**HYDRAULIC BALANCE CONCEPT AND
TUBESHEET LEAKAGE FFTF HYDRAULIC
FEATURE MODEL**

NOVEMBER 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

BATTELLE

NORTHWEST

BATTELLE MEMORIAL INSTITUTE

PACIFIC NORTHWEST LABORATORY

BATTELLE BOULEVARD, P. O. BOX 399, RICHLAND, WASHINGTON 99352

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.

PACIFIC NORTHWEST LABORATORY

RICHLAND, WASHINGTON

operated by

BATTELLE MEMORIAL INSTITUTE

for the

UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

PRINTED BY/FOR THE U.S. ATOMIC ENERGY COMMISSION

3 3679 00061 1725

BNWL-883

UC-80, Reactor Technology

HYDRAULIC BALANCE CONCEPT AND
TUBESHEET LEAKAGE FFTF HYDRAULIC
FEATURE MODEL

By

P. M. Jackson

Reactor Systems Evaluation Department
Engineering Development Division

November 1968

NOV 22 1968
DISTRICT 100

BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON

Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

TABLE OF CONTENTS

LIST OF FIGURES	v
INTRODUCTION	1
SUMMARY AND CONCLUSIONS.	2
DISCUSSION	4
Hydraulic Balance Model	4
Test Equipment	4
Test Procedure	4
Test Results	8
Tubesheet Configuration Model	17
Test Equipment	17
Test Results	17
ACKNOWLEDGEMENT	41
APPENDIX: ANALYSIS OF AXIAL FORCES ON CLOSE- ENDED FLOW DUCT WITH INFLOW AND OUTFLOW HAVING AN AXIAL VELOCITY COMPONENT.	A-1
DISTRIBUTION	Distr-1

LIST OF FIGURES

1	Hydraulic Balance Test Apparatus	5
2	Single Tube Model Hydraulic Balance Test	6
3	Outlet Area Configurations	9
4	Hydraulic Balance Test Upper Tubesheet ΔP Versus Leakage at Various Clearances	11
5	Hydraulic Balance Test Lower Tubesheet ΔP Versus Leakage at Various Clearances	12
6	Hydraulic Balance Test Leakage Versus Tubesheet Clearance at 75 psi	13
7	Hydraulic Balance Test Flow Versus Force (with Various Outlet Configurations)	14
8	Tubesheet Configuration Test Apparatus	18
9	Smooth Tube, 0.009-in. diam Clearance	20
10	Four Rectangular Groove Tube, 0.009-in. diam Clearance	21
11	Smooth Tube, 0.015-in. diam Clearance	22
12	Four Rectangular Groove Tube, 0.015-in. diam Clearance	23
13	Nine Triangular Groove Tube, 0.015-in. diam Clearance	24
14	Seven Rectangular Groove Tube, 0.015-in. diam Clearance	25
15	Nine Circular Groove Tube, 0.015-in. diam Clearance	26
16	Nine Circular Groove Tube, 0.015-in. diam Clearance	27
17	Smooth Concentric Tube, 0.015-in. diam Clearance	28
18	Seven Rectangular Groove Concentric Tube, 0.015-in. Clearance	29
19	Nine Circular Groove Concentric Tube, 0.015-in. diam Clearance	30
20	Tubesheet Configuration Test Apparatus for Seated Tubes	33
21	Seated Tube Fluid Velocity Versus ΔP	34
22	Seated 8-Slot Tube, 1/8-in. Wide, 0.015-in. diam Clearance, 0.00775-in. ² Slot Flow at 1580 lb Loading	35

23	Seated 8-Slot Tube, 1/8-in. Wide, 0.015-in. diam Clearance, 0.00775-in. ² Slot Flow Area at 2620-lb Loading	36
24	Seated 4-Slot Tube, 1/8-in. Wide, 0.025-in. diam Clearance, 0.00625 in. ² Slot Flow Area at 1580-lb Loading	37
25	Seated 4-Slot Tube, 1/4-in. Wide, 0.025-in. diam Clearance, 0.0125-in. ² Slot Flow Area at 1580-lb Loading	38
26	Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.02318-in. ² Slot Flow Area at 2620-lb Loading	39
27	Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.0112-in. ² Slot Flow Area at 2620-lb Loading	40
A-1	Axial Forces on Close-Ended Flow Duct	A-2

HYDRAULIC BALANCE CONCEPT AND
TUBESHEET LEAKAGE FFTF HYDRAULIC
FEATURE MODEL
P. M. Jackson

INTRODUCTION

Pacific Northwest Laboratory has been assigned project management of the Fast Flux Test Facility and performance of portions of the associated development program. The subject of this report is the evaluation of the inlet plenum hydraulic balance concept and leakage rates resulting from various tube-to-tubesheet configurations. This evaluation constitutes one of a series of "feature" or sectional tests to be performed in the overall hydraulic development program in support of the FFTF.

The hydraulic balance concept employs two tubesheets in the inlet zone to provide a force balance. The tube side inlet ports are incidental because the tube penetrates both tubesheets and the lower tube end is closed. This balanced design eliminates the large axial forces normally associated with an end entry. The reactor coolant bypasses the fuel ducts by leaking through the annular clearance between tube and tubesheet to provide coolant to the reactor core and to some reflector tubes.

The initial feature test apparatus contained one shortened version of a fuel duct assembly with chambers for collection and measurement of the leakage flow through the tubesheets, and an axial force measuring dynamometer. The coolant outlet section is also constructed with side outlet ports to allow the continuation of the fuel duct through the reactor cover.

The purpose of this test program was to evaluate the hydraulic balance concept under various operating conditions by measuring the axial forces acting upon the fuel duct and the water leakage rates through the tubesheet penetrations.

This report describes the testing program, the test apparatus, and the results obtained. All testing was performed using water as the flow media. The results of these tests, however, are presented in a form applicable to the flow of any liquid including sodium.

SUMMARY AND CONCLUSIONS

These tests have demonstrated that the resultant axial force on the FFTF fuel ducts can be controlled by the use of the hydraulic balance concept. The axial force on the fuel duct was found to be proportional to the coolant flow rate through the duct. All forces produced were in a downward direction with the exception of the test sequences where the leakage rate was high enough to cause a back pressure on the leakage collection chambers. The magnitude of the axial forces, using a 2.890-in. diameter tube, ranged from a low of 5 lb (4.3 lb with sodium at 750 °F) at a flow rate of 100 gal/min to a high of 47 lb (40 lb with sodium at 750 °F) at 350 gal/min flow, with corresponding diametral clearances of 0.005 and 0.017 in. The forces expected on a vertically oriented end entry tube would be about 500 lb in the upward direction at 75 psi tubesheet differential pressure.

A tubular shroud placed around the outlet ports to more closely simulate the normal reactor flow pattern from neighboring tubes resulted in an additional 18 lb of downward force at maximum test flow.

Duct outlet flow areas were varied from 7.95 to 43.1 in.² in a series of tests. These tests demonstrated that an increase in flow area would only negligibly affect the axial forces provided the shape of the discharge ports was unchanged. Changing outlet configuration from round holes to vertical slots increased the downward axial forces about 50%.

The tubesheet leakage rates were found to vary directly with increased annular clearance and as the square of the differential pressure across the tubesheet. The maximum leakage with a diametral clearance of 0.040 in. and 75 psi differential pressure was about 28 gal/min (water) per tubesheet penetration. Similarly, the minimum leakage, at the smallest diametral clearance of 0.005 in., measured 2 gal/min (water) per tubesheet penetration at 75 psi differential pressure. These values would convert to approximately 40 gal/min and 3 gal/min for sodium at 750 °F and 100 psi ΔP .

Leakage evaluations with the single tubesheet test apparatus compared favorably with the results obtained from the hydraulic balance model. The leakage data presented in this report was derived from the single tubesheet model. Labyrinth type penetrations and the seated tube were evaluated in this test apparatus. The labyrinth type penetration was investigated as an alternative to the straight penetration for obtaining equal leakage rates with larger clearance values. The larger tube-to-tubesheet clearances would provide greater fabrication tolerances and ease of installation and removal. Although a reduction in the leakage rates was evident in the testing conducted, the magnitude was not significantly large. The leakage rates were found to vary up to about 35% dependent on the position of the tube within the tubesheet. Concentric, diagonal, eccentric and free positions were investigated. The free positions were not included in the data as they fell randomly within the spread of the others. The seated tube style was selected for study because of its horizontal and vertical fuel duct reference and use in regulating leakage independent of clearance values. Predictable leakage rates can be obtained for a seated tube arrangement with a known flow area.

DISCUSSION

The discussion of the test program is divided into two sections. These sections are the test work conducted using (1) the hydraulic balance model, and (2) the tubesheet configuration model.

HYDRAULIC BALANCE MODEL

Test Equipment

The hydraulic balance model, shown in Figures 1 and 2, consists of a full scale fuel duct and an inlet plenum region consisting of two parallel tubesheets through which the ducts penetrate and into which ambient temperature water is introduced. The shortened fuel duct was supported from a dynamometer at the upper end capable of measuring changes in axial load on the fuel duct. The flow pattern was arranged so the coolant would enter the inlet slots in the duct, flow upward through a variable flow restrictor, and exit from the tube through side outlet ports. Leakage collection chambers were provided to measure the volume of coolant leakage through the annular clearance between the fuel duct and upper and lower tubesheets. The coolant flow rate was variable between zero and 350 gal/min at ambient temperature.

Test Procedure

Measurements of various flow rates with the variable restrictor in a fixed position were made to establish leakage rates and the forces upon the fuel duct (Table 1). The maximum differential pressure condition allowable with this test apparatus was 75 psi. The same tube section was used throughout the entire testing program. The tube was machined periodically to reduce the diameter and thus increase the clearance value (Test Sequence I-V, Table 1). The outlet zone was altered to produce larger fuel duct outlet areas (Test Sequence VI-IX, Table 1). A shroud tube was placed around the

FIGURE 1. Hydraulic Balance Test Apparatus

FIGURE 2. Single Tube Model Hydraulic Balance Test

TABLE 1. Test Data

VARIATIONS IN ANNULAR CLEARANCE (DIAMETRAL)													VARIATIONS IN OUTLET FLOW AREA																				
TEST SEQUENCE I CLEARANCE: U - 0.005 L - 0.005						TEST SEQUENCE II CLEARANCE: U - 0.012 L - 0.011				TEST SEQUENCE III CLEARANCE: U - 0.017 L - 0.011				TEST SEQUENCE IV CLEARANCE: U - 0.025 L - 0.025			TEST SEQUENCE V CLEARANCE: U - 0.040 L - 0.040			TEST SEQ. VI		TEST SEQ. VII		TEST SEQ. VIII		TEST SEQ. IX		TEST SEQ. X					
SERIES	FLOW GPM	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE	ΔP psi	LEAKAGE GPM		FORCE
			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER			UPPER	LOWER	
1	350	75	2.0	1.0	33	74	6.0	3.5	26	75	10	3.9	25	75	15.0	15.0	75	28.6	26.5	75	33	75	45	75	53	75	67						
	300	52.5	1.5	0.9	25	53	5.5	3.0	21.3	53	8.6	3.2	18	54	12.0	12.0	55	23.5	22.5	52.5	25	52	22	52	36	53	31	54	47				
	250	36	1.1	0.7	15	35.5	4.3	2.5	14	37	7.5	2.5	12	37.5	10.0	10.0	37	20.0	18.7	36	15	36	16	36	24	37	20	37	30				
	200	22	0.7	0.4	11	22.5	3.2	1.9	9	23.5	5.5	1.8	8	24	8.6	7.5	23	15.4	15.0	22	11	22	8	22.5	12	22.5	10	24	18				
	150	13.5	0.5	0.2	7.2	13.0	2.1	1.2	7.3	13	4.6	1.2	8	13	6.3	5.6	13	12.0	11.3	13.5	7.2	13	5	12.5	8.5	13	7	13.5	9				
	100	6	0.2	0.1	4.7	6.0	0.9	0.5	5.3	6	2.2	0.6	3	6	3.7	3.3	6	8.7	8.0	6	4.7	6	2	6	5.5	5.5	3.5	5.5	5				
2	350	60	1.6	0.9	44	60	5.5	5.7	18	60	10	3.8	22	60	14.3	12.5	60	25.0	25.0	60	44	60	40	60	46	60	47	60	65				
	300	43	1.2	0.7	31	41.5	5.0	4.8	14.5	44	8.6	3.2	14	44	10.7	11.5	43	20.7	20.0	43	31	42	23	43	34	42.5	31.5	43	44				
	250	29	0.9	0.5	20	29	4.0	3.7	12	30	6.7	2.5	10	32	9.2	8.8	29	17.6	17.1	29	20	28	13	30	23	29.5	19	30.5	31				
	200	18	0.6	0.3	11	18.5	3.0	2.8	9	19	5.0	1.8	6	18	7.9	6.5	17.5	13.6	12.7	18	11	17.5	5	18	11	19	10	19	17				
	150	10	0.4	0.1	7	10.2	1.9	1.9	7	11.5	3.5	1.2	3	11	5.9	5.1	11	11.1	9.8	10	7	10.5	4.5	11	9	10	7	10.5	9				
	100					4	0.9	1.1	2	5	2.1	0.5	2	5	3.5	2.9	5	7.7	6.5			4.5	3	5	5.5	4.5	2.5	4.5	5.5				
3	350	50	1.3	0.8	44	50	5.5	4.6	15.0	50	8.6	3.4	14	50	11.5	11.5	50	23.5	22.2	50	44	50	36	50	46	50	44	50	65				
	300	37	1.0	0.6	31	36	4.6	4.0	11.5	36	7.5	2.9	9.5	37	10.3	10.0	37	20.0	18.7	37	31	37.5	24.0	37	34	35	31	36	47				
	250	25	0.8	0.4	19	24.5	3.5	3.4	7.5	24	6.0	2.2	5.5	24.5	9.2	7.9	25	16.2	15.4	25	19	25.5	10	25	21	24	18.5	25.5	33				
	200	13.5	0.5	0.2	10	15.5	2.7	2.5	6.0	15	4.4	1.5	2.5	15	7.0	6.2	15	13.0	12.0	13.5	10	16	5.5	16	11.5	15	10.5	16	17				
	150	9	0.3	0.1	7	9.0	1.9	1.8	4.5	8.5	3.2	0.9	2.0	8	5.1	4.4	9.5	10.5	9.4	9	7	9	3	9	9	9	7	9	9				
	100					4.0	1.0	1.0	1.5	4	1.7	0.4	1.0	4	3.0	2.5	4	6.4	6.2			4	2	4	5	4	3	4	5.5				
4	250	75	1.8	1.0	20	75	6.7	6.0	21	75	10	4.3	19	75	13.3	15.4	75	28.6	27.2	75	20	75	13	75	19	75	19	75	31				
	200	46	1.2	0.7	10	45.5	5.0	5.0	13.5	47	8.6	3.3	12	45	10.5	12.0	45.5	21.4	20.6	46	10	46	6.5	47	11.5	47	10.5	48.5	18				
	150	26.5	0.8	0.4	6	26	3.5	3.7	8.0	27	7.0	2.3	6	25	8.8	8.6	25.5	16.7	16.2	26.5	6	26	3	26	9	26	7.5	26.5	10				
	100	11	0.4	0.1	4	12	3.0	2.3	3.0	12	3.8	1.2	3	11	5.7	5.0	11	11.1	10.5	11	4	11.5	3	11	6	11	4	11	6				
5	200	75	1.8	0.9	13	75	6.7	4.6	19.5	75	10	4.3	18.0	75	8.6	16.7	75	27.3	27.3	75	13	75	10	75	11.5	75	11	75	18				
	150	42	1.2	0.6	10	40	5.0	3.7	12.5	40	7.5	3.2	10.5	39	5.7	10.9	41	21.4	20.7	42	10	42.5	8	43	9	44	8	42	12				
	100	17	0.5	0.2	3	19	3.1	2.9	2.0	19	5	1.9	3.0	17	2.7	6.7	17	14.0	13.6	17	3	16.5	3	18	6	18	4	17	8				

outlet zone of the fuel duct to simulate the effect of impinging streams from adjacent fuel ducts. This test (Sequence X, Table 1 and Figure 3) was conducted with the same tube outlet area configuration used in Sequence IX.

Test Results

The tabulation of data for Test Sequences I to X are shown in Table 1. Results are described under the following subsections.

Axial Forces on Tube

The axial forces produced upon the fuel duct were determined to be proportional to the flow rate of the coolant. All net duct forces acted downward. In Test Sequences IV and V (Table 1) the high leakage rates caused a pressure buildup within the collection chambers which invalidated the force data. Since the fuel duct had a cross sectional area of 6.6 in.² a 1 psi back pressure would influence the axial load by 6.6 lb.

The magnitude of the downward axial forces varied from a low of about 5 lb at 100 gal/min (water) to a maximum of about 47 lb at 350 gal/min flow. Forces expected with the use of a similarly oriented open ended axial entry tube would be about 500 lb upward at 75 psi differential pressure.

At times during some of the testing, it became necessary to free the duct from the tubesheet. Apparently, small particles would cause binding within the tubesheets. This binding, while merely a nuisance in the test apparatus, could cause a problem in fuel duct removal should small particles collect in this area.

Tubesheet Leakage

The tubesheet leakage was found to vary directly with the annular clearance between the fuel duct and the tubesheet, and as the square of the differential pressure across the tubesheets.

Sequence VI

Holes
18 Each 3/4 diam
7.95 in.² Area

Tube OD = 2.900 in.
Tube Wall = 0.195 in.

Sequence VII

Holes
36 Each 3/4 diam
15.9 in.² Area

Slots
6 Each
3/4 Wide x 6 in. Long
29.64 in.² Area

Sequence VIII

Slots
6 Each
1 in. Wide x 6.4 in. Long
43.14 in.² Area

Sequence IX

Sequence X

FIGURE 3. Outlet Area Configurations

The values of water leakage through the tubesheets are tabulated in Table 1. Figures 4, 5, and 6 are included to show the relationship of leakage versus tubesheet ΔP and the tubesheet clearance variations.

Variations in Outlet Flow Area

Variations in the area of the fuel duct coolant outlet zone were studied to determine the effect of this area on the net axial forces (Figures 3 and 7). It was established that the outlet areas has only a small effect upon the axial tube force provided the configuration of the outlets is not changed. Doubling the outlet area by doubling the number of holes was noted to reduce force by 12%. Similarly, nearly doubling the area of outlet slots by widening these slots decreased the force only 5%. However, an 86% increase in the outlet configuration area by elongating the holes into slots increased the force 28%.

The results from Sequences VI to X, in which the outlet configurations of the flow ducts was varied, exhibit the trends predicted by the analysis in the Appendix. The analysis yielded:

$$R_x = Q^2 \left(\frac{\tan \theta_1}{A_1} - \frac{\tan \theta_2}{A_2} \right)$$

θ_1 = inlet angle

θ_2 = outlet angle

A_1 = inlet area

A_2 = outlet area

where the reaction force on the duct is defined as positive upward, subscript 1 refers to inlet conditions, and subscript 2 refers to outlet conditions. Between Sequences VI and VII and between Sequences VIII and IX the outlet flow area, A_2 , was

FIGURE 4. Hydraulic Balance Test Upper Tubesheet ΔP Versus Leakage at Various Clearances

FIGURE 5. Hydraulic Balance Test Lower Tubesheet ΔP Versus Leakage at Various Clearances

FIGURE 6. Hydraulic Balance Test Leakage Versus Tubesheet Clearance at 75 psi

FIGURE 7. Hydraulic Balance Test Flow Versus Force
(with Various Outlet Configurations)

increased without significantly changing the height to width ratio of the outlet holes (i.e., without significantly changing θ_2). Thus the smaller negative term in the preceding equation indicates a smaller downward force. This force can be observed from Figure 7. Between Sequences VII and VIII, the outlet flow area was again increased, but the configuration of the exit area was changed from a series of circular holes to slots with a height to width ratio of about 7. An observed increase in the measured downward force would indicate the increase in downward force due to change in the exit flow angle to be greater than the reduction in the downward force due to the flow area increase. In Sequence X, the net effect of placing a shroud tube over the outlet portion of the flow duct was found to be an increased downward reaction force. This increased force is explicable, according to the analysis, in terms of an increased exit flow angle, θ_2 .

It should also be noted that the analysis predicts the reaction force to vary as the square of the flow rate. An increase in reaction force with flow was observed (Figure 7). However, the fact that the square relationship was not strictly obeyed indicates that changes in the inlet and/or outlet flow angles may have resulted as the flow rate was varied. Construction of the test apparatus did not permit measurements of these flow angles.

Shrouded Outlet Zone

An effort was made to more closely simulate the flow pattern in the outlet region of the reactor by placing a tubular shroud around the outlet ports (Figures 3 and 7). This shroud was sized and located to simulate the interface of the coolant streams from the surrounding fuel ducts at the outlet zone elevation. This test resulted in an axial duct force increase of about 18 lb, at a flow rate of 350 gal/min (water).

Conversion of Water Data to Sodium

Tubesheet Leakage. The test data obtained using the hydraulic balance model was limited to ambient temperature with tubesheet differential pressures up to 75 psi. The introduction of the single tubesheet test apparatus allowed an increase in the test conditions to cover temperatures to 160 °F and pressures to 175 psi. Although the hydraulic balance model tubesheet leakage data is tabulated (Table 1), no graphical representation showing the relationship with sodium coolant is provided. This water leakage data can be converted to approximate sodium conditions by use of the following equation

$$\frac{Q_{Na}}{Q_{H_2O}} = \left[\frac{\Delta P_{Na}}{\Delta P_{H_2O}} \left(\frac{\rho_{H_2O}}{\rho_{Na}} \right)^{0.8} \left(\frac{\nu_{H_2O}}{\nu_{Na}} \right)^{0.2} \right]^{0.55}$$

Tube Axial Forces. (See Appendix for derivation) The axial forces produced by the coolant flowing through the fuel duct will follow the relationship as follows:

$$\frac{Rx_{H_2O}}{Rx_{Na}} = \frac{\rho_{H_2O} Q_{H_2O}^2}{\rho_{Na} Q_{Na}^2} \left(\frac{\frac{\tan \theta_1}{A_1} - \frac{\tan \theta_2}{A_2}}{\frac{\tan \theta_1}{A_1} - \frac{\tan \theta_2}{A_2}} \right)$$

θ_1 = inlet angle

θ_2 = outlet angle

Thus, if the fuel duct geometry is the same for both cases and assuming the shear at the leakage area is neglected and the angles equal, then the relationship becomes

$$\frac{Rx_{H_2O}}{Rx_{Na}} = \frac{(\rho Q^2)_{H_2O}}{(\rho Q^2)_{Na}}$$

If, for a given flow, the water data is obtained at 50 °F and the desired sodium condition is 750 °F,

$$\frac{Rx_{H_2O}}{Rx_{Na}} = \frac{62.42}{53.63} , \text{ and}$$

$$Rx_{Na} = 0.86$$

Therefore forces for sodium would be 86% of the water forces.

TUBESHEET CONFIGURATION MODEL

Test Equipment

The hydraulic balance test apparatus was developed to investigate the overall hydraulic balance concept. However, it became apparent during testing that a device for studying tube-to-tubesheet configurations would be quite desirable. A small test fixture for evaluating various configurations was constructed (Figure 8). This apparatus permitted the analysis of a single tubesheet penetration at conditions beyond the capacity of the hydraulic balance model and allowed quick, easy, testing of various configurations. Testing at differential pressures at 175 psi and temperatures to 165 °F was conducted with this apparatus. The goal of this investigation was to evaluate alternate configurations to determine whether an arrangement with large tubesheet clearances could be made to yield smaller leakage rates than with straight clearances. Labyrinth type penetrations and seated tube arrangements were studied. The descriptions and results follow.

Test Results

Labyrinth Tests

The initial tests used a smooth tube configuration so that data previously obtained from the hydraulic balance test

FIGURE 8. Tubesheet Configuration Test Apparatus

apparatus could be compared with the labyrinth configurations. Leakage data obtained from the two test rigs compared favorably. The data obtained from the single tubesheet test apparatus was utilized in this report because:

- The method of leakage collection allowed a uniform back pressure rather than an increasing back pressure.
- The available tubesheet differential pressure could be extended to the 170 to 180 psi range rather than to a 75 psi limit.
- The extension of test temperatures to 165 °F produced Reynolds numbers more closely simulating expected sodium inlet characteristics than were available with 40 to 50 °F water.
- The tube could be easily positioned for measuring variations in leakage due to tube position.
- Modifications to the tube or tubesheet could be easily and economically performed.

In all labyrinth tests, the position of the tube within the tubesheet was investigated with the tube:

- concentric
- diagonal
- eccentric
- free

The free data fell randomly within the limits of the first three positions and, therefore, was not included in the analysis. The data spread for these positions was about 35% for smooth tube tests, with diametral clearances of 0.009 and 0.015 in. Leakages were from about 4 to 9 gal/min (water) at 90 psi differential pressure for these clearances. Figures 9 through 19 describe the relationship of orifice coefficient versus Reynolds number for all labyrinth configurations studied. The data for these figures is included in the Appendix. The "S" curves shown in Figures 9 through 19 (also subsequent curves) is a representative method of

FIGURE 9. Smooth Tube, 0.009-in. diam Clearance

FIGURE 10. Four Rectangular Groove Tube,
0.009-in. diam Clearance

FIGURE 11. Smooth Tube, 0.015-in. diam Clearance

FIGURE 12. Four Rectangular Groove Tube,
0.015-in. diam Clearance

FIGURE 13. *Nine Triangular Groove Tube,
0.015-in. diam Clearance*

FIGURE 14. Seven Rectangular Groove Tube,
 0.015-in. diam Clearance

FIGURE 15. *Nine Circular Groove Tube,
0.015-in. diam Clearance*

FIGURE 16. Nine Circular Groove Tube,
0.015-in. diam Clearance

FIGURE 17. Smooth Concentric Tube, 0.015-in. diam Clearance

FIGURE 18. Seven Rectangular Groove Concentric Tube, 0.015-in. Clearance

FIGURE 19. Nine Circular Groove Concentric Tube, 0.015-in. diam Clearance

describing the anticipated sodium conditions. The intersection of the two curves (orifice coefficient versus Reynolds number and the "S" curve) gives the anticipated orifice coefficient and Reynolds number in sodium for the tube and tubesheet configuration described. A separate "S" curve is shown for three typical sodium temperatures 500, 700, and 900 °F. The "S" curve is defined by the following relationship:

$$S^* = \frac{(P^1 D^3 \rho)}{\mu}^{1/2} = \text{Re} \left(\frac{f}{2} \right)^{1/2}$$

where

P^1 = pressure gradient $\frac{\Delta P}{\ell}$

D = hydraulic diameter

ρ = fluid density

μ = fluid dynamic viscosity

f = friction factor.

This "S" factor was modified to incorporate the orifice coefficient C instead of the friction factor f thus:

$$\frac{\text{Re}}{C} = \frac{D}{\mu} (2\Delta P \rho)^{1/2}$$

The original water leakage data is included in the Appendix. It was determined that leakage values could be reduced about 20% by the addition of the circumferential grooves (labyrinths); however, the most significant change occurred in the data spread between the tube positions. This spread was reduced from 35% for the smooth tubes to about 10% for any test configuration with grooves.

* *Fluid Mechanics*, R. C. Binder Prentice Hall, New York, July 1953.

Seated Tube

The seated tube arrangement, Figure 20, was selected for study because of the inherent core alignment characteristics, and because leakage could be controlled by a seat while allowing greater tube-to-tubesheet clearances for ease of fabrication, tube installation, and removal with a controlled leakage rate past the seat. The upper edge of the tubesheet hole was tapered 30° , and a similar 30° tapered seat was formed on the fuel duct (Figure 20). The flow direction, reversed to simulate the upper tubesheet conditions, produced an arrangement similar to that of a needle valve. Initial tests on an unslotted seated tube showed zero leakage. Additional tests were made on tubes with slots of varying width machined through the seat to obtain desired bypass flows. For a given ΔP , the leakage through this arrangement was found proportional to the flow area of the slots. Figure 21 shows the relationship of the tubesheet differential pressure versus the orifice velocity for various slot configurations. Figures 22 through 27 show the orifice coefficient versus the Reynolds number for the configurations studied. The data for these figures are included in the Appendix. The variations in Figures 22 and 23 show the effect of increasing the loading on the seat. Apparently the tube was rising from the seat slightly at the higher pressures. The variations in Figures 26 and 27 show the effect of the flow area changes. In Figure 26, the four $3/8$ -in. wide slots were undercut about 0.003 in. providing a larger flow area while, in Figure 27, the slots were cut tangent to the tube to leave a 0.005 in. lip at the edge of the slots and thus yield a much smaller flow area. The respective areas are 0.02318 in.^2 (Figure 26) and 0.0112 in.^2 (Figure 27).

This seal arrangement has several advantages in that (1) greater clearance is available for initial reactor assembly and subsequent replacement, (2) there is less potential for collecting

FIGURE 20. *Tubesheet Configuration Test Apparatus for Seated Tubes*

FIGURE 21. Seated Tube Fluid Velocity Versus ΔP

FIGURE 22. Seated 8-Slot Tube, 1/8-in. Wide, 0.015-in. diam Clearance, 0.00775-in.² Slot Flow Area at 1580 lb Loading

FIGURE 23. Seated 8-Slot Tube, 1/8-in. Wide, 0.015-in. diam Clearance, 0.00775-in.² Slot Flow Area at 2620-lb Loading

FIGURE 24. Seated 4-Slot Tube, 1/8-in. Wide, 0.025-in. diam Clearance, 0.00625 in.² Slot Flow Area at 1580-lb Loading

FIGURE 25. Seated 4-Slot Tube, 1/4-in. Wide, 0.025-in. diam Clearance, 0.0125-in.² Slot Flow Area at 1580-lb Loading

FIGURE 26. Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.02318-in.² Slot Flow Area at 2620-lb Loading

FIGURE 23. Seated 8-Slot Tube, 1/8-in. Wide, 0.015-in. diam Clearance, 0.00775-in.² Slot Flow Area at 2620-lb Loading

FIGURE 25. Seated 4-Slot Tube, 1/4-in. Wide, 0.025-in. diam Clearance, 0.0125-in.² Slot Flow Area at 1580-lb Loading

FIGURE 26. Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.02318-in.² Slot Flow Area at 2620-lb Loading

FIGURE 27. Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.0112-in.² Slot Flow Area at 2620-lb Loading

FIGURE 27. Seated 4-Slot Tube, 3/8-in. Wide, 0.025-in. diam Clearance, 0.0112-in.² Slot Flow Area at 2620-lb Loading

particles which might make replacement more difficult, and (3) a reasonable control of bypass flow is provided. A difficulty may arise from the possibility of "wire drawing" or erosion of the seat relief and/or tubesheet caused by the high coolant velocity through the small orifice slots. An investigation of this potential problem is being conducted.

Data Conversion

All leakage tests were conducted with sanitary water at temperatures ranging from 50 to 165 °F. Data provided relative to reactor operating conditions must be converted into values of sodium leakage rates. These data have been plotted showing the orifice coefficient versus Reynolds number applicable to sodium conditions. The preceding section on Labyrinth Tests describes the data presentation for the orifice coefficient versus Reynolds number curves.

ACKNOWLEDGEMENT

The author gratefully acknowledges the assistance of R. G. Sullivan and F. H. Nunamaker during apparatus fabrication and testing, T. C. Reihman of the Thermal Hydraulics Analysis Section for his analysis of the axial forces on the fuel duct (Appendix), and to L. R. Sweetin for his overall technical consultation.

APPENDIX

ANALYSIS OF AXIAL FORCES ON CLOSE-ENDED
FLOW DUCT WITH INFLOW AND OUTFLOW HAVING
AN AXIAL VELOCITY COMPONENT

APPENDIX

ANALYSIS OF AXIAL FORCES ON CLOSE-ENDED
FLOW DUCT WITH INFLOW AND OUTFLOW HAVING
AN AXIAL VELOCITY COMPONENT

Consider the fluid contained within the fixed control volume, V_o , enclosed by the control surface, S_o (shown dotted in Figure A-1). To this fluid we apply the momentum theorem:

$$F = \int_{V_o} \frac{\partial}{\partial t} (\rho \vec{U}) dV + \int_{S_o} \rho \vec{U} \vec{U} \cdot \vec{n} dS ,$$

where $\vec{n}$ is a unit vector directed along the outward normal to S_o at every point.

Since we have a steady-state process, the first integral is zero. Also, the axial forces due to pressure on the tube ends balance each other. Thus, the only remaining axial forces which must be considered are due to an axial momentum flux crossing the system boundary:

$$F_x = \int_{S_o} \rho U_x \vec{U} \cdot \vec{n} dS .$$

For the entering fluid:

$$\begin{aligned} \int_{A_1} \rho U_x \vec{U} \cdot \vec{n} dS &= \rho U_1 \sin \theta_1 (-U_1 \cos \theta_1) A_1 \\ &= -\rho \left(\frac{Q^2}{A_1} \right) \tan \theta_1 \end{aligned}$$

upon noting that $Q = A_1 U_1 \cos \theta_1$.

FIGURE A-1. Axial Forces on Close-Ended Flow Duct

For the leaving fluid:

$$\begin{aligned} \int_{A_2} \rho U_x \vec{U} \cdot \vec{n} \, dS &= \rho U_2 \sin \theta_2 (U_2 \cos \theta_2) A_2 \\ &= \rho \left(\frac{Q^2}{A_2} \right) \tan \theta_2 \end{aligned}$$

upon noting that $Q = A_2 U_2 \cos \theta_2$.

The net axial force on the fluid within the control volume is thus:

$$F_x = -\rho Q^2 \left(\frac{\tan \theta_1}{A_1} - \frac{\tan \theta_2}{A_2} \right),$$

and hence the net axial reaction force on the tube is:

$$R_x = \rho Q^2 \left(\frac{\tan \theta_1}{A_1} - \frac{\tan \theta_2}{A_2} \right),$$

where the positive direction is upward.

DATA CONVERSION FOR LABYRINTH TEST,
FIGURES 10 THROUGH 20

DATA OBTAINED DURING TESTING

- Weight of water leakage
- Time period required for collection
- Temperatures of fluid
- Pressure of fluid.

DATA REDUCTION

h = head in feet corrected for temperature

Q = flow rate gal/min corrected for temperature.

V_1 = theoretical velocity ft/sec = $\sqrt{2gh}$

V_2 = actual velocity (through annulus) ft/sec = Q/A

C = orifice coefficient = $\frac{V_2}{V_1}$

Re = Reynolds number = $\frac{D V_1}{\nu}$

DEVELOPMENT OF "S" CURVES FOR LABYRINTH TESTS

$$S = \frac{Re}{C} = \frac{D}{\mu} (2\Delta P \rho)^{1/2}$$

where

ΔP = 100 psi

D = hydraulic diameter

ρ = sodium density lb/ft³

@ 500 °F = 55.6

@ 700 °F = 53.9

@ 900 °F = 52.3

μ = sodium viscosity lb sec/ft²

@ 500 °F = 7.94×10^{-6}

@ 700 °F = 6.13×10^{-6}

@ 900 °F = 5.10×10^{-6}

FIGURE 10 DATA
SMOOTH TUBE, 0.009-in. diam CLEARANCE

ECCENTRIC POSITION

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
25	58	1.5	61	11.8	0.194	3590
50	115	2.6	86	20.7	0.241	5060
75	173	3.5	105	27.1	0.257	6200
92	212	3.9	116	30.6	0.263	6850

DIAGONAL POSITION

25	58	0.9	61	7.0	0.114	3590
50	115	1.7	86	13.1	0.153	5060
75	173	2.3	105	17.8	0.170	6200
92	212	2.6	116	20.7	0.180	6850

CONCENTRIC POSITION

25	58	0.7	61	5.7	0.093	3590
50	115	1.4	86	11.1	0.129	5060
75	173	2.2	105	17.1	0.163	6200
92	212	2.6	116	20.4	0.175	6850

FIGURE 11 DATA
FOUR GROOVES, 0.009-in. diam CLEARANCE

ECCENTRIC POSITION

<u>ΔP,</u>	<u>h,</u>	<u>Q,</u>	<u>V_1,</u>	<u>V_2,</u>	<u>C</u>	<u>Re</u>
<u>psi</u>	<u>ft</u>	<u>gal/min</u>	<u>ft/sec</u>	<u>ft/sec</u>		
25	58	1.5	61	11.7	0.192	3590
50	115	2.4	86	18.8	0.218	5060
75	173	3.1	105	24.0	0.228	6200
92	212	3.5	116	27.3	0.234	6850

DIAGONAL POSITION

25	58	1.2	61	9.1	0.149	3590
50	115	2.0	86	15.4	0.179	5060
75	173	2.6	105	20.4	0.193	6200
92	212	3.0	116	23.6	0.203	6850

CONCENTRIC POSITION

25	58	1.1	61	8.7	0.142	3590
50	115	1.9	86	14.8	0.172	5060
75	173	2.8	105	21.8	0.207	6200
92	212	3.0	116	23.2	0.200	6850

FIGURE 12 DATA
SMOOTH TUBE, 0.015-in. diam CLEARANCE

ECCENTRIC POSITION

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
25	58	4.1	61	19.4	0.318	5980
40	92	5.8	77	27.3	0.354	7560
50	115	6.4	86	30.2	0.351	8430
60	138	7.2	95	33.8	0.358	9270
75	173	7.8	105	36.8	0.349	10300
84	194	8.2	112	38.4	0.344	10900

DIAGONAL POSITION

25	58	2.2	61	10.4	0.170	5980
50	115	3.8	86	17.8	0.207	8430
75	173	5.1	105	24.1	0.229	10300
82	189	5.4	110	25.6	0.232	10800

CONCENTRIC POSITION

25	58	2.7	61	12.7	0.208	5980
50	115	5.1	86	23.8	0.277	8430
75	173	6.8	105	31.9	0.303	10300
84	194	7.5	112	35.2	0.315	10900

FIGURE 13 DATA
FOUR SQUARE GROOVES, 0.015-in. diam CLEARANCE

ECCENTRIC POSITION

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
25	58	3.2	61	15.0	0.245	5980
50	115	4.8	86	22.5	0.262	8430
75	173	6.1	105	28.7	0.272	10300
84	194	6.5	112	30.7	0.275	10900

DIAGONAL POSITION

25	58	2.8	61	13.0	0.213	5980
50	115	4.3	86	20.1	0.234	8430
75	173	5.4	105	25.6	0.243	10300
84	189	5.8	110	27.3	0.247	10800

CONCENTRIC POSITION

25	58	2.7	61	12.8	0.210	5980
50	115	4.3	86	20.1	0.234	8430
75	173	5.4	105	25.6	0.243	10300
84	194	5.8	112	27.3	0.244	10900

FIGURE 14 DATA
NINE TRIANGULAR GROOVES

ECCENTRIC POSITION

ΔP , psi	h, ft	Q, gal/min	V ₁ , ft/sec	V ₂ , ft/sec	C	Re
15	35	2.2	47	10.3	0.218	4630
30	69	3.3	67	15.4	0.230	6550
45	104	4.2	82	19.7	0.240	8020
60	138	4.8	95	22.6	0.238	9270
75	173	5.5	105	26.0	0.247	10300
87	201	6.1	114	28.7	0.252	11100

DIAGONAL POSITION

15	35	1.9	47	8.8	0.186	4630
30	69	2.8	67	13.3	0.199	6550
45	104	3.6	82	16.9	0.206	8020
60	138	4.3	95	20.1	0.213	9270
75	173	4.9	105	23.1	0.220	10300
88	203	5.4	114	25.6	0.224	11200

CONCENTRIC POSITION

15	35	1.9	47	8.9	0.189	4630
30	69	2.8	67	13.3	0.199	6550
45	104	3.6	82	16.9	0.206	8020
60	138	4.2	95	19.7	0.208	9270
75	173	4.9	105	22.9	0.217	10300
89	205	5.4	115	25.2	0.219	11300

FIGURE 15 DATA
SEVEN RECTANGULAR GROOVES

ECCENTRIC POSITION

ΔP , psi	h , ft	Q , gal/min	V_1 , ft/sec	V_2 , ft/sec	C	Re
15	35	2.2	47	10.3	0.218	4630
30	69	3.4	67	16.0	0.239	6550
45	104	4.3	82	20.4	0.249	8020
60	138	5.1	95	24.1	0.255	9270
75	173	5.9	105	27.7	0.263	10300
87	201	6.4	114	30.2	0.266	11100

DIAGONAL POSITION

15	35	2.2	47	10.2	0.216	4630
30	69	3.2	67	15.2	0.228	6550
45	104	4.1	82	19.2	0.234	8020
60	138	4.9	95	22.9	0.242	9270
75	173	5.6	105	26.1	0.248	10300
88	203	6.1	114	28.7	0.251	11200

CONCENTRIC POSITION

15	35	1.9	47	9.0	0.191	4630
30	69	2.1	67	14.1	0.211	6550
45	104	3.9	82	18.2	0.222	8020
60	138	4.6	95	21.4	0.226	9270
75	173	5.3	105	24.9	0.236	10300
89	205	5.9	115	27.7	0.241	11300

FIGURE 16 DATA
NINE CIRCULAR GROOVES 1/16-in. DEEP

ECCENTRIC POSITION

ΔP , psi	h, ft	Q, gal/min	V ₁ , ft/sec	V ₂ , ft/sec	C	Re
15	35	2.2	47	10.1	0.215	4630
30	69	3.2	67	14.8	0.222	6550
45	104	4.0	82	18.6	0.227	8020
60	138	4.6	95	21.7	0.229	9270
75	173	5.3	105	24.9	0.236	10300
92	212	5.9	117	27.7	0.238	11400

DIAGONAL POSITION

15	35	1.9	47	8.9	0.189	4630
30	69	3.0	67	14.0	0.209	6550
45	104	3.8	82	17.8	0.217	8020
60	138	4.5	95	21.1	0.224	9270
75	173	5.1	105	23.8	0.226	10300
91	210	5.6	116	26.4	0.227	11400

CONCENTRIC POSITION

15	35	1.8	47	8.6	0.182	4630
30	69	2.8	67	13.3	0.199	6550
45	104	3.6	82	16.9	0.206	8020
60	138	4.0	95	19.0	0.201	9270
75	173	4.8	105	22.5	0.214	10300
91	210	5.4	116	25.2	0.217	11400

FIGURE 17 DATA
NINE CIRCULAR GROOVES, 1/8-in. DEEP

ECCENTRIC POSITION

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V₁, ft/sec</u>	<u>V₂, ft/sec</u>	<u>C</u>	<u>Re</u>
15	35	2.2	47	10.2	0.217	4630
30	69	3.3	67	15.5	0.232	6550
45	104	4.1	82	19.2	0.235	8020
60	138	4.8	95	22.5	0.238	9270
75	173	5.4	105	25.2	0.239	10300
89	205	5.8	115	27.3	0.237	11300

DIAGONAL POSITION

15	35	2.1	47	9.7	0.205	4630
30	69	3.1	67	14.7	0.220	6550
45	104	4.0	82	19.0	0.232	8020
60	138	4.6	95	21.7	0.229	9270
75	173	5.3	105	24.9	0.236	10300
85	196	5.6	111	26.4	0.237	10900

CONCENTRIC POSITION

15	35	2.0	47	9.4	0.199	4630
30	69	3.0	67	14.1	0.211	6550
45	104	3.8	82	17.8	0.217	8020
60	138	4.4	95	20.9	0.221	9270
75	173	5.7	105	23.8	0.226	10300
85	196	5.4	111	25.6	0.230	10900

FIGURE 18 DATA
SMOOTH TUBE NO. 2, COLD

<u>ΔP,</u> <u>psi</u>	<u>h,</u> <u>ft</u>	<u>Q,</u> <u>gal/min</u>	<u>V_1,</u> <u>ft/sec</u>	<u>V_2,</u> <u>ft/sec</u>	<u>C</u>	<u>Re</u>
1	2	0.2	12	0.9	0.079	1300
2	5	0.4	17	1.8	0.106	1850
3	7	0.5	21	2.2	0.108	2260
4	9	0.7	24	3.2	0.131	2610
5	12	0.9	27	4.2	0.155	2910
7	17	1.4	33	6.4	0.192	3560
10	23	1.7	39	7.8	0.202	4120
12	29	2.0	43	9.3	0.215	4610
15	35	2.5	47	11.9	0.252	5040
20	46	3.2	54	14.8	0.272	5820
25	58	3.7	61	17.2	0.283	6510
30	69	4.3	67	20.3	0.304	7140
35	81	4.9	72	22.8	0.317	7700
40	92	5.3	77	24.8	0.322	8240
45	104	5.6	82	26.4	0.323	8720
50	115	6.0	86	28.1	0.327	9200
60	139	6.5	94	30.7	0.325	10100
70	162	6.9	102	32.5	0.319	10900
80	185	7.3	109	34.4	0.316	11600
90	208	7.7	116	35.9	0.310	12400
100	231	8.0	122	37.5	0.308	13000
120	277	8.6	133	40.2	0.301	14200
140	323	9.1	144	42.8	0.297	15400
160	370	9.5	154	44.5	0.289	16500
167	386	9.7	157	45.6	0.290	16800

FIGURE 18 DATA
SMOOTH TUBE NO. 1, HOT

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
5	12	1.8	28	8.3	0.303	8010
10	24	2.6	39	12.0	0.307	11400
15	35	3.1	48	14.5	0.304	13900
20	47	3.5	55	16.3	0.295	16000
25	59	3.8	62	18.0	0.292	17900
30	71	4.2	68	19.6	0.290	19600
35	83	4.5	73	21.1	0.289	21200
40	95	4.7	78	22.2	0.284	22700
45	106	5.0	83	23.4	0.282	24000
50	118	5.3	87	24.7	0.283	25400
60	142	5.6	95	26.2	0.274	27800
70	165	6.0	103	28.3	0.275	30000
80	189	6.5	110	30.3	0.275	32000
90	213	6.9	117	32.3	0.276	34100
100	236	7.2	123	33.9	0.275	35800
110	260	7.5	129	35.2	0.272	37600
120	284	7.8	135	36.8	0.272	39200
125	295	8.0	138	37.6	0.272	40100

FIGURE 19 DATA
SEVEN RECTANGULAR GROOVES, COLD

<u>ΔP,</u> <u>psi</u>	<u>h,</u> <u>ft</u>	<u>Q,</u> <u>gal/min</u>	<u>V_1,</u> <u>ft/sec</u>	<u>V_2,</u> <u>ft/sec</u>	<u>C</u>	<u>Re</u>
1	2	0.3	12	1.4	0.116	1300
2	5	0.5	17	2.4	0.141	1850
3	7	0.7	21	3.3	0.158	2260
4	9	0.9	24	4.1	0.167	2610
5	12	1.0	27	4.8	0.177	2910
7	17	1.4	33	6.8	0.202	3560
10	23	1.7	39	7.9	0.204	4120
12	29	1.9	43	8.8	0.204	4610
15	35	2.1	47	10.0	0.212	5040
20	46	2.5	54	11.9	0.218	5820
25	58	2.9	61	13.7	0.225	6510
30	69	3.3	67	15.5	0.232	7140
35	81	3.6	72	16.7	0.232	7700
40	92	3.9	77	18.2	0.235	8240
45	104	4.1	82	19.4	0.238	8720
50	115	4.4	86	20.7	0.241	9200
60	139	4.9	94	23.1	0.245	10100
70	162	5.4	102	25.2	0.247	10900
80	185	5.8	109	27.2	0.250	11600
90	208	6.3	116	29.6	0.256	12400
100	231	6.7	122	31.3	0.256	13000
120	277	7.3	133	34.4	0.258	14200
140	323	8.0	144	37.6	0.261	15400
160	370	8.6	154	40.2	0.261	16500
170	393	8.9	159	41.7	0.262	17000

FIGURE 19 DATA
SEVEN RECTANGULAR GROOVES, HOT

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
5	12	1.5	28	7.1	0.258	8010
10	24	2.2	39	10.1	0.258	11400
15	35	2.7	48	12.7	0.266	13900
20	47	3.2	55	14.9	0.270	16000
25	59	3.6	62	16.8	0.272	17900
30	71	3.9	68	18.4	0.272	19600
35	83	4.2	73	19.9	0.273	21200
40	95	4.5	78	21.0	0.270	22700
45	106	4.8	83	22.4	0.271	24000
50	118	5.1	87	24.0	0.275	25400
60	142	5.5	95	25.8	0.270	27800
70	165	5.9	103	27.9	0.270	30000
80	189	6.3	110	29.8	0.270	32100
90	213	6.8	117	31.7	0.271	34100
100	236	7.1	123	33.2	0.269	35800
110	260	7.4	129	34.9	0.270	37600
120	284	7.8	135	36.4	0.270	39200
125	295	7.9	138	37.2	0.269	40100

FIGURE 20 DATA
NINE CIRCULAR GROOVES, COLD

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
1	2	0.4	12	2.0	0.166	1300
2	5	0.6	17	2.8	0.164	1850
3	7	0.8	21	3.8	0.178	2260
4	9	1.0	24	4.5	0.183	2610
5	12	1.2	27	5.8	0.212	2910
7	17	1.4	33	6.8	0.202	3560
10	23	1.7	39	8.0	0.207	4120
12	29	2.0	43	9.2	0.213	4610
15	35	2.1	47	1.0	0.212	5040
20	46	2.5	54	11.6	0.212	5820
25	58	2.8	61	13.1	0.215	6510
30	69	3.1	67	14.6	0.218	7140
35	81	3.4	72	15.9	0.221	7700
40	92	3.7	77	17.2	0.223	8240
45	104	3.9	82	18.4	0.225	8720
50	115	4.2	86	19.6	0.228	9200
60	139	4.7	94	21.9	0.232	10100
70	162	5.0	102	23.8	0.233	10900
80	185	5.4	109	25.6	0.234	11600
90	208	5.8	116	27.0	0.235	12400
100	231	6.1	122	28.8	0.236	13000
120	277	6.8	133	31.9	0.239	14200
140	323	7.4	144	34.8	0.242	15400
160	370	7.9	154	37.1	0.241	16500
170	393	8.2	159	38.4	0.241	17000

FIGURE 20 DATA
NINE CIRCULAR GROOVES, HOT

<u>ΔP,</u> <u>psi</u>	<u>h,</u> <u>ft</u>	<u>Q,</u> <u>gal/min</u>	<u>V_1,</u> <u>ft/sec</u>	<u>V_2,</u> <u>ft/sec</u>	<u>C</u>	<u>Re</u>
5	12	1.4	28	6.5	0.237	8010
10	24	2.0	39	9.4	0.240	11400
15	35	2.6	48	12.3	0.257	13900
20	47	3.0	55	14.0	0.255	16000
25	59	3.3	62	15.3	0.248	17900
30	71	3.6	68	16.8	0.248	19600
35	83	3.8	73	18.0	0.247	21200
40	95	4.1	78	19.2	0.246	22700
45	106	4.4	83	20.8	0.251	24000
50	118	4.7	87	21.9	0.251	25400
60	142	5.1	95	24.0	0.251	27800
70	165	5.5	103	25.8	0.250	30000
80	189	5.8	110	27.4	0.249	32100
90	213	6.2	117	29.3	0.250	34100
100	236	6.6	123	30.9	0.250	35800
110	260	6.9	129	32.6	0.252	37600
120	284	7.2	135	33.6	0.249	39200
125	295	7.4	138	34.6	0.251	40100

DATA CONVERSION FOR SEATED TUBE TEST,
FIGURES 22 THROUGH 27

DATA OBTAINED DURING TESTING

- Weight of water leakage
- Time period required for collection
- Temperature of fluid
- Pressure of fluid

DATA REDUCTION

h = head in feet corrected for temperature

Q = flow rate gal/min corrected for temperature

V_1 = theoretical velocity ft/sec = $\sqrt{2gh}$

V_2 = actual velocity (through slots) ft/sec = Q/A

C = orifice coefficient = $\frac{V_2}{V_1}$

Re = Reynolds number = $\frac{D V_1}{\nu}$

DEVELOPMENT OF "S" CURVES FOR SEATED TUBE TESTS

$$S = \frac{Re}{C} = \frac{D}{\mu} (2\Delta P \rho)^{1/2}$$

where

ΔP = 100 psi

D = hydraulic diameter

ρ = sodium density lb/ft³

@ 500 °F = 55.6

@ 700 °F = 53.9

@ 900 °F = 52.3

μ = sodium viscosity lb sec/ft²

@ 500 °F = 55.6×10^{-6}

@ 700 °F = 53.9×10^{-6}

@ 900 °F = 52.3×10^{-6}

FIGURE 22 DATA
EIGHT SLOTS 1/8-in. WIDE BY 0.015 in., COLD

<u>ΔP, psi</u>	<u>h, ft</u>	<u>Q, gal/min</u>	<u>V_1, ft/sec</u>	<u>V_2, ft/sec</u>	<u>C</u>	<u>Re</u>
1	2	0.2	12	6.7	0.549	1340
2	5	0.3	17	13.3	0.775	1890
3	7	0.3	21	14.4	0.680	2320
4	9	0.4	24	18.1	0.746	2680
5	12	0.5	27	19.7	0.725	2990
7	17	0.6	33	25.9	0.775	3660
10	23	0.7	39	30.3	0.787	4240
12	29	0.8	43	34.4	0.803	4720
15	35	0.9	47	38.6	0.820	5180
20	46	1.1	54	45.1	0.829	5980
25	58	1.2	61	51.7	0.847	6700
30	70	1.4	67	56.9	0.852	7340
35	81	1.5	72	60.1	0.834	7920
40	92	1.6	77	67.1	0.876	8420
45	104	1.7	82	72.3	0.886	8970
50	115	1.9	86	76.8	0.893	9460
60	139	2.0	94	83.8	0.887	10400
70	162	2.2	102	93.2	0.914	11200
80	185	2.4	109	98.7	0.906	12000
90	208	2.6	112	106.4	0.953	12300
100	231	2.7	122	113.0	0.926	13400
120	277	3.0	134	125.4	0.939	14700
140	323	3.3	144	136.8	0.950	15800
160	370	3.6	154	150.6	0.978	16900
180	417	4.0	164	163.9	1.00	18000

FIGURE 22 DATA
EIGHT SLOTS 1/8-in. WIDE BY 0.015-in. CLEARANCE, HOT

ΔP , psi	h , ft	Q , gal/min	V_1 , ft/sec	V_2 , ft/sec	C	Re
1	2	0.3	12	10.8	0.873	3430
2	5	0.3	17	12.6	0.724	4850
3	7	0.4	21	18.3	0.855	5930
4	9	0.5	25	20.8	0.845	6850
5	12	0.5	28	21.7	0.789	7660
7	18	0.7	34	28.9	0.854	9390
10	24	0.8	39	33.0	0.845	10900
12	30	1.0	44	39.9	0.916	12100
15	35	1.1	48	43.6	0.912	13300
20	47	1.2	55	50.2	0.910	15300
25	59	1.4	62	56.9	0.924	17100
30	71	1.5	68	62.5	0.925	18800
35	83	1.6	73	66.9	0.918	20300
40	95	1.8	78	73.4	0.941	21700
45	106	1.9	83	76.7	0.927	23000
50	118	1.9	87	80.3	0.921	24200
60	142	2.1	95	86.7	0.907	26500
70	165	2.3	103	95.4	0.925	28700
80	189	2.5	110	102.4	0.929	30700
90	213	2.6	117	108.2	0.923	32600
100	236	2.9	123	118.3	0.960	34300
110	260	3.0	129	123.1	0.951	36000
120	284	3.0	135	125.0	0.926	37500
130	307	3.2	141	133.8	0.951	39100
135	319	3.3	143	136.3	0.952	39800

FIGURE 23 DATA
EIGHT SLOTS 1/8-in. WIDE BY 0.015-in. CLEARANCE, COLD*

ΔP , psi	h , ft	Q , gal/min	V_1 , ft/sec	V_2 , ft/sec	C	Re
1	2	0.2	12	7.2	0.590	1340
2	5	0.3	17	10.5	0.608	1890
3	7	0.3	21	13.0	0.615	2320
4	9	0.4	24	15.6	0.637	2680
5	12	0.4	27	17.6	0.648	2980
7	17	0.5	33	22.8	0.684	3660
10	23	0.7	39	27.9	0.724	4240
12	29	0.8	43	31.8	0.741	4720
15	35	0.9	47	37.2	0.789	5180
20	46	1.0	54	42.8	0.787	5980
25	58	1.2	61	48.8	0.801	6700
30	69	1.3	67	52.9	0.792	7340
35	81	1.4	72	59.1	0.821	7920
40	92	1.5	77	62.1	0.811	8420
45	104	1.6	82	66.5	0.815	8970
50	115	1.7	86	70.3	0.817	9460
60	139	1.9	94	78.5	0.831	10400
70	162	2.0	102	83.8	0.822	11200
80	185	2.2	109	89.9	0.824	12000
90	208	2.3	112	96.9	0.868	12300
100	231	2.5	122	102.1	0.837	13400
120	277	2.7	134	113.0	0.846	14700
140	323	3.0	144	123.2	0.855	15800
160	370	3.2	154	133.2	0.866	16900
180	417	3.4	164	142.0	0.867	18000

* Seating load on tube increased from 1580 to 2620 lb.

FIGURE 23 DATA
EIGHT SLOTS 1/8-in. WIDE BY 0.015-in. CLEARANCE,
HOT-ADDED WEIGHT*

$\Delta P,$ psi	$h,$ ft	$Q,$ gal/min	$V_1,$ ft/sec	$V_2,$ ft/sec	C	Re
1	2	0.2	12	10.1	0.816	3430
2	5	0.3	17	12.7	0.730	4850
3	7	0.4	21	16.5	0.772	5930
4	9	0.5	25	20.2	0.818	6850
5	12	0.5	28	22.3	0.808	7660
7	18	0.7	34	28.6	0.845	9390
10	24	0.8	39	33.9	0.867	10900
12	30	0.9	44	37.4	0.858	12100
15	35	1.0	48	41.4	0.867	13300
20	47	1.2	55	47.9	0.869	15300
25	59	1.3	62	54.1	0.878	17100
30	71	1.4	68	58.4	0.865	18800
35	83	1.6	73	65.2	0.894	20300
40	95	1.7	78	70.0	0.897	21700
45	106	1.8	83	74.0	0.894	23000
50	118	1.9	87	78.6	0.901	24200
60	142	2.0	95	83.8	0.878	26500
70	165	2.2	103	91.4	0.887	28700
80	189	2.4	110	97.8	0.887	30700
90	213	2.5	117	104.4	0.890	32600
100	236	2.7	123	110.6	0.897	34300
110	260	2.8	129	115.6	0.894	36000
120	284	2.9	135	121.1	0.897	37500
130	307	3.0	140	125.0	0.889	39100
135	319	3.1	143	128.3	0.897	39800

* Seating load on tube increased from 1580 to 2620 lb.

DISTRIBUTION

No. of
Copies

OFFSITE

1	<u>AEC Chicago Patent Group</u> G. H. Lee, Chief
258	<u>AEC Division of Technical Information Extension</u>
30	<u>AEC Division of Reactor Development and Technology</u> M. Shaw, Director, RDT Asst Dir for Nuclear Safety Analysis and Evaluation Br, RDT:NS Environmental & Sanitary Engrg Br, RDT:NS Research & Development Br, RDT:NS Asst Dir for Plant Engrg, RDT Applications & Facilities Br, RDT:PE Components Br, RDT:PE Instrumentation & Control Br, RDT:PE Liquid Metal Systems Branch, RDT:PE Asst Dir for Program Analysis, RDT Asst Dir for Project Mgmt, RDT Liquid Metals Projects Br, RDT:PM FFTF Project Manager, RDT:PM (3) Asst Dir for Reactor Engrg Control Mechanisms Br, RDT:RE Core Design Br, RDT:RE (2) Fuel Fabrication Br, RDT:RE Fuel Handling Br, RDT:RE Reactor Vessels Br, RDT:RE Asst Dir for Reactor Tech Coolant Chemistry, RDT Fuel Recycle Branch, RDT Fuels & Materials Br, RDT:RT Reactor Physics Br, RDT:RT Special Technology Br, RDT:RT Asst Dir for Engrg Standards
1	<u>AEC Idaho Operations Office</u> <u>Nuclear Technology Division</u> C. W. Bills, Director
1	<u>AEC San Francisco Operations Office</u> <u>Director, Reactor Division</u>

No. of
Copies

4	<u>AEC Site Representatives</u> Argonne National Laboratory Atomics International Atomic Power Development Assoc. General Electric Co.
2	<u>Argonne National Laboratory</u> R. A. Jaross LMFBR Program Office
6	<u>Atomics International</u> D. J. Cockeram (5) Liquid Metal Engrg Center R. W. Dickinson
1	<u>Atomic Power Development Assoc.</u> Document Librarian
2	<u>Babcock & Wilcox Co.</u> <u>Atomic Energy Division</u> S. H. Esleeck G. B. Garton
5	<u>Bechtel Corporation</u> J. J. Teachnor, Project Administrator, FFTF
1	<u>Combustion Engineering</u> <u>1000 MWe Follow-On Study</u> W. P. Staker, Project Manager
2	<u>Gulf General Atomic Inc.</u> <u>General Atomic Div.</u> D. Coburn
5	<u>General Electric Co.</u> <u>Advanced Products Operation</u> Karl Cohen (3) Bertram Wolfe Nuclear Systems Programs D. H. Ahmann

No. of
Copies

1	<u>Idaho Nuclear Corporation</u> D. R. deBoisblanc
1	<u>PNL Representative</u> N. A. Hill (ZPR III)
1	<u>Stanford Univerisity</u> Nuclear Division Division of Mechanical Engrg R. Sher
1	<u>United Nuclear Corporation</u> Research and Engineering Center R. F. DeAngelis
10	<u>Westinghouse Electric Corporation</u> Atomic Power Division Advanced Reactor Systems J. C. R. Kelly

ONSITE-HANFORD

1	<u>AEC Chicago Patent Group</u> R. K. Sharp
4	<u>AEC Richland Operations Office</u> FFTF Program J. M. Shivley (3) C. L. Robinson
4	<u>AEC Site Representatives - PNL</u> P. G. Holsted (2) L. R. Lucas A. D. Toth
3	<u>Battelle Memorial Institute</u>
1	<u>Bechtel Corporation</u> D. H. Weiss
1	<u>Westinghouse Electric Corp.</u> R. Strzelecki

No. of
Copies

63

Battelle-Northwest

F. W. Albaugh	C. A. Munro
E. R. Astley	D. J. Oakley
D. L. Ballard	A. Padilla
J. M. Batch	L. T. Pederson
J. D. Berg	R. E. Peterson
D. C. Boyd	D. E. Rasmussen
J. R. Carroll	R. C. Reihman
W. L. Chase	R. L. Roske
D. L. Condotta	R. J. Squires
F. G. Dawson	L. R. Sweetin
L. J. Defferding	J. C. Tobin
L. M. Finch	K. G. Toyoda
J. C. Fox	R. C. Walker
W. J. Grady	P. C. Walkup
K. D. Hayden	G. R. Waymire
R. E. Heineman	J. F. Wett
R. J. Hennig	M. R. Wood
P. L. Hofmann	F. W. Woodfield
P. M. Jackson	J. M. Yatabe
B. M. Johnson	F. R. Zaloudek
E. M. Johnston	FFTF Files (10)
F. J. Kempf	Technical Information (5)
H. Leigh	Technical Publications (2)
W. B. McDonald	Legal (2)