

The loss due to the deceleration of the fluid depends on the area of the vena-contracta and the downstream flow area. The area of the vena contracta can be obtained from Figure 1 using A_e (or δA_2) and A_1 for the area ratio of the contraction. The total loss of the non-abrupt contraction is then calculated as

$$\Delta P = K_T \frac{\rho V_2^2}{2g_c} = \frac{\rho V_2^2}{2g_c} \left[\frac{.065 \left(1 - \frac{A_e}{A_1}\right)}{\delta^2} + \left(\delta \frac{A_{v.c.}}{A_e} - 1\right)^2 \left(\frac{A_e}{A_{v.c.}}\right)^2 \left(\frac{1}{\delta^2}\right) \right]$$

K_T is plotted as a function of A_e/A_1 and r/d_2 in Figure 2. Figure 3 shows how a "correction factor", which can be applied to the pressure loss coefficient for an abrupt contraction, varies with r/d_2 . From experiments⁽⁴⁾ it can be deduced that reattachment takes place downstream from the chamfer when $20^\circ \leq \alpha \leq 25^\circ$ and $l \leq 0.3 d_2$, for a large range of area ratios.

(b) Double Vena-Contracta

In the above sketch of the non-abrupt contraction, two restrictions were placed on the chamfered entrance, namely the angle and the depth of the chamfer. This was primarily to insure that a "double contraction" was avoided. If the depth of the chamfer is too large, a double contraction will occur as illustrated in the following sketch.

EFFECT OF ROUNDED OR CHAMFERED ENTRANCE ON CONTRACTION COEFFICIENT

CORRECTION FACTOR FOR ROUNDED OR
CHAMFERED ENTRANCE

Figure 3

SKETCH d

Also if the angle of the chamfer is very large, the above model would overpredict the correction factor because again the flow would re-attach and be required to separate again at the second entrance.

SKETCH e

A generalized model capable of handling all angles and depths of the chamfers would be very cumbersome to manipulate and make it very difficult to predict even the simple cases. The need for such a model is required only on rare occasions and it is felt the specific instances should be treated separately by applying the reasoning outlined above. Rouse and Abul-Fetouh⁽⁵⁾ present the jet profiles for various area ratios from which it is easily determined if a double contraction occurs for a given chamfer.

Rounded Entrance

This same concept, which was applied to the chamfered entrance, is valid for a rounded entrance provided r is replaced by the radius of curvature

of the entrance. A well rounded entrance is generally considered as one where $r/d_2 \approx 0.12$ or greater and whose coefficient is about 0.04. This agrees very well with Figures 2 and 3. Also there is experimental evidence⁽⁴⁾ that an orifice with a 20 to 25° (half-angle) chamfer and a depth of $0.2 d_2$ to $0.3 d_2$ behaves very similar to the well rounded entrance. This would correspond to a r/d_2 of ≈ 0.12 , and agrees with the results shown in Figure 2.

Comparison with Experimental Results

A literature search revealed experimental data collected by Hamilton⁽⁶⁾ with the radius on the entrance varying from fully abrupt to a radius of rounding equal to one half the diameter of the pipe. These experiments were confined to tests on two sizes of pipe, one with a 1.5" diameter and the other with a 6" diameter. In both cases, the ratio of the entrance flow area to the upstream flow area was of the order of 0.02. These results were converted to obtain a correction factor to be applied to his measured value of the abrupt contraction loss and are presented in Figure 3. This figure illustrates the good agreement between the proposed model and experimental results, thus confirming the validity of the model.

Short Chamfered Restrictions

In reactor design, very short sections are often encountered, such as those in the core support castings, core plates, and fuel assembly end plates. A short section will be defined as one in which the length over the entrance diameter is less than 1, as this insures the flow will not expand from the vena-contracta and reattach to the bore of the restriction before expanding in the downstream section.

It is usually desired to calculate an overall pressure loss coefficient for a given component. This loss is composed of an acceleration loss and one deceleration loss, since the flow expands from the vena contracta directly to the downstream flow area without reattaching. The acceleration loss from V_1 to $V_{v.c.}$ is the same as before since it is not affected by the downstream conditions. The deceleration loss coefficient, based on the velocity in the vena-contracta, now becomes $(\frac{A_{v.c.}}{A_3} - 1)^2$. Thus the total loss may be expressed as

$$\Delta P = \frac{\rho V_2^2}{2g_c} \left\{ \frac{.065}{8^2} (1 - A_e/A_1) + \left(\frac{A_{v.c.}}{A_3} - 1 \right)^2 \left(\frac{A_2}{A_{v.c.}} \right)^2 \right\}$$

This result is valid whenever the flow does not reattach to the walls. If the length is sufficient for reattachment, two separate deceleration losses should be computed: one from the vena-contracta to the bore and the other from the bore to the downstream flow area.

Conclusions and Recommendations

An analytical model for predicting the pressure loss coefficients for non-abrupt contractions and expansions was presented. This model is semi-empirical as it was developed from the understanding of flow behavior gained from experimental studies on abrupt contractions and expansions. The measured pressure loss was decomposed into an acceleration loss from the upstream condition to the vena-contracta and a deceleration loss from the vena contracta to the downstream conditions. This concept was then extended to predict the losses for non-abrupt entrance conditions by considering the effect of the entrance shape on the flow area at the vena-contracta. The validity of this concept was verified by the excellent agreement between measured pressure loss coefficients and the coefficients predicted by this analytical model.

In applying this approach to designs where the minimum pressure loss is desired, it is important to avoid "over-chamfering" the entrance. If the angle or length of the chamfer is too large, the flow will not reattach smoothly at the bore of the restriction; instead, a double contraction

will occur and this results in a higher pressure loss. This double contraction can be avoided if the length of the chamfer is less than three-tenths the diameter of the bore of the restriction and the half angle does not exceed 25° .

References

- (1) Streeter, V. L., Handbook of Fluid Dynamics First Edition, McGraw Hill, 1961.
- (2) Kays, W. M. and London, A. L., "Compact Heat Exchangers--A Summary of Basic Heat Transfer and Flow Friction Data", Technical Report No. 23, Department of Mechanical Engineering, Stanford University, 1954.
- (3) Weisbach, J., "Die experimental Hydraulik", J. S. Engelhardt, Freiberg, 1855.
- (4) Lichtarowicz, A., and Markland, E., Discussion to "Discharge Coefficient of Small Submerged Orifices", by Spikes, R. H., and Pennington, G. A., Proceeding of Institution of Mechanical Engineers, Vol. 73, 1959.
- (5) Rouse, H., and Abul-Fetouh, A., "Characteristics of Irrotational Flow through Axially Symmetric Orifices", ASME Transactions, Vol. No. 72, 1950.
- (6) Hamilton, J. B., "Suppression of Pipe Intake Losses by Various Degrees of Rounding", Bulletin No. 51, University of Washington Engineering Experiment Station, 1929.

Acknowledgements

The author wishes to acknowledge Mr. E. A. McCabe, Jr., Manager of the PWR Thermal and Hydraulic Design Group, for his suggestions and supervision during this program and for reviewing this report. He would also like to acknowledge Mr. T. S. Kvamme for the mechanical design of the fuel assemblies, Mr. E. I. Nelson for the mechanical design of the test cell, and Mr. L. J. Derzansky and his staff of technicians for conducting the experimental phase of the program.